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Milestone 4

Thrust Structure Concepts & IHM Screening Graphite Composite Primary Structure (GCPS)

Cooperative Agreement NCC1-193

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INTRODUCTION

This document represents candidate "Thrust Structure Concepts" and the "Integrated Health Monitoring Screening" for the Graphite Composite Primary Structure. This report satisfies the requirements of Milestone 4 of TA2 (Cooperative Agreement NCC1-193).

Integrated Health Monitoring Sensor Screening

TA2 GCPS
Task 7, Subtask 2

SSTO THRUST STRUCTURE
MILESTONE 4, TASK 4

TASK DESCRIPTION:
SELECT UP TO THREE PROMISING THRUST STRUCTURE CONSTRUCTIONS AND SELECT MATERIALS FOR SCREENING TESTING

SUMMARY OF TASK 4 ACCOMPLISHMENTS.
THRUST STRUCTURE CONCEPTS

The thrust structure concepts selected are shown on the attached figures. These concepts are dependent on the vehicle concept considered. A reinforced conical shell is proposed for all vehicle concepts except no. 4. The primary consideration here, since the fuselage cross section is round and the aft tank is near the thrust structure, is to distribute the engine loading into the fuselage as uniformly as possible.

Two concepts are shown for vehicle concept no. 4. The first is a truss type structure, assuming a breadloaf type fuselage interface and the second is again a reinforced conical shell. Vehicle concept no. 4 differs from the others in that the payload bay is in the rear and heavier point loads can be introduced into the fuselage, since a greater distance is available to shear these into the fuselage skins.

CONCEPT FOR BASELINE VEHICLE 2A

The first concept, shown in Figures 1.1 through 1.5, consists of a truncated conical shell with two external longerons, supported by interior frames, at each engine location. An aft frame serves to support and react the engine mounting forces while the forward frame interfaces with the vehicle skirt. Four intermediate frames are provided for stability. Stringers between the longeron sets, which are only shown schematically on the sketches, will be spaced as required. The details of the longerons/stringers/frames and skin panels will be developed in subsequent work.

This concept will be our baseline, applicable to vehicle 2A, but will be representative of the design for all vehicles except concept no. 4. In this concept the heavy engine thrust loads would feed directly into paired longerons and be sheared into the skin over the length of the longerons. The goal here would be to distribute the axial load on the forward frame, and eventually the aft tank, as uniformly as possible. Also in this concept, the thermal protection blanket would be attached directly to the thrust structure walls. Two longerons are shown for each engine. Sets of longerons are separated by stringers, which will be optimally sized and spaced. External longerons were chosen over internal ones. External versus internal longerons provide a 12% reduction in skin area and an 8% reduction in frame length. Pumps and propulsion boxes would be on the outside of the shell making them accessible after removing

access covers. Also there would be no penetration of the thrust structure shell by hot gases. An insulated secondary structure would close out the plane of the aft frame, which supports the engine thrust pads.
Composite materials will be utilized on all thrust structure components wherever feasible. The principal load carrying fittings will be metal. probably titanium, interfacing with composite structure where it is feasible. The longerons, stringers, frames and stiffened skin panels should be of composite construction. Material selection is still in progress, however the present baseline composite is 977-2/IM7 epoxy/carbon.

FIRST DESIGN FOR VEHICLE CONCEPT NO. 4

This design concept is represented by a truss type structure as shown in Figures 2.1 through 2.2. This design would be applicable to vehicle concept no. 4 only. The vehicle concept here would feature a breadloaf section for the aft payload bay area which interfaces with the thrust structure. The truss design is appealing for this vehicle concept since the payload bay is in the back. The heavy truss loads can be transferred directly into the longerons of the payload bay and sheared out into the skin over a considerable distance before the tank wall is encountered. This insures that a fairly uniform loading on the external shell will be obtained forward of the tank wall. Since this is a truss type structure, the heavy loads will remain in the truss members and be imposed directly on the aft bulkhead of the payload bay. From there they will be sheared into the payload bay shell by longerons and stringers in the payload bay area. A stiffened bulkhead will close out the aft end of the payload bay area. This will serve to reinforce the truss structure. Secondary structure panels will be required between the longerons to closeout the truss structure and will serve to mount the insulation blankets and some of the system hardware. The engine mounting plane shown in figure 2.1 will contain structural beams which will reinforce the truss structure and support close-out panels and thermal insulation. Again composites will be utilized where feasible. The fittings should be metallic, probably titanium. The truss rods will be composite where possible. Materials and construction details are still to be determined.

SECOND DESIGN FOR VEHICLE CONCEPT NO. 4

This design concept is represented by a conical shell using skin/stringer type construction, as shown on figures 3.1 and 3.2.. It differs from the previous vehicle no. 4 concept in that the payload bay interface with the thrust structure is circular, rather than a breadloaf section. This concept, using a skin/stringer conical shell, is much like that for vehicle 2A, except that it does not have to distribute the axial loading as uniformly into the aft frame of the payload bay area, since the tank interface is forward of this section. The cutout for the payload bay doors ,at the top of the fuselage, cannot carry axial load. This concept avoids loading that area by bringing the load from the two upper paired engine support longerons into a point at the aft end of the payload bay sill longerons. The aft frame of the payload bay section should not receive substantial axial load from the engine thrust loads in the area of the payload bay doors. Again, as in the previous design for vehicle no. 4, the wing is beneath the fuselage.

The discussion of design details will be much the same as for concept 2A, with the exceptions noted above.

The materials will also be composite where feasible and very similar to those considered for vehicle 2A.

FIGURE 1.0 ADVANTAGES/DISADVANTAGES OF THRUST STRUCTURE CONCEPTS

ADVANTAGE/DISADVANTA	CONCEPT SHELL FOR VEH. 2A	TRUSS FOR VEH. 4	SHELL FOR VEH. 4
LOADS FUSELAGE INTERFACE UNIFORMLY	YES	NO	YES*
SECONDARY STRUCTURE REQUIRED FOR CLOSEOUT& HEAT SHIELD SUPPORT	NO	YES	NO
PROVIDES ATTACH STRUCTURE FOR SYSTEMS	YES	NO	YES
PENETRATION OF STRUCTURE REQUIRED FOR PROPELLANT LINES	NO	NO	NO
PERCENT OF LIGHTER WEIGHT COMPOSITE STRUCTURE	HIGH	LOWER	HIGH

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TASK DESCRIPTION :
MATERIALS WILL BE SELECTED FOR SCREENING

Materials will be selected for preliminary screening . The materials selected will be those that are considered most suitable for the thrust structure cone, longerons, engine support fittings and frames. A variety of manufacturing processes will be considered for the fabrication of these parts. Due to the size of some of these structural components only a few processes can be considered as applicable for their fabrication. These processes, in turn, limit the applicable materials.

The selection process to determine a candidate materials will involve the following considerations:

1. The primary weight parameter is specific compressive strength. Specific tensile strength and specific stiffness are also considerations.
2. Maximum material hot/wet operating temperature.
3. Material toughness. This is a consideration, however impact should not be as significant a factor due to the heavy composite sections anticipated in this design.
4. Suitability of the material to the proposed manufacturing processes. Material out-time will also become a major consideration for the fabrication of the large structures required.
5. The maturity of the material system is an important consideration together with the risk involved in using a non-mature system.
6. Moisture should be less of a problem due to the thickness of the laminate sections, since it would appear that fully moisturizing the actual structure would be difficult to accomplish.. However to be conservative the hot, wet allowables will be used.
7. Resistance to hydraulic fluids, etc. should be less of a problem due to the stated goal of reducing the use of such fluids wherever possible.
8. Reparability of the material system will be considered but will not be a major weighting factor.
9. Cost will not be considered a major factor unless it is disproportionate to the other material/process combinations.

It should be noted that only a short period of time is available for the selection and testing of these materials. Materials considered must have current usage and be available in time to support the test schedule. Thus many materials will be de-selected on this basis. To satisfy the requirements above the material system categories listed below have been selected as screening candidates for the thrust structure

1. Conventional carbon/ epoxy systems. One of these, 977-2/IM7, will be considered as the baseline material. These materials can exhibit high specific strength, high toughness and temperature capabilities up to 300 degrees F, when properly formulated. 977-2/Im7 however is limited to approximately 230 degrees F usage.

2. Higher temperature systems-such as carbon/BMI, capable of temperatures up to 400 degrees F.
3. Low temperature cure resins with carbon fibers - For possible application to non-autoclave, low temperature curing of the thrust structure shell . The size of this structure may dictate the consideration of such a process.
4. Materials for application to the pultruded rod process-Such as high strength carbon fibers with thermoplastic resins. These might have longeron applications, if sufficient compression capability can be shown.
5. Boron fiber hybrid systems with suitable resins might also offer potential for longeron applications.

SELECTION OF SYSTEMS

Conventional Carbon/Epoxy Systems-

The baseline for this structure has been agreed as Fiberite 977-2/IM7. It is an advanced toughened system and the IM7 offer good fiber properties. One other system might be selected from this group. Candidates are 977-3/IM7, Hexcel 3900/IM7 or Toray's 3900/H800.

High Temperature Material

Candidate materials evaluated for higher use temperatures, included both Bismaleimides and Cyanate Esters. Polyimides were initially considered, but it was determined that the higher operating temperature was not needed. Because of the following rationale, BMI materials were chosen for the higher temperature applications.

BMI materials meet the operating temperature criteria.
A larger database exists for the BMI materials.
The BMI systems are more mature.
The BMI systems are more readily available.
Total cost is less for the BMI systems.

Candidate BMI systems included Narmco 5250-3, 5250-4. Narmco 5250-3 is the baseline for the wings of the vehicle. The F22 uses Narmco 5250-4.
Narmco 5250-4 with IM7 fibers was selected as the BMI candidate material since -3 was found to be unavailable within our project timetable. Also it has a much larger database.

Low Temperature Curing Materials

These resins are being considered because of their out of autoclave, low temperature, processing. Advanced Composites LTM resins are available locally and can be received on a just in time basis. Both LTM series 20 and LTM series 40 resins are toughened epoxies.

The LTM 20 series materials has a marginal T_g. LTM 40 series is a more highly toughened system. Of that group LTM45 has a larger database, but has an out-time of 5-6 days. LTM 48 has similar properties, but has an out-time of 30 days. It is necessary to have the longer out-time for fabrication of large structures, such as the thrust cone. The supplier of these materials, Advanced Composites Group inc., recommended their MT9F system, another member of the LTM40 series, over the LTM45 or LTM48. It has an out time comparable with LTM48, has good 270 degree F wet and CAI properties, and has greater usage with a larger database.. Thus the LTM45 and LTM48 were eliminated, and the only remaining low temperature curing material candidate was MT9F. This will be considered with IM7 fibers.

Pultrusions

Pultrusion is an automated process. Since we are dealing with large structures, automation of the process is a plus. Higher fiber volumes and straighter fiber orientation. can be achieved using the pultrusion process. Pultrusion is a viable candidate process for truss structure or for longeron stiffening, if acceptable compression properties can be obtained.

Thermoset and thermoplastic resins can both be pultruded. Because of cure characteristics vs a process dictated cure time, the number of thermoset resins that lend themselves to the pultrusion process is limited . Most thermoset resins that can be pultruded do not have the required mechanical properties .The DMLCC program is evaluating a pultruded thermoset rod made by Neptco. This rod is not acceptable for this program, due to a dry use temperature of 220F. Thus only the thermoplastics will be considered for the pultrusion applications.

Most composite thermoplastic resins, including Polyphenylene Sulfide (PPS), and PEEK, have a use temperature that is lower than required for this program. For this reason, PEKK is probably the only viable thermoplastic candidate for this application. PEKK will be evaluated with either M7 or AS4 fibers and with Hybor/IM7 hybrid fibers.

<u>Fibers</u>

Both IM7 and IM9 fibers can be impregnated with a thermoplastic or thermoset resin. The baseline fiber chosen is IM7. IM9 was investigated, but was discarded for the following reasons..

The increase in properties was not as much as initially thought.
IM9 is not as mature and does not have a large database.
IM9 is not readily available in large quantities.

Published data for a hybrid boron/carbon fiber manufactured by Textron indicates superior compressive strength. This material can be impregnated with either thermoplastic or thermoset resin. This is another option that is being considered. The thermoplastic resin will be PEKK and the thermoset resin will be NCT301. Textron has a lot of experience with this resin system.

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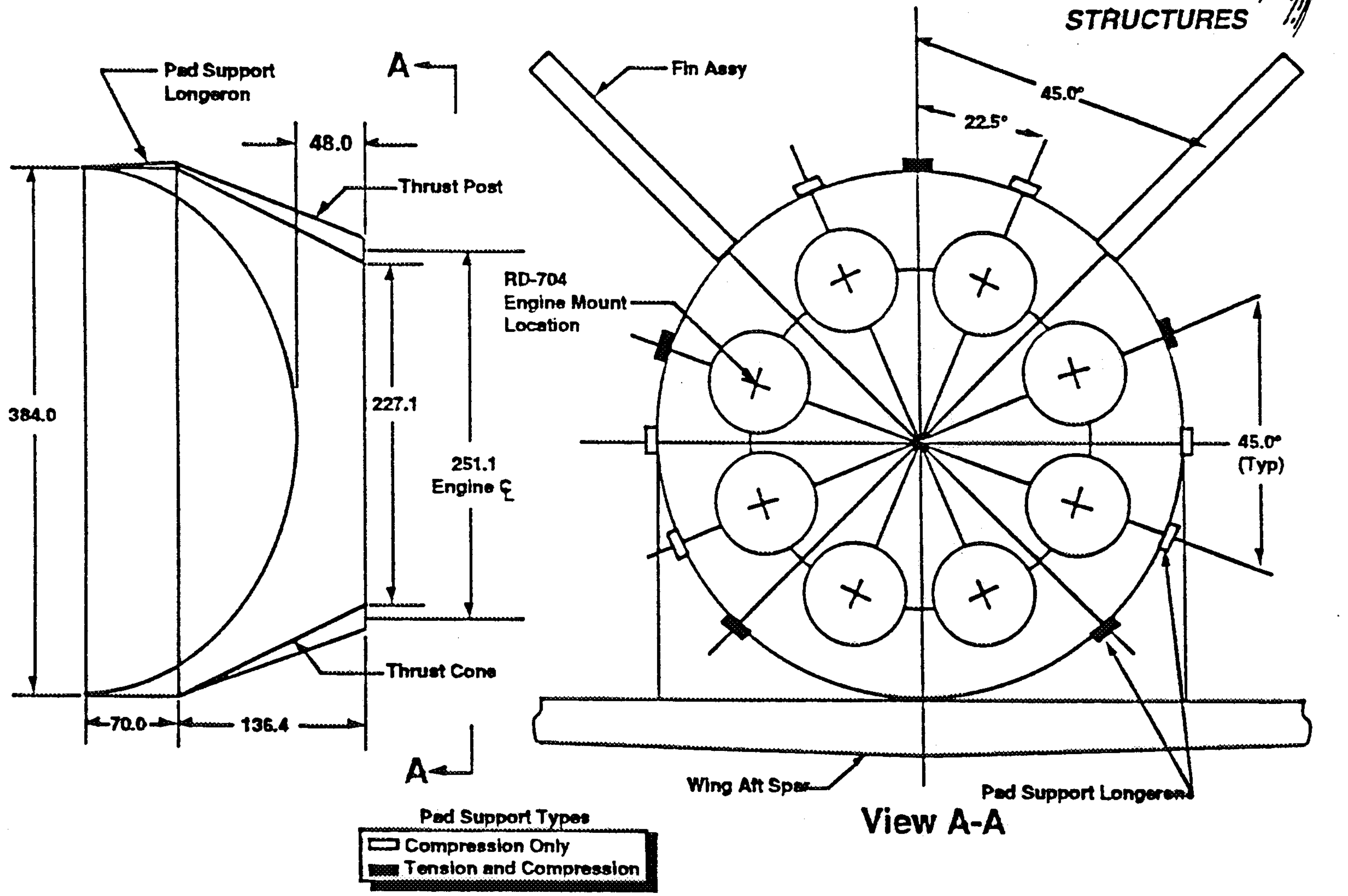
Configuration 2A Thrust Structure Layout 8 Engines

COMPOSITE STRUCTURES



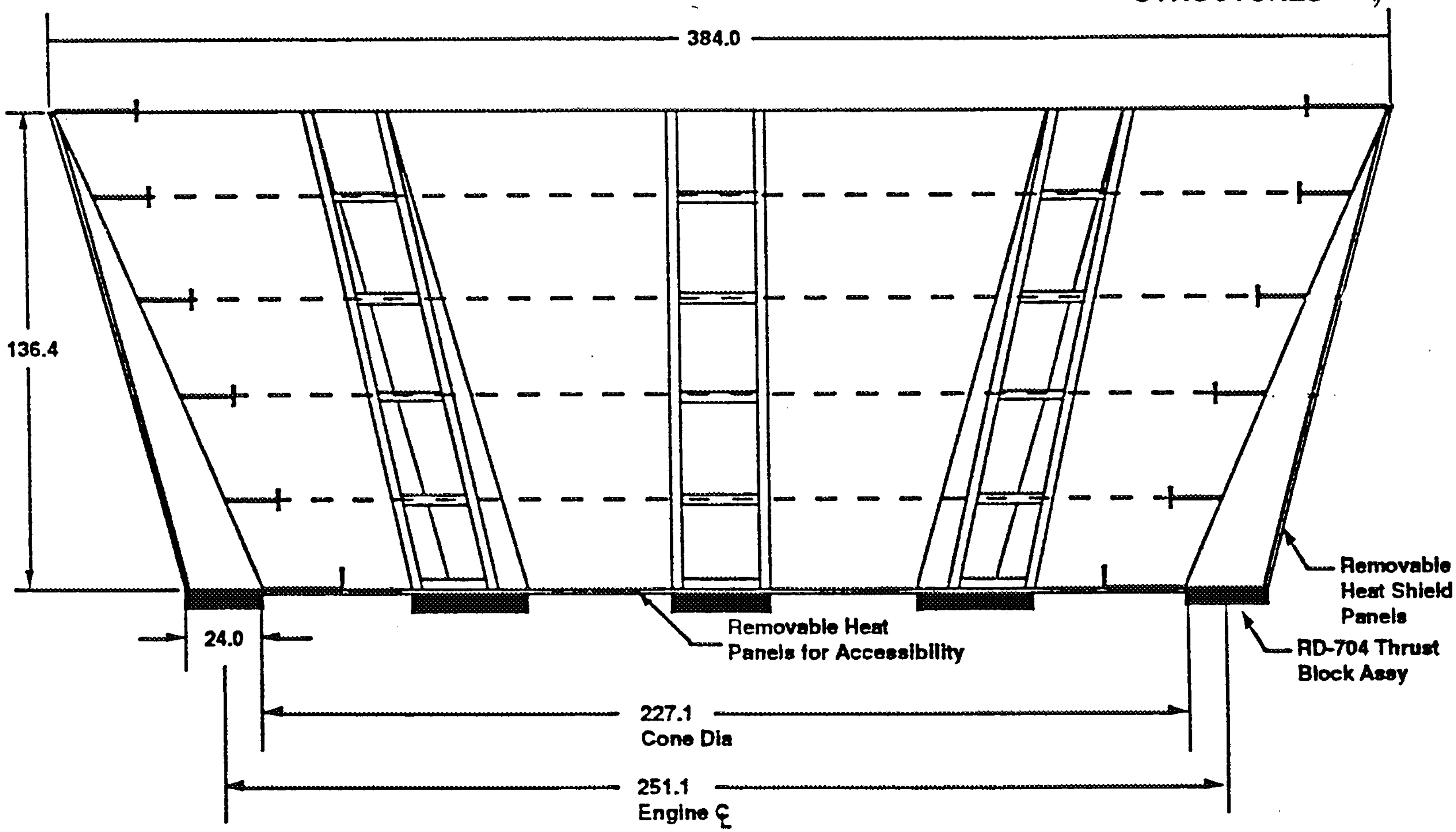
NASA - ROCKWELL/SSD - NORTHROP/GRUMMAN - ROCKWELL/NAAD/TULSA

COMPETITION SENSITIVE

FIG1.1

Configuration 2A Thrust Structure Layout-Elevation View

COMPOSITE STRUCTURES



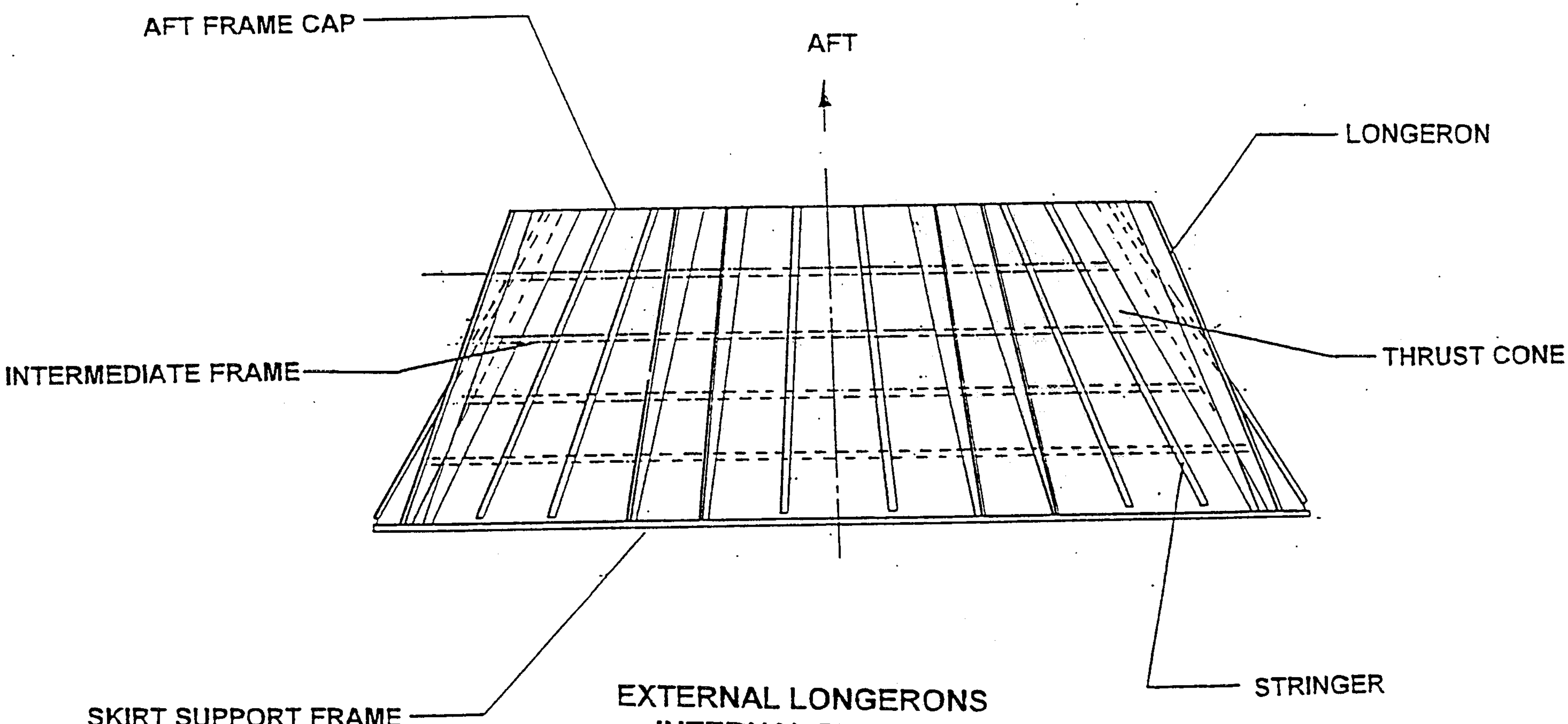
Elevation View

Note: 1) Gr/Ep Skin/Stringer Construction

SKIN/STRINGER CONCEPT

THRUST STRUCTURE DESIGN
APPLICABLE TO VEHICLE CONCEPT NO. 2A

COMPOSITE STRUCTURES



EXTERNAL LONGERONS
INTERNAL FRAMES

NASA - ROCKWELL/SSD - NORTHROP/GRUMMAN - ROCKWELL/NAAD/TULSA

COMPETITION SENSITIVE

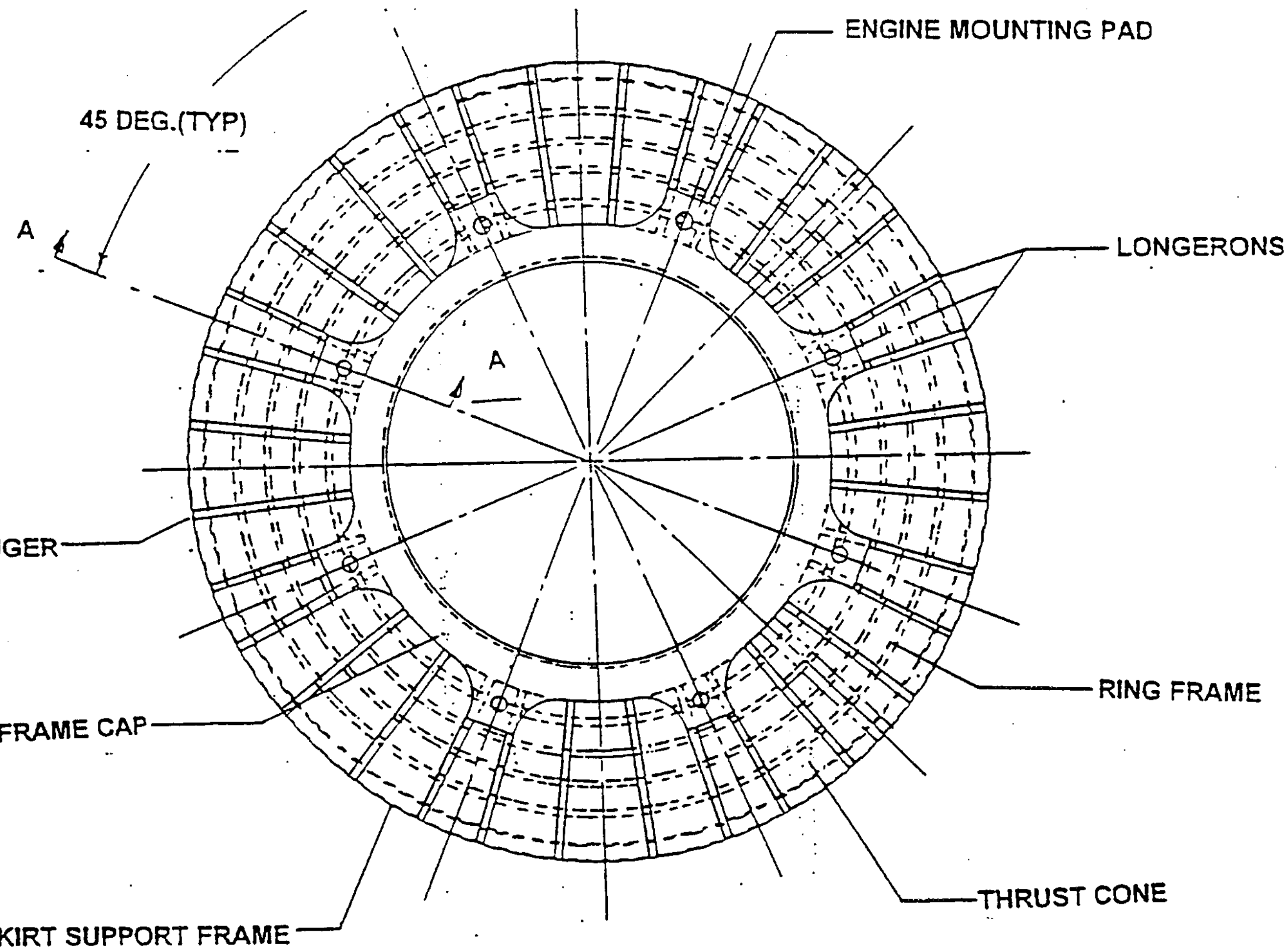
FIG 1.3

SKIN/STRINGER CONCEPT

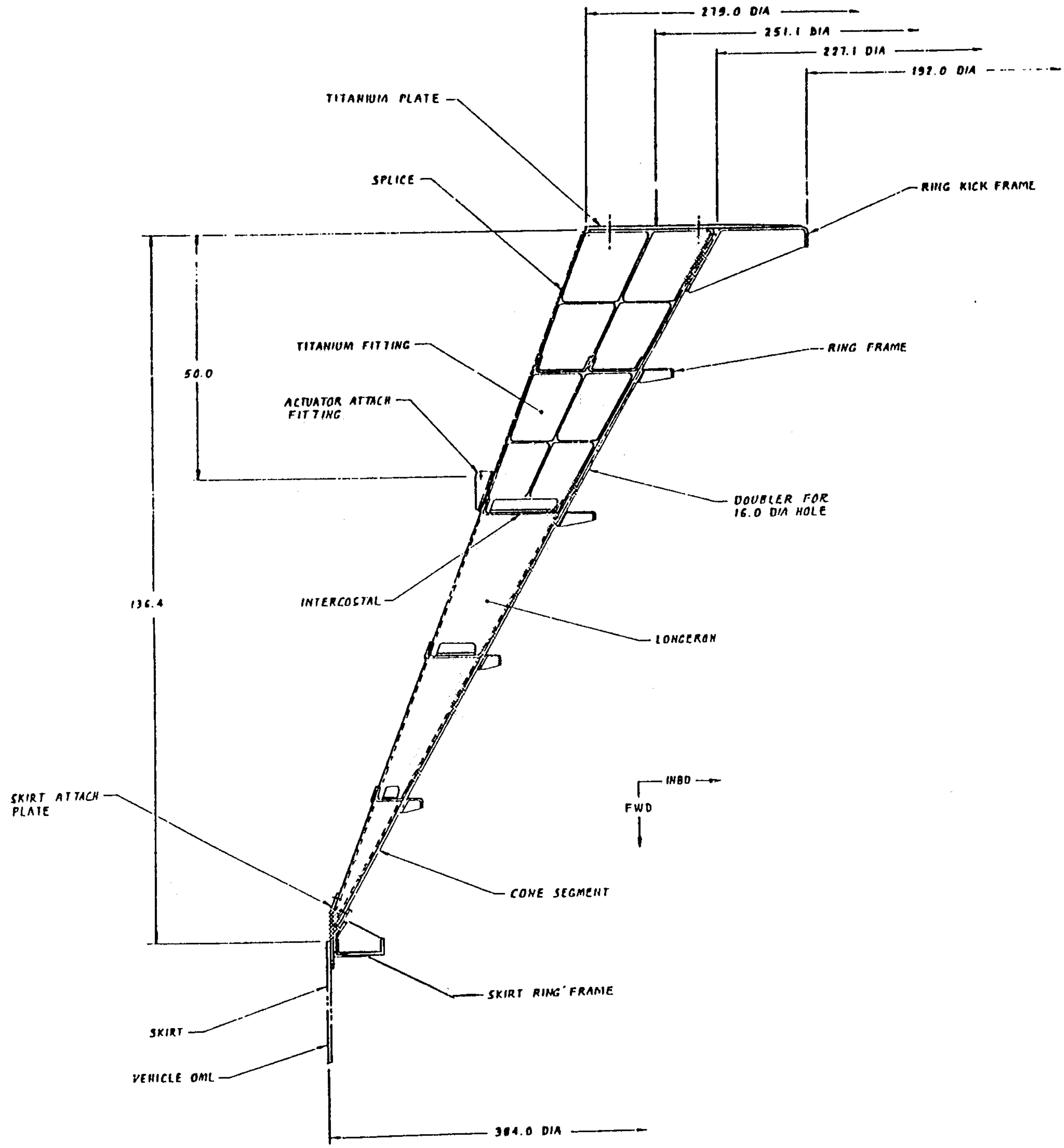
THRUST STRUCTURE DESIGN

COMPOSITE

APPLICABLE TO VEHICLE CONCEPT NO. 2A



THRUST STRUCTURE DESIGN CONCEPT-VEHICLE 2A
TYPICAL LONGERON

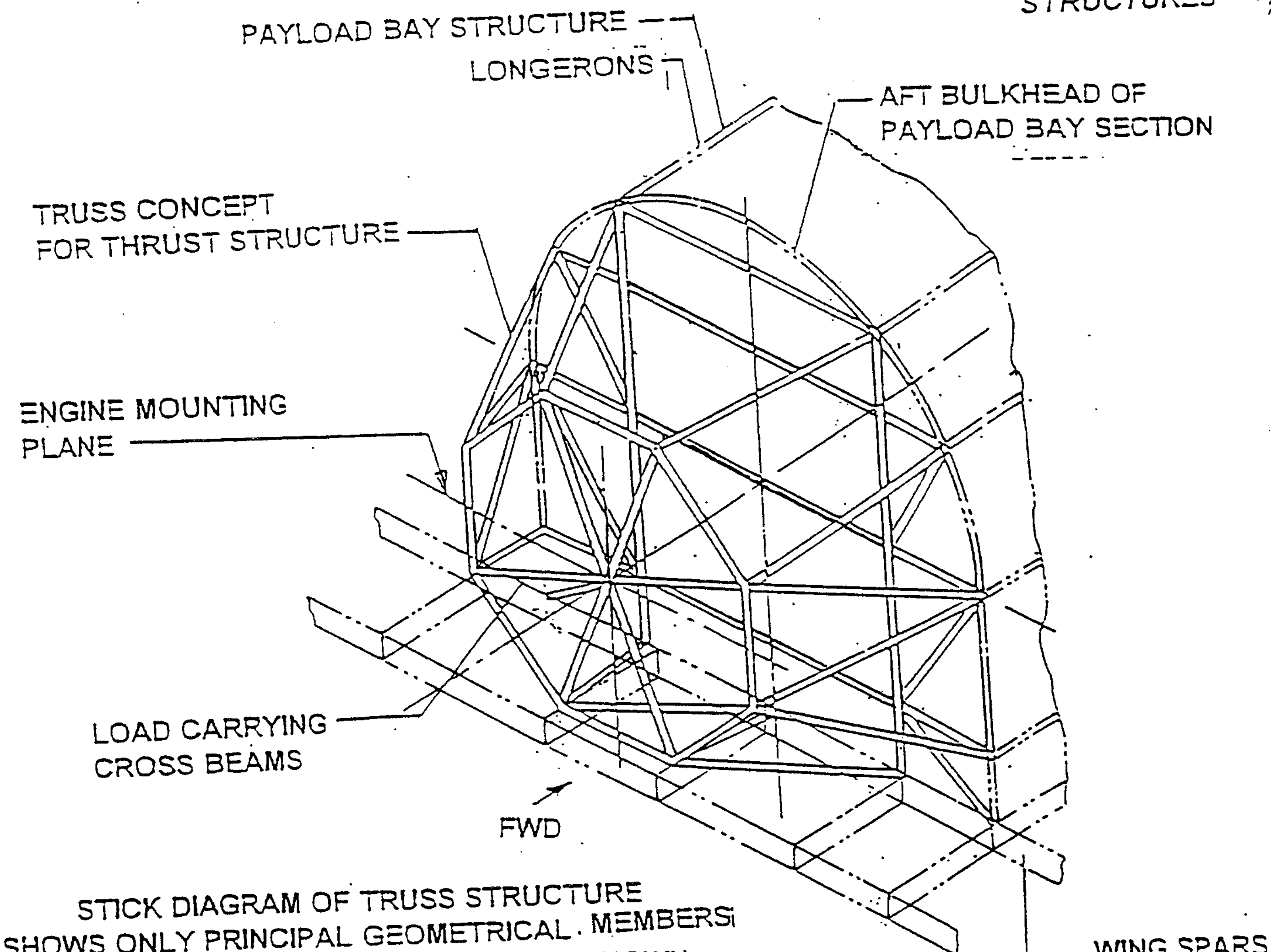


SECTION A-A

FIG 1.5

CONFIGURATION 4, TRUSS TYPE THRUST STRUCTURE

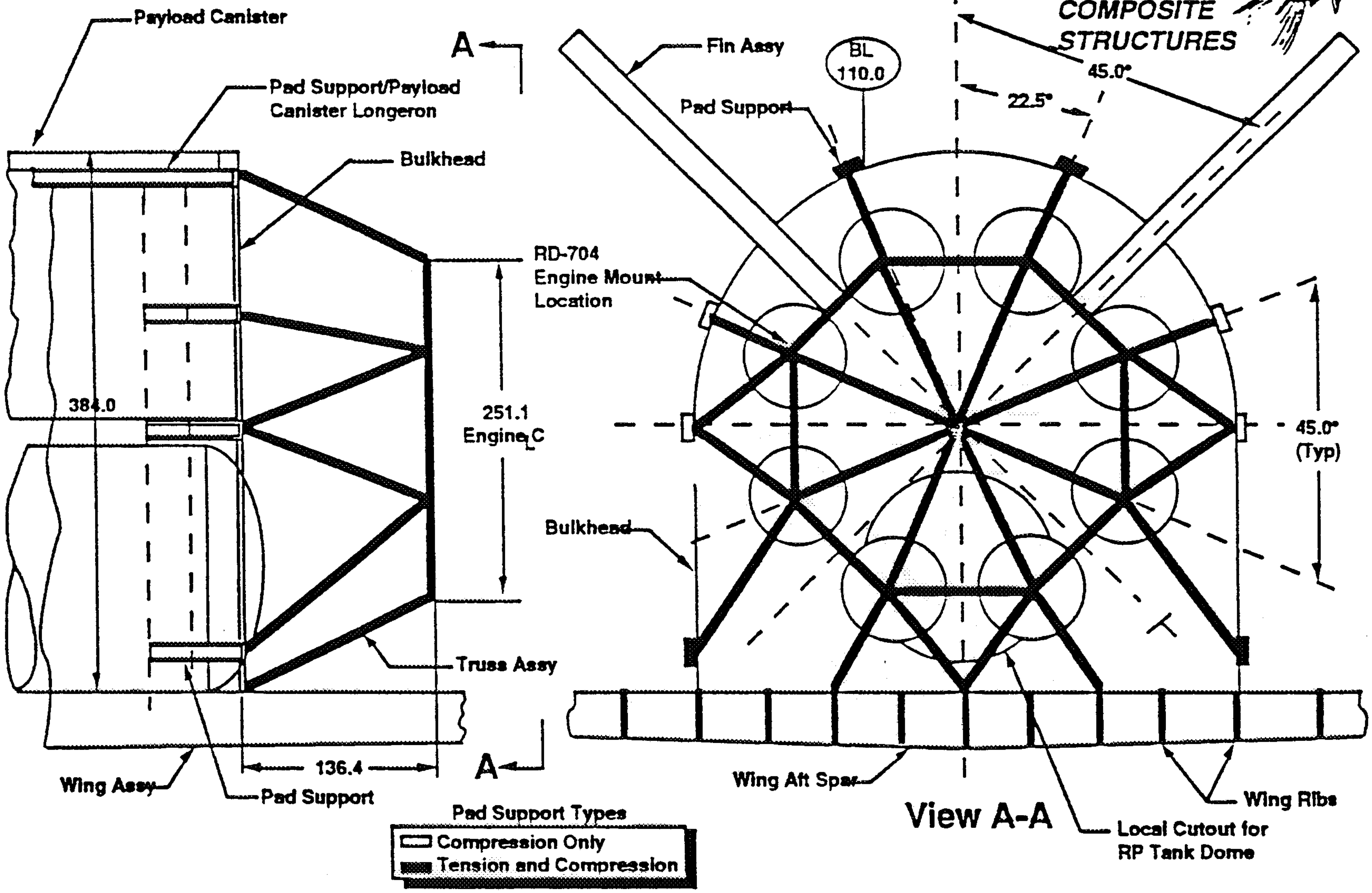
COMPOSITE STRUCTURES



STICK DIAGRAM OF TRUSS STRUCTURE
SHOWS ONLY PRINCIPAL GEOMETRICAL MEMBERS
SUB-STRUCTURE TRUSS WORKS NOT SHOWN

Configuration 4 Thrust Structure Layout-8 Engines

COMPOSITE STRUCTURES

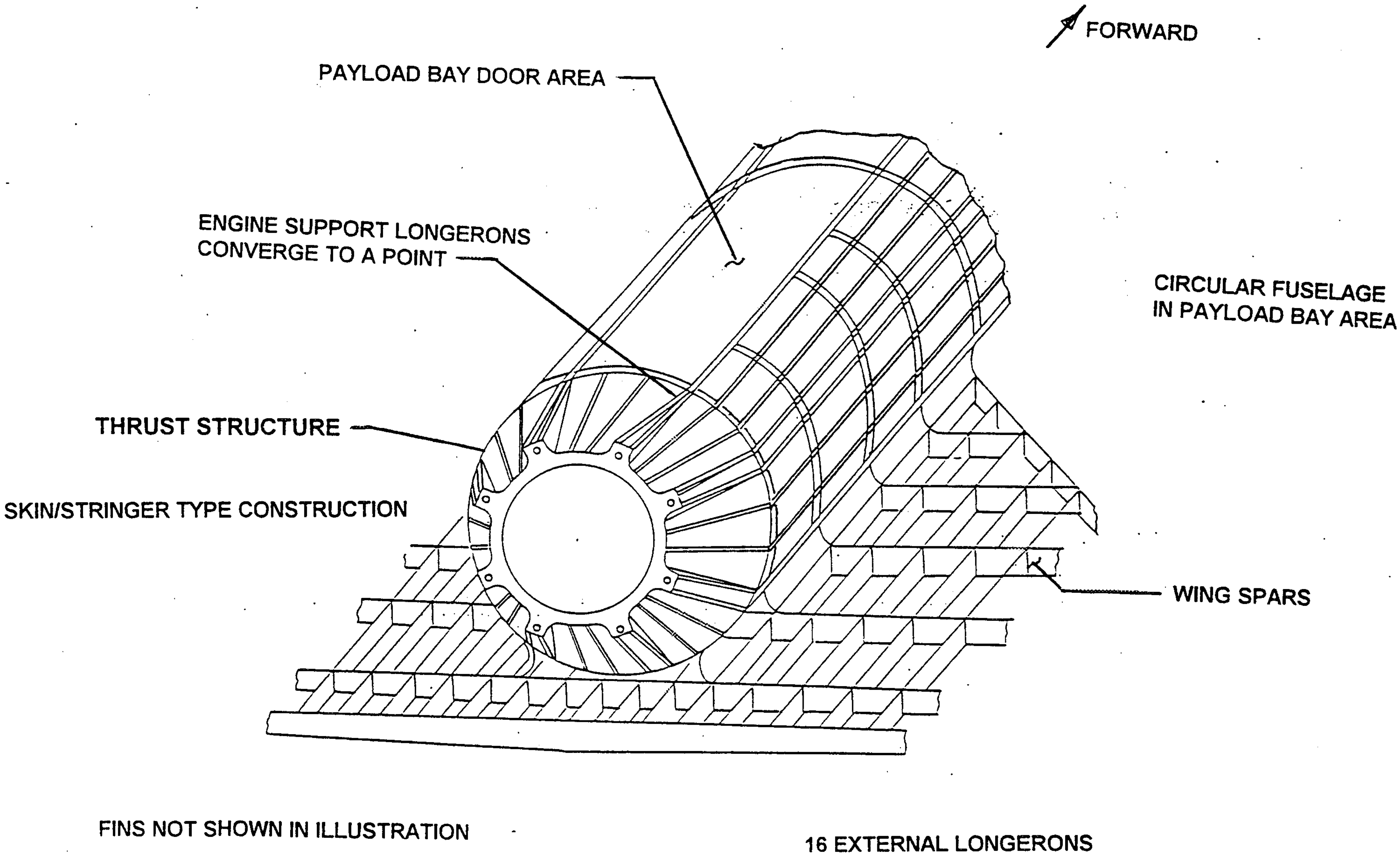


NASA - ROCKWELL/SSD - NORTHROP/GRUMMAN - ROCKWELL/NAAD/TULSA

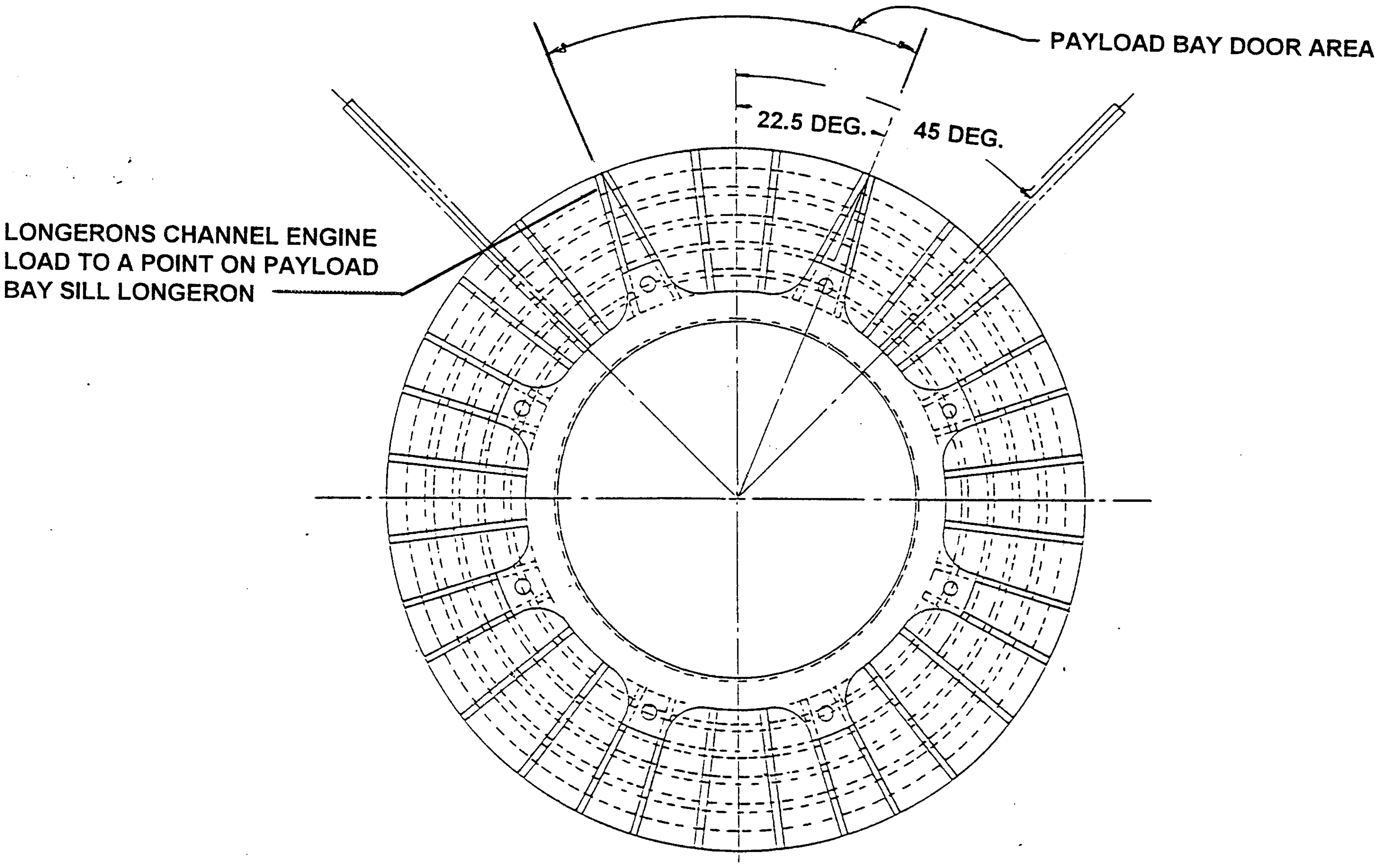
COMPETITION SENSITIVE

FIG. 2.2

CONFIGURATION 4-SKIN/STRINGER TYPE THRUST STRUCTURE



CONFIGURATION 4-SKIN/STRINGER TYPE THRUST STRUCTURE



VIEW LOOKING FORWARD

FIG. 3.2

Thrust Structure Concepts

TA2 GCPS

Objective

Application of integrated health management (IHM) to the composite primary structure of a launch vehicle is necessary to reduce operational costs and processing time delays. This is accomplished in two ways. First, enforce robust design of the composite structures to provide the confidence to eliminate many inspection processes, and second, to apply appropriate nondestructive evaluation and inspection (NDE/I) sensors to handle the fault modes which will inevitably occur. Even with successful development of robust structural designs some form of monitoring will be necessary to detect and identify external threats to the structural integrity and evaluation the impact of damage sustained during operation.

Part of the NDE/IHM task is to acquire and develop (if necessary) NDE/I sensor technologies and to integrate those sensors into the full scale test articles (FSTA) which will be produced under the TA2 program. This effort will not only develop the sensing technologies necessary, but also provide a knowledge base of direct experience, for the implementation of an integrated health management (IHM) system for an operational flight vehicle.

The NDE/I sensor screening is intended to serve as a first cut to reduce the number of competing sensor technologies to several promising candidates Three or four of the most applicable technologies will be retained for further investigation and development, through laboratory testing of instrumented coupons and panels, while the others will be noted for future reference. It is intended that this evaluation be reassessed periodically to ensure that technological developments, which could alter the findings, are incorporated as the program proceeds.

Discussion

The NDE/I sensor screening is driven by the need to assess the structural health of the composite primary structure of the Full-Scale Test Articles (FSTA) for the wing, intertank, and thrust structure of a single-stage-to-orbit (SSTO) launch vehicle. Inspection of these structures by conventional means is complicated by three factors: (1) the composite material properties differ significantly from metallic materials, (2) the primary structure of an operational SSTO will be covered by a thick thermal protection system (TPS) which prevents direct access to the structural surface, and (3) conventional methods have been labor intensive and time consuming (especially inspection of the entire vehicle). Implementation of a highly autonomous IHM system relies on embedding as many of the sensors and data interpretation mechanisms on the vehicle as is feasible. This system can then provide real time and continuous structural health monitoring during all power on phases of the mission--including most of the ground preparation tests and checkout--thereby eliminating much ground support equipment (GSE).

The TA2 NDE/I and sensor screening process approach was to conduct a literary search to provide the largest sample of available sensor technologies. Additionally, the NRA8-12 team members, government agencies (NASA, DOD, national labs), aerospace and commercial industries were contacted to gather promising NDE/I sensor technologies for screening. Contacts were initiated with several NDE/I and sensor technology vendors as well as research universities. Review of these inputs identified eleven sensor technologies for evaluation and provided sufficient information about each technology to draw initial conclusions about the fitness of individual technologies to meet the TA2 Task 7 requirements.

The TA2 sensor technology screening ran in conjunction with similar surveys for TA1 and TA3 to maintain an integrated approach to fault mode identification and NDE/I sensor selection.

Selection Criteria

The selection criteria for this first NDE/I sensor technology screening are based on a hierarchical need list: (1) the sensor must be able to detect the fault modes of the composite primary structures; (2) the sensor (or technology) must be applicable to the intended operational environment; (3) the sensor hardware (and software) must mature enough to meet the TA2 schedule with little or no development required; (4) the sensors must be affordable (development, operations) to implement on the full-scale test articles as well as an operational vehicle. One difficulty with the final criterion is the availability of the cost information. While many researchers and technologists are eager to share the technical merits of a particular sensing technology, they are either unaware of, or reluctant to divulge, their costs for development and implementation. However, relative estimates can be established by comparing the maturity of the sensor technology (development cost), or, the number of sensors and the amount of supporting hardware (cables, wiring, control, etc.) required to provide similar areas of coverage (implementation cost).

To effect selection of candidate sensor technologies, which will provide the greatest benefit while incurring the least liabilities, four selection criteria were utilized: (1) detection capability (area of coverage, fault modes), (2) ground based and in-situ (on-board) application, (3) maturity (availability and development required), (4) operational benefit, liability, and relative complexity.

Sensor Technology Identification

The sensor technologies are divided into two categories: conventional and advanced. The conventional NDE sensor technologies are those that are available and/or established methods, techniques, off the shelf equipment and training materials. Advanced sensor technologies build on the conventional technologies and in some manner enhance the performance of the methods in either a generic or application specific manner.

The conventional NDE sensor technologies include but are not limited to: resistive strain gauge, ultrasonic, eddy current, x-ray, penetrant, and visual.

Resistive Strain Gauge - Electro-resistive strain gauges have been used within the aerospace industry for many decades to measure flight loads on aircraft. The principle that the electrical resistance of the sensor element (thin wire or photochemically etched conductor) is proportional to the length of the sensor element and hence the strain of the bonded material. The prevailing design of strain gauges is to direct the conductor path back and forth parallel to the direction of the strain measurement to enhance the sensitivity of the detector. Usually several strain gauges are used in different orientations to provide a complete assessment of the strain environment at the sensor location.

Ultrasonic- Contact ultrasonic technology utilizes piezoelectric transducers to transmit and receive data. Transducers are placed on the inspection surface and used individually (pulse-echo) or in pairs (through transmission). When an individual transducer is used in pulse-echo mode, access from only one side is required. The transducer pulses sound energy into the specimen and listens for an echo. This method is commonly used for small area inspections. The through transmission method requires access to both sides of the specimen and meets the needs of process control monitoring during the manufacturing and fabrication of the graphite primary structure. Tests will evaluate capability and effectiveness and detect and quantify flaws and damage such as porosity, cracks and delaminations. Contact ultrasonic inspection technology typically requires a couplant such as water, gel, or epoxy to provide adequate energy transmission into the material. Specialized air scan systems may also be evaluated for capability to locate and quantify anomalies in integrated assemblies such as debonds between layers of insulation and substrate. Ultrasonic inspection is routinely used during the manufacture of composite structures, but has not been applied to in-situ monitoring on flight vehicles.

Eddy Current - Eddy Current inspection is an electromagnetic process that measures minute changes in the magnetic field (due to eddy currents in the test material) between two current carrying coils. The magnetic field was changed if the distance to or thickness of the measured conducting medium changes. Due to low conductivity, Gr/Ep materials do not respond well to eddy current examination. Metal matrix composites also appear to respond to eddy current inspection. However, eddy current may not be a useful inspection technology for IHM of composite material structures unless adequate sensitivity can be demonstrated.

X-Ray Radiography - X-ray technology may be used as needed during manufacturing and fabrication to verify indications revealed by other NDE/I methods, but safety and complexity considerations rule it out as an IHM technology. Advanced radiographic techniques using computer enhancement to evaluate flaws in the materials and structures may be employed to determine structural integrity during fabrication and was evaluated for assessing materials for flaws during ground based maintenance.

Dye Penetrant - Penetrant technology may be used as needed during manufacturing and fabrication but will not be considered for use as an IHM technology. Penetrant is a labor intensive technology used primarily on metals. The detection sensor is the operators' eyes and fluid penetration into the structure is to be avoided. Besides, the development cost of automating this process is out of the scope of this project.

Advanced NDE technologies build on the conventional NDE technologies and in some manner enhance the performance of the methods in either a generic or application specific manner. Examples include but are not limited to; acoustic emission, laser based ultrasonic (LBU), fiber optics, shearography, thermography, and microwave. Usually these are technologies that offer a unique approach or application of state-of-the-art technology in innovative manners.

Acoustic Emission - Acoustic emissions are detected by attaching ultrasonic transducers to the surface of the material at strategic points to record the stress emissions generated within the structure. Low level sonic or ultrasonic emissions may be generated by stress relief at cracks and flaws under load resulting in local material deformation, degradation or damage, in response to structure impacts and as a result of leaks. (ref. 1) Emission in the structures generate characteristic pulses which can be monitored to identify the type of flaw, the location and the rate of growth. Acoustic Emission can be used to gather data during the manufacturing and test programs to establish baselines for the detection of flaws generated during flight. The data is gathered and reviewed by computer to monitor the integrity of the structures and to monitor the growth of anomalies. This versatile technology is used as a tool to study mechanical behavior of materials, as an NDT technique and as a quality control method. As an NDT method it is calibrated to a structure and then waits to detect and process low level events while the structure is under load.

Laser-Based Ultrasonic Inspection - Laser Based Ultrasonics is a non-contacting derivative of standard ultrasonic inspection. Ultrasonic pulse energy is introduced into the test specimen by pulses of light from a laser. The reflected or transmitted ultrasound pulse is detected with a fiberoptic interferometer that detects motion of the surface. Laser generated pulses typically have much lower energy that contact ultrasonics so frequency locking is used to filter the signal from the noise. This emerging technology was screened for IHM applicability. Preliminary test results of a Gr/Ep panel using the Rockwell International LBU system shows positive results for IHM applicability.

Fiber Optics - Fiberoptic sensors are a novel method for determining the health or condition of composite structures. The optical fibers, which usually measure for stress or temperature, are imbedded into the composite structure. Continuous strain readings can be made along the length of the fiber based upon the return time of the strain signal. Temperature sensors usually have a series of nodes along the fiber length. These sensors provide wide area coverage and are compatible to harsh environments. They provide composite curing information and can provide continuous information during manufacture, testing and flight. The main drawback to these sensors is the difficulty in replacing them if they should fail.

Shearography - Shearography is a form of interferometry that uses a laser to acquire stressed and stress free images of the test item. The nonstressed image is added in real time to the stressed images to produce interference patterns, observable on a TV monitor, which indicate areas experiencing minute movements during the process. These patterns may be interpreted to indicate flaws such as cracks, delaminations, debonds and other anomalies. Shearography appears to be most effective with flexible rather than stiff rigid materials.

Thermography - Thermography is a remote non-contacting method utilizing infrared imaging sensors for detecting a variety of surface and subsurface material defects and faults. Standard thermography is performed by heating a structure using quartz lamps (or equivalent) and scanning the surface of a structure with an infrared (IR) video camera. The camera detects small variations in temperature, thus, providing images of thermal conductivity patterns in the test specimen. The images are evaluated to ascertain if the patterns indicate anomalies such as surface flaws (pits and scratches), debonds, delaminations, cracks or other flaws. If the emissivity of the materials in the image are known, actual temperatures can be quickly and easily calculated.

Microwave - Microwave inspection is a form of radiography which holds tremendous potential. Microwaves are generated and emitted from a non-contacting wave guide toward the specimen. The microwaves penetrate dielectric materials (like TPS and Gr/Ep composites) and reflect from various internal irregularities. Thus, the return signal contains three-dimensional data about the status of each material and bondline which it encountered. Structural inspection with microwaves could occur while the TPS was still in place on the vehicle. However, like X-rays, there are safety concerns which have not been quantified at this time which may limit the applicability of microwave inspect in the ground based operations environment.

To gather data for sensor comparisons and selection of equipment and sensors, a Sensor Capability Classification Matrix (Table 1) was developed. This is a summary of the aforementioned NDE/I technologies and their capabilities to detect faults in a Gr/Ep composite structure. This matrix will continue to evolve as additional details become available and will be included it the TA2-Task 7 **Development Test Plan** updates.

To further assist in the selection of each method, the matrix was expanded to cross-reference the technology capability with the faults that are to be identified. This matrix was designed to help identify the most promising sensor technology to detect the potential fault modes.

Table 1 Sensor Capability Matrix

Comparison of Selected NDE Methods

Method	Properties (Sensed or Measured)	Typical Discontinuities Detected	Advantages	Limitations
Resistive Strain Gauge	material strain	strain/stress state, stress concentration near damaged areas	simple, inexpensive, very mature, flight qualified units exist	limited area coverage, measures only a single direction, not sensitive enough to detect most faults
Contact Ultrasonic Examination	Changes in acoustic impedance.	Cracks, voids, porosity, lamination, delaminations, and inclusions	Excellent penetration, readily automated, good sensitivity and resolution, requires access to only one side, permanent record, if needed.	Requires acoustic coupling to surface, reference standard usually required, highly dependent upon operator skill, relative insensitivity to laminar flaws which are parallel to the sound beam
Eddy current examination	Changes in electrical and magnetic properties caused by surface and near-surface discontinuities	In metal surfaces: cracks, seams, laps, voids, and variations in alloy composition and heat treatment Dielectric and adhesives can be magnetically tagged to enable inspection.	Moderate cost, readily automated, portable, permanent record if needed	Conductive materials only, shallow penetration, geometry sensitive, reference standards often necessary.
X and Gamma Radiography	Changes in density from voids, inclusions, material variations, placement of internal parts.	Voids, porosity, inclusions, and cracks	Detects internal discontinuities, useful on a wide variety of materials, portable, permanent record	Cost, relative insensitivity to thin or laminar flaws such as fatigue cracks or delaminations which are perpendicular to the radiation beam, health hazard
Visual and Dye Penetrant	Changes in observable features (color, shape, pattern, etc.)	Scratches, pits, surface cracks, dents, contamination	Low cost equipment, parallel inspection	Highly dependent on operator skill,, penetrant contamination, surface inspection only
Acoustic Emission	Changes in acoustic impedance.	Cracks, voids, porosity, lamination, delaminations, and inclusions	In-situ monitoring, passive detection	Computationally intensive, requires numerous tests to characterize flaw signatures
Laser Based Ultrasonic Examination	Changes in acoustic impedance.	Cracks, voids, porosity, lamination, delaminations, and inclusions	Non-contacting, excellent penetration, readily automated, good sensitivity and resolution, requires access to only one side, permanent record, if needed.	Reference standard usually required, highly dependent upon operator skill, relative insensitivity to laminar flaws which are parallel to the sound beam
Fiber Optics	Changes in optical attenuation, frequency shift, time delay	Strain, fiber/matrix debond, temperature, cure state	Continuous coverage over length, in-situ throughout production and operation	Near field fault detection only, difficult to replace or repair.
Shearography	Interference of reflected laser pattern for unloaded and loaded conditions	Strain, delaminations, surface defects,	Non-contacting inspection, direct visual display of irregularities	Less sensitive for rigid materials, difficult to use in-situ
Thermography	Changes is emmissivity and thermal conductivity	Debonds, delaminations, voids, porosity, scratches, pits, surface cracks	Able to detect internal flaws, direct visual imaging,	Requires direct assess to the test sample, completely ineffective through TPS
Microwave examination	Anomalies in complex dielectric coefficient, surface anomalies in conductive materials	In dielectrics: debonds, delaminations, voids, and cracks In metal surfaces: surface cracks	Noncontacting, readily automated, rapid inspection, penetration of nonmetals including TPS, able to image multiple interface planes and internal defects	No penetration of metals, comparatively poor definition of flaws, health hazard

Fault Mode Identification

The main tenant of the IHM philosophy states that the implementation must occur at the lowest level possible to achieve maximum benefit. This means that the first step in improving the health status of the system is to eliminate as many fault modes as possible through robust design and controlled operational procedures. Experience with military and commercial aircraft which use composite structures indicate that a robust structural design is sufficient to eliminate the need to monitor most of the common fault modes (even ground crews). The faults which are large enough to detect before they are of sufficient size to endangering the structure and the vehicle are of primary interest as targets for in-situ IHM assessment. Four faults meet this need: cracks, delamination, debond, and surface damage.

Cracks - Cracks begin with a small discontinuities (voids, debonded fibers, chips or scratches in free edges, etc.) in the composite material and grow due to stress concentration around the crack itself. The growth rate depends on the size of the crack, its orientation, and the surrounding stress environment. Crack growth is the main fatigue mechanism which limits life.

Delamination - Delamination is a separation between ply lay-ups that occurs primarily due to impact and boundary discontinuity around free edges. The delamination results in a decrease in compressive stiffness and is subject to rapid growth in cyclic loading environments since the inter-ply bondline is the weakest point of the composite.

Debond - Debond arises from separation of joined structural elements (skin/stiffeners, lap joints, etc.). These elements will loose effectiveness as the debond grows due to stress concentration around the debond. Early detection of debonded elements allows repairs to be made in a timely manner. Most debonds result from voids in the joining adhesive or resin during manufacture, yet, debonds will result from impact and overloading conditions on the vehicle as well due to bond failure.

Surface Damage - Surface damage occurs when foreign materials contact the structure (e.g., scratches, pits, dents, erosion, penetrations, etc.) or through chemical corrosion. Surface flaws attract and retain moisture which can lead to corrosion and act as crack starts. Penetrations are particularly troublesome since environmental fluids and gases can pass inside the structure where inspection and cleanup are especially difficult.

Sensor Comparison

The sensor technology capabilities have been cross-referenced with the selection criteria and are in the following table.

Table 2. NDE Sensor Technology Comparison with Selection Criteria

	Fault Mode					Coverage	Application		Maturity	Operations		
Sensor Technology	Crack	Delamination	Disbond	Strain	Surface Damage		Ground Based	In-Situ		Advantages	Limitations	Complexity
Resistive Strain Guage (changes in sensor resistance due to strain of substrate)				✗		Local and directional		✗	Existing	Long history of use, flight qualified sensors	Limited utility in detecting any fault modes, significant post processing required to identify specific anomalies.	Simple
Contact Ultrasonic Inspection (changes in acoustic impedance)	✗	✗	✗		✗	Wide area	✗	✗	Existing for ground based, Development required for in-situ use	Excellent penetration, readily automated, good sensitivity and resolution, requires access to only one side, permanent record, if needed	Direct access to inspected surface required, poor resolution of overlaid faults	Simple
Eddy Current (changes in electrical and magnetic properties)	✗				✗	Scan area	✗		Existing	Moderate cost, readily automated, portable, permanent record if needed	Conductive materials only, shallow penetration, geometry sensitive, reference standards often necessary	Simple
X and Gamma Radiography (changes in density)		✗	✗		✗	Scan area	✗		Existing	Detects internal discontinuities, useful on a wide variety of materials, portable, permanent record	Cost, relative insensitivity to thin or laminar flaws such as fatigue cracks or delaminations which are perpendicular to the radiation beam, health hazard	Complex, fully mature systems exist
Visual and Dye Penetrant (changes in observable features (color, shape, pattern, etc.))	✗				✗	Wide area; surface only	✗		Existing; Development need for automated visual inspection	Low cost equipment, parallel inspection	Highly dependent on operator skill,, penetrant contamination, surface inspection only	Simple
Accoustic Emmissions (changes in acousitc impedence)	✗	✗	✗		✗	Wide area	✗	✗	Existing, Development required to adapt to new materials and environments	In-situ monitoring, simple mechanical attachment	Computationally intensive, power and data cabling weight	Simple
Laser Generated Ultrasonic Inspection (changes in acousitc impedence)	✗	✗	✗		✗	Scan area	✗		Significant development required	Non-contacting, excellent penetration, readily automated, good sensitivity and resolution, requires access to only one side, permanent record, if needed	Reference standard usually required, highly dependent upon operator skill, relative insensitivity to laminar flaws which are parallel to the sound beam	Complex, will decrease with maturity
Fiber Optics (changes in optical attenuation, frequency shift, and time delay)		✗	✗	✗		Local to fiber; wide area by implimentation		✗	Existing in limited scale, some development to adapt to launch vehicle environment	Continuous coverage over length, in-situ throughout production and operationn	Near field fault detection only, difficult to replace or repair	Moderately complex, embedding and maintenance difficulties
Shearography (interference patterns between nonloaded and loaded images)	✗	✗	✗	✗		Scan area	✗		Existing, characterization of new materials and components needed	Non-contacting inspection	Direct access to inspected surface required, poor resolution of overlaid faults, less sensitive for rigid materials	Complex
Thermography (changes in emmissivity and thermal conductivity)	✗	✗	✗		✗	Scan area	✗		Existing	Non-contacting inspection	Direct access to inspected surface required, poor resolution of overlaid faults	Simple
Microwave (microwave reflection and attenuation, frequency shift, and time delay)		✗	✗		✗	Scan area	✗		Significant development required	Noncontacting, readily automated, rapid inspection; penetration of dielectrics (including TPS)	No penetration of metals, comparatively poor definition of flaws, health hazard	Complex, will decrease with maturity

Results

Review of the anticipated fault modes and the available sensor technology data indicates that three sensor technologies should be assess for the in-situ monitoring of the composite primary structure elements. These are: ultrasonics (dry contact), acoustic emissions, and fiber optics (embedded or attached). In fact, a combination of sensor technologies will be needed to detect and evaluate the fault modes; not only do sensor technology have specific capabilities and applicability, but, the three Gr/Ep primary structures being demonstrated under the TA2 effort have differing requirements based on their respective failure modes and designs.

Ultrasonics was selected because it can detect all of the failure modes and compatible with in-situ operation. The sensors themselves are inexpensive and simple. Ultrasonics can survey a fairly large area by addition of more sensors and can work in concert with other technologies such as acoustic emission.

Acoustic emission was selected for similar reasons. This technology is the only technology that actually detects the damage happening with the sensitivity to determine the energy being released (*e.i.*, magnitude)

Embedded fiber optics have been used on recent military aircraft and the processes for installation and data acquisition are well known. New and innovative detectors are being interfaced with the fibers to allow additional measurement capabilities. Fiber optics can provide continuous monitoring along a length (like a bondline) and are by nature an in-situ technology.

Laser based ultrasonics is a ground based sensor technology that may be of interest for rapid, non-contacting inspection of exposed (or removed) structural elements during the ground processing. The conventional suite of sensors (wet contact ultrasonics, X-ray and radiography, and visual) are acceptable for the production, assembly, and repair of the structural elements when the in-situ systems are unavailable.

The next step is to bring these technologies into the laboratory environment and begin characterization of the sensor output from the coupons and panels being constructed for this task. During the interim, between completion of this screening and the availability of dedicated test specimens, these sensor technologies will be non-intrusively added to ongoing tests for other tasks and projects where available. Development of sensor interfaces with the data collection system will also take place. This effort will be coordinated with the TA1 and TA3 tasks to ensure that maximum advantage of resources and testing opportunities is achieved.