NASA
SPACE VEHICLE
DESIGN CRITERIA
(STRUCTURES)

NASA SP-8104

STRUCTURAL INTERACTION WITH TRANSPORTATION AND HANDLING SYSTEMS

JANUARY 1973

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. A list of all published monographs in this series can be found at the end of this document.

These monographs are to be regarded as *guides* to the formulation of design requirements and specifications by NASA Centers and project offices.

This monograph was prepared under the cognizance of the Langley Research Center. The Task Manager was G. W. Jones, Jr. The coauthors were F. L. Rish, R. Weldon, and L. Kovalevsky of North American Rockwell Corporation. A number of other individuals assisted in developing the material and reviewing the drafts. In particular, the significant contributions made by the following are hereby acknowledged: H. P. Adam, C. P. Berry, H. C. Bjornlie, and L. D. Mutchler of McDonnell Douglas Corporation; H. K. Blomseth of Hughes Aircraft Company; E. Y. W. Chow of Jet Propulsion Laboratory; J. T. Foley of Sandia Corporation; J. F. Fowler of TRW Inc.; R. Kennedy of U.S. Army Transportation Engineering Agency; W. Mills of The Boeing Company; B. L. Newlander and R. F. Stevenson of North American Rockwell Corporation; F. E. Ostrem of General American Transportation Corporation; R. A. Sutton of General Dynamics Corporation; and E. J. Wolff of NASA Langley Research Center.

NASA plans to update this monograph periodically as appropriate. Comments and recommended changes in the technical content are invited and should be forwarded to the attention of the Structural Systems Office, Langley Research Center, Hampton, Virginia 23365.

January 1973

For sale by the National Technical Information Service
Springfield, Virginia 22151 · Price $3.00

GUIDE TO THE USE OF THIS MONOGRAPH

The purpose of this monograph is to provide a uniform basis for design of flightworthy structure. It summarizes for use in space vehicle development the significant experience and knowledge accumulated in research, development, and operational programs to date. It can be used to improve consistency in design, efficiency of the design effort, and confidence in the structure. All monographs in this series employ the same basic format – three major sections preceded by a brief INTRODUCTION, Section 1, and complemented by a list of REFERENCES.

The STATE OF THE ART, Section 2, reviews and assesses current design practices and identifies important aspects of the present state of technology. Selected references are cited to supply supporting information. This section serves as a survey of the subject that provides background material and prepares a proper technological base for the CRITERIA and RECOMMENDED PRACTICES.

The CRITERIA, Section 3, state what rules, guides, or limitations must be imposed to ensure flightworthiness. The criteria can serve as a checklist for guiding a design or assessing its adequacy.

The RECOMMENDED PRACTICES, Section 4, state how to satisfy the criteria. Whenever possible, the best procedure is described; when this cannot be done, appropriate references are suggested. These practices, in conjunction with the criteria, provide guidance to the formulation of requirements for vehicle design and evaluation.

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STRUCTURAL INTERACTION WITH TRANSPORTATION AND HANDLING SYSTEMS

1. INTRODUCTION

Space vehicles are designed primarily for flight environments; however, they must also withstand or be protected against the environments and loads to which they are subjected while being transported and handled from the fabrication site to the final launch position. Sophisticated facilities and systems are often developed or special compromises which affect the design of the vehicle are often necessary to make transportation and handling of space vehicles feasible. Protection against the transportation and handling loads and environments may be provided by special features incorporated in the space vehicle or its transportation and handling systems.

Inadequate attention to the problems and hazards of transporting and handling space vehicles can lead to vehicle failures. For example, lack of proper attention during design has led to such failures as the following:

- Collapse of empty liquid propellant tanks due to inadequate pressure venting during transport
- Failure of fragile structure because of shock and cyclical loading during transportation
- Excessive corrosion of metallic parts

This monograph presents criteria and recommends practices for properly accounting, in space-vehicle structural design, for interactions between space vehicles and their transportation and handling systems. Interactions of concern are limited to those occurring between fabrication and launch of the vehicle. Emphasis is given to the protection of vehicle structures against those environments and loads encountered during transportation and handling (including temporary storage) which would exceed the levels that the space vehicle can safely withstand. Methods of verifying that satisfactory compatibility between a particular space vehicle and its transportation and handling systems has been achieved are presented, current practices are appraised, and some of the capabilities and limitations of transportation and handling systems are summarized.

Critical loads experienced during transportation and handling are often different from the critical flight loads in direction, magnitude, and point of application. Certain elements of the natural environment encountered during transportion also are different from the mission environment. Thus, determining whether the transportation and handling loads and environments are critical is usually difficult and may involve considerable analytical and testing effort.

Ideally, the structural designer coordinates with other engineering disciplines to determine the severity and duration of all loads and environments likely to be encountered during transportation and handling and to evaluate the possibility of damage to the vehicle. If the effect of these loads and environments is found to be potentially damaging, several courses of action may follow: (1) restrict transportation and handling operations so that the vehicle will not be subjected to excessive loading; (2) design suitable devices to attenuate or restrict the loads and to provide protection against the natural environments; (3) design or select alternative transportation and handling systems that do not impose such severe loads; or (4) as a last resort, change the vehicle design to withstand the loading. More than one method may be selected for a particular vehicle.

This monograph is closely related to a companion monograph on transportation and handling loads (ref. 1) which is concerned with determination of the loads resulting from transportation and handling of space vehicles. Other monographs in this series on compartment venting (ref. 2) and structural vibration prediction (ref. 3) are also related.

2. STATE OF THE ART

Since space vehicles are designed and built primarily to withstand flight conditions, the desired goal is that the design be governed by flight loads and mission requirements other than those of transportation or handling and that the transportation requirements be satisfied when possible within overall vehicle weight, cost, and schedule constraints. Within the present state of the art, such a goal can be only partially achieved in most cases. Therefore, transportation and handling requirements can have an impact on configuration, weight, structure, cost, schedule, and fabrication of the space vehicle. Since space vehicles usually have rigid weight requirements, weight is increased to accommodate transportation and handling provisions only as a last resort.

During conceptual design, the basic structural configurations (particularly for large vehicles) must respond to limitations of feasible transportation and handling modes, such as cargo dimensions and weight capacity. In detail design, the loads transmitted to the space vehicle by transportation and handling systems are determined and evaluated to ascertain whether the loads, stresses, or deflections in the vehicle exceed the allowable levels defined in vehicle design requirements. Although current transportation and handling systems and operational procedures can attenuate most of the loads to acceptable levels, additional considerations related to the space-vehicle design usually are necessary to accommodate the transportation and handling loads. For example, the following methods are used in design to provide load paths for transportation and handling:

- Introduction of loads through existing major load paths of the space vehicle such as bulkheads, frames, longerons, and carry-through structure

- Utilization of ground support equipment to carry critical loads during ground conditions

- Addition of localized structure to the vehicle, such as fittings and back-up structure, where local loads are introduced to the vehicle. This structure may be made removable after the transportation or handling phase is complete

- Pressurization of tanks or compartments to avoid buckling caused by transportation and handling loads

The ability of the transportation and handling systems to protect the space vehicle against the natural environments encountered during transporting and handling is also examined. It is sometimes better to apply the protection directly to the vehicle (e.g., protective paints) rather than depend on packaging to protect it against natural environments.

2.1 Capabilities and Limitations of Transportation Vehicles and Handling Systems

2.1.1 Transport Vehicles

Transporting space vehicles over long distances usually requires the use of more than one mode of transportation. Although air transportation is the long-distance mode most frequently used, space vehicles are moved on highways at least a portion of the route. Large space vehicles exceeding the capacity of existing aircraft are transported by barges and ships. Smaller, relatively heavy components such as solid-rocket motor segments are usually transported by rail.

Transport vehicles such as trucks, aircraft, ships, and rail cars have nominal capacities and limitations which must be accommodated in the conceptual design of space vehicles, particularly large or heavy launch vehicles. The stages must be sized to fit the dimensions and/or weight capabilities of the type of transport vehicle selected. Comprehensive data on dimensional and weight limitations of transport vehicles and information on routes, clearances, port facilities, etc., are contained in references 4 through 27. Restrictions on the transport of hazardous materials, including solid-propellant motors, are contained in references 28 to 30.

2.1.1.1 Highway

Highway transportation is often preferred to the faster air transport because of flexibility of routing, variety of truck-trailer configurations, and lower costs. Even when space vehicles are shipped by other means of transport, they generally must be moved by highway for at least short distances to connect locally with the primary transport mode. Significant physical, structural, operational, and dynamic characteristics and limitations of the components and environments of highway transportation in the United States are given in reference 25. Size and weight limitations for highway transport are summarized as follows:

Size – For long-distance movement, maximum overall dimensions (including transporter and protective equipment) normally cannot exceed 4.57 m (15 ft) in width, 4.57 m (15 ft) in height, and 24.4 m (80 ft) in length. For larger vehicles, the cost of removing or relocating road obstructions generally becomes prohibitive. For short distances, space vehicles up to 13.1 m (43 ft) in overall height or 10.7 m (35 ft) width (Saturn S-II) have been moved by highway, with the exact maximum dimensions determined by a survey of the specific route.

Weight – The maximum transportable weight is controlled by state regulation and is based upon the load-bearing capacity of the highway and its structures. Normally, 266 800 to 444 800 N (60 000 to 100 000 lbf) is the maximum weight that is transportable over long distances. For short distances, weights of 889 600 N (200 000 lbf) and more can be moved by special transporters designed to distribute the load properly over the highway.

2.1.1.2 Water

Water transportation of space vehicles has generally been limited to those vehicles exceeding the weight or size limitations for land, rail, or air transport. Use of this mode has been limited because of such factors as the long transport time in comparison to other methods, the lack of immediately accessible water routes, and the lack of commercial water carriers to the desired destination. In some cases naval transport vessels have been used because commercial carriers were not available. Size and weight limitations of water transport vehicles are summarized as follows:

Size – For short-haul ocean trips and inland waterway transport, barges are available with clear deck areas of up to 57.9 m (190 ft) by 13.4 m (44 ft). However, maximum barge and cargo size for a specific route are determined by bridge clearance, lock widths, and water depth. For ocean transport, the size range of available commercial and military ships (up to aircraft carrier size) permits transport of all present space vehicles.

Weight – There is probably no limitation on the weight of current space vehicles that can be transported by water. The weight-carrying capacity of many ocean-going barges and vessels is much greater than the weight of the heaviest space vehicle.

2.1.1.3 Air

Air transport is generally preferred and used for long-distance transportation of space vehicles where practical. Primary factors favoring the use of air transport are speed (short transit time) and the overall favorable environmental conditions which include limited exposure to the natural environment. However, present aircraft are not capable of carrying the largest space vehicles. The Guppy-type cargo aircraft is used to transport the larger transportable space vehicles. When this type of aircraft is not available, another transportation method must be used or the vehicle delivery schedule must be revised. Occasionally, space vehicle structural segments have been transported by helicopter by external lift (refs. 27, 31, and 32). Size and weight limitations of the largest cargo aircraft are summarized in table I.

TABLE I. – AIR TRANSPORT CARGO CAPABILITY

Cargo Aircraft	Cargo Compartment*			Payload N(lbf)	Range, km (nmi) at payload	Environmental Control (Temperature and Pressure)
	Max. diam, m (ft)	Length, m (ft) at max. diam	Length, m (ft) at 15-ft diam			
B-377 PG (Pregnant Guppy)	6.00 (19.7)	4.21 (13.8)	18.3 (60)	126 600 (28 561)	926 (500)	NO
B-377 SG (Super Guppy)	7.62 (25)	9.36 (30.7)	18.3 (60)	170 000 (38 333)	1019 (550)	NO
B-377 (KC-97) (Mini Guppy)	4.66 (15.3)	22.9 (75)	22.9 (75)	137 800 (31 000)	2222 (1200)	NO
ASI-377 SGT (New Version of Super Guppy)	7.62 (25)	9.36 (30.7)	24.4 (80)	231 000 (52 000)	880 (475)	NO
C-5A	4.11 (13.5)	36.9 (121)	N.A.	1 178 000 (265 000)	4630 (2500)	YES
C-141	2.74 (9)	24.4 (80)	N.A.	253 000 (57 000)	7410 (4000)	YES
C-130 (Comm'l Equiv L-100)	2.44 (8)	12.2 (40)	N.A.	164 300 (37 000)	5000 (2700)	YES
747 F, Q'C	2.44 (8)	53.9 (177)	N.A.	1 155 000 (260 000)	5000 (2700)	YES
S-64 Helicopter	N.A.	N.A.	N.A.	111 000 (25 000)	37** (20)	NO

*Transport of space vehicles approaching the maximum envelope for payload capability of the aircraft must be coordinated with the aircraft operator to assure that clearances, weight, and cargo c.g. are within aircraft limitations.

**Range increases as payload is decreased.

2.1.1.4 Rail

Rail transport is not frequently used for complete space vehicles and many large or shock-sensitive space vehicle components because of its size limitations, long transit times, and unfavorable induced loads (e.g., high shock loads resulting from the coupling of rail cars), and because of lack of rail facilities at sending and receiving locations. Size and weight limitations of rail transport systems are summarized in the following paragraphs:

Size – Maximum overall dimensions of the rail car and protective equipment normally do not exceed 4.57 m (15 ft) in height, 4.57 m (15 ft) in width, and 15.2 m (50 ft) in length for long-distance movement. These restrictions are due to permanent obstructions such as tunnels, bridges, and railroad control equipment. For short distances, however, longer vehicles may be moved, with the exact maximum dimensions being determined by surveys of the specific route.

Weight – The maximum transportable weight is based upon the load-bearing capacity of the road-bed and railroad structures. Normally, weights of 533 700 N (120 000 lbf) can be transported without making special arrangements with a given railroad. Weights of 2 668 800 N (600 000 lbf) have been transported, but detailed planning and coordination were required.

2.1.2 Handling Systems

Handling methods for space vehicles are classified in this monograph as lifting, manipulation, and transfer.

2.1.2.1 Lifting

Lifting is accomplished with overhead hoists, portable cranes, or mobile power units, such as forklifts and lift-bed trucks. Interface connections for lifting are usually made with the space vehicle slings or adapter fittings attached either directly to hard points on the vehicle or to wide belts wrapped under it and designed to distribute the lifting loads to prevent excessive local distortion or damage of the vehicle structure. Pneumatic ring-type clamps are also used in hoisting. Although no attach points are needed with this method, the vehicle structure must be rigid enough to resist the clamp pad loads.

2.1.2.2 Manipulation

Manipulation is accomplished by rotation, positioning, or erection of the space vehicle with structural provisions similar to those required for lifting. Rotation about the

longitudinal axis of a space vehicle in the horizontal position is accomplished by means of adapter rings attached to hard points on the vehicle and supported by trunnions or cradles with roller mechanisms. Alternatively, the vehicle may rest directly on the roller cradles if the exterior surface of the space vehicle is smooth and sufficiently rigid.

In the vertical position, the vehicle can be rotated either by hoisting it free of the resting points and rotating about a swivel in the hoisting system, or by rotating the base structure on which the vehicle rests.

Some space vehicles are erected (i.e., moved from the horizontal to vertical position) while in a special transporter or shipping container; in such cases, added restraint of the space vehicle to the transporter or container is generally required. Erection is also accomplished by hoisting operations similar to lifting. In some instances, cranes or hoists are attached to both ends of the vehicle.

2.1.2.3 Transfer

Movement of vehicles over short distances while in a horizontal attitude, usually within the manufacturing site or after delivery to the launch site, is accomplished by methods and equipment similar to those used for shipment. Structural requirements for interface of vehicles with the handling equipment are substantially the same as those used for shipment.

Mobile launch platforms have been used to move large space vehicles such as the Saturn V and Titan III in the vertical attitude. The space vehicle tie-down structure at the interface with the mobile launch platform is designed to resist overturning loads, such as those induced by wind or accelerations of the mobile platform. The mobile platforms are operated at very low speeds to minimize shock, vibration, and inertia loads.

2.2 Accounting For Induced Loads and Natural Environments During Transportation and Handling

The various loads induced on a space vehicle during transportation and handling are accounted for in the structural design of the vehicle. In addition, the vehicle structure is protected against potentially detrimental effects from natural environments

encountered during transportation and handling, such as corrosive atmosphere or precipitation.

2.2.1 Induced Loads

The induced loads of concern are those induced on the vehicle by the transportation and handling systems.

2.2.1.1 Load Sources and Inputs

Sources of induced loads are primarily shock and vibration encountered during transportation; differential pressures in unvented structures such as tanks, caused primarily by changes in altitude during transportation; loads resulting from attachment of handling devices and subsequent handling operations; and loads due to attachment of transport restraint devices (tiedowns) and transport dollies or fixtures and the subsequent acceleration and/or distortion (e.g., racking) of the transport vehicles.

Reference 1 deals with the prediction and verification of transportation and handling loads for space vehicle structure. These loads must, together with tie-down loads and any differential-pressure or other loads, be utilized as inputs in an analysis to determine the vehicle response to these inputs in the form of stresses, internal loads, and deflections.

2.2.1.2 Vehicle Response Analysis

Response analyses for the space vehicle and supporting system are performed with conventional analytical methods. The static-load analysis and stress-analysis techniques employed are widely documented in many references (e.g., ref. 33). Dynamic response analyses generally require mathematical modeling of the stiffness and inertial properties of the combined space vehicle, support, and transportation systems. Some mathematical modeling techniques are discussed in references 3, 34, and 35.

A frequently used analytical method for obtaining dynamic response is to (1) determine the natural frequencies and mode shapes of the space vehicle structure as functions of nondimensional deflections (ref. 36), (2) use empirical data to determine amplification factors as functions of natural frequencies, and then (3) determine the maximum dynamic deflections. These deflections are converted to equivalent static loadings for individual-member stress analysis. As part of the stress analysis, the structure of the space vehicle is analyzed for failure or excessive deflection due to applied loads during transportation and handling.

2.2.1.3 Fatigue Analysis

Reduction in fatigue life of the space vehicle structure may result from many repetitive loadings during extensive transportation and handling. This effect is considered in the structural analysis by using methods such as those described in reference 37.

The designer or structural engineer is responsible for accounting for the expected repeated loadings throughout the vehicle's entire life (service-life loading spectrum), which includes transportation and handling. If the fatigue analysis indicates that transportation and handling loads may critically reduce the vehicle's fatigue life, modifications of the transportation and handling systems are made, as feasible, to reduce the loads or cycles to an acceptable level. Only as a last resort is the space vehicle design modified to enable it to withstand such loading.

2.2.1.4 Design for Transportation and Handling Loads

When the transportation and handling modes are selected, convenient hard points on the space vehicle—those capable of carrying support loads—are identified. Hard points usually are located on existing frames, bulkheads, or longerons that can adequately redistribute localized hard-point loads to the adjacent structure. Transportation and handling systems which attenuate vibration and shock-load input to these hard points are then selected. Structural modification to provide special hard points is avoided whenever possible.

Local failure of the external surface may result because the reactions at the supports may act as concentrated loads on the skin; therefore, the skin adjacent to the hard points is analyzed for local failure. If this analysis shows that the structure cannot sustain the transportation and handling loads, the support system is usually changed to provide a better load distribution. If necessary, critical areas of the skin can be reinforced locally for transportation using temporary or permanent reinforcement. (Permanent reinforcements are not desirable because of the added weight.)

Some methods that have been used to attenuate dynamic loads are:

- Controlling input loads from the transport vehicle by selection of a specific kind of vehicle, location in the vehicle, method of tiedown, and vehicle speed

- Placing shock and vibration attenuators (e.g., rubber mounts, steel springs, or hydraulic shock absorbers) between the transport vehicle and the space vehicle

- Providing damping to minimize vibration amplification at resonant frequencies
- Removing concentrated masses and shipping separately
- "Tuning" natural-frequency, shock-and-vibration-attenuation systems to avoid discrete frequencies
- "De-tuning" or reinforcing a critical element by adding temporary devices during handling or transport

Attenuation methods and materials are discussed in reference 38.

2.2.2 Natural Environments

Exposure to the natural environments during transportation and handling, including temporary storage, can cause a number of potentially detrimental effects on space vehicle structure; the structure must be protected from these effects either by the transportation and handling system or by the vehicle structural design. One means of identifying the significant environments for the space vehicle during transportation and handling is with the use of a logistics flow chart. The chart is used to specify in detail the various phases of the transportation and handling process and leads to the identification of the applicable natural environments. The severity, statistical frequency, and combinations of the environments are subsequently determined. Guideline data on natural environments are given in reference 39.

2.2.2.1 Environmental Effects

The natural environments to which space vehicles are most often exposed during transportation and their principal damaging effects are shown in table II. Environmental extremes which may be encountered during air, surface, and shipboard transport are presented in reference 40.

Other natural environments, including solar radiation, ozone, sand/dust, electromagnetic and particle radiation, lightning, and electrostatic discharge, do not represent major hazards for space vehicle structures during transportation and handling. These environments, however, may be hazardous to specific systems within the vehicle or may affect the characteristics of the transportation and load-attenuation system.

2.2.2.2 Protection from Natural Environments

Protective measures such as the following are often incorporated in vehicle structural design to minimize the detrimental effects of natural environments:

- Corrosion- and stress-corrosion-resistant structural materials, protective paints, or chemical coatings

- Non-moisture-absorbent materials or moisture-barrier coatings

- Skins resistant to hail impact

TABLE II. – DAMAGE FROM NATURAL ENVIRONMENTS DURING TRANSPORTATION AND HANDLING

Natural environment	Principal damaging effects
Precipitation (rain, snow, sleet, hail) Salt spray High humidity Smog (industrial areas)	Corrosion and stress-corrosion cracking – leading to structural failure. Moisture absorption –resulting in an overweight flight condition. Impact or erosion damage (e.g., hail)
High/low temperatures	Thermal expansion or contraction leading to structural failure; embrittlement at low temperature, leading to cracking of solid propellants; high-temperature aging, leading to deterioration of solid propellants
Wind	Application of excessive wind loads, leading to structural failure or overturning. Erosion from blowing sand and dust
Pressure changes with altitude	Collapse of improperly vented tanks, compartments, components, or protective containers from differential pressures sustained during altitude changes while being transported

Temporary environmental protection is usually provided during transportation by one, or a combination, of the following methods:

Control of Precipitation, Humidity, and Salt Spray – Space vehicles transported in these environments are protected by:

- Environmentally controlling transport vehicles or containers to provide humidity control and keep out precipitation and salt spray

- Desiccating the compartments or tanks with dry gas such as N_2 and sealing the compartments

Temperature Control – When temperature control is critical, shipment is usually made in a temperature-controlled transport vehicle or container. Temperature may be controlled by heating and cooling equipment or by passive means such as a heat sink with suitable control over the time of exposure to extreme temperatures. Shipment may also be made by special routes or by specific transport modes to avoid exposure to extreme temperatures.

Wind Protection – Space vehicles are shipped in closed transport vehicles or containers whenever possible to avoid exposure to the wind environment. The container or transport fixture is designed to resist overturning by wind loads.

Control of Pressure Changes – It is necessary to protect vehicle structure from differential pressures which may occur in sealed or inadequately vented tanks and compartments because of changes in altitude during transport, particularly in unpressurized aircraft. Reference 2 provides design practices and criteria for compartment venting.

Control of Other Environments – Protection of the space vehicle structure is not usually required for other environments such as solar radiation, ozone, sand/dust, electromagnetic and particle radiation, lightning, and electrostatic discharge. However, protective covers are often provided to shield specific systems from sand or dust and electrostatic discharge; these covers are generally the same ones used for moisture and humidity control. Protection from lightning or electrostatic discharge to prevent ignition of solid propellants or explosive devices is accomplished by grounded conductive covers or containers and transport shields that prevent buildup of static charges.

2.3 Transporting and Handling Various Types of Space Vehicles

2.3.1 Liquid-Propellant Launch Vehicles

Liquid-propellant vehicles have thin skins because they are designed primarily to withstand low internal pressures. These large structures may be difficult to transport, when empty, because of their size and the sensitivity of their thin skins to external loads and pressures. Individual vehicle segments or stages have been transported on cradles supporting the lower one-third of their circumference in an area of adequate stiffness, such as a bulkhead or stiffening ring. Since this arrangement does not support

the entire circumference, there is a tendency for the vehicle to distort in cross section under externally applied loads; therefore, this support method is usually feasible only for smaller vehicles which have relatively rigid exterior surfaces.

As the vehicle's diameter increases, the requirement for rigid ring-type support fixtures becomes more prevalent. The rings may be attached to either the stage-interface attach fittings or to reinforced hard points located in rigid areas of the skin. Attachment to the interface fittings is normally preferred because the interface structure is usually capable of sustaining the handling and transportation loads without the need for additional structural members.

For transportation of large stages, the transporter is often designed to minimize induced loads resulting from road slope or distortion of a ship's deck during rough seas. One method provides a 3-point suspension system for the vehicle cradle system, permitting the single forward suspension point to pivot in relation to the two aft suspension points. In addition, a stabilizing mechanism senses uneven surfaces and raises or lowers the individual wheel assemblies. This system is currently used by NASA in the marine transportation of large liquid-propellant vehicles. A description of this system, as applied to vehicle transport on the converted LSD (AKD-1) ocean-going barge, is presented in references 41 and 42.

Because of their flexible, thin-shell construction, some of the larger launch vehicles cannot sustain small external pressures or even their own weight without buckling. To prevent exposure to damaging pressure differentials during air transportation, the structure is vented to ambient atmosphere through a pressure-relieving device. Some structures are stabilized against buckling under loads or detrimental pressure differentials by providing positive internal pressure with dry air or nitrogen. In either case, an opening is required in the compartment structure to permit venting or pressurization.

2.3.2 Solid-Propellant Launch Vehicles

The problems of handling and transporting solid-propellant vehicles are similar to those of the liquid-propellant vehicles, except that the additional weight of the propellant poses a greater problem in the design of transport fixtures and choice of carrier vehicles. Because of their weight, which is two or three orders of magnitude greater than the weight of empty liquid-propellant vehicles, some large solid-propellant vehicles have been manufactured and shipped in segments, with a resultant flight-weight penalty due to the segment joints; however, a recent handling study of a solid-rocket motor [6.6 m (260 in.) diam. by 40.5 m (133 ft) length, with a weight of approximately 4 448 000 N (1 000 000 lbf)] indicates that transport without segmentation is possible (ref. 43). Another technique for handling and transporting

large solid-rocket motors is given in reference 44. The walls of solid-propellant rocket vehicles or motor segments are quite thick because their operating pressures are significantly higher than those of liquid-propellant vehicles. The buckling strength of the solid-rocket motor case is also higher because of the thicker wall and some additional support from the contained solid propellant. This combination of increased wall thickness and buckling strength therefore often allows the much heavier solid-propellant vehicles and motor segments to be handled like the empty liquid-propellant vehicles, namely by using cradles or ring-shaped fixtures attached to segment or motor attach points.

The solid-propellant motors are normally transported in temperature-controlled containers or transport vehicles to prevent differential-strain cracking in the propellant, separation of the bond between the propellant and motor wall structure, or excessive deformation of the propellant. To prevent inadvertent ignition, the propellant is protected from electric sparks and high-temperature sources, and grounding cables are mandatory for all handling operations.

Solid-propellant rocket motors are frequently transported by rail. To provide protection against loads induced in transit; however, the container or transport vehicle usually has shock-attenuation devices. In one program, the carrier vehicle was a 889 600 N (200 000 lbf) capacity hydraulically cushioned railroad flatcar capable of mitigating 18-g longitudinal shocks at the coupler to 1.8 g on the motor (ref. 45). Another suspension carriage was equipped with torsion-bar springs and hydraulic shock absorbers, and with running gear compatible with tracks installed in the shipping containers and transport vehicle (ref. 46).

2.3.3 Spacecraft and Scientific Payloads

Many spacecraft and scientific payloads are small enough to be transported by means of any transport mode. When feasible, they are transported in an attitude (usually vertical) that will allow the major transportation loads to be applied in the same direction as the axial flight loads. Distribution and/or reduction of loads is often provided by special handling fixtures, or by internal pressurization if the spacecraft has a pressure-stabilized structure.

Transport fixtures or containers for these structures generally have an integral system for attenuating shock and vibration. Temperature and humidity control is provided, as required, for protection against the natural environment. In some cases, spacecraft are shipped with explosive-actuating devices installed, and grounded conductive covers are used to dissipate static electricity; where possible, however, the explosive devices are removed for separate shipment and later installed at the launch site.

The Apollo CSM is an example of a large spacecraft shipped by air; the transport fixture uses rubber shear mounts for attenuation of shock and vibration. The spacecraft is enclosed in a sealed envelope with a desiccant for humidity control and is protected from low-temperature extremes by an electrical-resistance heating blanket. The surface of the spacecraft is protected from accidental impact by a rigid plastic cover (ref. 31).

2.4 Verification of Structural Compatibility With Transportation and Handling Systems

The structural compatibility between the transportation and handling systems and the space vehicle structure is normally verified initially by load and deflection analyses (as described in Section 2.2) to insure that the loads transmitted to the space vehicle result in vehicle stresses, internal loads, and deflections that are within allowable levels as specified in the design requirements.

Methods of experimentally verifying the analysis are varied in current practice. On the basis of engineering judgment as to the validity of the analysis, verification sometimes consists only of the use of minimal instrumentation to obtain limited data on the loads input to the vehicle or data on the vehicle responses at a few critical locations. At the other extreme, the experimental data may include both input loads and vehicle responses (stress, internal loads, deflections, accelerations, and frequencies) at most or all critical points.

Such testing is usually done on a test vehicle or, in many cases, loads are measured on production vehicles during the actual handling and delivery cycle (ref. 1). For example, the responses at selected locations on each Scout vehicle are continuously recorded during shipment.

Visual fit check is often used to verify such factors as clearance in the carrier vehicle or fit of the handling and transport equipment to the space vehicle. Also, for space vehicles where natural environments such as the temperatures and pressures encountered during transportation and handling are expected to be critical, monitoring measurements are made during transportation and handling to verify the adequacy of temperature- and pressure-control systems. Examples of some typical test programs and their results are presented in references 47 through 50.

3. CRITERIA

The space vehicle and its separable components, either individually or when combined, shall be capable of being handled and transported from the fabrication site to the final launch position without degradation of vehicle flightworthiness. The vehicle design shall be compatible with the transportation and handling system to the extent that (1) the size and weight of the vehicle or its transportable stages and segments shall not exceed the limitations of feasible transportation and handling systems; (2) no loads are induced on the vehicle during transportation and handling which will produce excessive stresses, internal loads, or deflections; and (3) the vehicle is adequately protected against the natural environment during transportation and handling. Verification of the compatibility of the space vehicle and its transportation and handling systems shall be demonstrated by suitable analysis and, as required, by experimental monitoring of actual transportation and handling loads, responses, and environments.

3.1 Compatibility of Structural Design With Transportation and Handling Systems

The space vehicle shall be designed to be transported and handled without degradation of flightworthiness from its manufacturing site to the final launch position by means of state-of-the-art transportation and handling systems. At least the following vehicle characteristics shall be analyzed during design for compatibility with the candidate transportation and handling systems:

- Size and configuration
- Weight
- Attitude
- Potentially hazardous components (e.g., radioactive or explosive components
- Sensitivity to shock and vibration
- Tolerance to the natural environment
- Strength and rigidity

3.1.1 Accounting for Induced Loads

The stresses, internal loads, and deflections of the space vehicle's structure in response to the load inputs from transportation and handling shall be determined analytically.

In addition, the predicted load spectrum from transportation and handling shall be included in the fatigue analyses of the space vehicle structure.

Whenever feasible, transportation and handling loads that would induce stresses, internal loads, or deflections in space vehicle structure that exceed the allowable levels specified in vehicle design requirements, or that would unacceptably degrade the fatigue life of the structure, shall be suitably attenuated by modification of the transportation and handling systems. If such modification cannot adequately attenuate these loads, then the space vehicle structure shall be modified so that it can adequately withstand these loads.

3.1.2 Accounting for Natural Envionments

The space vehicle shall be protected against detrimental effects of the natural environments encountered during transportation and handling, including temporary storage. At least the following natural environments as they affect the space vehicle shall be accounted for by suitable analyses and/or tests:

- Precipitation (e.g., rain, snow, sleet, and hail)
- Salt spray
- Humidity
- Temperature
- Wind
- Differential pressure
- Sand and dust
- Radiation (electromagnetic and particle)
- Static electricity

3.2 Verification of Structural Compatibility With Transportation and Handling Systems

Unless the analysis shows that vehicle response to transportation and handling loads is clearly not critical, the analytically predicted stresses, internal loads, and deflections

from transportation and handling shall be verified by experimental measurements on test or production vehicles.

Input loads and potentially critical stresses, internal loads, deflections, accelerations, and frequencies shall be experimentally monitored at selected locations on production vehicles as necessary to determine whether predicted levels are exceeded during transportation and handling.

Potentially harmful environments shall be experimentally monitored during transportation and handling, including temporary storage, of production vehicles, as necessary to insure that allowable levels have not been exceeded.

4. RECOMMENDED PRACTICES

The interactions between space vehicle structure and its transportation and handling systems should be properly accounted for throughout the structural design process. Verification of their satisfactory compatibility should be demonstrated for the completed designs. Close coordination should be established and maintained throughout vehicle development between the project structural designers, transportation and handling-system designers, logistics engineers, and packaging designers in order to achieve these goals.

The characteristics of the candidate transportation and handling system should be evaluated in relation to the characteristics of a projected vehicle design. This evaluation includes determination of the natural environments and the levels of shock, vibration, and other induced loads which may be encountered. The effects of the anticipated induced loads and natural environments on the vehicle are analyzed to determine the structure's adaptability to the candidate modes of transportation and handling. If the vehicle cannot withstand these effects, suitable means of attenuation or protection should be provided by the transportation or handling systems. When this is not feasible, modification of the space vehicle structure should be considered. The foregoing design procedure should then be iterated as the design progresses until, for the final design, satisfactory compatibility between the space vehicle structure and its transportation and handling systems has been demonstrated by a suitable combination of analyses and tests.

4.1 Compatibility of Structural Design With Transportation and Handling Systems

Throughout its development, space vehicle design should be coordinated with the transportation and handling systems to ensure safe transportability of the vehicle. During the conceptual design phase, the basic structural configuration should be adapted to the characteristics and limitations of feasible transportation modes (e.g., cargo compartment size and weight capacity). Space vehicle transportation and handling problems require preliminary resolution during the conceptual-design phase because they may have far-reaching impact on the program. If the proposed vehicle configuration exceeds the size or weight capacity of available standard transportation and handling modes, the following solutions should be evaluated:

1. Revisions of transportation and handling system

   - Modify existing system

Develop new transportation devices or system

2. Revisions of space vehicle design

   - Segment into stages of acceptable size and move individual stages separately

   - Segment below stage level

   - Revise size or proportions of vehicle and/or stages

   - Fabricate and assemble at launch site

During the detail design phase, the structural designer should ascertain that stresses, internal loads, and deflections will not exceed the allowable levels specified in the design requirements and that adequate protection will be provided against the anticipated hazards of the induced and natural environments encountered during transportation and handling.

4.1.1 Accounting for Induced Loads

Recommended design procedures to account for induced transportation and handling loads on a space vehicle are as follows:

- Determine the various loads predicted during transportation and handling in the form of load inputs to the space vehicle

- Using these load inputs, perform vehicle response analyses to determine vehicle stresses, internal loads, and deflections and to formulate load spectra for fatigue-life analysis

- Utilize the transportation and handling load spectra in the fatigue analyses for the space vehicle

- If the fatigue life is less than the level specified in the design requirements, or if the vehicle stresses, internal loads, and deflections exceed the allowable levels specified in design requirements, and if feasible modifications to the transportation and handling systems do not acceptably modify these levels, then the space-vehicle design must be changed

4.1.1.1 Determination of Load Sources and Inputs

The dynamic loads from the selected transportation and handling system should be determined at the interface of the space vehicle with its transportation and handling system, using one or more of the following methods (ref. 1):

- Analysis using limit load factors
- Analysis of partial system with composite load-bed inputs
- Scaling and extrapolation from similar system experience
- Analysis of full system with transportation medium inputs

Additional loads such as static tie-down loads should be estimated by analytical methods such as those in reference 33.

4.1.1.2 Space-Vehicle Response Analysis

The induced-load inputs to the space vehicle should be used in static and dynamic analyses to determine the vehicle responses to these input loads in the form of stresses, internal loads, and deflections.

The natural vibration frequencies and mode shapes in nondimensional form should be calculated for the space vehicle with the methods recommended in reference 36. The nondimensional modal data should be combined with the input dynamic loads in a dynamic response analysis using the practices described in reference 3 to determine the amplification factors and arrive at the maximum response deflections. A mathematical model for these analyses should be formulated with the techniques described in references 3, 30, and 36. The calculated response values should be converted into equivalent static loadings, which should then be combined with static load inputs. A stress analysis using accepted methods such as those of reference 33 should be performed to determine the internal stresses and verify the structural integrity. The dynamic response analysis should also compute the cumulative number of cycles of the dynamic load inputs and should formulate load spectra for the fatigue analysis.

If changes in atmospheric pressure are expected during transportation and handling, a structural analysis should be performed to determine the critical collapsing pressure of the space vehicle tanks or compartments. If the tanks or compartments cannot safely withstand the applied collapsing pressure during transportation and handling, the tank or compartment should be vented to ambient atmospheric pressure, or a positive internal pressurization system should be provided to prevent collapse.

4.1.1.3 Fatigue Analysis

Reduction of the structure's fatigue life caused by repetitive loadings during transportation and handling should be evaluated by a fatigue analysis with generally accepted methods (e.g., ref. 37). The objective of this analysis is to show the ability of the structure to withstand combined repetitive transportation, handling, and flight loads, to identify critical areas for redesign, or to identify the need for attenuation or reduction of the magnitude or number of the repeated loadings.

4.1.1.4 Design for Induced Loads

The interfaces between a space vehicle and its transportation and handling systems should be designed to use the existing load paths on the space vehicle, such as frames, bulkheads, or longerons, which are capable of distributing the localized transportation and handling loads to the adjacent space vehicle structure. Ideally, the only addition to the flight vehicle's structure for accommodating transportation and handling loads should be the local fittings and local reinforcements necessary to introduce the externally induced loads into the existing load paths. However, all structures adjacent to support points should be analyzed and strengthened, if necessary.

Critical stress concentrations (e.g., small fillets, notches, and holes) in parts subjected to fatigue loadings from transportation and handling should be identified. Where fatigue life is critical, the stress concentrations should be reduced or eliminated (ref. 35), since a small reduction in the operating-stress level will generally result in a much longer fatigue life. When the loads induced by transportation and handling are greater than the allowable loads specified in the design requirements, they should be eliminated or at least attenuated by modifying the transportation mode and/or by developing a load-absorbing package or handling fixture for the vehicle. This procedure is recommended because strengthening the vehicle's structure to sustain excessive nonflight loads usually increases its weight.

Recommended attenuation methods include the following, singly or in combination:

- Use of suitable shock and vibration attenuators between the transport carrier and the space vehicle, including elastomeric mounts, mechanical/fluid springs, and distributed resilient cushioning material; the attenuation system must be adjusted to avoid excessive amplification of the response of the space vehicle under resonant conditions

- Selection of a special carrier vehicle with built-in shock and vibration attenuators (e.g., a shock-controlled truck or rail car)

- Control of transport speed

- Removal of concentrated masses for separate shipment

- Reinforcement of critical elements with temporarily installed structure

When modifications such as these are made, the mathematical model or the input loads should be changed, as appropriate, and the responses should be re-analyzed. When modifications to the transportation and handling systems do not attenuate the stresses, internal loads, or deflections in the vehicle below allowable levels as specified in design requirements, the space vehicle structure should be modified to withstand the input loads.

4.1.2 Accounting for Natural Environments

The natural environments which will be encountered during transportation and handling, including temporary storage, should be identified and quantitatively described. These quantitative levels should then be compared with the capability of the space vehicle to resist those environments, and the need to control or completely eliminate the effects of the natural environments on the vehicle structure should be determined. The natural environments and methods for their control should be considered singly or in combination, as appropriate to the particular application.

The natural environments which generally require consideration and the recommended methods of protection against such environments are listed in table III. These environments are described for U.S. launch sites and some connecting waterways in reference 39.

4.2 Verification of Structural Compatibility With Transportation and Handling Systems

To verify the compatibility of the space vehicle structure with the transportation and handling systems, it is recommended that the final vehicle design and its transportation and handling systems comply with the following requirements:

- The results of the vehicle response analysis (Section 4.1.1.2) should show the stresses, the internal loads, and deflections to be less than the allowable levels specified in the design requirements

- A fatigue analysis of the space vehicle structure which includes the fatigue load spectra from transportation and handling (Section 4.1.1.3) should show

TABLE III. – RECOMMENDED METHODS OF PROTECTION AGAINST NATURAL ENVIRONMENTS

Natural environment	Recommended protective methods
Precipitation (rain, snow, sleet, and hail)	Corrosion- and stress-corrosion resistant structural materials Protective paints or chemical coatings (general corrosion) Non-moisture-absorbent materials or moisture barrier coatings Skin surface resistant to hail impact (thick skins) Closed transport vehicle or container
Salt spray	Corrosion- and stress-corrosion resistant structural materials Protective paints or chemical coatings (general corrosion) Closed transport vehicle or container
Humidity	Corrosion- and stress-corrosion resistant structural materials Protective paints or chemical coatings (general corrosion) Non-moisture-absorbent materials or moisture barrier coatings Closed transport vehicle or container Dehumidification system for transport vehicle or container Seal tanks or compartments and dehumidify, using dry gas (such as N_2) or dehydrating agent (such as silica gel)

TABLE III. – RECOMMENDED METHODS OF PROTECTION AGAINST NATURAL ENVIRONMENTS (Continued)

Natural environment	Recommended protective methods
Temperature	Auxiliary temperature-control equipment accompanying or mounted on the vehicle or vehicle container Temperature-controlled transport conveyance Special transport routing or restriction to specific modes of shipment Container insulation together with suitable control over the time of exposure to extreme temperature Reflective coatings
Wind	Closed transport vehicle Closed container Protective covers Supports to resist overturning moment
Differential pressure	Adequate venting Positive internal pressurization system
Sand and dust	Closed transport vehicle Closed container
Radiation	Protective covers
Static electricity	Grounded conductive covers

that the structure's fatigue life exceeds the expected vehicle life by an acceptable margin

- The effect of the predicted natural environments on the space vehicle structure when protected by its transportation and handling systems (Section 4.1.2) should not impair its integrity

Except where engineering judgment indicates that the vehicle responses determined by analysis are obviously not critical, experimental measurements of stress, internal load, and/or deflection should be made on test or production vehicles. As an example, the following practice may be used to verify structural compatibility with transportation and handling systems:

- Experimental measurements to determine vehicle responses (stresses, internal loads, and deflections) at analytically predicted critical locations should be made throughout at least one transportation and handling sequence on an engineering, prototype, or production space vehicle whenever the analytically determined responses (Section 4.1.1.2) are equal to or greater than 50 percent of the allowable levels specified in the design requirements

- Experimental measurements to monitor vehicle responses (stresses, internal loads, and deflections) at predicted most critical locations should be made throughout transportation and handling of all production models of a space vehicle if either or both of the following conditions exist:

  (1) A difference of 10 percent or less exists between the analytical (Section 4.1.1.2) and test (preceding paragraph) responses of the space vehicle to transportation and handling, but analysis and/or tests show response values equal to or greater than 70 percent of the allowable levels specified in the design requirements

  (2) A difference of greater than 10 percent exists between the analytical (Section 4.1.1.2) and test (preceding paragraph) responses of the space vehicle to transportation and handling and analysis and/or tests show response values equal to or greater than 50 percent of the allowable levels specified in the design requirements

When the predicted natural environments during transportation and handling, including temporary storage, are expected to impose conditions that threaten to impair the vehicle's structural integrity unless their effects are attenuated or controlled, the controlled environment should be monitored (maximum or continuous values, as appropriate) during production shipments to verify that the allowable limits specified in design requirements have not been exceeded.

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