UPDATED REQUIREMENTS FOR PRESSURIZED SPACE SYSTEMS

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ABSTRACT

Since the mid 1980s, pressure vessels and pressurized components used in military space systems have been designed to comply with MIL-STD- 1522A, "Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems." In recent years, many civilian space programs including NASA projects have adopted this standard. However, there are still some technical areas that are not covered in MIL - STD- 1522A. Furthermore, there are no requirements for ground support equipment. For these reasons, a rewrite has been initiated. This paper presents the proposed major changes and their technical rationale. The new requirements for pressurized structures such as die core vehicle of a launch system will be discussed in detail.

INTRODUCTION

Space systems such as satellites, launch vehicles, space shuttle and its payloads often contain pressure vessels and other pressure components. Launch vehicle fuel and oxidizer tanks, satellite propellant tanks, pressurant tanks and pressure components such as valves and fittings are typical examples. Any pressure vessel containing compressed gas constitutes a potential hazard because of the risk of inadvertent release of the stored energy. If a highly pressurized vessel bursts, the stored energy can be converted to hazardous fragments and a destructive blast wave. A leaking propellant tank is equally dangerous because propellants such as nitrogen tetroxide and hydrazine present toxicity and flammability hazards to personnel during ground handling and installation. From a mission reliability point of view, a leaking pressure vessel or other pressure component is clearly not acceptable.

Currently, all pressure vessels used in military space systems are designed, analyzed, and qualified per MIL - STD- 1522A, "Standard General Requirements for Safe Design and Operation of pressurized Missiles and Space Systems" [1]. The original version of this standard, MI L- STD- 1522 [2], was issued in the early 1970s. The primary reason for developing this document was to establish the design and testing requirements for pressurized missiles and aerospace vehicle equipment (AVE) in space systems. Because of the weight restrictions, most of the AVES cannot comply with the ASME Boiler and Pressure Vessel Codes [3], which require a burst factor of 4. "1522" allowed a minimum burst factor of 2, and a proof factor of 1.5 for all AVE pressure vessels. As the demand for performance increased, most of the space programs cut down the pressure vessel weight even more. At the end of the 1970s, a burst factor of 1.5 was widely used. The severe reduction of the ultimate safety factor has caused the decrease of damage tolerance capability of the pressure vessel substantially. To assure a high level of confidence in achieving safe operation and mission success, the United States Air Force (USAF) requested the revision of MIL-STD- 1522 primarily to include the safe-life requirements for pressure vessels that exhibit brittle fracture failure mode or contain hazardous commodity. Issued in 1984, this revision, which is known as "1522 A," contains detailed requirements for the design, analysis, fabrication, testing, quality assurance, operation, and maintenance for pressure vessels and pressurized systems used in AVE. Descriptions of this document and examples of how to Implement the safe-life requirements have been summarized by Chang [4]. At present, MIL-STD- 1522A is considered to be the most widely used requirement document for pressurized space systems in the space industry, Many civilian space programs including National Aeronautics and Space Administration (NASA) space shuttle payloads and space station have adopted this standard [5,6]. However, as was pointed out by Lou and Sutharshana [7], there are still some outstanding issues which are not covered in this document. These include damage tolerance control of composite pressure vessels, nondestructive inspection of thin-walled pressure vessels, and treatment of the residual stresses. Other

Proof Pressure (C)

The product of MEOP and a proof factor and a factor accounting for the difference in material properties between test and expected service environments (such as temperature). The proof pressure is used to provide evidence of satisfactory workmanship and material quality and/or establish maximum initial flaw sizes for safe-life demonstration.

MAJOR CHANGES IN AVE

One change in AVE requirements is to delete the option allowing pressure vessels to be designed by the "strength of material" approach since this option is already disallowed by both USAF and NASA. Figure I shows the allowed options for pressure vessel design verification. A few other changes in the aerospace vehicle equipment category were made in order to clearly define the requirements for hardware that either has similar functions as pressure vessels but cannot meet their requirements, or has totally different functions. This includes pressurized structures such as the main fuel and oxidizer tanks of a launch vehicle, and special pressurized equipment such as batteries, cryostats, heat pipes, and sealed containers. The following paragraphs highlight the proposed new requirements and provide the technical rationale when appropriate.

PRESSURIZED STRUCTURES

Pressurized structures are designed to cart-y both internal pressure and vehicle structural loads. The main propellant tanks of the launch vehicle are a typical example. Figure 2 showsa typical launch vehicle. Due to the weight constraint, performance demand, and test size limitation, it is not feasible to design and test this kind of hardware to comply with the requirements established for pressure vessels. Hence, different requirements for pressurized structures are developed. Basically, the pressurized structures are classified into two categories: (a) Pressurized Structures with Non - Hazardous Leak-Before-Break (LBB) Failure Mode, and (b) Pressurized Structures with Hazardous LBB or Brittle Failure Mode. Requirements for these two categories are similar in many areas and different in others.

A. Pressurized Structures With Non-hazardous LBB Failure Mode

Structures in this category should not contain any hazardous fluids..

LBB Failure Mode Demonstration

"The LBB failure mode shall be demonstrate . ..."

LBB failure mode can be demonstrated either by analysts or by test. It should show that an initial surface flaw with a flaw shape (a/2c) ranging from O.05 to 0.5 will propagate through the vessel thickness to become a through-the-thickness crack with a crack length ten times the vessel thickness and still stay stable when subjected to MEOP. If the demonstration is done by analysis, the state-of-the-art fracture mechanics and reliable fracture and crack growth data should be used.

Factor of Safety

"Unless otherwise specified, metallic *pressurized structures which satisfy the LBB failure mode, may be designed* with a *minimum ultimate safety of factor of 1.25 for unmanned systems and 1.40 for manned systems. "*

For weight constraint and performance demand, the pressurized structures in general cannot be designed to meet a 1.5 minimum ultimate design safety factor. Experience showed that most expendable launch vehicles (ELVs) are designed to a 1.25 design safety factor with a high success rate. For manned systems such as the space shuttle and its payloads, a 1.4 design safety factor is required.

Fatigue-Life Demonstration

"Conventional fatigue-life analysis shall be performed on the unflawed structure,... A life factor of five (5) shall *be used* in *the* analysis. " .

Qualification Testing

"Qualification testing shall be conducted on flight-quality hardware to demonstrate structural adequacy of the design. Because of the potential test size limitation, the qualification testing may be conducted on the component level, provided that the boundary conditions are correctly simulated. The loading sequences, combination *of* loading *conditions, load levels and durations, pressure, and* environments *shall demonstrate that design requirements have been met.* Qualification *testing shall include the pressure test and burst test,.,,..".*

Since most of the pressurized structures are rather large, the provision for allowing the qualification testing conducted at components is needed. Furthermore, since the pressurized structures are designed to carry both the vehicle loads (acceleration loads) and internal pressure, it is extremely important to apply external loads in combination with internal pressure at proper sequence, levels and durations, etc. The effects of environment conditions such as high temperature or cryogenic temperature on structural materials should be accounted for.

"a. Pressure Cycle Test

Requirements for application of external loads in combination with internal pressure during testing shall be evaluated based on the relative magnitude and on the destabilizing effect of stresses due to the external loads. If limit combined tensile stresses are enveloped by the MEOP stresses, the application of external load is not required. The peak pressure shall be equal to the MEOP during each pressure cycle, and the number of cycles shall be four (4) times the predicted number of operating cycles or 50 MEOP cycles, whichever is greater. If the application of external loads is required, the external loads shall be cycled for four (4) times the predicted number of operating cycles of the most severe design condition. For example, destabilizing load with constant minimum internal pressure or maximum additive load with MEOP.

b. Burst Test

After the pressure cycle testing, the test article shall be pressurized (pneumatically or hydrostatically, as applicable and safe) to the design burst pressure, while simultaneously applying the ultimate external loads, if appropriate. The design burst pressure shall be maintained for a period of time sufficient to assure that the proper pressure is achieved. Unless otherwise specified, the minimum design burst pressure shall be 1.25 times MEOP for unmanned systems, and 1.4 for manned systems."

Because there are many differences between a pressure vessel and a pressurized structure, the qualification test requirements of these two types of hardware are not the same, especially the number of applied pressure cycles. Other differences are: there is no requirement for random vibration testing, and it requires only one qualification test article. Furthermore, there is no requirement to carry the burst test all the way to failure. Table I shows the comparisons of the requirements on pressure vessels and pressurized structures.

Acceptance Test

"Acceptance tests shall be conducted on every pressurized structure before commitment to flight .... The following are required as a minimum.

a. Nondestructive Inspection

A complete inspection by the selected NDI technique(s) shall be performed prior to establishing the initial condition of the hardware.

b. Proof Pressure Test

Every pressurized structure shall be proof tested to verify that the materials, manufacturing processes, and workmanship meet design specification and that the hardware is suitable for flight. The proof pressure shall be 1.1X MEOP."

B. Pressurized Structures With Hazardous LBB or Brittle Failure Modes

For pressurized structures exhibiting brittle fracture failure mode or for those containing hazardous fluids such as the fuel tanks, additional fracture control which consists of safe-life demonstration and nondestructive inspection should be implemented.

Safe-Life Demonstration

Safe-life analysis of each pressurized structure should be performed under the assumption of pre-existing initial flaws or cracks in the structure. In particular, the analysis should show that the pressurized structure with flaws, placed in the most unfavorable orientation with respect to the applied stress and material properties, of sizes defined by the acceptance proof test or NDI and acted upon by the spectra of expected operating loads, pressure, and environments, will meet the safe-life requirement which is four (4) times the specified service life. Nominal values of fracture toughness and flaw-growth rate data associated with each alloy, tempered, product form, thermal "and chemical environments, and loading spectra should be used. Safe-life testing in lieu of safe-life analysis is an acceptable alternative.

Nondestructive Inspection (NDI)

NDI is needed to deter-mine if there are flaws or cracks existing in the pressurized structures, which may cause failure. Here the failure is defined as either the toxic fluids leaking out through the wall of the structure or the explosion of the pressurized hardware causing injury to the ground crew or destroying national assets such as the launch facility. Furthermore, NDI should be performed on fracture critical welds after proof testing

SPECIAL PRESSURIZED EQUIPMENT

Based on MIL-STD-1522A, pressurized equipment such as batteries, cryostats, heat pipes, and some of the sealed containers should comply with the requirements specified for pressure vessels if they meet the definition of pressure vessels. However, experience shows that it is either very difficult or impractical to implement the pressure vessel requirements on this hardware

Furthermore, special provisions that are not required for pressure vessels shall be implemented to assure their structural integrity and functionality. The common requirements of these types of equipment are summarized in Table 2. It can be seen from the table that random vibration testing, thermal vacuum testing, pressure cycle testing, and function testing are not required across the board for these types of pressurized equipment, hence unnecessary tests can be avoided. Special requirements for these types of equipment are as follows:

Batteries

Batteries should be designed such that battery cells are within containment devices (or cases). These containment devices shall be demonstrated to be able to prevent the escape of any hazardous contents over an insignificant quantity deemed acceptable by the procuring and safety agencies.

Cryostats (or Dewars)

Outer shells (i.e., vacuum jackets) shall have pressure relief capability to preclude rupture in the event of pressure container leakage. If pressure containers do not vent external to the cryostats or dewars but instead vent into the volume contained by outer shells, the relief devices of outer shells must be capable of venting at a rate to release full flow without outer shells rupturing. Relief devices must be redundant and individually capable of full flow. Furthermore, pressure relief devices must be certified to operate at the required condition of use.

REFERENCES

[1] MIL-STD- 1522A (USAF), "Standard General Requirements for Safe Design and Operation of Pressurized Missiles and Space Systems," 28 May 1984.

[2] MIL-STD-1522 (USAF), "Standard General Requirements for Safe Design and Operation of Pressurized Missiles and Space Systems," I July 1972.

[3] ASME Boiler and Pressure Vessel Codes, Section VIII, Division 1 and 2.

[4] Chang, J. B., "Space Flight Pressure Vessel Design," PVP-Vol.277, Recertification and Stress Classification Issues, The American Society of Mechanical Engineers, 1994.

[5] NHB 1700.7, "Safety Policy and Requirements for Payloads Using the Space Transportation Systems," NASA Headquarters, December 1980.

[6] NHB 8071.1 "Fracture Control Requirements for Payloads Using the National Transportation Systems (NSTS)," NASA Headquarters, September 1988.

[7] Lou, M.C. and Sutharshana, S., "Space Flight Pressure Vessel Design Requirements-A Review," PVP-Vol. 277, Recertification and Stress Classification Issues, The American Society of Mechanical Engineers, 1994.

[8] JSC 25863, "Fracture Control Plan for JSC Flight Hardware," NASA, Johnson Space Center, June 1992.

Table 1. Metallic Pressure Vessel and Pressurized Structure Requirements Comparison

Requirement	Pressurized Structures	Metallic Pressure Vessels
Factor of Safety (Burst)	1.4 for manned systems 1.25 for unmanned systems	1.5
Fatigue-Life Demonstration	Yes for LBB failure mode	Yes for LBB failure mode
Safe-Life Demonstration	Yes for hazardous LBB or brittle failure mode	Yes for HLBB or brittle failure mode
Qualification Testing [1]		
Random Vibration	No	Yes
Pressure Cycle	1.0 x MEOP for 4 Lifetime (50 MEOP cycles, min.)	1.5 x MEOP for 2 lifetime or 1.0 x MEOP for 4 lifetime (50 MEOP cycles min.)
Burst	One test article	Two test articles (one without pressure cycle)
Acceptance Tests		
(NDI)	Yes[2]	Yes[2]
Proof Test	].1 x MEOP	1.25 x MEOP

Notes:

1. For one-of-a-kind application, a proof test of the flight unit to a minimum of 1.5 times MEOP and a conventional fatigue analysis showing a minimum of 20 design lifetime may be used in lieu of the required pressure testing.

2 NDI shall be selected for crack detention.

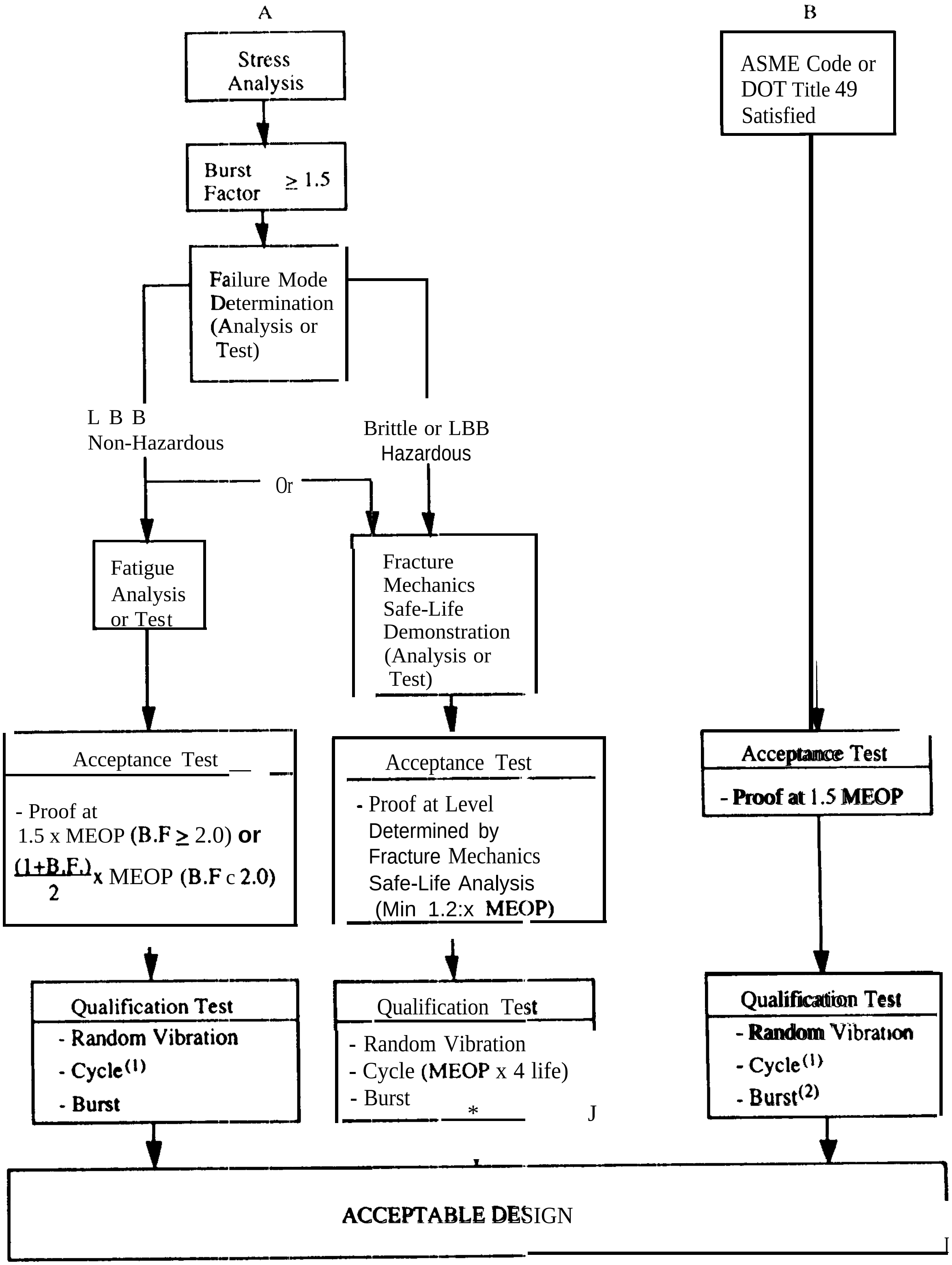
Table 2. Special Pressurized Equipment Design and Test Requirements

Type of Equipment	Safety Factor Burst	Qualification Testing' "	Proof Test	Acceptance ND1[2]
Batteries				
LBB	Is	RVT, TVT, BT	I .25	No
Hazardous LBB or Brittle	1.5	RVT, TVT, BT	1.25	Yes
Cryostats (or Dewars)				
LBB	1.5	RVT, BT	1.25	No
Brittle	1.5	RVT, BT	1.25	Yes
Heat Pipes				
Dia < 1.5 in	4.0	BT	1.5	No
Dia > 1.5 in	25	BT	1.5	No
Sealed Container				
Electronics	15	FT, RVT, TVT, TC, PST, BT	1.25	No
others	15		I .2s	No

Notes

1. RVT - Random Vibration Test
   TVT - Thermal Vacuum Test
   BT - Burst Test
   FT - Functional Test
   TCT - Thermal Cycle Test
   PST - Pyro Shock Test

2 For detecting cracks



NOTES: (1) Cycle test at either MEOP x 4-life or 1.5 MEOP x 2 life
(2) Burst or disposition vessel with approval of the procuring agency

Figure 1. Pressure Vessel Design Verification Options

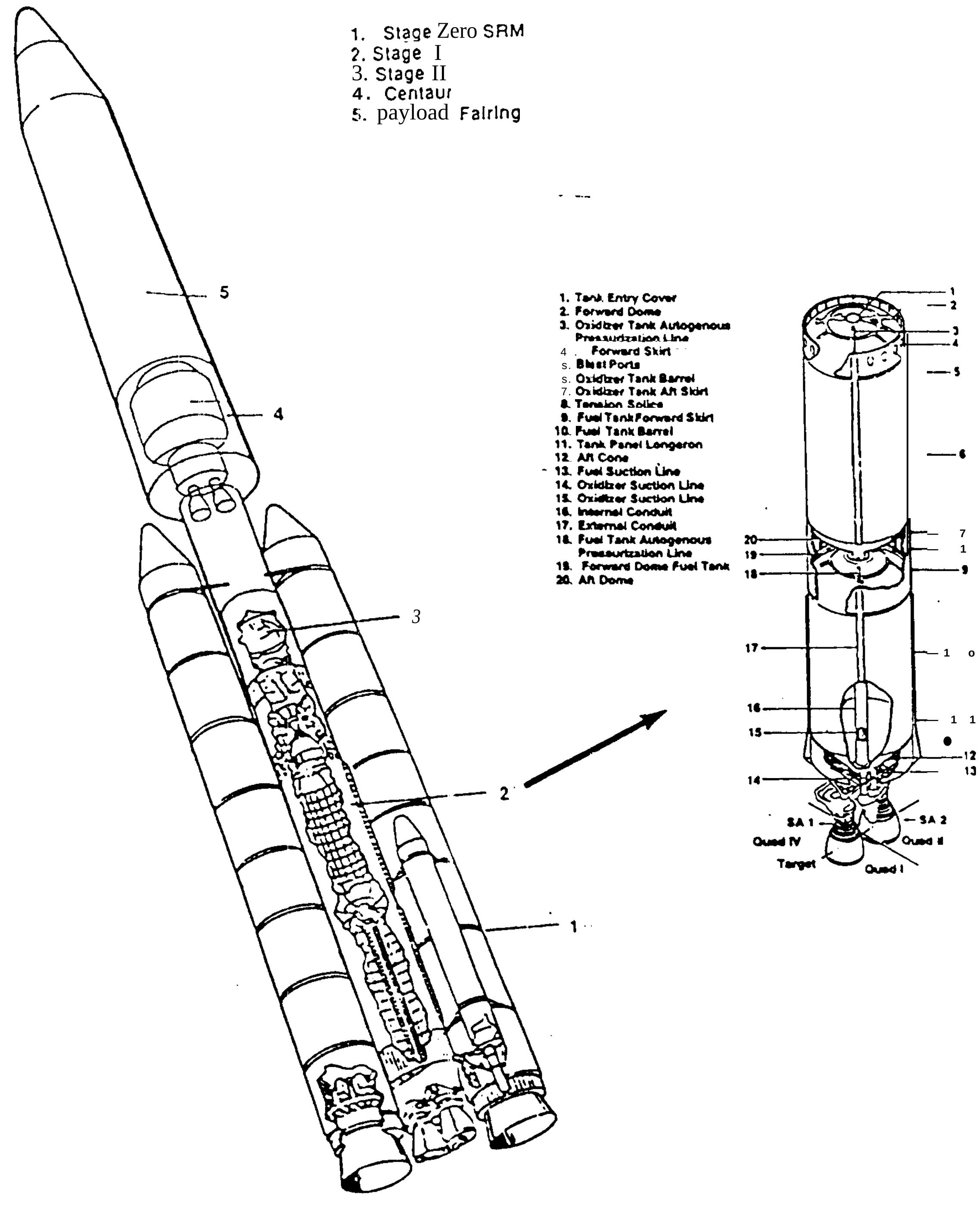


Figure 2. A Typical Launch Vehicle