PEGASUS® XL DEVELOPMENT AND L-1011 PEGASUS CARRIER AIRCRAFT

by

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Abstract

The Pegasus air-launched space booster has established itself as America's standard small launch vehicle. Since its first flight on April 5, 1990 Pegasus has delivered 13 payloads to orbit in the four launches conducted to-date. To improve capability and operational flexibility, the Pegasus XL development program was initiated in late 1991. The Pegasus XL vehicle has increased propellant, improved avionics, and a number of design enhancements. To increase the Pegasus launch system's flexibility, a Lockheed L-1011 aircraft has been modified to serve as a carrier aircraft for the vehicle. In addition, the activation of two new Pegasus production facilities is underway at Vandenberg AFB, California and the NASA Wallops Flight Facility, Wallops, Virginia. The Pegasus XL vehicle, L-1011 carrier aircraft, and Vandenberg production facility will be operational in the fall of 1993. This paper describes the Pegasus XL vehicle design, capability, development program, and payload interfaces. The L-1011 carrier aircraft is described, including its selection process, release mechanism vehicle and payload support capabilities, and certification program. Pegasus production facilities are described.

Background

The Pegasus air-launched space booster (**Figure 1**), which first flew on April 5, 1990, provides a flexible, and cost effective means for delivering satellites into low earth orbit.[1] Four launches have occurred to-date, delivering a total of 13 payloads to orbit. Launches have been conducted from both the Eastern (Kennedy Space Center, Florida) and Western (Vandenberg, California) Ranges. All of the vehicles launched to-date have been integrated using OSC's Vehicle Integration Building located at the NASA Dryden Flight Re-

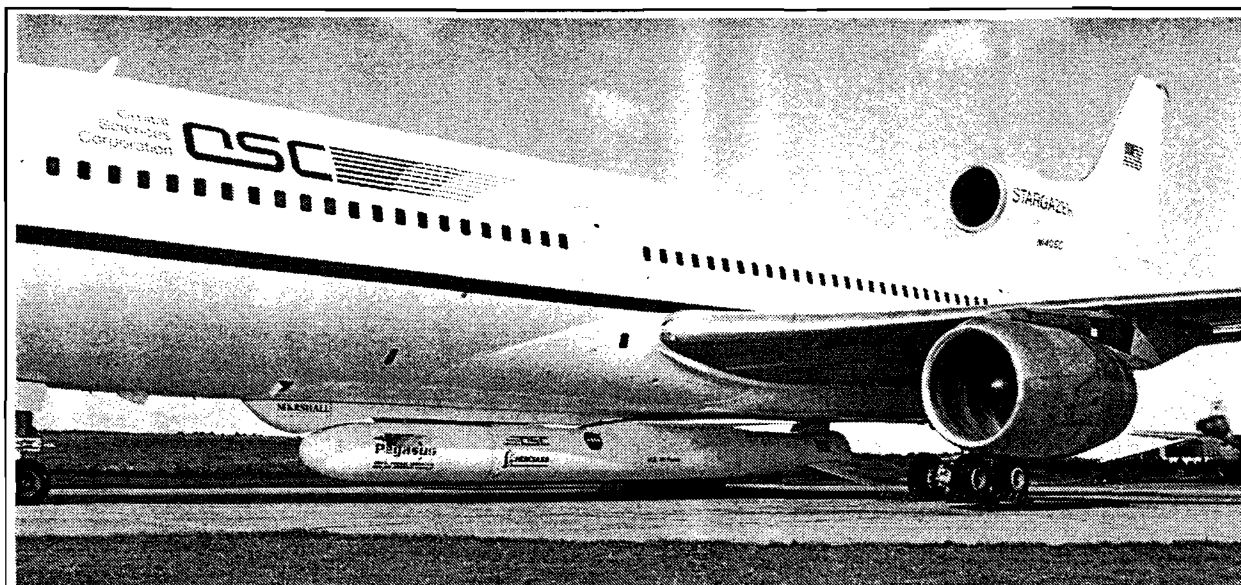

Figure 1. Pegasus XL and L-1011 Carrier Aircraft.

search Facility, Edwards AFB, California (NASA DFRF). Three of the launches were conducted off the coast of California within the control of the Western Test Range (WTR). The third mission, conducted in February 1993 for the Brazilian SCD-1 mission, demonstrated the Pegasus launch system's exceptional flexibility. For this mission, the vehicle was integrated at the OSC NASA DFRF VAB and Pegasus was then carried to the NASA Kennedy Space Center by the NASA B-52 and launched near the Florida coast. Seven launches are scheduled to occur within the next 12 months and future annual launch rates of four to six missions per year are planned.

Pegasus is the product of a three year privately funded joint venture of Orbital Sciences Corporation (OSC) and Hercules Aerospace Company. A "Turn-Key" launch service is provided, with OSC and Hercules responsible for all hardware and services necessary to deliver the payload(s) to the desired orbit. The standard Pegasus launch service includes design and production of the vehicle, mission specific hardware and integration support, payload integration, vehicle integration facilities, ground support equipment, carrier aircraft, and launch operations. The first six Pegasus missions were funded by DARPA as part of its Advanced Space Technology Program (ASTP) through the Advanced Vehicle Systems Technology Office (AVSTO). Support was also received from the NASA DFRF and the Air Force Space Division through agreements with DARPA. The vehicle was selected in 1991 as the U. S. Air Force Small Launch Vehicle (SLV) and by NASA for the Small Expendable Launch Vehicle Services (SELVS) program. The vehicle has also been selected by commercial customers and by foreign governments.

Baseline Vehicle Description

The baseline Pegasus vehicle (**Figure 2**) is 15.2 m (50 ft) long, has a diameter of 1.3 m (50 in), and weighs 19,000 Kg (42,000 lbs). Major components include three solid-propellant rocket motors, a delta wing, aft skirt assembly supporting three moveable aerodynamic fins, avionics/payload support structure, a two-piece payload fairing, two standard payload separation systems (23 and 38 inch diameter), an optional restartable Hydrazine (N_2H_4) Auxiliary Propulsion System (HAPS), and the PegaStar® integrated spacecraft bus.[2]

The vehicle's three Solid Rocket Motors (SRMs) and payload fairing were developed specifically for Pegasus by Hercules Aerospace. The SRMs have carbon composite cases and use HTPB class 1.3 propellant. The 6.7 m (22 ft) carbon composite delta wing provides lift during the early phases of flight. Three foam core graphite composite fins, which are controlled by electro-mechanical actuators, provide aerodynamic control through the end of Stage 1 operation. Pitch and yaw control during Stage 2 and Stage 3 burn is provided by electro-mechanical thrust vector control (TVC) actuators. Roll control after Stage 1 separation, and three-axis control during coast phases and post orbital insertion maneuvers, is provided by 55 N (12.5 lb) and 110 N (25 lb) nitrogen cold gas thrusters

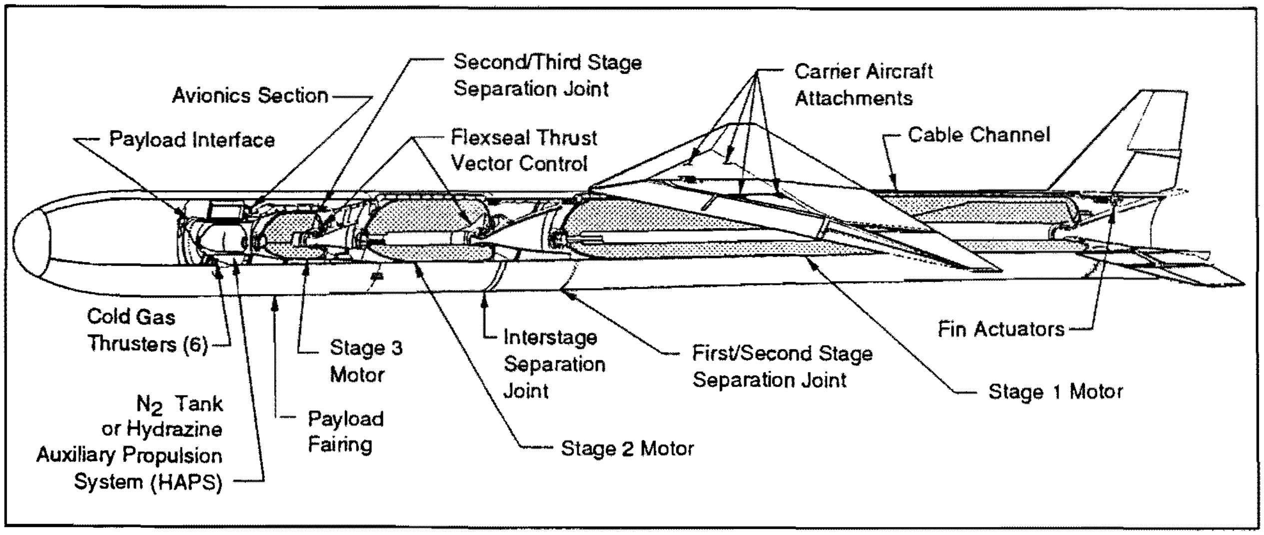

Figure 2. Pegasus Cutaway Drawing.

located on the avionics subsystem. A graphite composite avionics structure supports the payload and most vehicle avionics. A 1.3 m (50 in) outside diameter pyrotechnically separated two-piece graphite composite payload fairing encloses the payload, avionics subsystem, and S3 motor. Two standard marmon clamp type payload separation systems (23 and 38 inch diameter) are available. The optional Hydrazine Auxiliary Propulsion System (HAPS) provides up to 73 kg (160 lb) of N_2H_4 for orbit raising and/or precision orbital adjustment. When combined with the vehicle's on-board Global Positioning System (GPS) receiver, HAPS provides autonomous precision orbit injection capability. The PegaStar spacecraft bus can provide extended (5 to 10 year) on-orbit payload and sensor support including attitude control (three-axis, nadir pointing or spin stabilized), orbital make-up and adjustment propulsion, data storage, electrical power, and telemetry support for a wide variety of applications.[1]

Pegasus vehicles are currently integrated at OSC's Vehicle Integration Building (VAB) located at the NASA Dryden Flight Research Facility, Edwards AFB, CA (NASA DFRF). This 60 ft. x 80 ft. facility (**Figure 3**) is capable of processing one vehicle at a time. Vehicle integration is performed horizontally, using custom motor handling dollies and ground support equipment (GSE). During integration all vehicle components and subsystems are thoroughly tested using Personal Computer (PC) based electrical GSE and other conventional test equipment.

For launch, Pegasus is carried aloft by a NASA DFRF B-52-008 carrier aircraft, to a nominal level-flight drop condition of 12,200 m (40,000 ft) at high

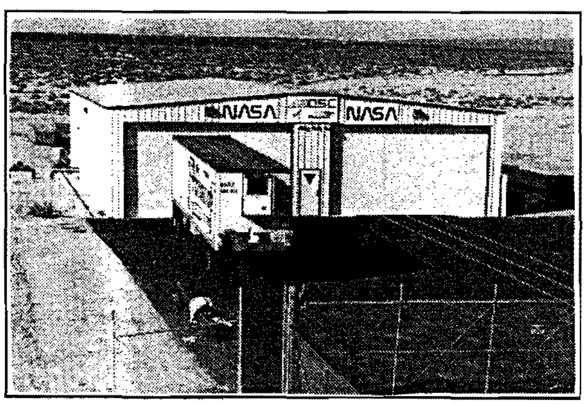

Figure 3. Pegasus Vehicle Assembly Building, Dryden Flight Research Facility, Edwards AFB, CA.

subsonic velocity. After release, the vehicle free falls to clear the carrier aircraft, while executing a pitch-up maneuver to achieve the proper attitude for motor ignition. After Stage 1 ignition, the vehicle follows a lifting-ascent trajectory to orbit (**Figure 4**).

Pegasus XL Concept

It was recognized early in the Pegasus program that additional payload capability would be needed for some missions. While providing precision orbital insertion capability for all orbits (**Figure 5**), HAPS can provide significant additional payload capability only for higher orbits. To identify the most cost effective means of improving payload performance for all orbits, a series of trade studies were undertaken beginning in early 1991. The ground rules for these studies were to improve the payload delivery capability to the maximum extent possible while minimizing the scope of the required modifications (to reduce development time, risk, and cost), to maintain the vehicle's overall reliability goal (currently calculated at 97%), and to minimize the impact on payload interfaces and environments (so that existing payloads designed for Pegasus could be flown on either vehicle).

Upon completion of the trade study evaluations, a conceptual design review for the Pegasus XL vehicle was conducted in December 1991. After reviews and discussions with NASA, the US Air Force, and other customers a final vehicle configuration was selected and the design frozen in February 1992. A formal system Preliminary Design Review (PDR) followed in May 92, with a final System Critical Design Review (CDR) in April 1993. The product of this effort (**Figure 6**), the Pegasus XL vehicle, is 16.8 m (55 ft) long and weighs 22,300 Kg (49,000 lbs).

Propulsion

The Solid Rocket Motors (SRMs) for the baseline Pegasus vehicle were originally designed using a very conservative 1.4 factor of safety. Based on the baseline vehicle SRM static fire results and flight data it was determined that margins could be reduced to a more traditional 1.25 without compromising vehicle reliability. However, simply modifying the design to reduce the design factors of safety (resulting in a decrease in vehicle's inert weight) could not provide the level of performance improvement desired. It became clear early in the

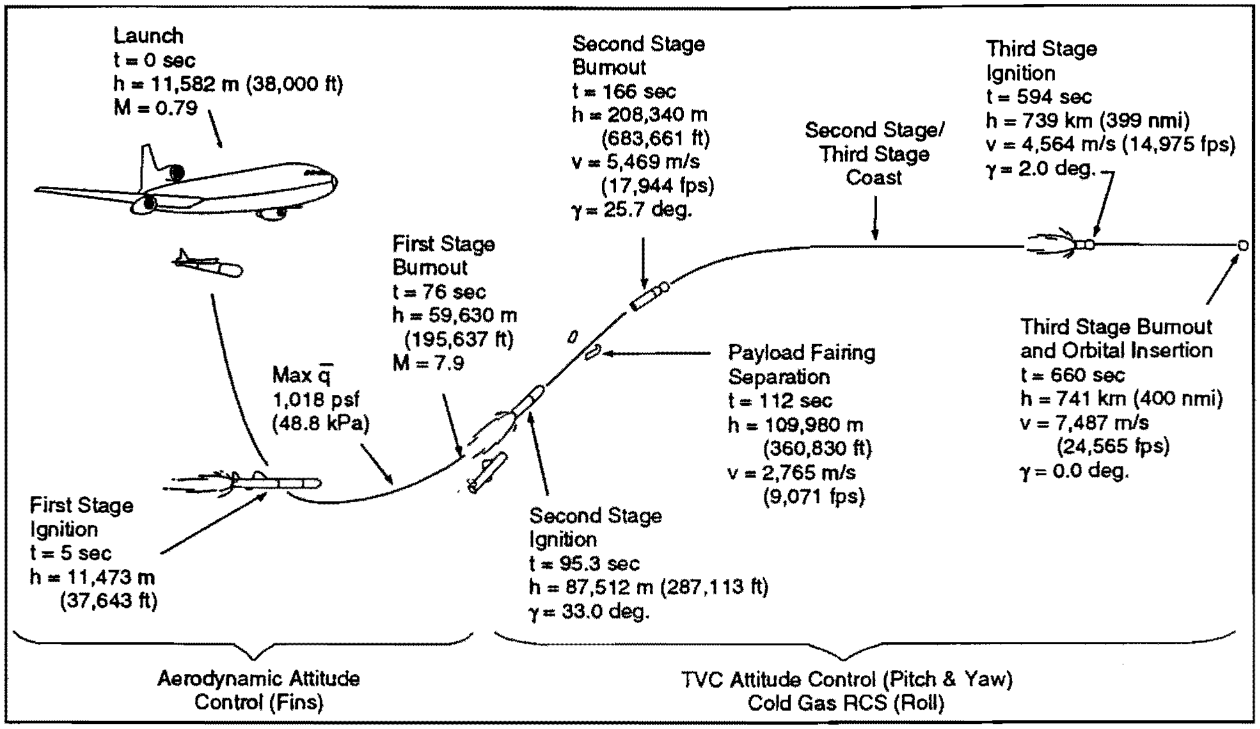

Figure 4. Typical Pegasus XL Mission Profile to 741 Km (400 nmi) Circular, Polar Orbit with a 230 Kg (509 lbm) Payload.

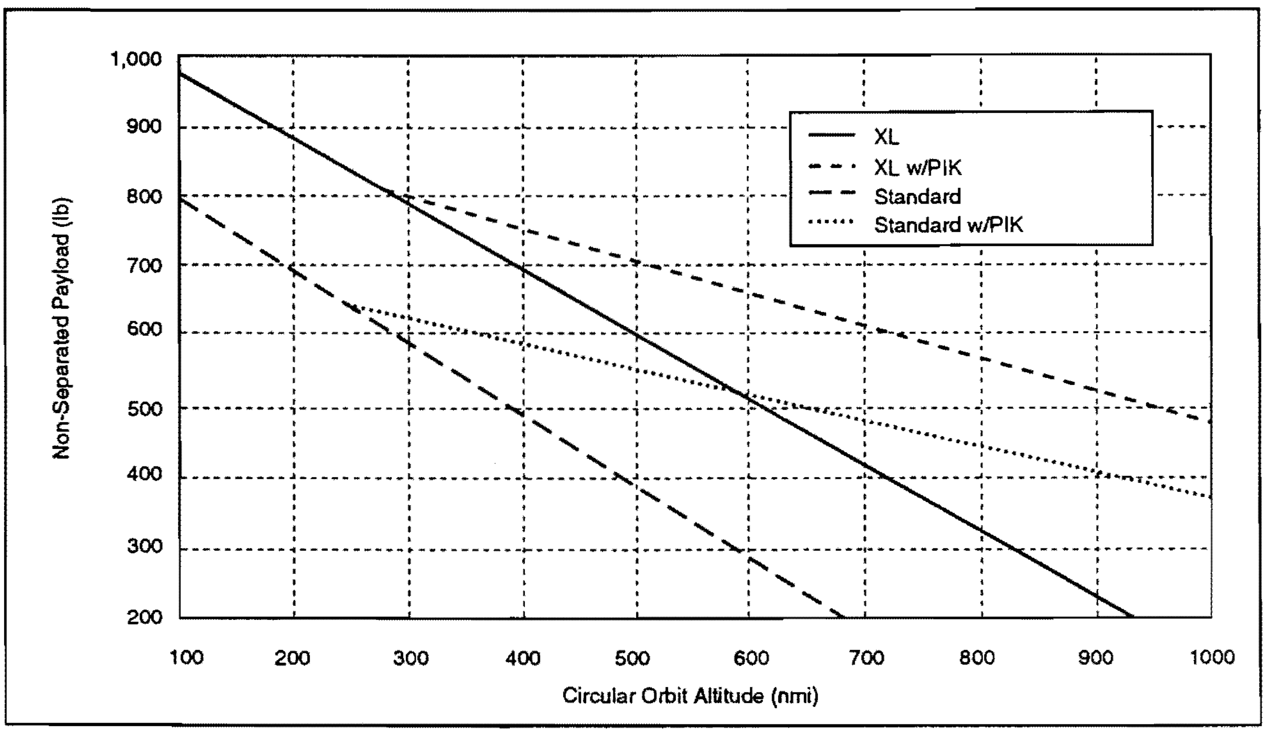

Figure 5. Pegasus Performance (0 Deg Inclination).

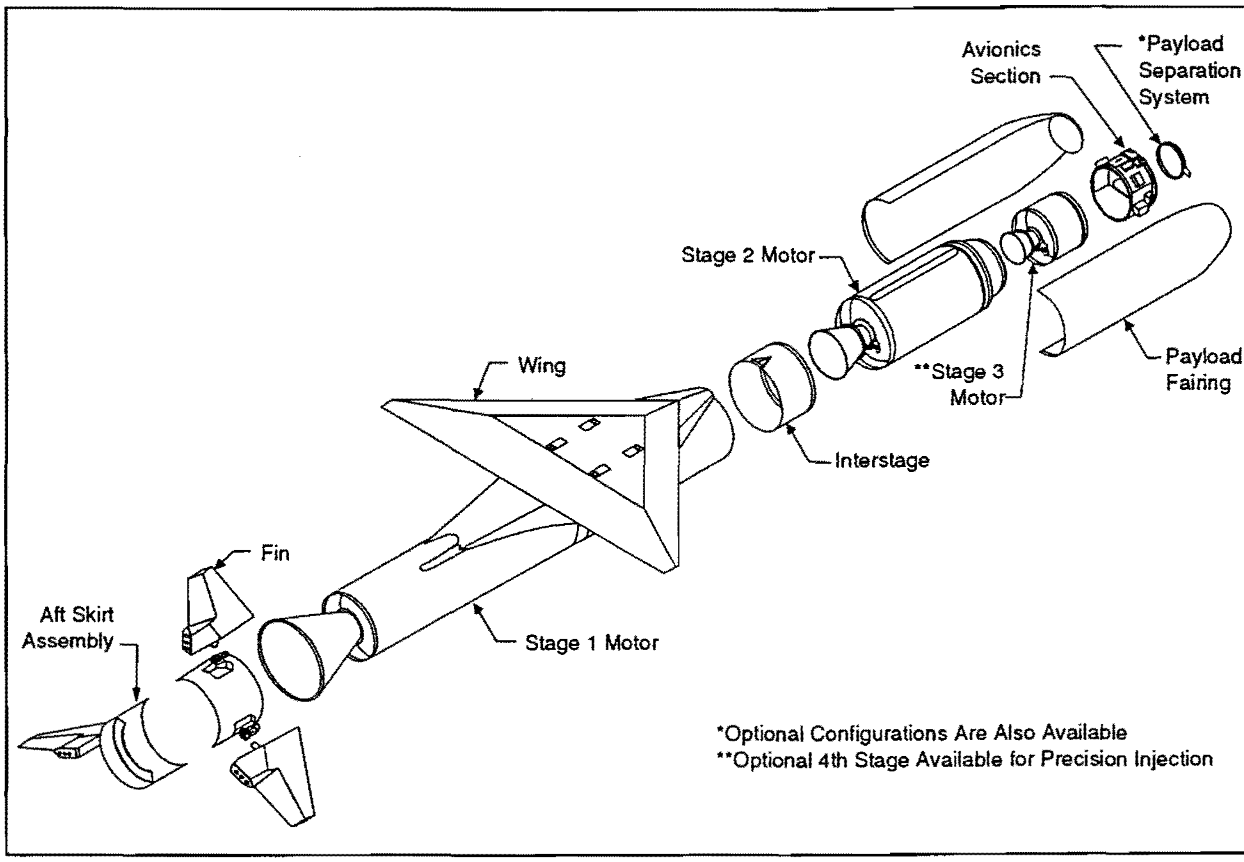

Figure 6. Expanded View of Pegasus XL Configuration.

configuration trade study process, that the size of the SRMs (in terms of total propellant load) would have to be increased. Conversion of one or more stages to a liquid mono- or bi-propellant configuration is under consideration, however the development time, risk, and cost rendered this option not cost effective for a near term vehicle upgrade.

To retain compatibility with existing tooling, ground support equipment and procedures, the baseline vehicle's 50 inch motor diameter was retained. A series of trade studies were conducted to optimized the increased propellant load (**Figure 7**) consistent with the program's performance and cost objectives. Factors considered during this parametric study phase included vehicle performance; development cost, risk and schedule; recurring cost; and the impact on production tooling, ground support equipment (GSE), vehicle integration, and carrier aircraft.

The final Pegasus XL vehicle design increases the propellant load in the Stage 1 motor by 6,372 Lbm (a 24% propellant increase resulting in a 55.4 inch extension of the motor case). The Stage 2

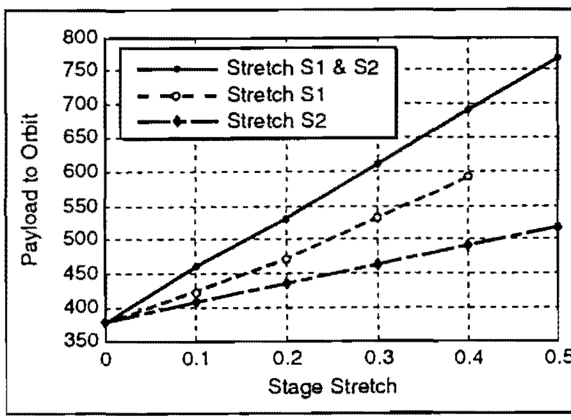

Figure 7. Stretch Motor Performance, Stage 1 and Stage 2 (400 nm 90 Deg).

SRM propellant load has been increased by 2,021 Lbm (a 30% increase resulting in a 17.7 inch extension of the motor case) In addition, the S2 SRM internal propellant fin design was modified to tailor the motor's thrust vs. time performance to reduce peak (end-of-burn) vehicle acceleration. The Stage 3 SRM propellant load was not changed from the baseline Pegasus vehicle, however its nozzle throat diameter was decreased somewhat to increase the motor's Maximum Expected Operating Pressure (MEOP) resulting in higher performance. After the final SRM configuration was selection in February 1992, Hercules Aerospace completed the detailed motor design, leading up to a propulsion system Preliminary Design Review (PDR) in June 1992, fabrication of the first SRM's of each type in the fall and winter of 1992/93 and finally by static firing of both motor types in the spring of 1993 (Stage 2 was successfully static fired on 22 May 1993 and the Stage 1 motor on 12 June 1993). Both SRM static fire tests were completely successfully and the performance results are as expected.

Structures

Once the optimum motor size was determined, the remaining vehicle structural components were reviewed and modified as required. Significant changes to the vehicle's structural components included the Stage 1 case SRM to Wing saddle and struts, carbon composite wing, aluminum aft skirt, and graphite avionics structure. Stage 1 saddle modifications were limited to increasing the material thickness in select local areas to support the vehicle's increased weight. The wing support struts were modified to increase load carrying capability and reduce manufacturing complexity. A "5th hook" attachment point was added on the forward skirt of the Stage 2 SRM to reduce the post-release lateral acceleration transient. Structural load testing of both the Stage 1 and Stage 2 SRM cases were successfully completed in February 1993. The aluminum aft skirt was modified to incorporate a fin anhedral (23 degrees) to clear the L-1011 gear doors and improve vehicle lateral stability. The baseline Pegasus vehicle's wing size and shape was not changed for Pegasus XL, however select material and other local internal modifications were required to handle the higher captive carry and flight aerodynamic loads. A structural load test on the Pegasus XL wing was successfully completed on 5 August 1993. The Pegasus XL avionics structure has been completely re-designed to maintain a constant 38" diameter from the Stage 3 forward skirt to the payload interface (the baseline Pegasus avionics structure provided a 23" diameter payload interface). This modification reduced the structure's height (which provides a somewhat increased payload envelope for some applications) and provides a 38" diameter attachment capability which is more appropriate for some heavier payloads. A 38" to 23" adapter has been qualified to allow existing payloads designed for the 23" interface to be flown on the XL vehicle.

Avionics

The Pegasus avionics subsystem provides monitoring and control of the vehicle throughout captive carry flight, launch, and post-orbital insertion maneuvers and operations. It's major functions include guidance, navigation and control (GN&C), sequencing and pyrotechnic device initiation, electrical power distribution and control, telemetry and tracking, and flight safety functions. The baseline Pegasus all digital avionics system (**Figure 8**) is simple, and robust. The only modifications required for Pegasus XL are GN&C software changes to account for the new vehicle's dynamic and aerodynamic differences (all relatively minor) and increases in the vehicle harness length to account for the longer Stage 1 and Stage 2 SRMs.

To improve the vehicle's avionics capability, several design improvements and upgrades were incorporated. These changes include: upgrading the vehicle's flight computer from the current 6U VME Motorola 68020/68000 based flight computer to a smaller, lighter weight, and lower power 3U VME Motorola 68030/68302 based system, modifying the vehicle's flight safety system to comply with recent range safety directives (to incorporate physical separation of the two independent range safety systems); and minor re-packaging of some components to improve manufacturing and testing. All changes have been incorporated and are completing qualification testing.

Carrier Aircraft

The increased weight and size of Pegasus XL, combined with operational requirements (such as extended captive carry requirements for equatorial missions and requirements for payload monitoring and control capabilities on-board the carrier aircraft) made it necessary to identify and implement an alternative for the current NASA DFRF B-52-008 carrier aircraft. A study was initiated in late 1991 to identify the optimum carrier aircraft for long term Pegasus launch operations. Some of the aircraft considered included the B-52G, Boeing 747, DC-10, and Lockheed L-1011. Some of the factors considered included performance capabil-

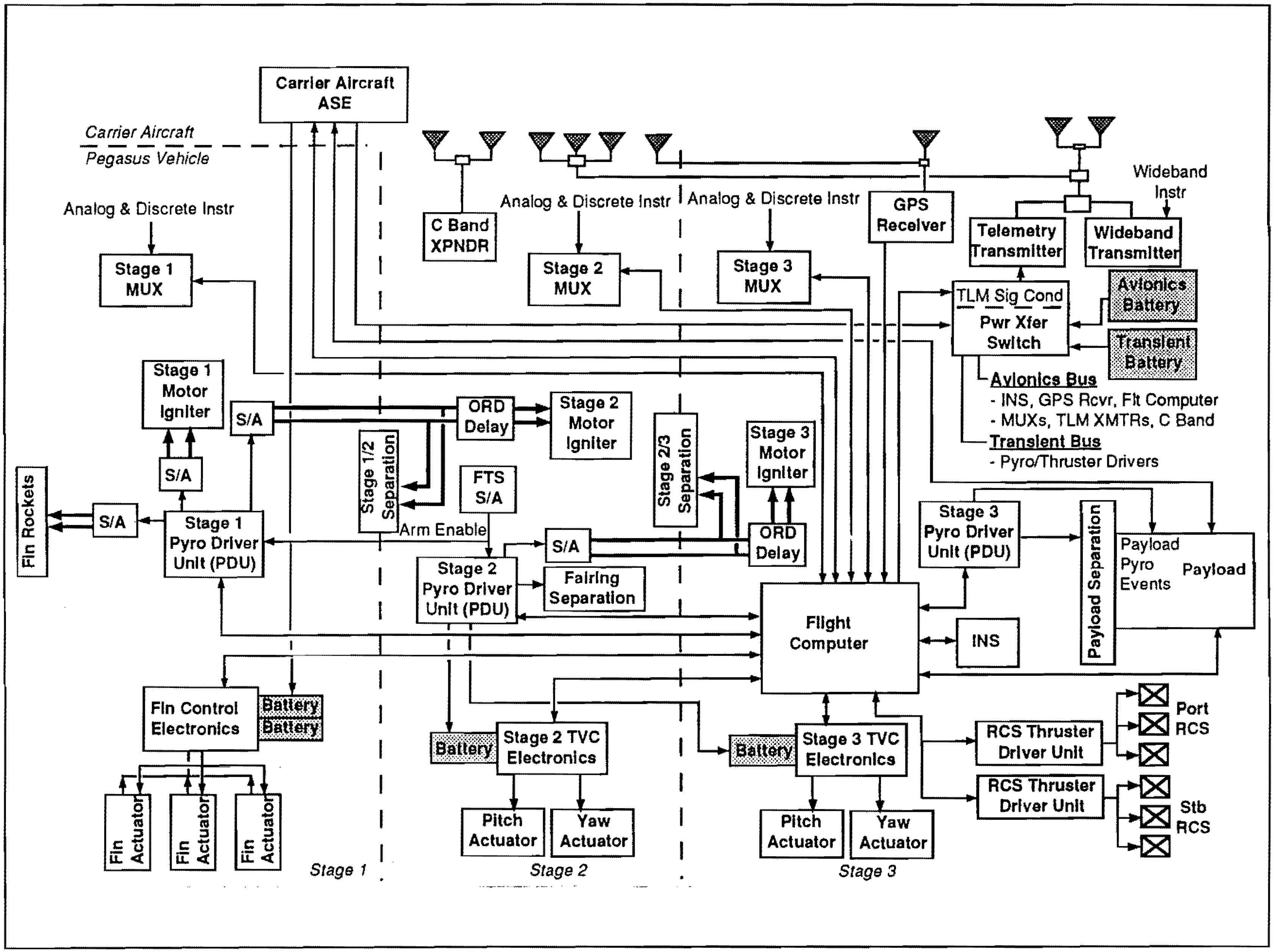

Figure 8. Pegasus Avionics Subsystem.

ity (altitude and speed capability for launch), aircraft range (both ferry and launch), modification complexity and cost, aircraft availability, acquisition cost and operational costs. Following a detailed trade study, the Lockheed L-1011 was selected for conversion to serve as a Pegasus carrier aircraft. Orbital Sciences acquired a L-1011 aircraft in May 1992, modifications to carry Pegasus are complete, and the aircraft is currently undergoing certification testing. The L-1011 is scheduled to be operational in the Fall of 1993.

The major modifications which have been performed to configure the L-1011 for use as a Pegasus carrier aircraft (**Figure 9**) include deletion of all unnecessary equipment and addition of equipment required to support Pegasus launch operations (a release mechanism; an opening for the Pegasus vertical stabilizer; equipment for monitoring and controlling Pegasus during captive carry flight; payload air-conditioning and nitrogen purge systems, and external video cameras).

Pegasus is attached to the L-1011 using four hydraulically actuated release hooks which interface with fittings inside the Pegasus wing (**Figure 10**). This interface is identical to that used for the baseline Pegasus vehicle. This release mechanism is attached directly to the L-1011 center wing box which has been strengthened by the addition of internal reinforcements, doublers and ribs (**Figure 11**). A forward "fifth hook" was added, which attaches to Pegasus on the forward skirt of the Stage 2 motor case. This forward attachment provides a constant 5,000 lbf vertical force on the vehicle during captive carry flight and it's release timing relative to the main hooks is tightly controlled to minimize the post release lateral transient.

To monitor and control Pegasus and its payload during captive carry flight a Pegasus Launch Panel Operator's (LPO) station has been installed aft of the cockpit area. From this station an OSC LPO can monitor Pegasus during flight and prepares the vehicle for launch. A second position at the station is available for an on-board payload representative (subject to FAA approval) and space is available in the LPO station for mission specific payload support equipment. A payload air-conditioning system on the L-1011 will maintain payload temperature throughout captive carry flight. Two external video cameras are installed to allow the LPO operator to examine the vehicle during flight.

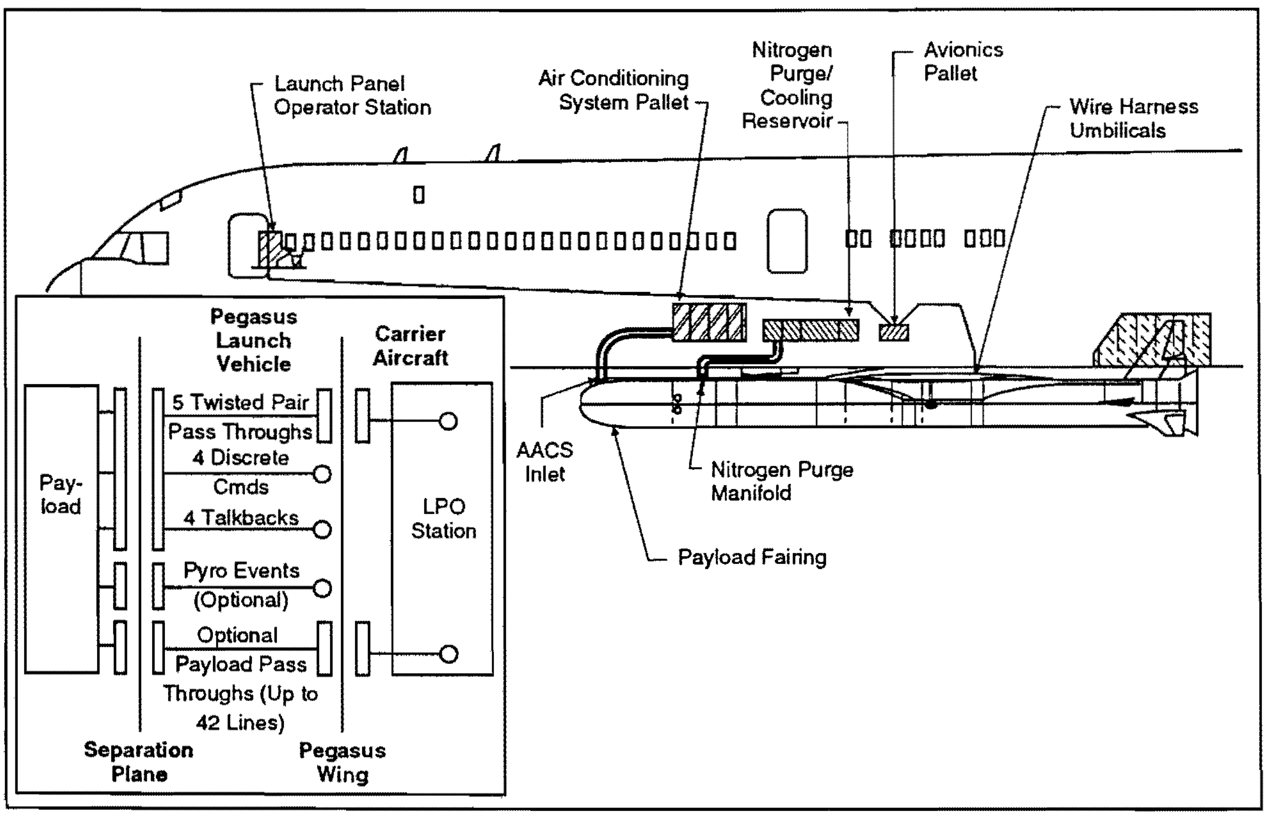

Figure 9. Pegasus/L-1011 Interface Details.

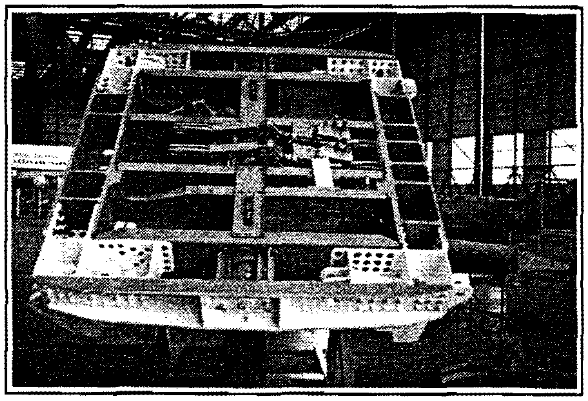

Figure 10. Pegasus L-1011 Release Mechanism.

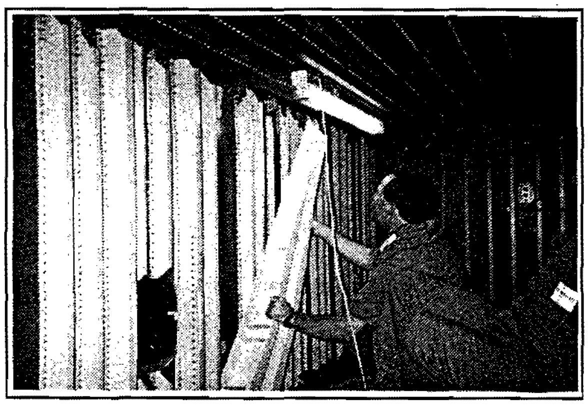

Figure 11. L-1011 Wing Box Internal Reinforcement

The modified L-1011 Pegasus carrier aircraft is capable of supporting both the baseline and Pegasus XL vehicles. While carrying Pegasus it provides a non-stop ferry range of over 4,500 nmi and a launch mission radius of over 1,000 nmi.

Vehicle Integration

Pegasus final integration requires minimal facilities and ground support equipment (GSE). Prior to delivery to the field integration site, all Pegasus components are integrated and tested to the highest possible levels. Horizontal integration (**Figure 12**) eliminates need for high-bays or equipment capable of lifting motor segments or other vehicle components. The facility must provided adequate air-conditioned floor space, be approved for processing the required quantities of propellant, and have access to a suitable runway.

The current Pegasus NASA DFRF VAB is limited to processing one vehicle at a time.

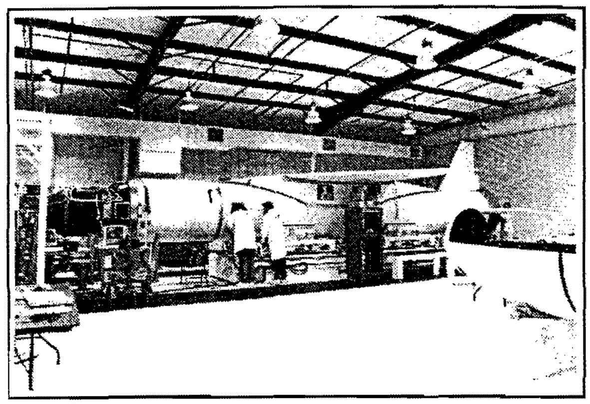

Figure 12. Pegasus Vehicle Integration.

Future launch rates and other program requirements made it necessary to find larger facilities for the long term program. Following a source selection study, two sites were identified as optimum for long term Pegasus launch operations: Vandenberg Air Force Base (VAFB AFB) on the west coast and NASA Wallops Flight Facility (NASA WFF) on the east coast. These two assembly/production facilities, which will be activated in 1993-1994, will provide full scale production and payload integration facilities on both U.S. Coasts

The VAFB VAB (**Figure 13**) can support processing of multiple launch vehicles and payloads. In addition to production support and in-process vehicle component storage areas, the VAFB VAB (**Figure 14**) provides two 6,000 Square foot vehicle processing high-bays and over 600 Square foot of adjacent payload processing areas. The VAFB VAB is currently in the final phases of activation and will be ready for SRM delivery and Pegasus XL processing in September 1993.

Figure 13. Pegasus Vandenberg AFB Vehicle Assembly Building.

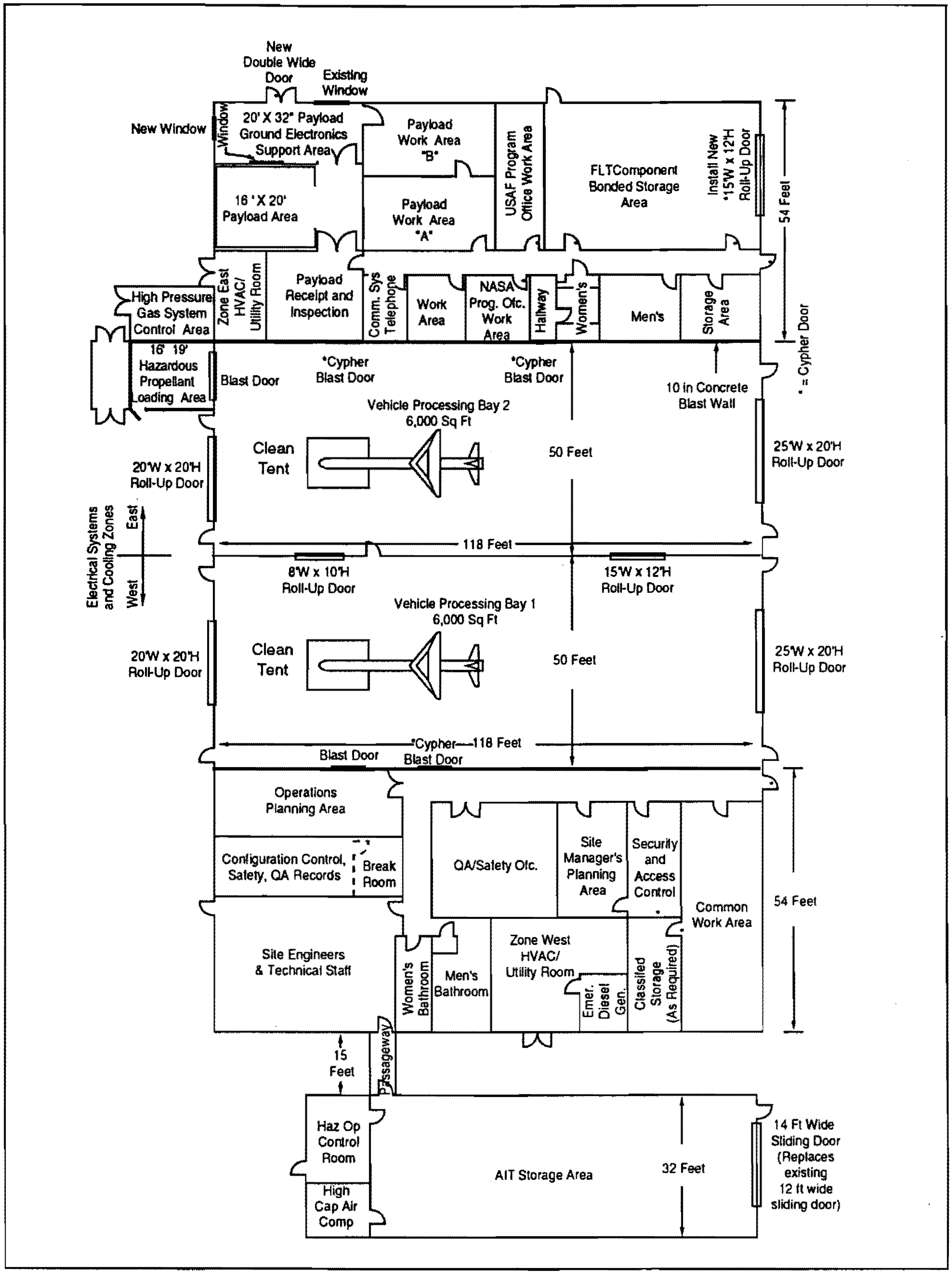

Figure 14. Vandenberg AFB Pegasus VAB General Layout (to Scale).

The NASA WFF VAB (**Figure 15**) can also support the processing of multiple launch vehicles and payloads. The NASA WFF VAB (**Figure 16**) provides 8,000 square foot of vehicle production area of which over 600 square foot is available for on-site payload processing. Design of the NASA WFF VAB is underway and activation of the facility is planned for 1994.

Figure 15. Pegasus NASA WFF VAB.

Both the VAFB VAB and the NASA WFF VAB are environmentally controlled and maintain the vehicle processing area at 74 +/- 10 degrees F and 40 +/- 10% relative humidity. The VABs are maintained in a visibly clean condition for vehicle integration and portable clean room facilities are available for processing sensitive payloads on a mission specific basis up to class 10,000.[3] Both facilities can support on-site hydrazine fueling operations for loading the Pegasus HAPS (when flown) and for fueling payloads (when required). OSC provided hydrazine propellant ground processing equipment (GSE) will be available at both sites.

Payload Capability and Interfaces

Pegasus XL's payload capability, as compared with the baseline Pegasus vehicle, is summarized in Figure 5. Information regarding payload performance to elliptical and other inclination orbits can be found in the Pegasus Payload Users Guide.[4]

Pegasus XL utilizes the same payload fairing as the baseline vehicle and can support payloads as large as 1.8 m (72 in) long and 1.2 m (46 in) in diameter (**Figure 17**). The fairing can be extended

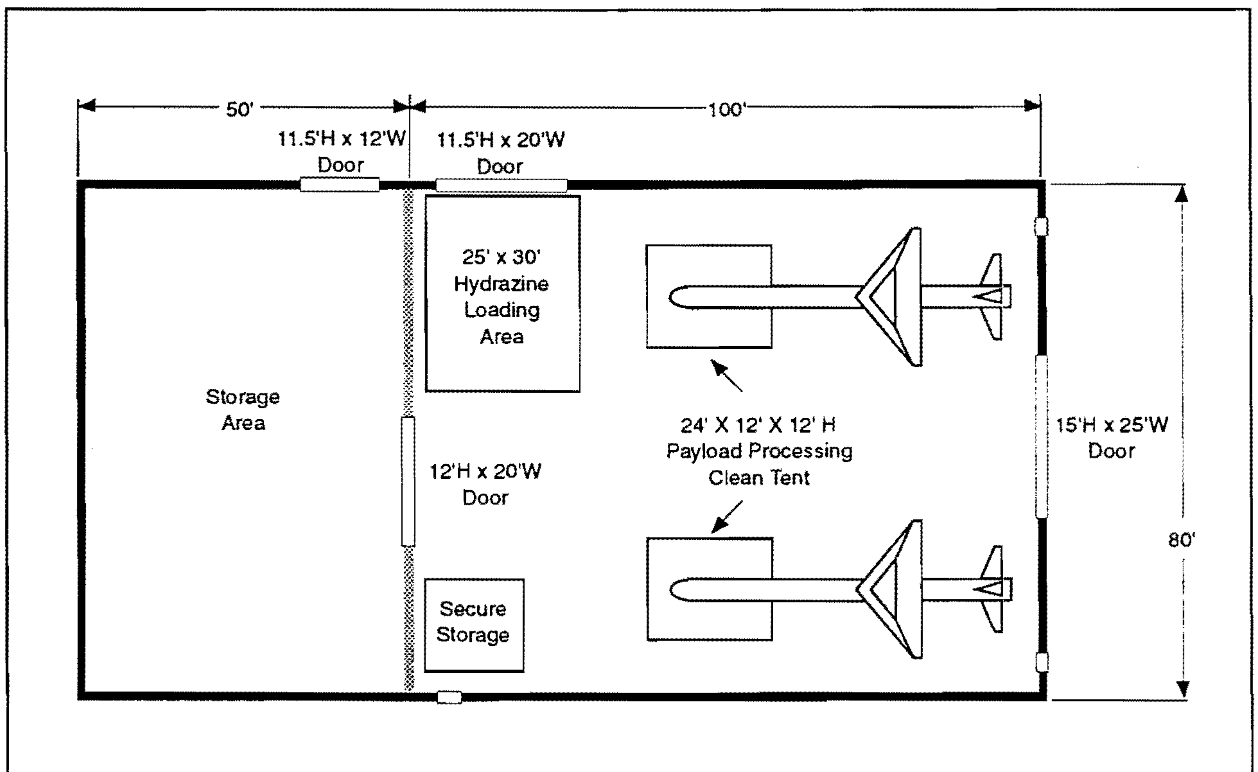

Figure 16. Pegasus VAB at NASA WFF General Layout (to Scale).

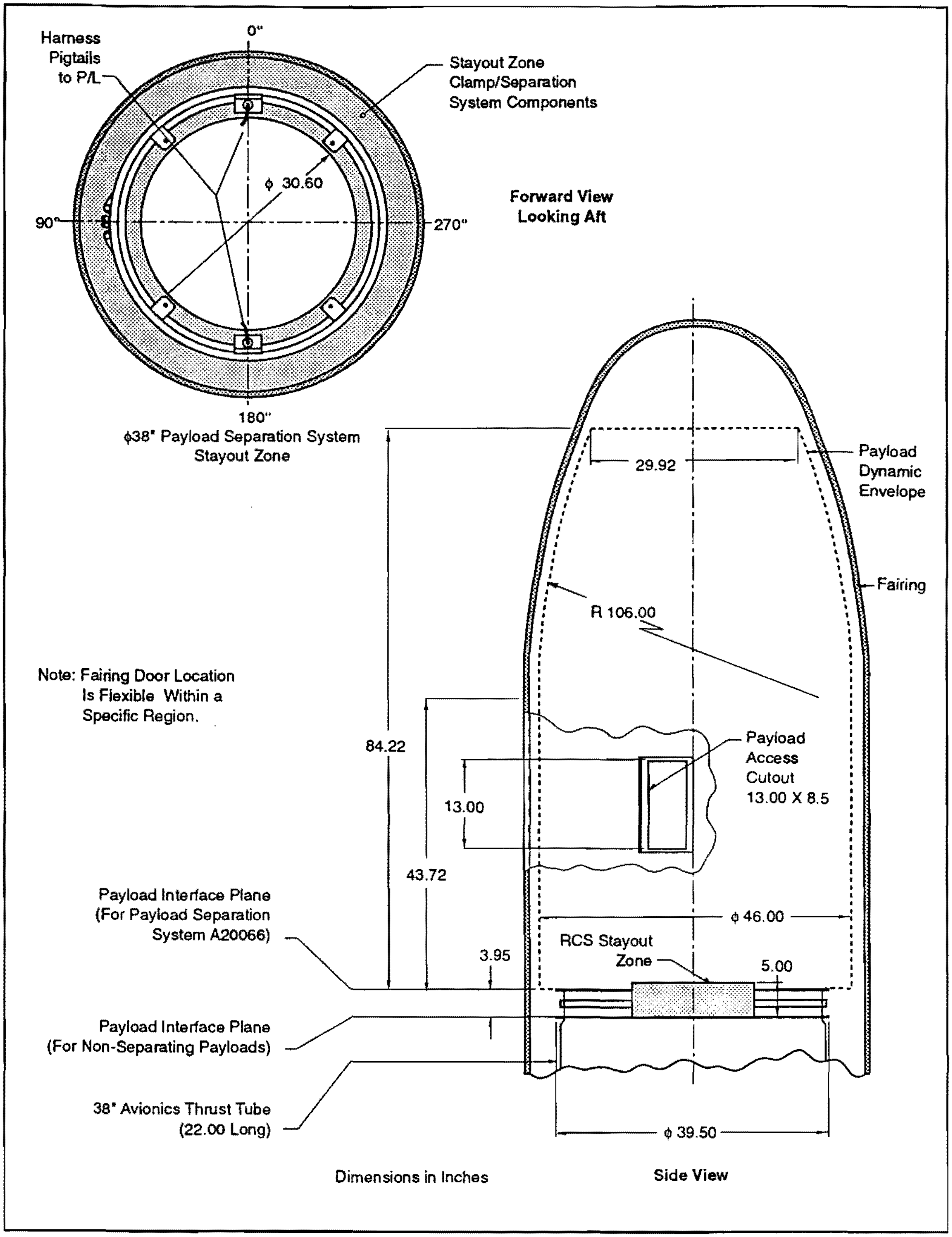

Figure 17. Payload Fairing Dynamic Envelope With 38 Inch Diameter Payload Interface.

up to an additional 60 cm (24 in) and access doors can be repositioned or added as optional services. The payload captive carry and launch environment for the Pegasus XL vehicle is very similar to the baseline Pegasus vehicle (**Figure 18.a** through **Figure 18.d**). The air launched method subjects payloads to relatively low structural and environmental loads compared with typical ground launch vehicles. Detailed information relative to payload design loads can be found in the references.[4,5]

Event	Acceleration Level, (g's)		
	Axial	Lateral at S/C Separation Plane	
		Horizontal	Vertical
Taxi, Captive Flight	±1.0	±0.5	+2.2/1.0
Drop Transient	0.0	±1.0	±4.0
Aerodynamic Pull-Up	-4.2	±1.5	+3.6
Stage Burn-Out	*	±1.2	±1.2
Abort Landing	±0.6	±0.6	±3.5

*Dependent on Payload Mass

** Assumes a Payload Fundamental Lateral Frequency Greater than 20 Hz when Hardmounted at the Payload Separation Plane.

Figure 18.a. Pegasus Payload Acceleration Environment.

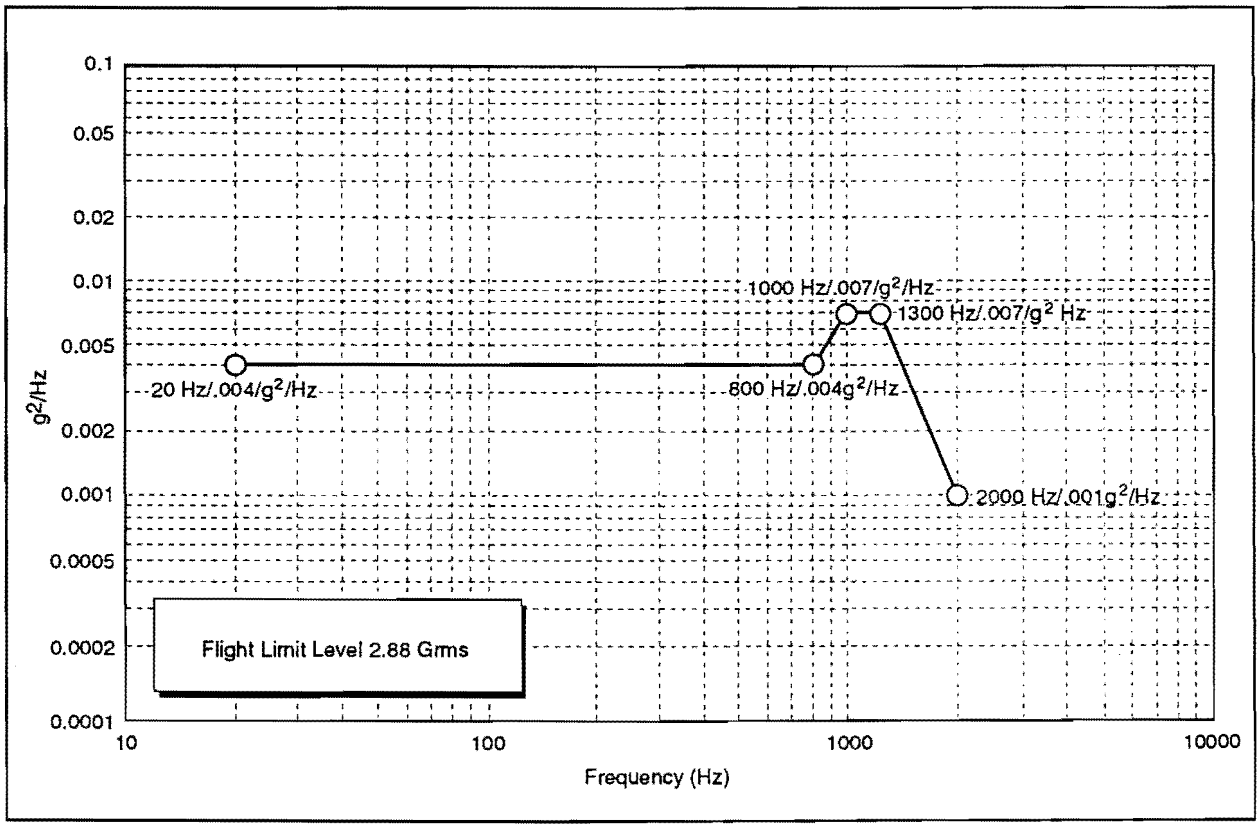

Figure 18.b. Payload Random Vibration Environment.

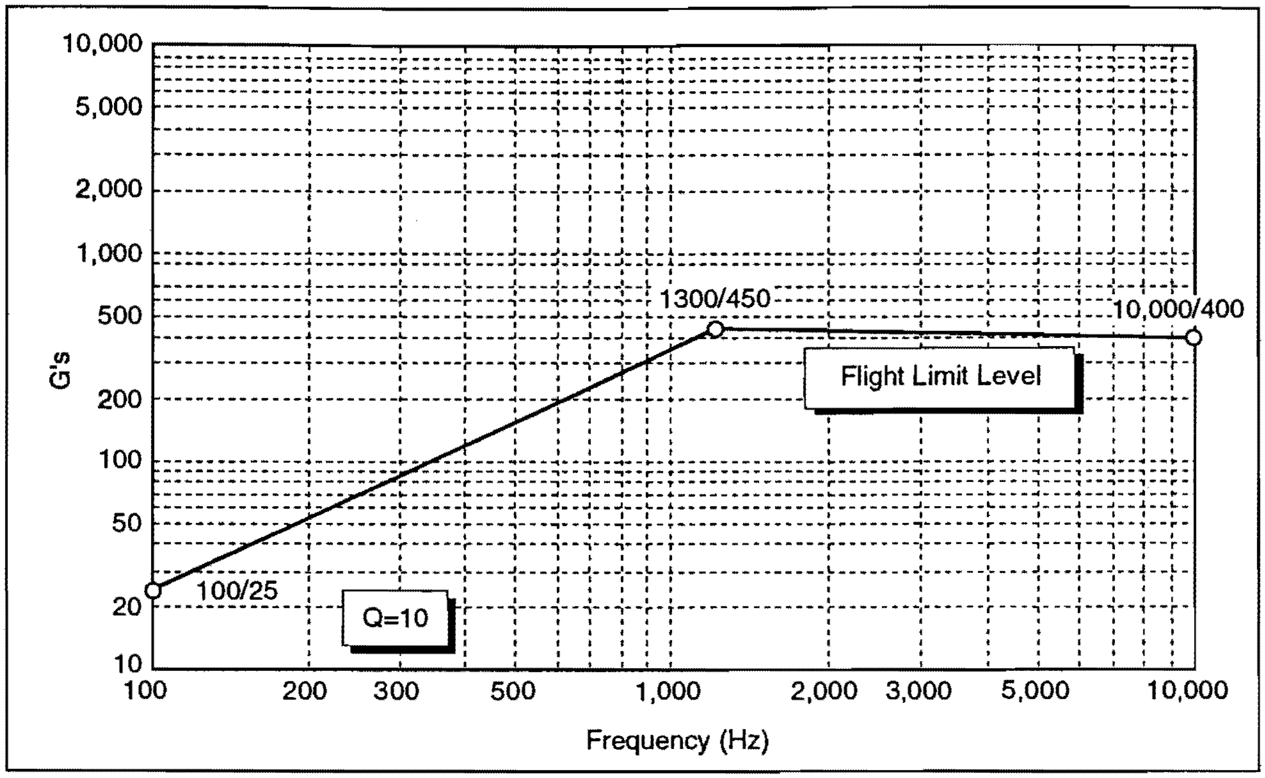

Figure 18.c. Pegasus XL Launch Environments (Shock at the Payload Interface Excluding Payload Separation System).

Environment	Temp Range[3]		Control	Humidity (%)	Purity Class[2]
	Deg C	Deg F			
VAB/Ground Operations	18 to 29	64 to 84	Filtered A/C[1]	<50	100K
Carrier Mate	18 to 29	64 to 84	Filtered A/C	<60	100K
L-1011 Taxi	18 to 29	64 to 84	Filtered A/C	<60	100K
L-1011 Captive Carry	18 to 29	32 to 84	Filtered A/C	<60	100K
L-1011 Abort/Contingency Site	18 to 29	32 to 84	Filtered A/C	<60	100K

[1] Filtered Air Conditioning (A/C)
[2] Class 10K Can Be Maintained Throughout Operation on a Mission-Specific Basis.
[3] Temperature at A/C Inlet

Figure 18.d. Payload Thermal Environment.

Conclusion

Pegasus provides a flexible and cost effective method for placing payloads into low earth orbit. Pegasus XL increases the vehicle's payload capability while retaining the vehicle's simple and robust design to ensure maximum system reliability. Development of the Pegasus XL launch vehicle is nearing completion, with the first launch scheduled to occur in late 1993. Activation of the two new production vehicle processing facilities will allow the program to simultaneously process multiple vehicles on both U.S. Coasts. The transition to the L-1011 carrier aircraft will significantly improve the Pegasus launch system's operational flexibility.

Authors

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[4] *Commercial Pegasus® Launch System Payload Users Guide* (Release 3.00), 1 September 1993.

[5] *Loads and Design Criteria - Pegasus Launch Vehicle*, Orbital Sciences Corporation DOC A10020 Revision A.

Marty R. Mosier

Mr. Mosier is the Pegasus XL and L-1011 Program Manger and has been with the Pegasus program since its inception. Mr. Mosier is responsible for all aspects of the development of the Pegasus XL vehicle as well as modification and certification of the L-1011 Pegasus Carrier Aircraft. Prior this assignment, he was Pegasus Program Manager with responsibility for vehicle production, design improvements, field operations and ground support equipment. Mr. Mosier acted as Vehicle Engineer for the Pegasus development program. He is OSC's chief pilot and is certified as a Pegasus B-52 launch panel operator. Prior to joining OSC, Mr. Mosier was project manager for the Naval Postgraduate School ORION small satellite development program and has held a variety of mechanical and electronic design positions in the aerospace industry. Mr. Mosier is a registered Professional Engineer, holds a MS in Management from the University of Southern California, and has a BS in Engineering from Harvey Mudd College.

Mr. Ed Rutkowski

Mr. Rutkowski is the Pegasus Range Operations Manger for Orbital sciences Corporation. He has been responsible for completing the transfer of Orbital's operations from the NASA Dryden Flight Research Facility at Edwards Air Force Base to new facilities at both Vandenberg Air Force Base on the West Coast and at the NASA Wallops Flight Facility on the U.S. East Cost. Prior to assuming his most recent responsibilities he was the Space System's Division's Director of Marketing for civil Programs. Mr. Rutkowski was the technical Director for Integrated Systems Analysts, Inc. from 1984 through 1989. Prior to 1984, he completed a 24 year career as a Naval Submarine officer. Ed and his family live in Centreville, Virginia.