Systems Analysis and Structural Design of an
Unpressurized Cargo Delivery Vehicle

K. Chauncey Wu (1), Jonathan N. Cruz (2), Jeffrey Antol (3) and Washito A. Sasamoto (4)
NASA Langley Research Center, Hampton, VA 23681-2199

Abstract

The International Space Station will require a continuous supply of replacement parts for ongoing maintenance and repair after the planned retirement of the Space Shuttle in 2010. These parts are existing line-replaceable items collectively called Orbital Replacement Units, and include heavy and oversized items such as Control Moment Gyroscopes and stowed radiator arrays originally intended for delivery aboard the Space Shuttle. Current resupply spacecraft have limited to no capability to deliver these external logistics.

In support of NASA's Exploration Systems Architecture Study, a team at Langley Research Center designed an Unpressurized Cargo Delivery Vehicle to deliver bulk cargo to the Space Station. The Unpressurized Cargo Delivery Vehicle was required to deliver at least 13,200 lb of cargo mounted on at least 18 Flight Releasable Attachment Mechanisms. The Crew Launch Vehicle design recommended in the Exploration Systems Architecture Study was used to launch one annual resupply flight to the International Space Station.

The baseline vehicle design developed here has a cargo capacity of 16,000 lbs mounted on up to 20 Flight Releasable Attachment Mechanisms. Major vehicle components are a 5.5m-diameter cargo module containing two detachable cargo pallets with the payload, a Service Module to provide propulsion and power, and an aerodynamic nose cone. To reduce cost and risk, the Service Module is identical to the one used for the Crew Exploration Vehicle design.

Nomenclature

APAS	Androgynous Peripheral Attachment System
CEV	Crew Exploration Vehicle
CLV	Crew Launch Vehicle
CM	Center of mass
COTS	Commercial Orbital Transportation Services
CBM	Common Berthing Mechanism
CMG	Control Moment Gyroscope
ESAS	Exploration Systems Architecture Study
ESP-2	External Stowage Platform-2
EVA	Extravehicular activity
FRAM	Flight Releasable Attachment Mechanism
FRGF	Flight Releasable Grapple Fixture
g	Acceleration due to gravity, 32.2 ft/s^2
ISS	International Space Station
klb	1000 lbs
LAS	Launch Abort System
LIDS	Low Impact Docking System
MMOI	Mass moment of inertia

(1) Aerospace Engineer, Vehicle Analysis Branch, SACD. Mail Stop 451.
(2-4) Aerospace Engineer, Space Mission Analysis Branch, SACD. Mail Stop 462.

MT/MBS	Mobile Transporter/Mobile Base System
Nx	Axial line load, lb/in.
nmi	Nautical mile(s)
ORU	Orbital Replacement Unit
PAS	Payload Attach System
PDGF	Power Data Grapple Fixture
P3	ISS truss segment, port side number 3
SACD	Systems Analysis and Concepts Directorate
SM	Service Module
SSRMS	Space Station Remote Manipulator System
S3	ISS truss segment, starboard side number 3
UCDM	Unpressurized Cargo Delivery Module
UCDV	Unpressurized Cargo Delivery Vehicle

Introduction

After the planned retirement of the Space Shuttle in 2010, there will still be a need to deliver new Orbital Replacement Units to the International Space Station in its approximately 240-nmi, 51.6-degree inclination orbit. These ORUs are existing line-replaceable units for continuing on-orbit maintenance and repair of the ISS, and include both massive and oversized items originally designed for delivery to the ISS aboard the Space Shuttle. Examples of these ORUs include the Control Moment Gyroscopes, High-Pressure Oxygen Tanks, and stowed radiator arrays. With the exception of the Space Shuttle, existing resupply spacecraft like the H-II Transfer Vehicle cannot carry the largest ORUs to the ISS, while the Automated Transfer Vehicle, Soyuz and Progress vehicles cannot deliver any external logistics (Ref. 1).

In June 2005, the Systems Analysis and Concepts Directorate at the NASA Langley Research Center was tasked with performing a conceptual design study to develop an Unpressurized Cargo Delivery Vehicle that would support the ISS program in the post-2010 time frame. This work was initially done as part NASA's 90-day Exploration Systems Architecture Study (Ref. 2). This paper presents an overview of the UCDV system requirements, vehicle configuration, concept of operations, and structural design and layout that were performed for both the ESAS and during a follow-on study conducted later in 2005.
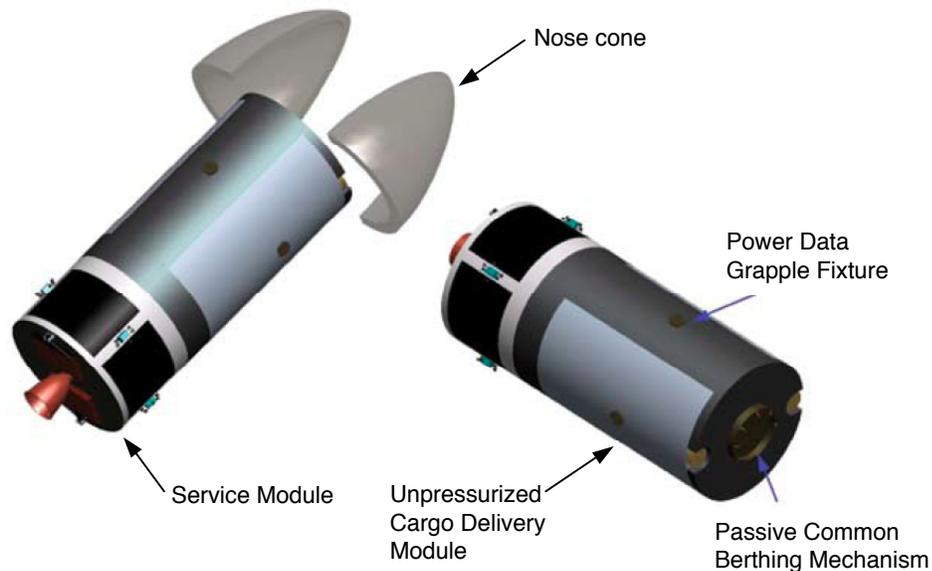

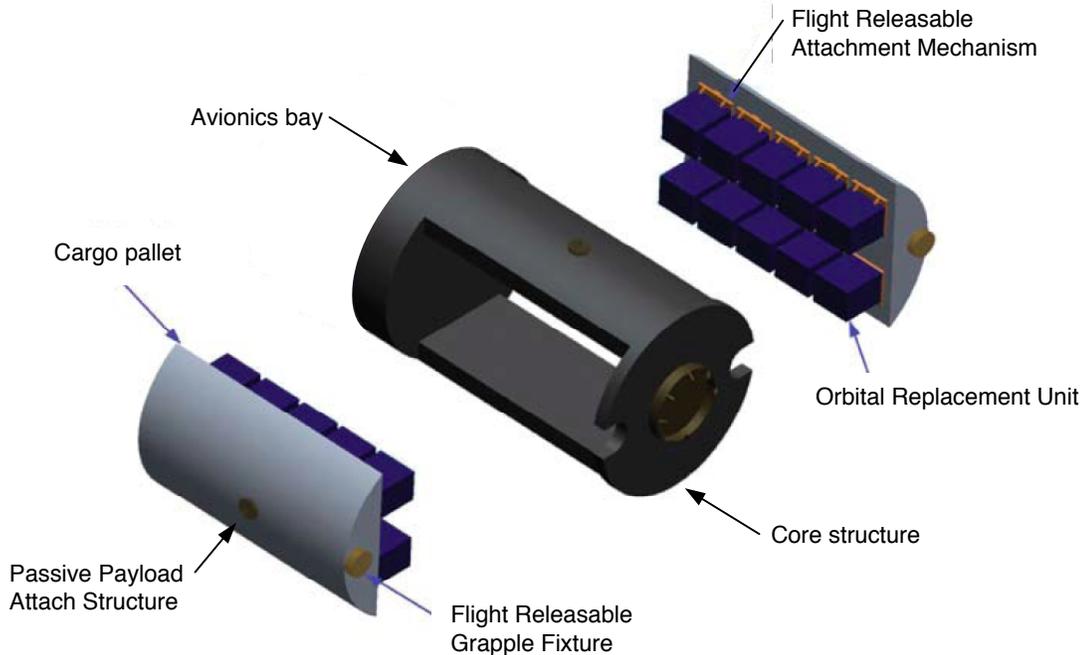Figure 1. Unpressurized Cargo Delivery Vehicle

Figure 2. Unpressurized Cargo Delivery Module.

Major components identified for the UCDV (Figure 1) are the Unpressurized Cargo Delivery Module (Figure 2) comprised of a core structure and two detachable cargo pallets holding the ORUs, an aerodynamic nose cone, and a Service Module to provide on-orbit propulsion and power for the UCDM. The attached SM is assumed to be identical to the design used for the Crew Exploration Vehicle, thus reducing the overall system development schedule, cost and risk. However, the amount of propellant required for the UCDV to reach the ISS is substantially less than necessary for the crewed Lunar mission used to size the SM tankage. To maximize the cargo capacity for the unpressurized cargo resupply mission, only the minimum amount of propellant required for ISS rendezvous and later disposal is carried on the UCDV.

System Requirements

System design specifications called for the UCDV to deliver a minimum of 13,200 lb of cargo to the ISS, with the ORUs mounted on at least 18 Flight Releasable Attachment Mechanisms (Ref. 3). The UCDV concept of operations developed here called for one resupply flight for unpressurized cargo per year to the ISS atop a Crew Launch Vehicle (designated as LV 13.1 in Ref. 2). This launch vehicle, shown in Figure 3 with a CEV payload, 4-segment Solid Rocket Booster first stage and Space Shuttle Main Engine-powered second stage, can deliver an estimated payload of 50,480 lbs to a 51.6-degree, 30 x 160 nmi ISS transfer orbit. A Launch Abort System is not required since the UCDV is uncrewed. Removal of the 9300 lb LAS will also improve the CLV ascent performance since the LAS does not need to be carried to its 212,000 ft jettison altitude. A rough estimate for the increased payload resulting from removal of the LAS is (9300 lb)/7 or 1329 lbs, but this additional performance is not credited to the CLV for this study.

The FRAM system (Figure 4) provides a standard structural and mechanical interface for accommodating cargo during transport to, stowage and handling on the ISS. The FRAM is comprised of active and passive components, where the ORU is attached to the Active FRAM and the Passive FRAM components are fitted to the UCDV structure. The FRAMs are also designed to be compatible with both human and robotic handling aboard the ISS. For this study, nominal dimensions of an equivalent *cargo unit* comprised of an Active FRAM and ORU are 36 x 47 x 49 inches (48 ft^3), with a nominal mass of 800 lbs.

However, the actual ORUs vary greatly in both mass and volume, and range from very small ones that require only a fraction of a cargo unit's mass and volume, to larger ones such as a CMG which, at 600 lbs mass and 65 ft^3 volume, would need to be book-kept as two cargo units since its volume (but not its mass) exceeds the reference value. The largest actual ORU is the stowed radiator array, with a mass of 2473 lbs and a volume of 289 ft^3.
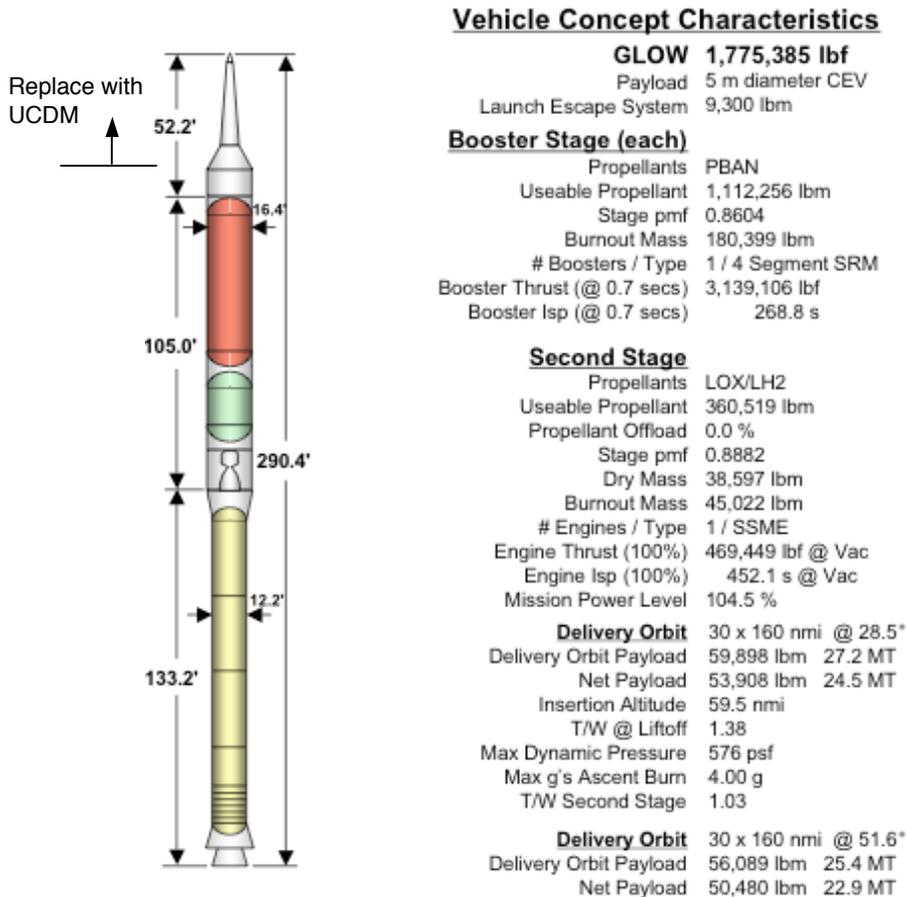
Replace with UCDM

52.2'

16.4'

105.0'

290.4'

12.2'

133.2'

Vehicle Concept Characteristics

GLOW	**1,775,385 lbf**
Payload	5 m diameter CEV
Launch Escape System	9,300 lbm

Booster Stage (each)

Propellants	PBAN
Useable Propellant	1,112,256 lbm
Stage pmf	0.8604
Burnout Mass	180,399 lbm
# Boosters / Type	1 / 4 Segment SRM
Booster Thrust (@ 0.7 secs)	3,139,106 lbf
Booster Isp (@ 0.7 secs)	268.8 s

Second Stage

Propellants	LOX/LH2
Useable Propellant	360,519 lbm
Propellant Offload	0.0 %
Stage pmf	0.8882
Dry Mass	38,597 lbm
Burnout Mass	45,022 lbm
# Engines / Type	1 / SSME
Engine Thrust (100%)	469,449 lbf @ Vac
Engine Isp (100%)	452.1 s @ Vac
Mission Power Level	104.5 %

Delivery Orbit	30 x 160 nmi @ 28.5°	
Delivery Orbit Payload	59,898 lbm	27.2 MT
Net Payload	53,908 lbm	24.5 MT
Insertion Altitude	59.5 nmi	
T/W @ Liftoff	1.38	
Max Dynamic Pressure	576 psf	
Max g's Ascent Burn	4.00 g	
T/W Second Stage	1.03	

Delivery Orbit	30 x 160 nmi @ 51.6°	
Delivery Orbit Payload	56,089 lbm	25.4 MT
Net Payload	50,480 lbm	22.9 MT

Figure 3. Crew Launch Vehicle.

ORU adapter plate

Active FRAM

Passive FRAM

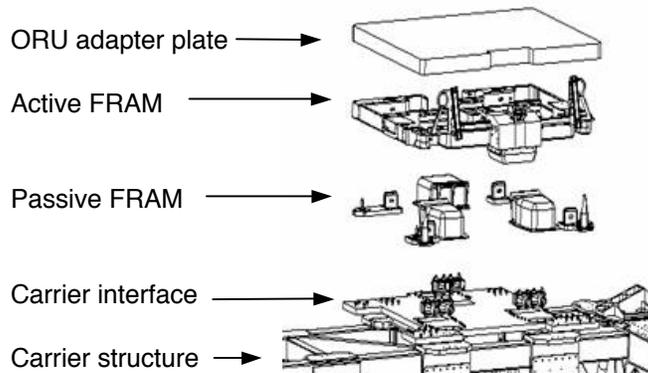Carrier interface

Carrier structure

Figure 4. FRAM system.

To illustrate their variability, size definitions for the large and medium ORUs carried aboard the UCDV are presented. A medium ORU is one that is FRAM-compatible with a mass between 200 and 500 lbs. The average mass of the approximately 20 known medium ORUs is 283 lbs, with an average volume of 18 ft^3. A large ORU is either greater than 500 lbs mass, or requires unique flight support equipment to mount to the carrier structure. The average mass of the approximately 30 large ORUs is 621 lbs, with an average volume of 82 ft^3. The variability of these data illustrates the scope of issues that must be addressed during development of a single UCDV design that must accommodate at least 18 cargo units. To handle the logistics needs of the ISS and the wide range of dimensions and masses of the ORUs, the cargo manifests of each UDCV flight must be carefully tailored to meet pallet mass and stowage volume constraints, as well as requirements for cargo storage and handling aboard the ISS. However, accommodation of actual ORU combinations was not addressed during this study.

Vehicle Configuration

During the ESAS, the diameters of both the CEV and CLV second stage varied as the different concepts were refined. At the time of this study, the diameter of the CEV for the ISS missions was 5.5 meters (Ref. 2). Since the UCDV used the same SM as the CEV, its outer mold line was also sized at 5.5m in diameter. Several "tower" UCDM configurations, shown as end views in Figure 5, were developed and evaluated during the early stages of this study. The UCDMs in these concepts each contained (from left to right) a total of 20, 20 and 18 cargo units attached to an approximately 2m-diameter central structure that was, respectively, five, four and three cargo units in length (where each cargo unit was 4 feet long). The entire tower and attached cargo units were then completely enclosed in a full-length disposable payload fairing to protect the cargo during ascent, and an integral nose cone was also fitted to streamline the vehicle.
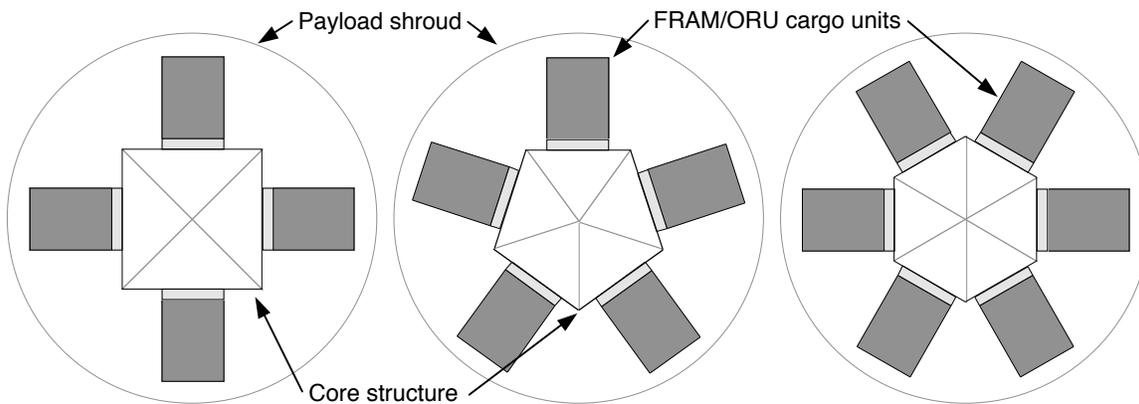

Figure 5. End views of preliminary UCDM designs.

Concerns raised regarding these designs included their low packaging efficiency within the fairing, as well as their capability to accommodate certain oversized ORUs, such as stowed radiators, which required attachment to several coplanar FRAMs. The notional concept of operations for these UCDV designs called for the vehicle to be berthed to the ISS using a Passive Common Berthing Mechanism (Ref. 4). The individual ORUs would then be removed from their FRAMs and either stowed or installed on the ISS. However, these cargo transfer operations were expected to take longer than the 30-day maximum time that the UCDV was allowed to occupy the Active CBM port on the ISS. In addition, the tower configuration's low bending stiffness and natural frequency both atop the SM and when attached to the ISS, as well as possible conflicts with ISS requirements on mass moments of inertia and center of mass for attached vehicles, were recognized as posing problems for the implementation of these designs. These factors led to reevaluation of these proposed designs, and finally led to development of the UCDM configuration shown in Figures 1 and 2.
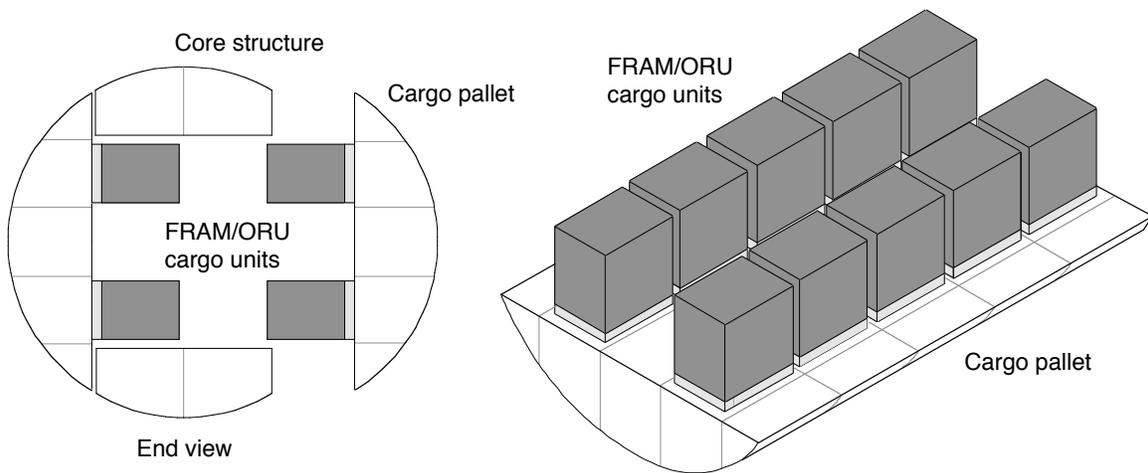
Figure 6. UCDM configuration with (2 x 5) pallet.

For the selected UCDM pallet design shown in Figure 6, the vehicle outer mold line was expanded out to the full 5.5m diameter of the attached SM. This eliminated the separate payload fairing and allows use of the fairing dynamic envelope for the primary structure. This arrangement does incur a slight performance penalty, since the launch vehicle is now carrying the "fairing" mass all the way to the ISS orbit instead of jettisoning it at the same time as the nose cone. However, all of the load-bearing structural elements in this arrangement are now located towards the maximum diameter of the UCDM, where they provide structural benefits for this design like increased bending stiffness.

The UCDM core structure is comprised of two deep box beams attached to two disk-shaped end caps. The avionics bay in the aft end cap contains flight electronics, batteries and other subsystems, as well as providing the interfaces with the SM. The forward end cap supports both the Passive CBM for berthing to the ISS and the base of the nose cone. During launch, the two large UCDM cargo pallets shown in Figure 6 are mechanically connected along their edges to the UCDV core structure, thus forming a very stiff integrated configuration. After the UCDV is berthed to the ISS, these mechanical latches are released remotely to allow the pallets and attached cargo units to be removed from the UCDV. As a contingency, these latching devices must also be manually releasable by astronauts during an extravehicular activity, since the FRAMs are not accessible through the Passive CBM. More detailed structural design effort is needed to help determine whether the pallets will transfer all of the ORU inertial loads and vehicle flight loads as shear through the latches into the core beams, or to share some of the load as compression through the pallet outer mold line and into the aft end cap.
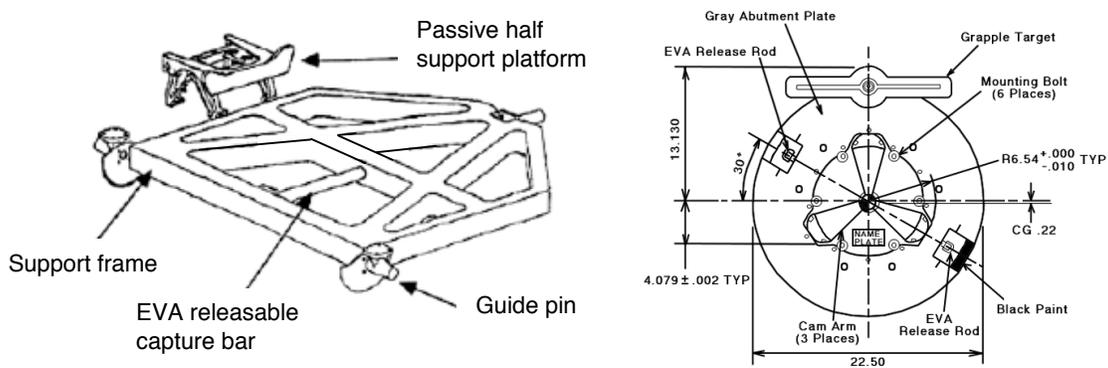

Figure 7a (left), 7b (right). Passive PAS and FRGF mechanisms.

A total of 20 cargo units are stored on these two pallets, and each (2 x 5) pallet has two rows of five columns of cargo units separated by a 4-foot wide aisle for astronauts to reach the base of the FRAMs during EVA. This arrangement allows excellent access for removal of the ORUs using EVA or telerobotic systems, while still allowing maximum flexibility for stowage and transport of large and irregularly shaped cargo elements. A Passive Payload Attach System (see Figure 7a) and a Flight Releasable Grapple Fixture (Figure 7b) are also mounted on each pallet to provide for attachment to and transport around the ISS structure. Further details of these mechanisms are provided in Reference 4.

After completion of the ESAS activity, the UCDV design was revisited to determine if more efficient vehicle configurations were possible, and to account for new requirements, constraints and operational considerations. Relaxation of the EVA access requirement and subsequent use of the central aisle to carry additional cargo allowed a more compact pallet arrangement of three rows of four columns of cargo units (see Figure 8) to be evaluated. This (3 x 4) pallet configuration would increase the total cargo capacity to a maximum of 24 cargo units and also reduce the overall UCDM length, resulting in better packaging efficiency and a higher natural frequency atop the CLV. The structural mass of the pallets and core beams could also be reduced by about 20 percent or 1650 lbs (using a mass estimate of 8268 lbs reported in Table 1 for the long pallets and core beams of the ESAS design), since they are now shorter than the original design in Figure 6 by one FRAM unit. However, if four additional cargo units were carried, the cargo mass could increase by 3200 lbs, for a net increase of 1550 lbs in the UCDM mass.
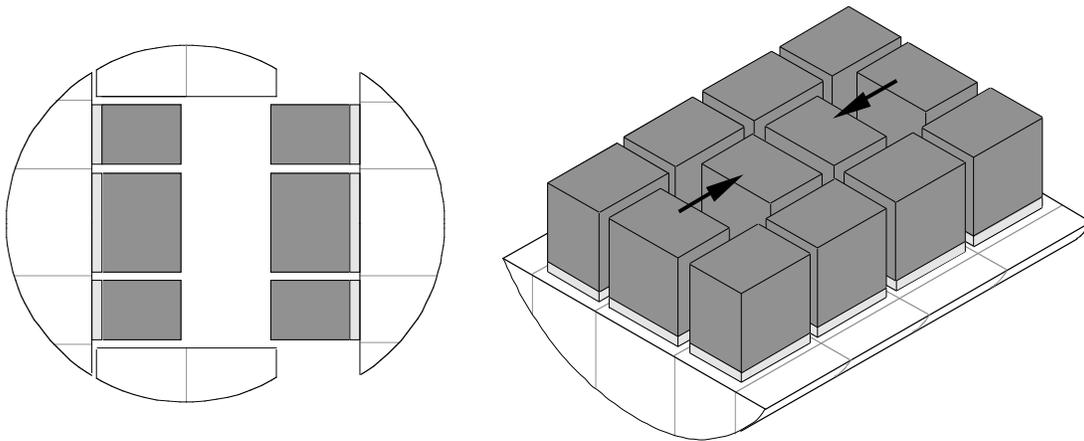

Figure 8. Alternate (3 x 4) pallet configuration.

The central column of cargo units in this pallet design must also be rotated by 90 degrees because the FRAM mechanism has a required direction for access to a stowed ORU (as indicated by the arrows in Figure 8). An additional constraint is then imposed on what can be stowed in the central two FRAM locations, since they are completely blocked in by surrounding cargo units. One solution would require positioning of lower-priority cargo on these central FRAMs, which could then be accessed only after the more urgently needed ORUs on the outboard locations are removed. Another possible concern with this pallet design is that reorientation of the central cargo units reduces the depth of the core beams on each side (compare Figures 6 and 8), resulting in a reduction in bending stiffness and natural frequency as well as the bearing area for attachment of the cargo pallets.

More detailed manifesting analyses with actual ORU masses and volumes must still be performed to determine the loaded pallet masses, MMOIs and CMs while stowed aboard the ISS. If requirements on these quantities were to be violated by using the longer pallet design shown in Figure 8, then each large pallet could be further subdivided into two smaller (3 x 2) pallets (see Figure 9a) with three rows of cargo units in two columns. However, this arrangement would be more massive than the single (3 x 4) pallet, since each (3 x 2) pallet would require some additional structure as well as a separate FRGF and Passive PAS (253 lbs). In addition, various combinations (e.g., two long, one long and two short, or four short) of

these pallets could be carried on the UCDV as dictated by ISS logistics requirements. However, operational penalties (e.g., increased number of payload mounting locations and separate transfer operations) are also incurred by increasing the number of pallets.

If necessary to save mass, the pallet design in Figure 8 could be shortened yet again to carry nine cargo units in three columns of three rows. This (3 x 3) pallet, shown in Figure 9b, would still meet the minimum requirement for the UCDV to deliver 18 cargo units to the ISS on each flight. The mass of the pallets and core beams of this shortened design could be as much as 40 percent less than the mass of the baseline design in Figure 6. Using the structural mass of 8268 lbs noted above, the (3 x 3) pallet design below could save up to 3300 lbs from the reduced pallet length, as well as 1600 lbs from the reduced cargo capacity of this design (18 cargo units instead of 20).
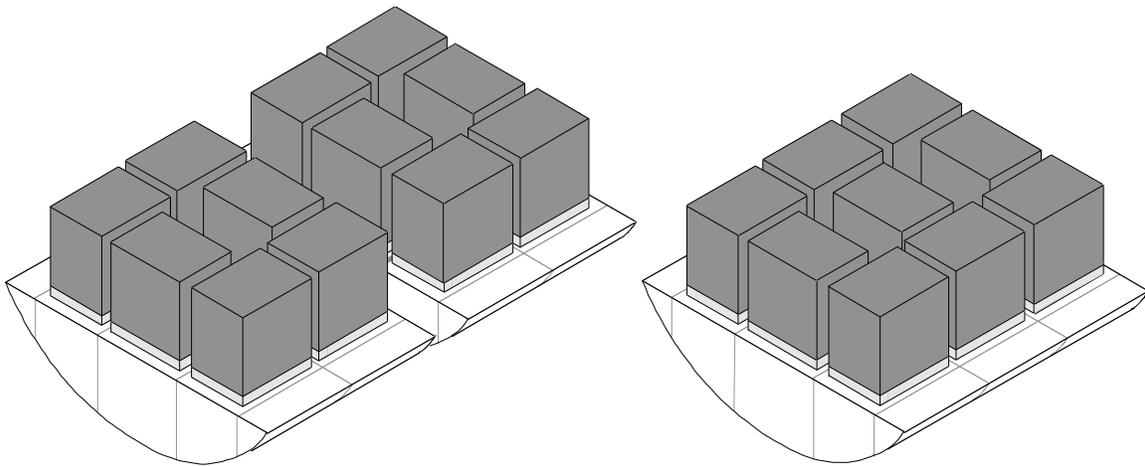

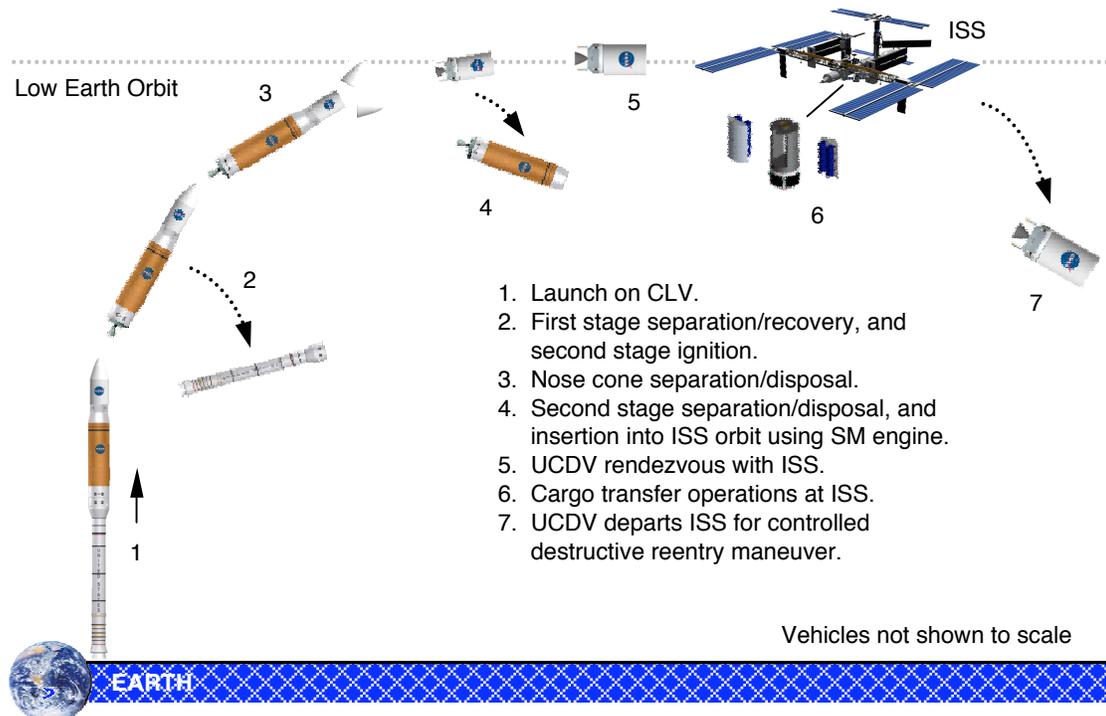Figure 9a (left), 9b (right). Small pallet configurations.

Low Earth Orbit

ISS

1. Launch on CLV.
2. First stage separation/recovery, and second stage ignition.
3. Nose cone separation/disposal.
4. Second stage separation/disposal, and insertion into ISS orbit using SM engine.
5. UCDV rendezvous with ISS.
6. Cargo transfer operations at ISS.
7. UCDV departs ISS for controlled destructive reentry maneuver.

Vehicles not shown to scale

EARTH

Figure 10. UCDV concept of operations.

UCDV Concept of Operations

The UCDV concept of operations is described in this section, with the launch and in-space portions shown in Figure 10. Prior to launch, the individual ORUs are prepared for flight and integrated with their Active FRAMs in a processing facility at the NASA Kennedy Space Center. The empty cargo pallets are mounted horizontally in ground support equipment, and the Passive FRAMs are installed in their designated locations. The ORUs are then installed on the pallets in their proper locations and orientations required to satisfy mass, CM and MMOI constraints on the UCDV, CLV and ISS. The loaded cargo pallets are rotated 90 degrees to a vertical orientation and swung into their launch positions on the core structure. The mechanical latches are fastened to lock the pallets to the core structure.

After integration of the SM and nose cone, the assembled UCDV is stacked on a CLV, and the combined vehicles are rolled out to the launch pad where final flight preparations are made. The UCDV is launched on the CLV to a 30 x 160 nmi, 51.6-degree inclination transfer orbit. While the CLV is designed with a maximum axial acceleration of 4g, its ascent trajectory with the UCDV spacecraft could be easily tailored to a maximum 3g axial acceleration, thus maintaining compatibility with the Space Shuttle design heritage of the existing ORUs. This would eliminate the need to redesign or recertify the ORUs for the higher ascent load, but does result in a small performance penalty calculated at approximately 100 lbs of payload.
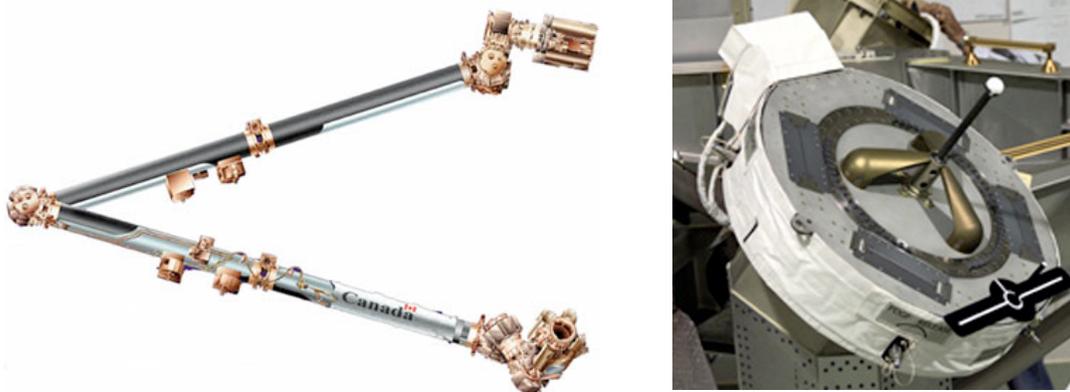

Figure 11a (left), 11b (right). SSRMS and PDGF mechanisms.

The nose cone is separated from the UCDV when the dynamic pressure becomes negligible shortly after second stage ignition. After achieving insertion into the desired transfer orbit, the UCDV separates from the second stage, which then reenters into the Pacific Ocean. The SM engine then fires to provide the remaining propulsion required to reach the ISS orbit. For rendezvous with the ISS, the UCDV approaches the ISS and enters the berthing box in a station-keeping mode, where it is captured with the Space Station Remote Manipulator System arm (shown in Figure 11a) on a Power Data Grapple Fixture (Figure 11b) mounted on the UCDM core structure.

The UCDV is then berthed to an open Active CBM port on the ISS, which also provides a power and data link between the two vehicles. Several different options for this ISS interface have been investigated that can leverage existing space-rated hardware and experience. A Passive CBM (see Figure 12a) is shown installed on the front of the UCDM in Figures 1 and 2, and several ports on the ISS are already fitted with Active CBMs. Other possible interface mechanisms shown in Figures 12b and 12c are the Low Impact Docking System (Ref. 5) originally developed for the X-38 Crew Return Vehicle, and the Russian-built Androgynous Peripheral Attachment System (Ref. 6) used on the Space Shuttle and Soyuz spacecraft for docking to the ISS, as well as some inter-module connections on the ISS. Potential issues with these

systems include the fact that no new CBMs are currently being produced, the relatively low development level of the LIDS, and the high dynamic forces required to engage the APAS latches.
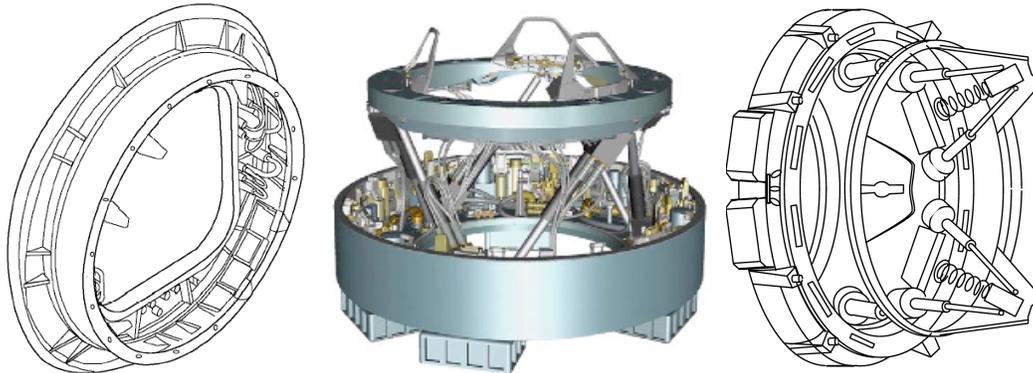

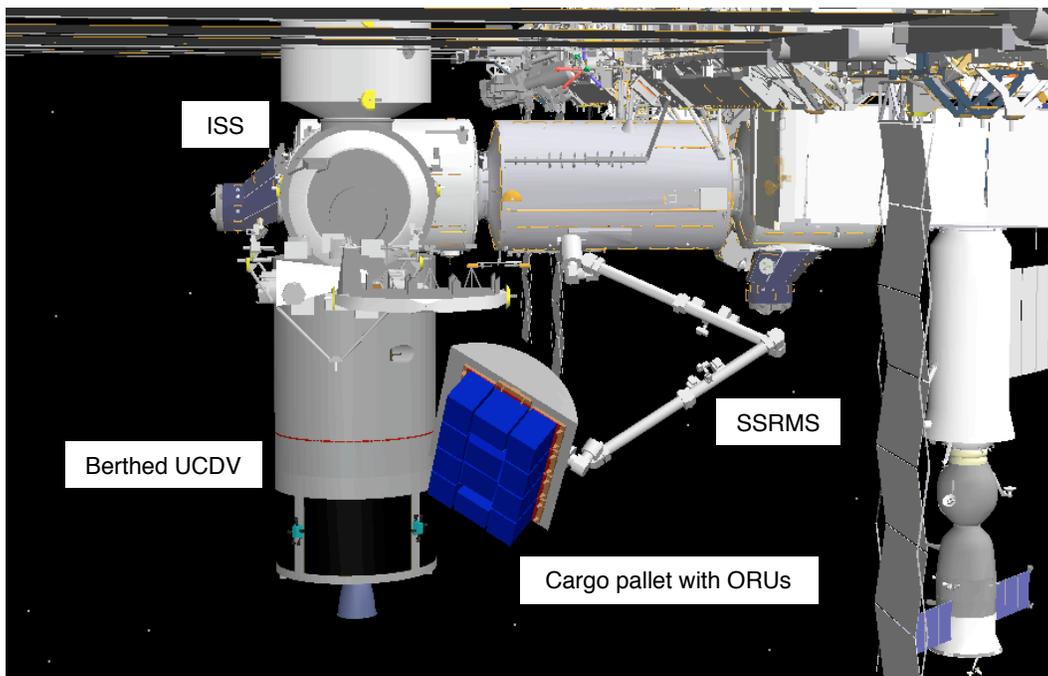Figure 12a (left), 12b (center), 12c (right). Passive CBM, LIDS and APAS mechanisms.

Figure 13. UCDV and cargo pallet transfer operations on ISS.

After berthing the UCDV to the ISS, one end effector on the SSRMS grapples a PDGF on the Mobile Transporter/Mobile Base System. The other SSRMS end effector then grasps a FRGF on a pallet, releases the latches, and extracts that pallet with its attached cargo from the UCDM core structure (see Figure 13). The MT/MBS with attached SSRMS and pallet then moves along the ISS truss to an unoccupied Active PAS location on either the P3 or S3 truss to stow the pallet, as shown in Figure 14. For the first UCDV flight to the ISS, the UCDM core structure and attached SM are then unberthed and deorbited, leaving two full pallets of new ORUs on the ISS. The ISS crew then removes and installs the ORUs using EVAs or the SSRMS, and then load the unserviceable ORUs back onto the stowed pallet. When a new UCDV arrives with fresh ORUs, these full pallets are removed from the UCDV and stored on the ISS. The two old pallets, now full of unserviceable ORUs, are then reattached to the newly arrived UCDV using the SSRMS and MT/MBS. The UCDV remains berthed to the ISS for a maximum of 30

days, after which it is unberthed and departs the ISS for disposal of the vehicle and unserviceable ORUs in a controlled destructive deorbit maneuver.
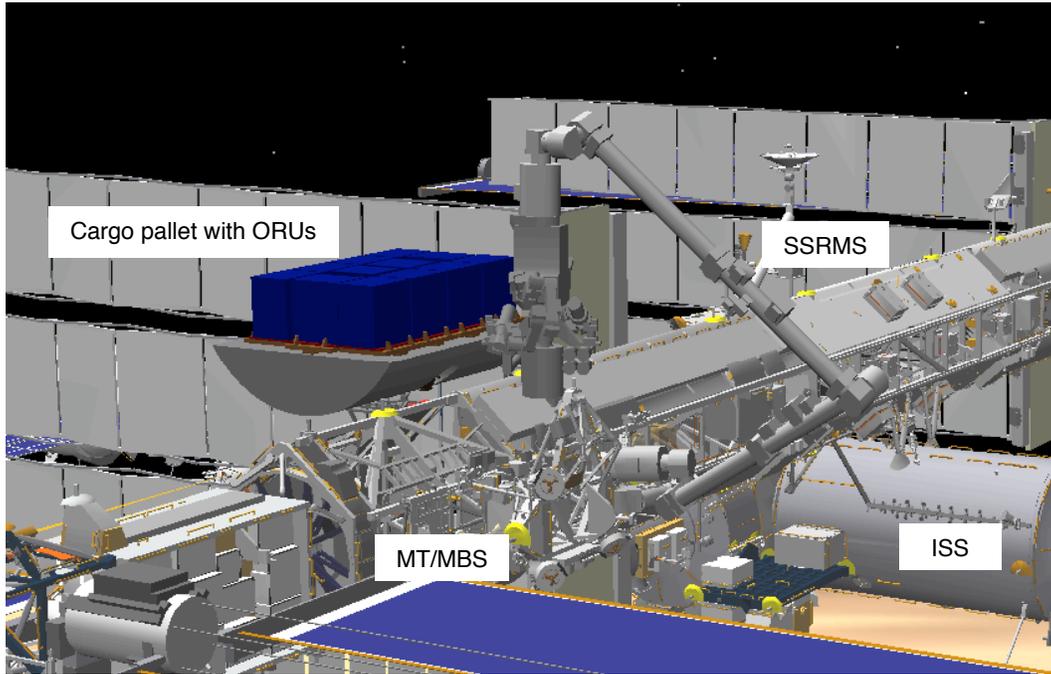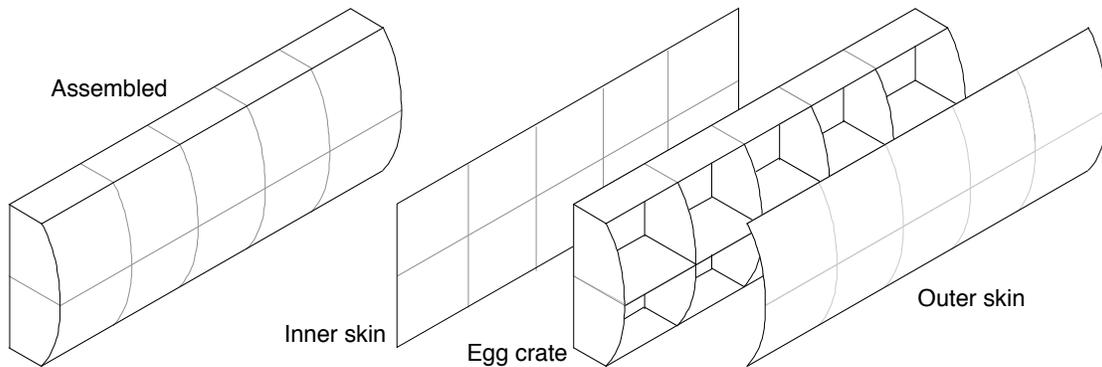

Figure 14. Cargo pallet on ISS stowage site.

Figure 15. UCDM core beam and subcomponents.

Structural Layout and Sizing

As the vehicle layout and concept of operations were being developed, the structural configuration was also defined. Both metallic and composite structures were considered, and a graphite-epoxy composite face sheet and metallic honeycomb sandwich structure was chosen for the acreage structure. Each UCDM pallet was built up of an internal orthogonal "egg crate" structure to support the FRAM corners and core latch attachment points, and then skinned with composite sandwich panels. The box beams for the UCDM core structure were also designed in a similar fashion with internal bulkheads and cover panels. These construction methods were chosen to minimize part count and simplify fabrication. An expanded view of the core beam and major structural subcomponents is shown in Figure 15, with the cargo pallet and its subcomponents shown in Figure 16.
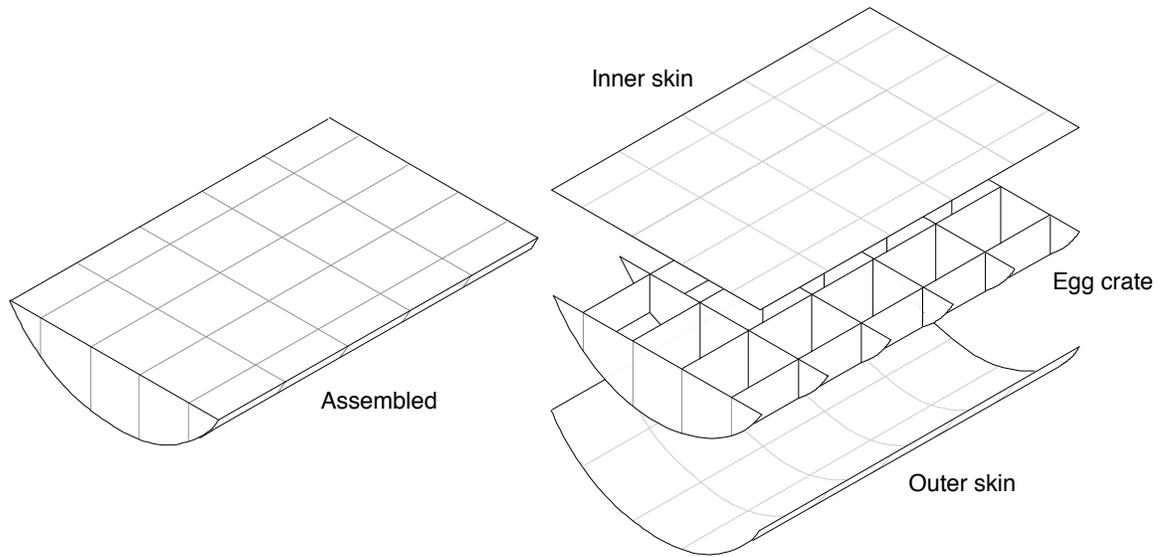
Figure 16. (2 x 5) cargo pallet structure and subcomponents.

For preliminary sizing, an areal density of 2 lb/ft^2 is used to estimate the masses of the UCDM composite sandwich structures. This value was chosen using experience gained with a graphite-toughened bismaleimide composite and metallic honeycomb sandwich wing box (Figure 17, Ref. 7) developed for NASA's High-Speed Research program. This highly loaded structure had wing surface areal densities ranging from 2.5 to 3.2 lb/ft^2, and 1.3 lb/ft^2 for the spar webs. The corresponding design loads of 10 to 20 klb/in. in-plane tension and compression, and 2.5 klb/in. in-plane shear are plotted with their associated areal densities in Figure 18. A rough estimate of the maximum compressive load Nx at the UCDM/SM interface plane is computed here as the product of the largest possible mass forward of the separation plane (50.5 klb CLV performance – 15.3 klb SM mass), the 4g peak axial acceleration and a 1.25 factor of safety, all divided by the SM circumference, or

$$Nx = (35.1 \text{ klb x 4g x 1.25 FS})/(2\pi \text{ x 2.75m x 39.37 in/m}) = 258 \text{ lb/in.} \tag{1}$$

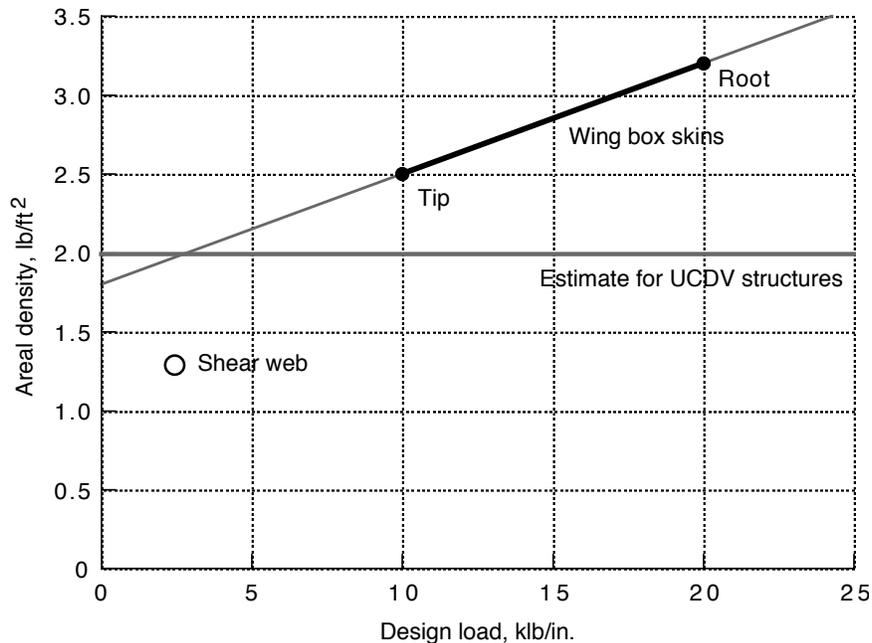Figure 17. Composite sandwich wing box.

Figure 18. Wing box structural element sizing.

The result computed in Equation 1 assumes that the UCDM inertial load is evenly distributed around its circumference at the interface plane. Depending on how the loaded cargo pallets are designed to transfer their inertial loads through into the core structure, the local loads at the latches may be much higher than this estimate. However, the running load in Equation 1 is still an order of magnitude lower than the lowest wing box design load. Since the compressive loads at the UCDM/nose cone interface will be even lower due to the lower supported mass above, these results indicate that the overall UCDV structural loads should be lower than the wing box design loads.

As a point of reference to determine the validity of these high-level mass estimates, a comparison was made with the External Stowage Platform-2 payload (Ref. 8). The ESP-2 is an unpressurized logistics carrier that was delivered to the ISS on the STS-114 mission in July 2005. The dry mass of the ESP-2 flight hardware is reported as 5900 lbs, and it carries ORUs mounted on eight FRAMs. Division of these two values gives a normalized ESP-2 system mass of 738 lbs/FRAM. Division of the 15,889 lb UCDM dry mass reported in Table 1 (and discussed in more detail in the following section on Vehicle Sizing and Performance) by 20 FRAMs gives a normalized UCDM system mass of 794 lbs/FRAM, which is within ten percent of the corresponding value for the ESP-2. Based on these estimates and the analyses described above, the 2 lb/ft^2 areal density chosen for preliminary sizing of the UCDM may be somewhat conservative (as is appropriate at this early stage of design), and the as-built structures may prove to be lighter.

Further finite element analysis and structural sizing of the UCDM were performed using commercial software and are described in Reference 9. Various structural concepts, including both composite and metallic sandwich panels and skin-stringer constructions, were examined in this study. As expected, high local stress concentrations were noted around the discrete attachment points where the pallets connect to the core beam structure. The composite honeycomb structure was also determined to be the minimum-weight construction, with an areal density well below 1 lb/ft^2. While not surprising for this level of analysis, inclusion of practical design details such as edge close-outs and local reinforcements required to support fasteners and other point loads will tend to drive the weight higher. These design details and other considerations are typically lumped into a single "non-optimal" factor for the purposes of preliminary design studies.

Vehicle Sizing and Performance

Using the layout described above for the UCDM, the mass of the primary vehicle structure (pallets and core beams) is estimated as 8,268 lbs. Addition of other mechanisms (Passive CBM, Passive PAS, Passive FRAMs, FRGF, PDGF, etc.) results in a total structural mass of 11,010 lbs. Addition of the various other subsystem masses yields a UCDM dry mass estimate of 13,241 lb, and 20 percent growth margin is applied to obtain a design mass with margin of 15,889 lb. The UCDM mass of 15,889 lb is added to the 16,000 lb payload (20 cargo units x 800 lbs each), the 15,241 lb SM mass and the 2205 lb node cone mass and performance impact, resulting in an estimate of 49,335 lbs for the complete UCDV. These mass estimates are also shown by Work Breakdown Structure element in Table 1 for the vehicle design evaluated for the ESAS. Considering the estimated CLV performance of 50,480 lbs to the 30 x 160 nmi ISS transfer orbit, the actual dry UDCM growth margin is just under 29 percent.

The system performance estimates presented here use the same data reported for the crewed version of the CLV in the ESAS final report. These analyses are sufficient for the conceptual level of design in this study. However, an ascent trajectory performance and loads analysis that accounts for all of the particular details of the UCDV design (aerodynamics, no LAS, maximum 3g axial acceleration, nose cone separation, etc.) is still required to determine if this spacecraft design is compatible with the launch vehicle. These more detailed analyses would be required if this concept were to be matured further.

Concluding Remarks

The system requirements, vehicle configuration, concept of operations, and structural design and layout for the UCDV concept are presented in this paper. The initial concept study was performed in support of NASA's ESAS activity at the NASA Langley Research Center. The vehicle design presented in the ESAS final report can deliver 20 cargo units with a mass of 16,000 lb to the ISS, exceeding the given requirements by 2 cargo units and 2800 lbs of payload. Modified pallet designs can accommodate up to 24 cargo units with 19,200 lbs of cargo, but this may exceed the launch vehicle capability. Therefore, the basic UCDV design and options investigated offer a high degree of flexibility to accommodate a wide range of future unpressurized cargo manifests.

After conclusion of the ESAS, additional design and development of the UCDV were performed at NASA Langley. However, a NASA decision to develop the ISS unpressurized cargo resupply capability within the commercial market under the Commercial Orbital Transportation Services program resulted in termination of this internal effort. Since continuing support for the ISS is a high priority for NASA, the UCDV spacecraft design presented here remains available as a fallback option to the COTS program. Despite substantial changes in the launch vehicle design from the version presented in the ESAS report, this UCDV concept is still compatible in most respects with the current Ares I launch vehicle design, performance and requirements.

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1.0 Structure	**Quantity**	**4995**	**kg**	**11010**	**lb**
Pallet structure (1250 kg each)	2	2500		5512	
Core structure	1	1250		2756	
Passive PAS (115 kg each)	2	230		506	
Passive FRAM (15 kg each)	20	300		660	
FRGF (2) & PDGF (1)	3	38		84	
Passive CBM	1	177		390	
Avionics bay	1	500		1102	
2.0 Protection		**100**	**kg**	**220**	**lb**
Insulation		100		220	
3.0 Propulsion		**0**		**0**	
4.0 Power		**290**	**kg**	**638**	**lb**
Cabling		290		638	
5.0 Control		**0**		**0**	
6.0 Avionics		**623**	**kg**	**1373**	**lb**
Command, control & data handling		156		344	
Guidance, navigation & control		112		247	
Communications		128		282	
Instrumentation & cabling		227		500	
7.0 Environment		**0**		**0**	
8.0 Other		**0**		**0**	
9.0 Growth Margin		**1202**	**kg**	**2648**	**lb**
20 percent		1202		2648	
10.0 Non-Cargo		**0**		**0**	
11.0 Cargo		**7260**	**kg**	**16000**	**lb**
Cargo unit (363 kg each)	20	7260		16000	
includes ORU & Active FRAM					
12.0 Non-Propellant		**0**		**0**	
13.0 Propellant		**0**		**0**	
UCDM Gross Mass		**14470**	**kg**	**31889**	**lb**
SM Gross Mass		**6912**	**kg**	**15241**	**lb**
Nose Cone Mass and performance impact		**1000**	**kg**	**2205**	**lb**
Total UCDV Mass		**22382**	**kg**	**49335**	**lb**
CLV Performance to 30 x 160 nmi, 51.6 deg. orbit		**22900**	**kg**	**50480**	**lb**

Table 1: UCDV system mass estimates.