JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 45, No. 5, September–October 2008

Systems Analysis and Structural Design of an Unpressurized Cargo Delivery Vehicle

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DOI: 10.2514/1.32661

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. This 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 would be used to launch one annual resupply flight to the International Space Station. The baseline vehicle design has a cargo capacity of 16,000 lb mounted on up to 20 flight releasable attachment mechanisms. Major vehicle components are an 18.0 ft-diam cargo module containing two detachable pallets with the payload, a service module to provide propulsion and power, and a jettisonable nose cone. To reduce cost and risk, the service module is identical to the one used for the crew exploration vehicle design.

Nomenclature

g = Earth-standard acceleration due to gravity, 32.2 ft/s^2
Nx = axial line load, lb/in.

Introduction

AFTER the planned retirement of the space shuttle in 2010, there will still be a need to deliver new orbital replacement units (ORUs) to the International Space Station (ISS) in its approximately 180 n mile circular, 51.6 deg 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 control moment gyroscopes (CMGs), high-pressure oxygen tanks, and stowed radiator arrays. Most of the current or planned ISS resupply spacecraft (automated transfer vehicle and Progress) cannot deliver any external logistics payloads [1], whereas the H-II Transfer Vehicle can only carry up to six smaller ORUs with a total mass (including attachments and integration hardware) of 3300 lb [2].

In June 2005, the Systems Analysis and Concepts Directorate at the NASA Langley Research Center performed a conceptual design study to develop an unpressurized cargo delivery vehicle (UCDV) that would support the external cargo needs of the ISS program in the post-2010 time frame. This work was initially done as part of NASA's 90-day Exploration Systems Architecture Study (ESAS) [3]. 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-up study conducted during the second half of 2005.

Three major components are identified for the UCDV and are shown in Fig. 1. The unpressurized cargo delivery module (UCDM), Fig. 2, consists of a core structure and two detachable cargo pallets holding the ORUs. A jettisonable aerodynamic nose cone protects the ISS interface mechanisms during ascent, and a service module (SM) provides 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 (CEV), thus reducing the overall system development schedule, cost, and risk. However, the amount of propellant required for the UCDV to reach the ISS orbit is substantially less than that 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

Predicted external cargo replacement needs for the ISS indicated an annual requirement of at least 13,200 lb of logistics contained in 18 cargo units. Each cargo unit is the standard volume and mass handling capability of a flight releasable attachment mechanism, or FRAM [4]. These ISS requirements determined the UCDV system requirements for delivery of a minimum of 13,200 lb of cargo on at least 18 FRAM attachment points. The ESAS ground rules dictated that the UCDV would be launched to the ISS once each year on a crew launch vehicle, or CLV (designated as LV 13.1 in [3]). This launch vehicle, shown in Fig. 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 lb to a 51.6 deg, 30×160 n mile ISS transfer orbit. A launch escape system (LES) is not required here because the UCDV is uncrewed, and removal of the 9300 lb LES will also improve the CLV ascent performance. A rough estimate for the increased payload gained by removal of the LES (which would normally be carried to its 212,000 ft jettison altitude) is one-seventh of the LES mass, or 1329 lb. This additional performance is not credited to the CLV in this study and would provide additional mass margin for the system.

The FRAM system (Fig. 4) provides a standard structural and mechanical interface for accommodating cargo during transport to,

Presented as Paper 2329 at the 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, HI, 23–26 April 2007; received 6 June 2007; accepted for publication 9 December 2007.

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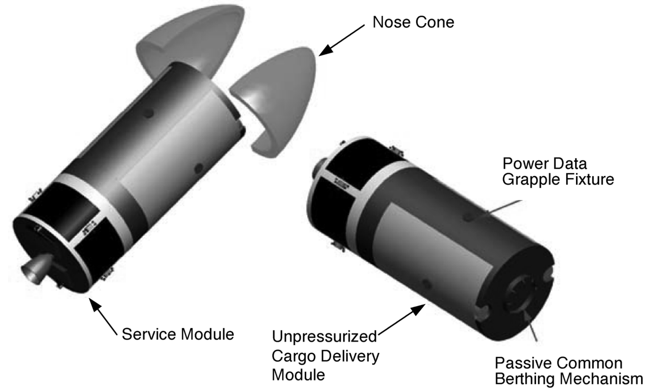


Fig. 1 Unpressurized cargo delivery vehicle.

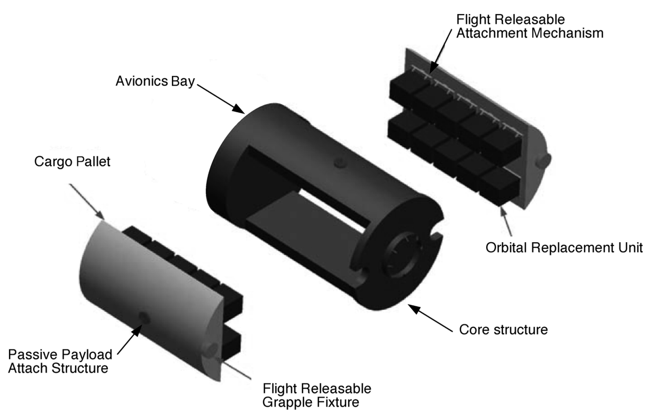
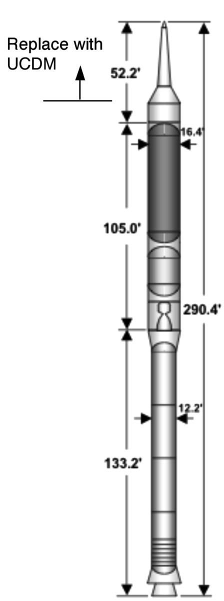


Fig. 2 Unpressurized cargo delivery module.



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

Fig. 3 Crew launch vehicle.

and stowage and handling on, the ISS. The FRAM is composed of both active and passive components, where the ORU is attached to an adapter plate above the active FRAM, and the passive FRAM components are fitted to the UCDV structure. The FRAMs are also designed to be handled by both humans and robots aboard the ISS. For this study, nominal dimensions of a cargo unit composed of an ORU, active FRAM, and flight support equipment are $36 \times 47 \times 49$ in. (48 ft^3) with a mass of 800 lb. However, the actual ORUs vary

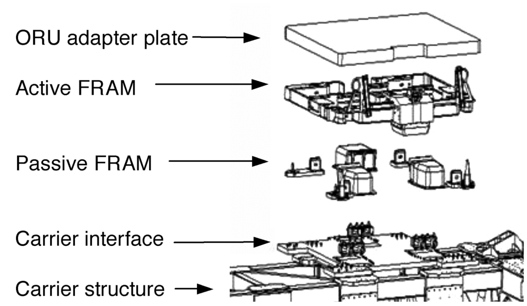


Fig. 4 FRAM system.

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 much larger ones such as a CMG. At 1212 lb mass and 84 ft^3 volume with flight support equipment, a CMG is equivalent to two cargo units because its mass and volume both exceed the reference values. The largest ORU is the stowed radiator array, with a mass of 2473 lb and a volume of 289 ft^3 without flight support equipment.

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 lb. The average mass of the approximately 20 known medium ORUs is 283 lb, with an average volume of 18 ft^3. A large ORU is either greater than 500 lb mass or requires unique flight support equipment to mount to the carrier structure. The average mass of the approximately 30 large ORUs is 621 lb, 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 UCDV 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 m, or 18 ft [3]. Because the UCDV used the same SM as the CEV, its outer mold line was also sized at 18 ft in diameter. Several "tower" UCDM configurations, shown as end views in Fig. 5, were proposed 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 6 ft-diam central core structure that was, respectively, 5, 4, and 3 cargo units in length (where each cargo unit was 4 ft long). The entire core structure and attached cargo units were then completely enclosed in a full-length disposable payload fairing to protect the cargo and streamline the vehicle during ascent.

Evaluation of these designs raised concerns about their low packaging efficiency within the fairing, as well as their capability to accommodate certain oversized ORUs, such as stowed radiators, which require 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 (CBM) [5] installed on the forward bulkhead of the core structure. 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 berthing 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 (MMOI) and center of mass (c.m.) for attached vehicles, were recognized as posing problems for the implementation of these

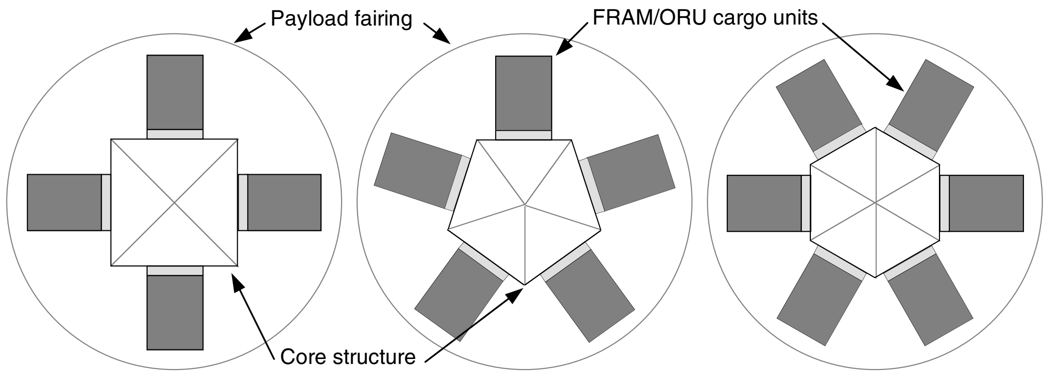


Fig. 5 End views of preliminary UCDM designs.

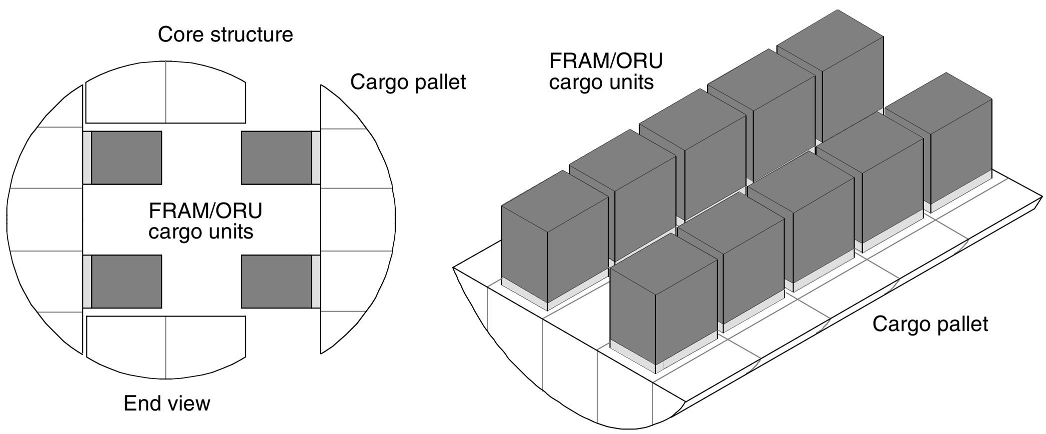


Fig. 6 UCDM configuration with (2 × 5) pallet.

designs. These factors led to reevaluation of these proposed designs and finally led to development of the UCDM configuration shown in Figs. 1 and 2.

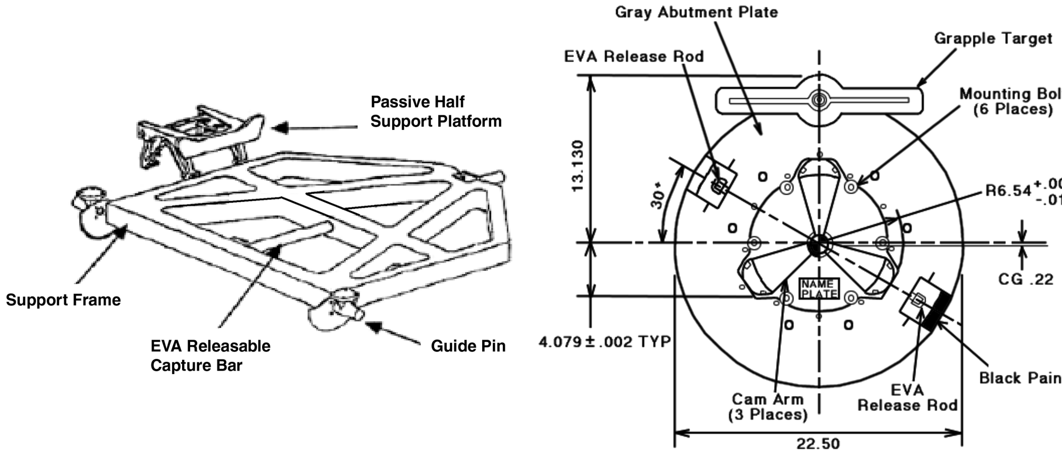
For the selected UCDM design shown in Fig. 6, the vehicle outer mold line is expanded out to the full 18.0 ft diameter of the attached SM, allowing elimination of the separate payload fairing and use of the full fairing dynamic envelope for the UCDM primary structure. This arrangement does result in a performance penalty because the launch vehicle is now carrying the "fairing" mass all the way to the ISS instead of jettisoning it along with the nose cone. However, all of the load-bearing structural elements in this arrangement are now located toward the maximum diameter of the UCDM, where they provide structural benefits such as increased bending stiffness.

The UCDM core structure is composed 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, and provides 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 Fig. 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 (EVA), because the stored ORUs are not accessible through the passive CBM. A detailed structural design effort is needed to determine whether the pallets will shear the ORU inertial loads and vehicle flight loads through the latches into the core beams, or transfer the load as compression through the pallet skin into the aft end cap.

A total of 20 cargo units are stored on these two pallets, and each (2 × 5) pallet has two rows of five columns of cargo units separated by a 4-ft-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 (PAS) (see Fig. 7a) and a flight releasable grapple fixture (FRGF) (Fig. 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 [5].

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 and four columns of cargo units (see Fig. 8) to be evaluated. This (3 × 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%, or 1650 lb [using a mass estimate of 8268 lb reported in Table 1 for the (2 × 5) pallets and core beams of the ESAS design], because they are now shorter than the original design in Fig. 6 by one FRAM. However, if four additional cargo units were carried, the cargo mass would increase by 3200 lb, for a net increase of 1550 lb in the UCDV mass.

The central column of cargo units in the (3 × 4) pallet design must also be rotated by 90 deg because the FRAM mechanism has a required direction for access to a stowed ORU (as indicated by the arrows in Fig. 8). This design places an additional constraint on what can be stowed in the central two FRAM locations, because they are completely blocked in by surrounding cargo. One possible solution would require positioning of lower-priority cargo on these central FRAMs, which could then be accessed only after removal of more urgently needed ORUs on the outboard locations. Another concern



a) b)

Fig. 7 Mechanisms: a) passive PAS and b) FRGF.

with this pallet design is that reorientation of the central cargo units reduces the depth of the core beams on each side (compare Fig. 6 and Fig. 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 are needed to determine the loaded pallet masses, MMOIs, and centers of mass while stowed aboard the ISS. If requirements on these quantities were violated by the (3×4) pallet design shown in Fig. 8, then each large pallet could be further subdivided into two smaller (3×2) pallets (see Fig. 9a) with three rows of cargo units in two columns. However, two (3×2) pallets would be more massive than the single (3×4) pallet, because each smaller pallet would require some additional structure as well as a separate FRGF and passive PAS (a combined mass of 253 lb). In addition, various combinations of these long and short pallets could also 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 separate pallets.

If further reductions in mass were necessary, the pallet design could be reconfigured to carry nine cargo units in three columns of three rows. This (3×3) pallet, shown in Fig. 9b, would still meet the minimum requirement for the UCDV to deliver 18 cargo units to the ISS on each flight. When compared with the baseline design in Fig. 6, mass savings of up to 3300 lb from the shorter pallets and core beams of this design, as well as 1600 lb from the reduced cargo capacity of this design (18 cargo units instead of 20) can be achieved.

Unpressurized Cargo Delivery Vehicle Concept of Operations

The UCDV concept of operations is described in this section, with the launch and in-space portions shown in Fig. 10. Before launch, the

Table 1 UCDV system mass estimates

1.0 Structure		**Quantity**	**4995 kg**	**11,010 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%		1202	2648
10.0 Noncargo			**0**	**0**
11.0 Cargo			**7260 kg**	**16,000 lb**
	Cargo unit (363 kg each) includes ORU & active FRAM	20	7260	16,000
12.0 Nonpropellant			**0**	**0**
13.0 Propellant			**0**	**0**
UCDM gross mass			**14,470 kg**	**31,889 lb**
SM gross mass			**6912 kg**	**15,241 lb**
Nose cone mass and performance impact			**1000 kg**	**2205 lb**
Total UCDV mass			**22,382 kg**	**49,335 lb**
CLV performance to 30 × 160 n mile, 51.6 deg. orbit			**22,900 kg**	**50,480 lb**

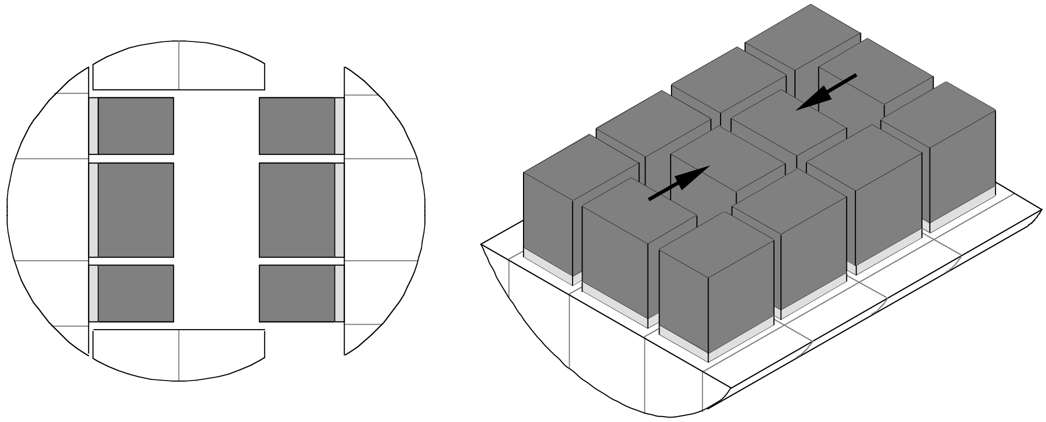
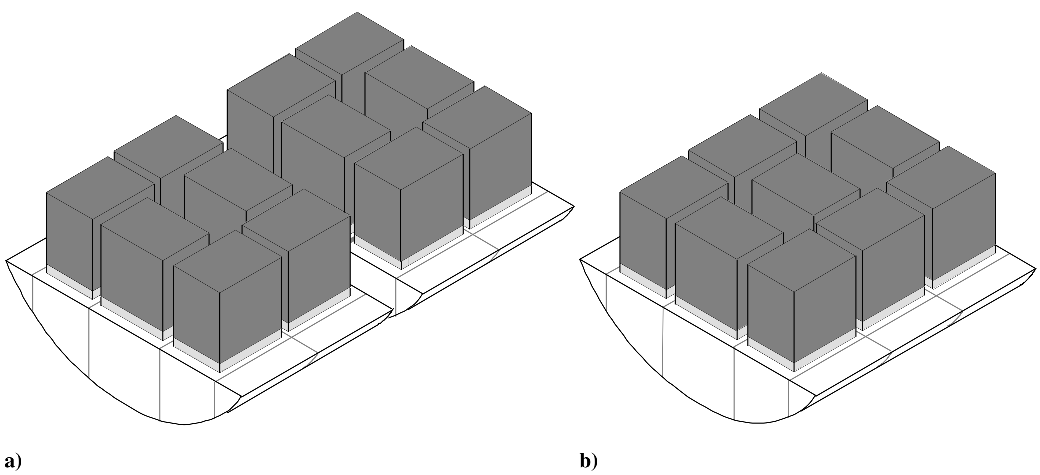


Fig. 8 Alternate (3 × 4) pallet configuration.



a) b)

Fig. 9 Small pallet configurations: a) (3 × 2) and b) (3 × 3).

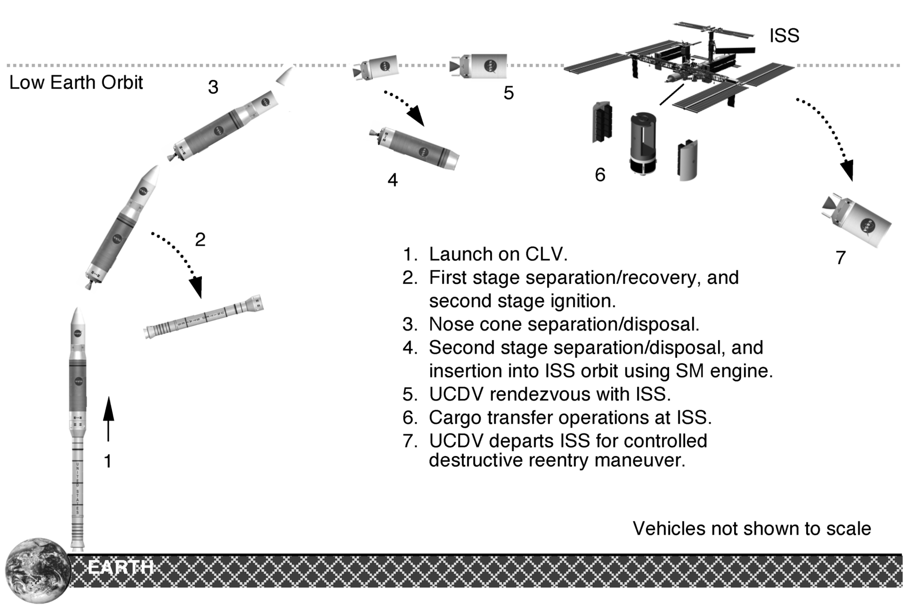
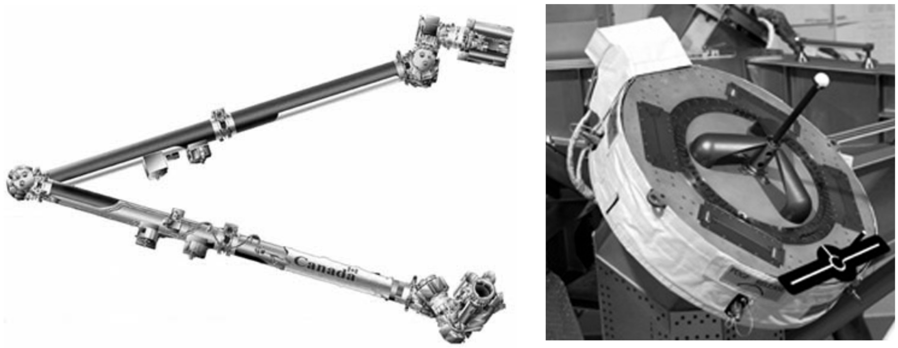


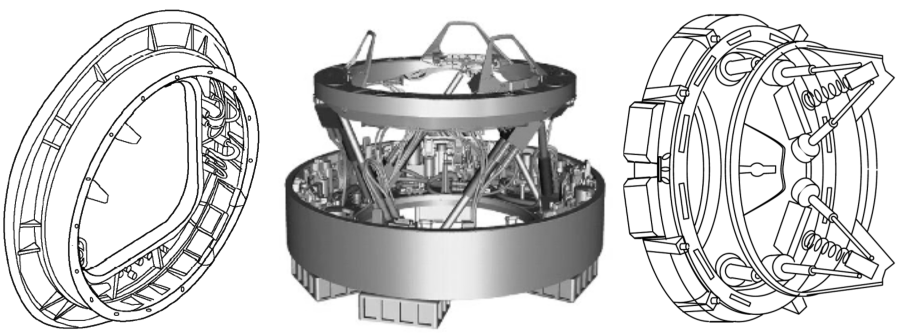
Fig. 10 UCDV concept of operations.

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, c.m., and MMOI constraints on the UCDV, CLV, and ISS. The loaded cargo pallets are rotated 90 deg to a vertical orientation and swung into their launch positions on the core structure. The mechanical latches are then fastened to lock the pallets to the core structure.



a) b)

Fig. 11 Mechanisms: a) SSRMS and b) PDGF.



a) b) c)

Fig. 12 Mechanisms: a) passive CBM, b) LIDS, and c) APAS.

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 30×160 n mile, 51.6 deg inclination transfer orbit. Although the CLV is designed with a maximum axial acceleration of 4 g, its ascent trajectory with the UCDV spacecraft could be easily tailored to a maximum 3 g 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 also results in a minimal performance penalty estimated at approximately 100 lb of payload.

The nose cone is separated from the UCDV when the ascent heating and dynamic pressure become negligible shortly after second-stage ignition. After insertion into the desired transfer orbit, the UCDV separates from the second stage, and 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 (SSRMS) arm (shown in Fig. 11a) on a power data grapple fixture (PDGF) (Fig. 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 Fig. 12a) is shown installed on the forward bulkhead of the UCDM in Figs. 1 and 2, and several ports on the ISS are already fitted with active CBMs. Other possible interface mechanisms, shown in Figs. 12b and 12c, are the Low-Impact Docking System (LIDS) [6], originally developed for the X-38 crew return vehicle, and the Russian-built Androgynous Peripheral Attachment System (APAS) [7], used on the space shuttle and Soyuz spacecraft for docking to the ISS, as well as some intermodule connections on the ISS. Potential issues with these systems include the fact that no new CBMs are currently being produced, the relatively low technology readiness level of the LIDS, and the high dynamic forces required to engage the APAS latches.

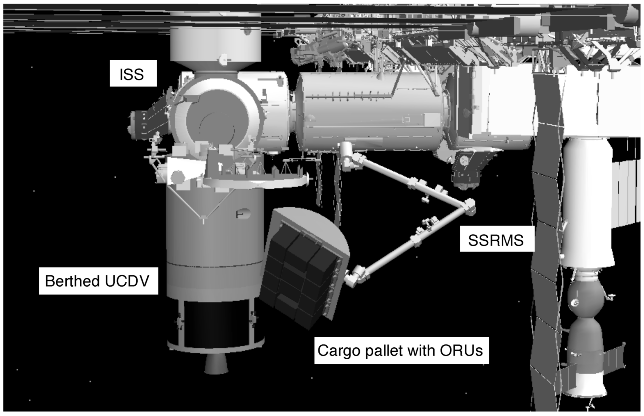


Fig. 13 Berthed UCDV and cargo pallet transfer operations on ISS.

After berthing the UCDV to the ISS, one end effector on the SSRMS grapples a PDGF on the Mobile Transporter/Mobile Base System (MT/MBS). 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 Fig. 13). The MT/MBS with attached SSRMS and pallet then moves along the ISS truss to stow the pallet on an unoccupied active PAS location on either the P3 or S3 truss (see Fig. 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 new ORUs using either EVAs or the SSRMS and special purpose dexterous manipulator (SPDM) (as shown in Fig. 14), and then loads the unserviceable ORUs back onto the pallet. When a new UCDV arrives with new ORUs, these full pallets are removed from the UCDV and stored on the ISS. The two

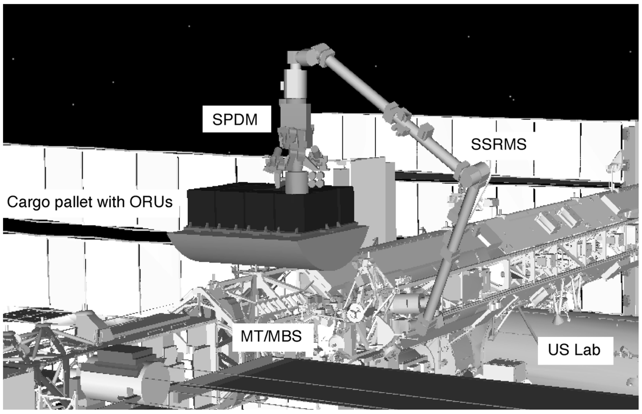


Fig. 14 Cargo pallet on ISS stowage site.

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.

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 sandwich configuration with graphite-epoxy composite face sheets and metallic honeycomb core was chosen for the acreage structure. Each UCDM pallet was built around 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 Fig. 15, with the cargo pallet and its subcomponents shown in Fig. 16.

For preliminary sizing, an areal density of 2 $\mathrm{lb/ft^2}$ was used to estimate the masses of the UCDM composite sandwich structures. This representative value was chosen using data from a large, heavily loaded composite honeycomb sandwich wing box [8] developed as part of NASA's High-Speed Research program. This highly loaded structure had wing surface areal densities ranging from 2.5 to 3.2 $\mathrm{lb/ft^2}$, and 1.3 $\mathrm{lb/ft^2}$ for the spar webs. The corresponding design loads of 10–20 klb/in. in-plane tension and compression, and 2.5 klb/in. in-plane shear, are plotted with their associated areal densities in Fig. 17. A rough estimate of the maximum compressive load Nx at the UCDM/SM interface plane may be computed as the product of the largest possible mass forward of the separation plane (50.5 klb CLV performance − 15.2 klb SM mass), the 4 g peak axial acceleration, and a 1.25 factor of safety, all divided by the SM circumference, or

$$\begin{aligned} Nx &= (35.3\ \text{klb} \times 4\ g \times 1.25)/(2\pi \times 9.0\ \text{ft} \times 12\ \text{in./ft}) \\ &= 260\ \text{lb/in.} \end{aligned} \tag{1}$$

The result computed in Eq. (1) assumes that the UCDM inertial loading is uniformly distributed around its circumference at the interface plane. Depending on how the loaded cargo pallets are designed to transfer their inertial loads into the core structure, the local loads at the latches may be much higher than this estimate.

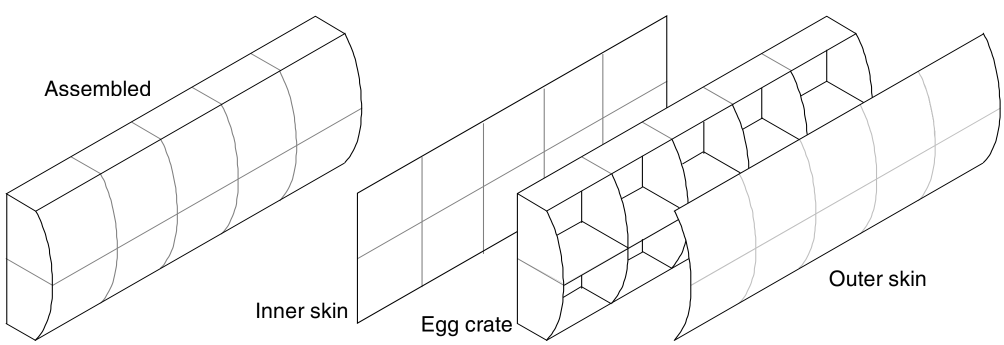


Fig. 15 UCDM core beam and subcomponents.

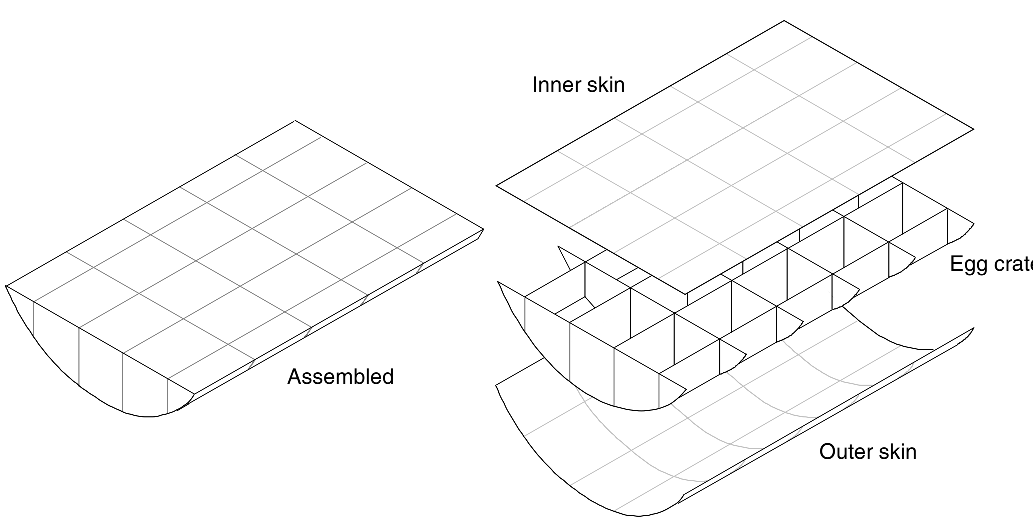


Fig. 16 Baseline 2 × 5 cargo pallet and subcomponents.

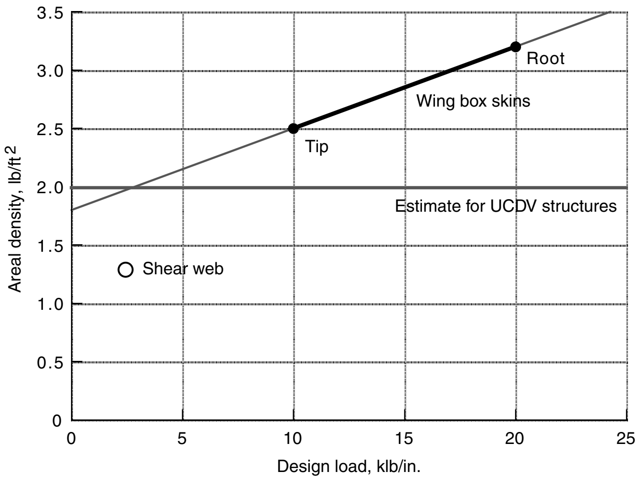


Fig. 17 Wing box structural element sizing.

However, the line load in Eq. (1) is still an order of magnitude lower than the wing box shear web design load of 2.5 klb/in. Because the compressive loads at the UCDM/nose cone interface will be even lower than those at the SM interface, these results all indicate that the overall UCDV structural loads should be much lower than those on the wing box.

As a way to determine the validity of these high-level estimates, the UCDM mass was compared with the mass of the External Stowage Platform-2 (ESP-2) payload.[§] 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 5900 lb, and it carries ORUs mounted on eight FRAMs. Division of these two values gives a normalized ESP-2 system mass of 738 lb/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 yields a normalized UCDM system mass of 794 lb/FRAM, which is within 10% of the corresponding value computed for the ESP-2. Based on these estimates and the analyses described earlier, the 2 lb/ft^2 areal density chosen for preliminary sizing of the UCDM should be somewhat conservative (as is appropriate at this early stage of design).

Further finite element analysis and structural sizing of the UCDM were performed using commercial software and are described in [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. Although not surprising for this level of analysis, inclusion of practical design details, such as edge closeouts 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 "nonoptimal" factor for the purposes of preliminary design studies.

Vehicle Sizing and Performance

Using the layout previously described for the UCDM, the mass of the primary vehicle structure (pallets and core beams) is estimated as 8268 lb. Addition of other mechanisms (passive CBM, passive PAS, passive FRAMs, FRGF, PDGF, etc.) results in a total structural mass of 11,010 lb. Addition of the various other predicted subsystem masses yields a UCDM dry mass estimate of 13,241 lb, and a 20% growth factor is applied to obtain a design mass with a margin of 15,889 lb. The UCDM mass of 15,889 lb is added to the 16,000 lb payload (20 cargo units $\times$ 800 lb each), the 15,241 lb SM mass, and the 2205 lb nose cone mass and performance impact, resulting in an estimate of 49,335 lb for the complete UCDV. These mass estimates are also shown by the work breakdown structure element in Table 1 for the vehicle design evaluated for the ESAS. Considering the predicted CLV performance of 50,480 lb to the 30 $\times$ 160 n mile ISS transfer orbit, the actual dry UCDM growth margin is just under 29%.

The launch vehicle 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 LES, maximum 3 g axial acceleration, nose cone separation, etc.) is needed to determine if this spacecraft design is fully compatible with the launch vehicle. These more detailed analyses would be required if this concept were to be matured further.

Conclusions

The system requirements, vehicle configuration, concept of operations, and structural design and layout for the UCDV concept were 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 two cargo units and 2800 lb of payload. Modified pallet designs can accommodate between 18 and 24 cargo units with 14,400–19,200 lb of cargo, allowing the design to be easily scaled up or down to meet launch vehicle performance requirements. Therefore, the baseline 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 was 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 (COTS) program resulted in termination of this internal effort. Because 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 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.

Acknowledgments

The authors recognize the contributions to this work of the many people in the Systems Analysis and Concepts Directorate, Systems Engineering Directorate, and their contractors at the NASA Langley Research Center. The authors are particularly grateful to Jon Chrone and Tim Shekoski, both of Analytical Mechanics Associates, Inc., for providing many of the computer-generated images used in this report.

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