Large Payload Ground Transportation and Test Considerations

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Abstract

Many spacecraft concepts under consideration by the National Aeronautics and Space Administration's (NASA's) Evolvable Mars Campaign take advantage of a Space Launch System payload shroud that may be 8 to 10 meters (m) in diameter. Large payloads can theoretically save cost by reducing the number of launches needed--but only if it is possible to build, test, and transport a large payload to the launch site in the first place. Analysis performed previously for the Altair project identified several transportation and test issues with an 8.973 m diameter payload. Although the entire Constellation Program—including Altair—has since been canceled, these issues serve as important lessons learned for spacecraft designers and program managers considering large payloads for future programs. A transportation feasibility study found that, even broken up into an Ascent and Descent Module, the Altair spacecraft would not fit inside available aircraft. Ground transportation of such large payloads over extended distances is not generally permitted, so overland transportation alone would not be an option. Limited ground transportation to the nearest waterway may be possible, but water transportation could take as long as 67 days per production unit, depending on point of origin and acceptance test facility; transportation from the western United States would require transit through the Panama Canal to access the Kennedy Space Center launch site. Large payloads also pose acceptance test and ground processing challenges. Although propulsion, mechanical vibration, and reverberant acoustic test facilities at NASA's Plum Brook Station have been designed to accommodate large spacecraft, special handling and test work-arounds may be necessary, which could increase cost, schedule, and technical risk. Once at the launch site, there are no facilities currently capable of accommodating the combination of large payload size and hazardous processing such as hypergolic fuels, pyrotechnic devices, and high pressure gasses. Ironically, the limiting factor to a national heavy lift strategy may not be the rocket technology needed to throw a heavy payload, but rather the terrestrial infrastructure—roads, bridges, airframes, and buildings—necessary to transport, acceptance test, and process large spacecraft. Failure to carefully consider where and how large spacecraft are manufactured, tested, and launched could result in unforeseen cost to modify existing (or develop new) infrastructure, or incur additional risk due to increased handling operations or eliminating key verifications. Although this paper focuses on the canceled Altair spacecraft as a case study, the issues identified here have wide applicability to other large payloads, including concepts under consideration for NASA's Evolvable Mars Campaign.

Nomenclature

m	=	meter
$M	=	Million Dollars

I. Introduction

MANY spacecraft concepts under consideration by the National Aeronautics and Space Administration's (NASA's) Evolvable Mars Campaign take advantage of a Space Launch System payload shroud that may be 8 to 10 meters (m) in diameter[1]. Large payloads can theoretically save cost by reducing the number of launches needed--but only if it is possible to build, test, and transport a large payload to the launch site in the first place. Analysis performed previously for the Altair project identified several transportation and test issues with the 8.9 m diameter lunar lander payload. These issues serve as important lessons learned for spacecraft designers and program managers considering payloads greater than about 7 m diameter for future programs.

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The Altair lunar lander was intended to launch on an Ares V rocket and dock with an Orion crew capsule in low Earth orbit. Altair would insert Orion into low Lunar orbit, carry the Orion crew to the lunar surface, and then return them to Orion. Altair consisted of four elements: Descent Stage, Ascent Stage, Airlock, and Earth Departure Stage (EDS) Adapter. The initial Altair stowed diameter was 7.5 m, sized to fit within the Ares V's payload shroud. When the Ares V design expanded to a 10 m shroud, Altair's stowed diameter increased to 8.973 m, as shown in Figure 1. At the end of the third design analysis cycle, the Altair assembled height was 10.09 m—taller than a two-story house; the Descent Stage alone was 6.5 m tall when mounted onto the EDS Adapter.

To put Altair's scale into perspective, Figure 2 compares launch diameter with several other payloads[†]. Even at the original 7.5 m diameter, Altair would have exceeded large spacecraft handling and transportation experience, both in the United States and among international partners; at 8.973 m, Altair would be more than twice the diameter of even the largest Space Shuttle payloads.

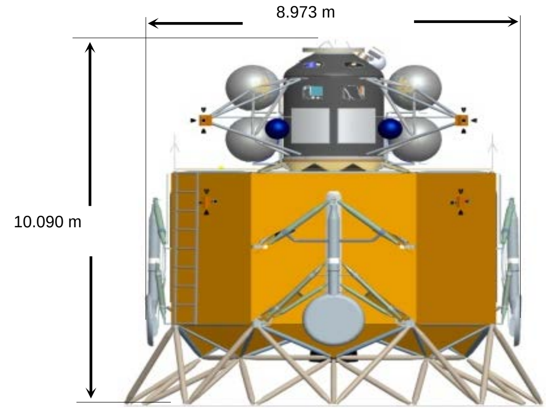

Figure 1. Altair lunar lander.

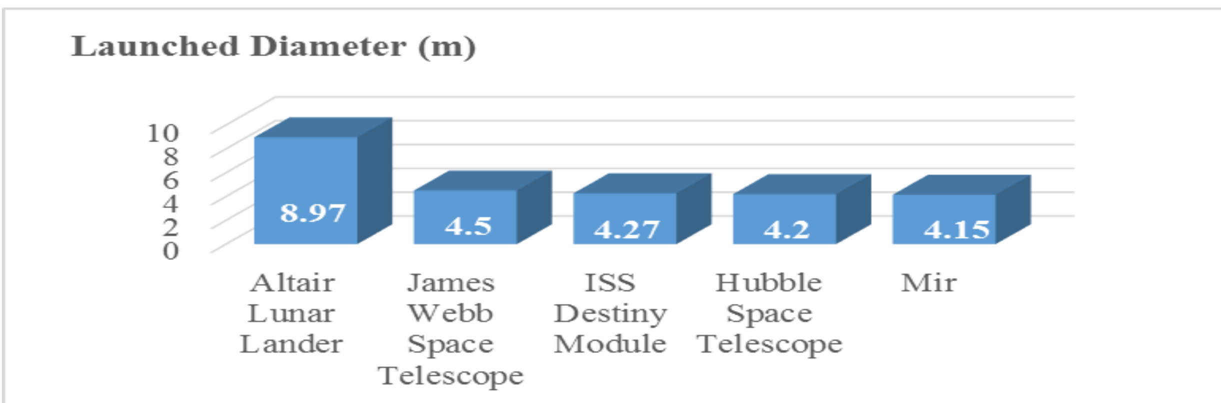

Figure 2. Comparison of launched payload diameters *(in meters)*.

II. Analysis Approach and Assumptions

A. Altair Transportation and Test Analysis Approach

The Constellation Ground Operations (CxGO) Project worked with the Altair test and verification lead to analyze potential transportation routes between hypothetical vendor points of origin, available integrated spacecraft certification test facilities, and finally to the launch site. This exercise involved tracing the payload from initial fabrication, through likely qualification or acceptance tests, transportation, handling, and launch processing.

B. Ground Transportation Destination Assumptions

The Ares V and its Altair payload were intended to launch from the NASA Kennedy Space Center (KSC), at Cape Canaveral, Florida. Although a procurement strategy was never formally developed, there was a possibility that the various stages could be built at different locations, with integrated test and verification occurring at the launch site or some intermediate location. A likely intermediate location was the Integrated Environmental Test facility being developed for Orion at the NASA Glenn Research Center's Plum Brook Station (PBS) in Sandusky, Ohio. As a starting point, conceptual production timelines assumed Altair modules would be transported to PBS for

[†] James Webb Space Telescope is expected to launch on an Ariane 5; the ISS Destiny Module and Hubble Space Telescope were launched in the Space Shuttle payload bay; the Mir core module was launched on a Proton rocket.

environmental acceptance testing, and then delivered to KSC for integration and launch. CxGO was tasked with performing a feasibility study to identify possible routes from two hypothetical vendors—one in the Eastern half of the United States, and the other in the Western United States—to PBS, then to the KSC launch site.

C. Feasibility Study Assumptions

For the purposes of this study, specific geographical locations had to be identified in order to assess actual bridges, roads, and ports. Because the intermediate way point was Ohio, the Altair Project created a Hypothetical Western Vendor located in Southern California simply on the rationale that it would bound most overland routes west of the Mississippi River. A Hypothetical Eastern Vendor was assumed to be in the Huntsville, Alabama area, in order to study inland waterway routes, as well as overland routes to Atlantic Coast ports.

CxGO made several other assumptions in preparing their transportation study:

1) The spacecraft would be transported as four discrete modules (rather than assembled).
2) Modules would be packaged in shipping containers that were environmentally controlled for all modes, throughout the duration of transport; shipping containers would be crane-lifted onto transport vehicles for all modes.
3) Impacts of potential future road/bridge/port construction projects were not assessed.
4) Routes assumed current Federal/local permit requirements and restrictions.
5) Pyrotechnic devices would be present.

III. Transportation Challenges

A. Air Transportation

Including ground transport to/from airports at the origin and destination, CxGO estimated the total transportation time from a vendor to PBS and then to KSC would take between 6 and 11 days. However, CxGO found that neither the Altair Ascent nor Descent Stage would fit inside available transportation aircraft. Airframes studied included Military C-5 and C-17 aircraft; commercial Boeing 747, Antonov AN-124, and Airbus A300-600 ST (Beluga) cargo aircraft; and the NASA Super Guppy (Boeing 377SG). As shown in Figure 3, the Super Guppy hull could accommodate the Altair Descent Stage height, but the diameter exceeded the cargo envelope by more than 1.5 m.

Although the Ascent Stage was considerably smaller than the Descent Stage, the long Reaction Control System (RCS) booms extended to the Descent Stage diameter, as shown in Figure 4. The booms could have been removed for air transport, but that would have invalidated any assembly workmanship screens or integrated acceptance testing performed prior to transportation.

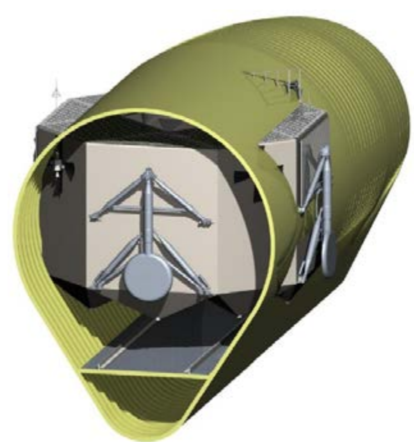

Figure 3. Altair Descent Stage in Super Guppy cargo envelope. *Graphic courtesy of David Zeiters, ASRC Aerospace (KSC CxGO)*

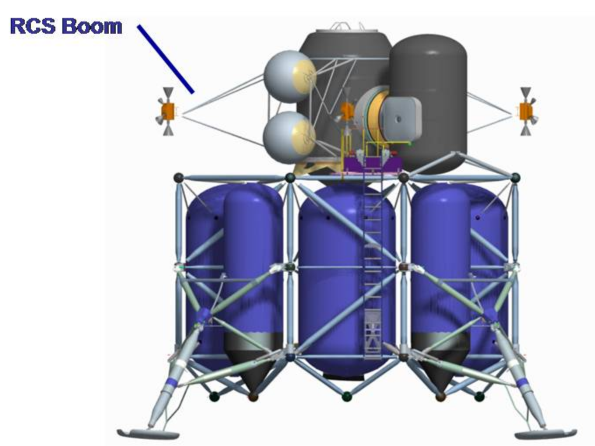

Figure 4. Altair Ascent Module with extended RCS booms. *Graphic courtesy of Tim Collins, (NASA Langley Research Center)*

NASA’s modified Boeing 747 Shuttle Carrier Aircraft (SCA) could be modified to accommodate an externally-mounted Altair, but would require a new container of some sort (Figure 5), as well as special loading/unloading infrastructure at the vendor(s), PBS, and KSC (Figure 6). Carrier structure design and certification costs would depend on the final spacecraft design chosen, but would likely require a substantial investment. Long-term operational costs must also be considered. For example, a crew of 170 people typically required a week to prepare the Space Shuttle and SCA for a cross-country flight, with each flight costing in excess of $230,000 (in 2003 U.S. dollars)[2]. In 2004 the Flight Crew Operations Directorate estimated SCA maintenance and operations costs at $3.0 million (M) to $3.7 M per year[3] for fiscal years 2005 through 2010.

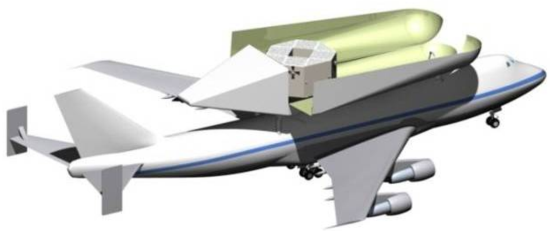

Figure 5. Shuttle Carrier Aircraft container concept. *Graphic courtesy of David Zeiters, ASRC Aerospace (KSC CxGO)*

Figure 6. Loading structure concept. *Graphic courtesy of David Zeiters, ASRC Aerospace (KSC CxGO)*

B. Truck Freight

CxGO found that ground transportation of a load this large over extended distances is generally not permitted. For example, the State of Florida[4] severely restricts movement of loads greater than 4.88 m wide or 5.49 m tall. This means that overland transportation alone is not an option.

In discussions with select state and local municipalities, CxGO was assured that *limited* trucking to the nearest Port would likely be allowed, assuming the spacecraft could clear bridges or other obstacles along selected routes. At least one commercially available ground transportation vehicle was identified for this purpose: the Parameter 13-Axle trailer can be configured with a deck length of up to 27.43 m and deck width up to 6.1 m, and is capable of straddling divided roadways[5] as shown in Figure 7. Depending on the final spacecraft design, detailed analysis of potential obstructions would be necessary for each leg of the route.

Figure 7. Parameter 13-Axle Trailer. *Graphic courtesy of Diamond Heavy Haul, Inc.*

C. Rail Freight

Rail transportation was not explicitly evaluated by CxGO, because domestic railways do not typically handle cargo taller than 5.18 m, or wider than 3.35 m.[6] Loads measuring 5.79 m high and 5.49 m wide may be possible over limited routes, but would require special equipment and permits.

D. Waterway Transportation

CxGO found that water routes to PBS were simpler from a hypothetical vendor in the Eastern United States than from the west coast. From a vendor near the NASA Marshall Space Flight Center (MSFC) in Alabama, the spacecraft could be barged from the Decatur, Alabama port through the Tennessee and Mississippi Rivers to the Illinois River, entering the Great Lakes at Chicago, Illinois and continuing to the Ohio coast, as shown in Figure 8.

CxGO estimated 10 to 12 days for the river journey, another 2 to 4 days across the Great Lakes, and 1 to 2 days at each end for trucking to/from the Ports, for a total of 14 to 20 days. It was also noted that transit in winter conditions may require assistance and escort from U.S. Coast Guard Ice Breakers, further adding to transportation costs and schedule. *Note that in the following figures, river routes are indicated by green lines, lake routes by red lines, and ocean routes by black lines.*

Water routes from the Western United States were more problematic. CxGO found that the only feasible route from Southern California was via the Pacific Ocean, through the Panama Canal to the Caribbean Sea, then across the Gulf of Mexico to Mobile, Alabama (see Figure 9). After navigating the Tennessee Tombigbee Waterway to the Illinois River, the remainder of the route to PBS would be the same as for shipping from an Eastern vendor. The ocean voyage adds 15 to 18 days, and the additional river portion would add 3, for a total of 32 to 41 days one-way from a Western vendor to PBS. It was also noted that transit through the Panama Canal, including international cargo inspections, may add several more days.

Figure 8. Waterway route from MSFC area to Plum Brook Station. *Map courtesy of Googlemaps.*

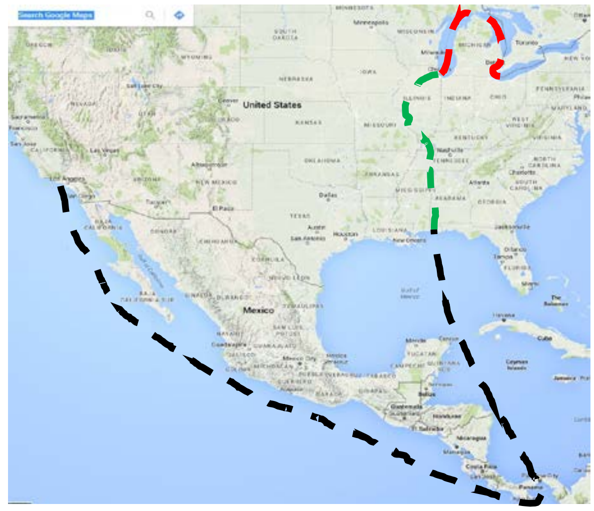

Figure 9. Waterway route from southern California to Plum Brook Station. *Map courtesy of Googlemaps.*

From PBS, transporting a large spacecraft to the KSC launch site would require back-tracking through the Great Lakes to Chicago, down the Illinois River to the Tennessee Tombigbee Waterway, into the Gulf of Mexico at Mobile, then around the Florida Keys to the Atlantic Ocean, finally docking near KSC (Figure 10). Estimated transit time is 20 to 26 days, not including additional time for winter conditions in the Great Lakes, or potential summer hurricane delays along the Gulf or Atlantic coasts.

Schedule aside, there are additional costs impacts that must be considered. Ocean transportation may require a different type of vessel than the river barges currently used for other NASA Programs, necessitating a buy vs. rent discussion, including long-term maintenance and repair costs. If the spacecraft must be transferred from one type of vessel to another for different parts of the journey, additional time and money will be required for each transit, and there will be increased handling risk.

Note that the transportation problem may become even more complicated if large diameter components of future heavy lift payloads are fabricated at international partner facilities outside the United States, particularly if they must undergo integrated environmental testing somewhere other than the launch site.

Figure 10. Waterway route Plum Brook Station to KSC. *Map courtesy of Googlemaps.*

IV. Facility Issues

In addition to the transportation challenges, a number of test and integration facility gaps and constraints were also identified for large, complex payloads.

A. Plum Brook Station (PBS)

1. Reverberant Acoustic Testing

The Reverberant Acoustic Test Facility at PBS was designed and built for a maximum 10 m diameter “concept payload.”[7] At 8.973 m diameter, Altair would have fit through the 10.52 m wide x 17.37 m tall doorway, but would have to be positioned closer to the chamber walls than generally recommended for this type of test. A number of work-around options were investigated, including positioning the payload off-center within the room and testing one side at a time, or testing the payload in pieces. These approaches would have incurred additional cost and schedule for test article repositioning or disassembly/reassembly, plus analysis to knit together the results.

2. Mechanical Vibration Testing

The PBS Mechanical Vibration Facility (Figure 11) was also designed to accommodate an Altair-sized "concept payload." However, two constraints were imposed: first, testing in orthogonal axes required rotating the payload 90 degrees between tests; and, second, modal testing would have to be performed on a locked-down shaker table, rather than a dedicated modal floor. Note that neither of these constraints were necessary for the smaller diameter Orion spacecraft.

Rotating a large payload to test multiple axes is technically simple, but costs money, takes time, and increases handling risk by adding another critical lift to the process flow. The smaller Orion footprint allowed enough space to install shakers in two orthogonal axes, eliminating the need to rotate that spacecraft. Modal testing on a locked-down shaker table is also technically feasible, but because it has never been attempted on such a large scale, there is some technical risk. A fall-back position would be to develop a separate modal test area in another part of the test facility, but that would incur additional facility design and construction expense.

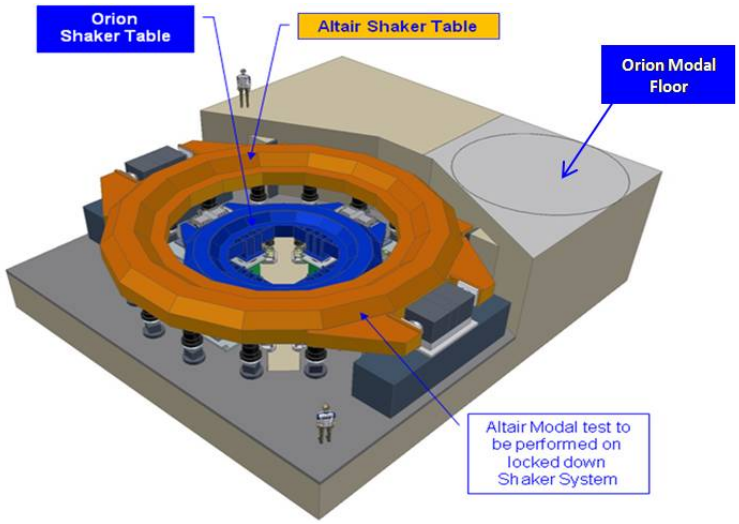

Figure 11. Plum Brook Station Mechanical Vibration Facility.

3. High Altitude Propulsion Testing

Although the PBS B2 Spacecraft Propulsion Research Facility test chamber (Figure 12) measures 10.67 m diameter, the door opening is only 8.23 m wide. For integrated testing of the Altair propulsion subsystem, the spacecraft's landing legs could have been removed to allow the descent module to fit through the door, then reattached once inside. Although technically feasible, this adds complexity, cost, and schedule to integrated propulsion testing, and potentially alters the order of testing to prevent invalidating landing system tests or workmanship screens already completed. While relatively insignificant for one-time qualification testing, this could be a significant life cycle cost impact for production unit integrated hot-fire acceptance testing.

Figure 12. Plum Brook Station B2 propulsion test chamber.

B. Kennedy Space Center

1. Vacuum Testing

Integrated environmental test opportunities at the KSC launch site are limited, but may include vacuum testing using the Operations & Checkout (O&C) Building's Apollo-era vacuum chambers (Figures 13 and 14). The chambers measure 10 m diameter x 18 m tall, accessible via a lift-off chamber lid. At 8.973 m, the Altair spacecraft would have fit inside the chamber, but access platforms around the test article would have to be removed, complicating test article set up and instrumentation. With little room to install thermal conditioning equipment, testing would also likely be limited to ambient temperature, rather than flight-like thermal vacuum conditions.

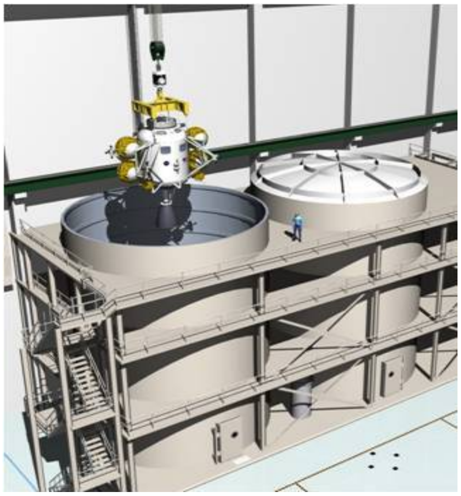

Figure 13. Altair Ascent Module relative to KSC O&C vacuum chamber.

Figure 14. Internal view of KSC O&C vacuum chamber.

2. Hazardous Processing and Encapsulation

The Altair design would have required several hazardous processing operations at the launch site, including:

1) Install and arm pyrotechnic devices
2) Fill, drain, and service hypergolic fuel reaction control systems
3) Fill, drain, and service high pressure oxygen tanks
4) Fill, drain, and service cryogenic oxygen and hydrogen tanks
5) Lift and stack large spacecraft elements

The CxGO project evaluated the Space Station Processing Facility (SSPF), Vehicle Assembly Building (VAB), and Orbiter Processing Facility (OPF), all on KSC property. The National Reconnaissance Office Eastern Processing Facility (NRO EPF), located on the Air Force side of Cape Canaveral, and the commercial Astrotech Facility, located in Titusville, were also assessed.

While many of the KSC facilities could accommodate some of these operations, no single facility was capable of performing all of these functions on a large diameter spacecraft. Preliminary studies indicated that the OPF may be able to accommodate hypergolic fuel servicing with modest upgrades to the facility. However, the OPF's close proximity to the VAB may result in access restrictions during hazardous operations in the VAB. Using different facilities for different operations is another option, but would require a project to budget the annual overhead needed to maintain multiple buildings and provide inter-facility transportation and critical lift capabilities.

Hazardous processing could be deferred to the launch pad, though that would compromise the Agency's desire for rapid pad turnaround, as well as drive technical risk. If problems were encountered during hazardous processing at the pad, there would be limited options for a vehicle roll-back, particularly for a hypergolic fuel leak. Repairs at the pad would impact other vehicle's launch schedules, driving cost and schedule risk for other stakeholders.

V. Options

There are several options for mitigating the issues outlined above.

A. Design Smaller Spacecraft

Just because the launch system can handle a large payload, doesn't mean that all spacecraft must be designed for the maximum envelope. Program managers must carefully weigh the benefits of a large payload against the cost, schedule, and risk of handling spacecraft that exceed current transportation and test capabilities.

B. Manufacture At or Near the Launch Site

Manufacturing large diameter payloads closer to the launch site could reduce transportation schedule and cost, though savings would may be off-set by the need to build new test and verification facilities at or near the launch site. This approach also raises programmatic challenges, as it concentrates a large portion of a spacecraft's life cycle—and therefore budget—at a single field center, with implications to Agency operating plans, international partnering agreements, and procurement strategies.

C. Waive Integrated Environmental Testing

Rather than build new environmental acceptance test and verification facilities closer to the launch site, some integrated tests or verifications could be waived or eliminated altogether. This approach may be cost-effective for inexpensive, uncrewed payloads, but would prompt vigorous discussion for expensive or crewed spacecraft. In an Aerospace Corporation study[8] of 454 U.S. satellites, an exponential relationship was identified between percentage of satellite failures and Environmental Test Thoroughness Index (ETTI), the degree to which a spacecraft's acceptance and qualification test program complied with MIL-STD 1540B[9]. As shown in Figure 15, the study found that less than 10% of spacecraft fully complying with the MIL-STD suffered failures, but that number jumped to *more than 60%* when only half of the recommended environmental tests were performed. For Altair, simply waiving integrated environmental tests would have been at odds with the Constellation Program's high reliability requirements of 1 in 20 for loss of Lunar sortie mission, and 1 in 100 for loss of Lunar sortie crew[10].

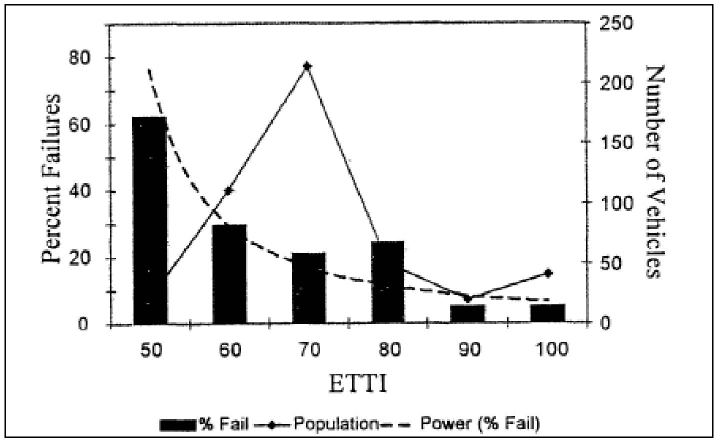

Figure 15. Percentage of satellite failures versus Environmental Test Thoroughness Index (ETTI)[8].

D. Test Only at Lower Levels of Assembly

Rather than perform fully integrated tests with over-sized test facilities, another option is to test at a lower level of assembly in smaller facilities. This method was often used for Space Shuttle testing but it should be noted that since each Shuttle Orbiter was a reusable vehicle, each flight essentially served as an integrated acceptance test for subsequent flights. By contrast, each Altair was intended for one-time use, and would not have had the benefit of prior test flights (or of post-flight inspection to verify performance). Even if acceptance testing were performed at a lower level of assembly for production units, large test facilities may still be required for qualification testing, as was done with the Space Shuttle (Figure 16).

Figure 16. Shuttle Enterprise being prepared for mated vertical ground vibration test[11].

VI. Conclusions

At an estimated 6 to 11 days per production unit, air transportation is clearly the more desirable mode of transport from hypothetical spacecraft vendors on the East or West coast to Plum Brook Station or the Kennedy Space Center, but analysis found that an 8.973 m diameter spacecraft would not fit inside currently available airframes. Future spacecraft designers will be constrained to fit their payloads—including shipping or environmental protection containers—into existing airframes, or face long surface transportation timelines.

As shown in Table 1, surface transportation to Plum Brook Station and then the Kennedy Space Center may be twice as fast—and likely much less expensive—if originating on the east coast, rather than on the west coast of the United States. Analysis found that transportation from the western United States would require transit through the Panama Canal, with total transport times up to 67 days per production unit. Even from an east coast origin point, the journey may still takes up to 34 days per production unit and would require numerous critical lift operations to transfer between the various transport vehicles used on different legs of the journey.

Table 1. Summary of Transportation Times

Transport Mode		Western Vendor to PBS	Eastern Vendor to PBS	PBS to KSC	TOTAL TRANSPORT TIME
Surface Transport	**Total Surface Transport Time**	**32 to 41 days**	**14 to 20 days**	**20 to 26 days**	**34 days (minimum from Eastern Vendor) to 67 days (maximum from Western Vendor)**
	Truck to/from port	2 to 4 days	2 to 4 days	2 to 3 days	
	On River	13 to 15 days	10 to 12 days	13 to 15 days	
	On Ocean	15 to 18 days	--	3 to 4 days	
	On Lake	2 to 4 days	2 to 4 days	2 to 4 days	
Air Transport	**Total Air Transport Time**	**3 to 6 days**	**3 to 6 days**	**3 to 5 days**	**6 to 11 days**
	Truck to/from Airport	2 to 4 days	2 to 4 days	2 to 3 days	
	On Airplane	1 to 2 days	1 to 2 days	1 to 2 days	

NOTE: times do NOT include possible delays for cargo inspection through the Panama Canal, or for ice-breaker service on the Great Lakes during winter conditions.

Analysis indicates that environmental test facilities at Plum Brook Station could accept payloads up to 8.973 m diameter (or could be modified to do so), assuming transportation issues were resolved. If transportation to a dedicated environmental test facility is not feasible, options include performing integration and acceptance testing at the launch site, eliminating some acceptance testing altogether, or testing at lower levels of assembly. However, these solutions may increase technical and safety risk, or incur additional expense to upgrade or build new facilities. Once at the launch site, handling and hazardous processing of a large spacecraft is also challenging, and may require maintaining multiple facilities, modifying existing infrastructure, or building new, dedicated assets. Depending on the payload point of origin, intermediate way-points, and selected launch site, transportation infrastructure upgrades may prove more cost effective than building new test facilities or eliminating integrated environmental testing. Note that agreements between Federal, State, and local authorities to upgrade roads, bridges, runways, or ports may require several fiscal year budget cycles to negotiate, fund, and implement. Likewise, mobile assets such as trucks, aircraft, barges, or ships will require careful long-term purchase or lease and maintenance planning.

Ironically, the limiting factor to a national heavy lift strategy may not be the rocket technology needed to throw a heavy payload, but rather the terrestrial infrastructure—roads, bridges, airframes, and buildings—necessary to transport, acceptance test, and process large spacecraft. Failure to carefully consider where and how large spacecraft are manufactured, tested, and launched could result in unforeseen cost to modify existing (or develop new) infrastructure, or incur additional risk due to increased handling operations or eliminating key verifications. Although this paper focuses on the canceled Altair spacecraft as a case study, the issues identified here have wide applicability to other large payloads, including concepts under consideration for NASA's Evolvable Mars Campaign.

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References

[1]Hill, B and S. Creech, "NASA's Space Launch System: A Revolutionary Capability for Science," presentation to NASA Advisory Council (NAC), https://www.nasa.gov/sites/default/files/files/NAC-July2014-Hill-Creech-Final.pdf [cited April 13, 2016].

[2]Gillette, F., "How Does the Space Shuttle Fly Home?" *Slate*, http://www.slate.com/id/2124238/fr/rss/ [cited August 9, 2005].

[3]2004 Program Operating Plan, Quarterly Program Management Review, Space Shuttle Program, National Aeronautics and Space Administration, Houston, 2004.

[4]Florida Administration Code (FAC) 14-26.012, Florida Department of Transportation, February, 2013.

[5] Diamond Heavy Haul, Inc., Ohio, http://www.diamondheavyhaul.com/gallery/Perimeter-Dual-Lane-Trailers/ [cited April 14, 2016].

[6] BNSF Railway, http://www.bnsf.com/customers/pdf/machinery_crg.pdf, [cited April 14, 2016].

[7]CxP 72205, Revision F, "Crew Exploration Vehicle (CEV) Facility Requirements for the CEV CREW Space Environmental Test (SET) Capability at the NASA Plum Brook Station Space Power Facility," National Aeronautics and Space Administration, October 7, 2009.

[8]Tosney, William F, Bruce L. Arnheim, and James B. Clark, "The Influence of Development and Test on Mission Success," ESA SP-467, Proceedings 4th International Symposium on Environmental Testing for Space Programmes, Liege, Belgium, 12-14 June, 2001.

[9]MIL-STD-1540B (USAF), "Military Standard, Test Requirements for Space Vehicles," United States Department of Defense, October 10, 1982.

[10]CxP 70000 Revision D, Constellation Architecture Requirements Document," National Aeronautics and Space Administration, December 11, 2009.

[11]Image 7992403, Marshall Space Flight Center, National Aeronautics and Space Administration, October 4, 1978.