CubeStack Wafer Adapter for CubeSats on Small Launch Vehicles

Gregory E Sanford, Kenneth J Brunetto
LoadPath LLC, Albuquerque, New Mexico
gsanford@loadpath.com, kbrunetto@loadpath.com (866)411-3131

Joseph R Maly, James C Goodding
Moog CSA Engineering, Mountain View, California
jmaly@csaengineering.com, jgoodding@csaengineering.com (650)210-9000

Hans-Peter Dumm
Air Force Research Laboratory Space Vehicles Directorate
Kirtland Air Force Base, New Mexico
afrl.rvsv@kirtland.af.mil

ABSTRACT

The CubeSat has progressively evolved from a platform for student projects to become a viable spacecraft configuration utilized by numerous government and commercial organizations. The Poly Picosatellite Orbital Deployer (P-POD), from Cal Poly, San Luis Obispo, is the common dispenser for the 3U (three-CubeSat) configuration, and CubeSats are typically launched from dispensers as tertiary payloads, often attached onto an unused surface of the launch vehicle for deployment after completion of the primary mission. The proliferation of CubeSats throughout the small satellite community gives rise to the requirement for more launch opportunities via the addition of multi-payload adapters, coupled with the development of more capable dispensers having 6U and larger form factors.

LoadPath and CSA Engineering, under contract to the Air Force Research Laboratory Space Vehicles Directorate, are developing a multi-payload adapter for CubeSats in support of government and commercial missions. The *CubeStack* adapter is a 10-inch-tall "wafer" similar to the NanoSat Launch Adapter System (NLAS) adapter developed at NASA Ames. The wafer mounts between the rocket upper stage and its primary payload and accommodates eight 3U dispensers, e.g. P-PODs, four 6U CubeSat dispensers, or other combinations of 3U and 6U dispensers. The modular CubeStack wafer features both ∅38.81 inch and ∅24.00 inch primary-spacecraft interfaces and is sized for several launch vehicles including Athena, Minotaur I, Taurus, Pegasus and Falcon 1.

CubeStack was developed using requirements derived from launch vehicle specifications, customer needs, and lessons learned from the NLAS adapter fabrication and test. CubeStack features include a small part count, minimized weight, and ease of satellite dispenser integration. The CubeStack is expected to be available in 2012. This paper describes the CubeStack development program and design requirements, presents test and validation plans, and details the spacecraft and launch vehicle interfaces.

INTRODUCTION

Multi-Payload Adapters (MPAs) are an efficient way to provide access to space for small satellites by using excess spacelift capacity.[1] MPAs have been demonstrated on two recent STP missions: the EELV Secondary Payload Adapter (ESPA) flew on the Atlas V STP-1 Mission in March 2007, and a flat plate adapter for similar auxiliary payloads flew on the Minotaur IV STP-S26 Mission in November 2010.

Recently, NASA/Ames Research Center (ARC) developed the NanoSat Launch Adapter System (NLAS), which can accommodate multiple CubeSats or CubeSat-derived spacecraft on a single launch vehicle. [2] The CubeStack adapter uses the NLAS adapter as a baseline, and it is designed to accommodate CubeSats as tertiary payloads along with a primary spacecraft (Figure 1). The CubeStack MPA is being designed under a Small Business Innovative Research Program (SBIR) with the Air Force Research Laboratory Space Vehicles Directorate (AFRL/RV).
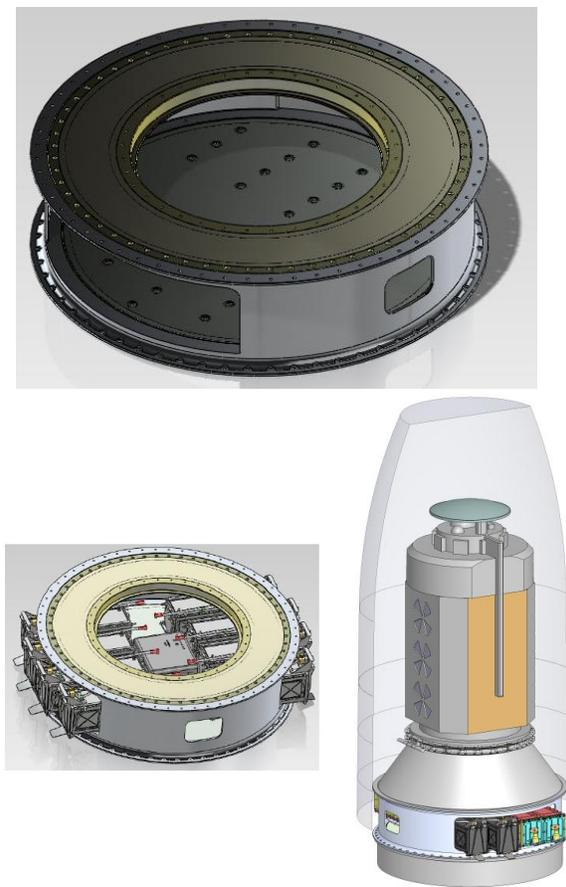
Figure 1. CubeStack with CubeSat dispensers and primary spacecraft in fairing

The CubeStack team used a rigorous, tailored systems analysis approach to generate requirements in three areas:

- Performance Requirements driven by primary payload and CubeSat dispenser properties, operation, and use,

- Mission Requirements driven by the environments of the candidate launch vehicles,[3] and

- Verification Requirements established by data needs.

The design objective for the CubeStack was to provide a mounting system for a primary payload and accommodate CubeSat dispensers within the launch vehicle. The approach was to provide a 10-inch-tall stackable adapter for installation in the launch vehicle stack between the vehicle interface and the primary payload.

CONCEPT OF OPERATIONS (CONOPS)

The CubeStack CONOPS has been defined for assembly, payload integration, system-level testing, and launch integration.

CubeStack integration starts when the dispensers have been identified and their positions within the CubeStack have been assigned. At this point, the adapter plates are drilled to match the individual payload mounting bolt patterns. The CubeStack with the decks and adapter plates are then shipped to the integration facility.

Payload integration occurs at the customer integration facility, using a breakover fixture to support the CubeStack and dispensers during integration. Each CubeSat payload is attached to its assigned adapter plate, and the resulting adapter plate assembly is mounted to the CubeStack lower deck. This is repeated for each of the adapter plate assemblies. Finally, the sequencer electronics package is installed and the electrical mates completed. The CubeStack is designed to be used with a sequencer that provides power to each dispenser. When the sequencer receives a signal from the launch vehicle, it will power the dispensers one at a time to initiate payload ejection.

If the CubeStack is a "first article" flight item, it is tested at the system level under representative vibration environments. This testing ensures that the assembly and installation of all the subsystems and components has been completed satisfactorily to withstand the environments of flight. Successful operation of the payloads is the success criteria for this testing. If the configured CubeStack is a repeat payload, it is recommended, but not required to conduct system level testing.

After successful completion of the system level testing, the CubeStack is shipped to the launch integration facility, where it becomes part of the manifested payload suite, and thus the Launch Vehicle Contractor's responsibility for installation and electrical connection. The CubeStack system supports both horizontal and vertical launch vehicle integration.

DESIGN

The 10-inch-tall cylindrical adapter is designed to mount at the standard interface for small launch vehicles. It has a Ø38.81 inch bolt circle interface with sixty (60) Ø.257" equally spaced through holes, shown in Figure 2. The CubeStack is sized to carry a 1000 lb spacecraft at this interface with a maximum center of gravity (CG) location of 34.7" forward of the interface (including any separation system height). The adapter also features a Ø24.00 inch interface with thirty-six (36) ¼-28 UNF tapped holes equally spaced for a 500

lb spacecraft with a maximum CG location 29.1 inch forward of the interface (including any adapters and separation systems).
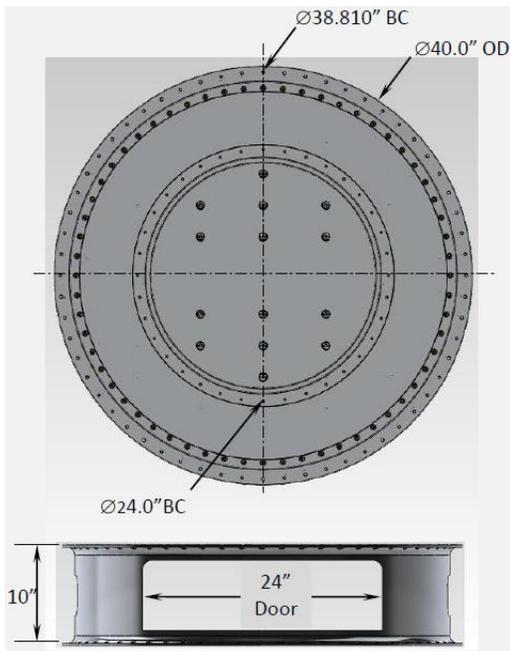
**Figure 2. CubeStack views with primary dimensions**

The CubeStack has a 40 inch outer diameter and 10 inch height. Two aft interfaces are available: 60 Ø.190 inch or Ø.257 inch through holes on a Ø38.810 inch bolt circle depending on the specific launch vehicle interface.

Adapter material and construction consists of a primary cylindrical structure machined from a solid 7075-T6 forged aluminum alloy ring and removable sandwich panel decks constructed of 5056 aluminum alloy honeycomb core and 7075-T6 aluminum alloy facesheets, shown in Figure 3. The empty assembled weight of the CubeStack adapter is 101 lb.

Interior access is provided via two 24 x 7 inch main payload doors and two 6 x 4 inch access doors, as well as through the approximately Ø24 inch opening on the upper deck.

In order to secure each CubeSat payload to the CubeStack, adapter plates are mounted to each CubeSat dispenser, then attached to the lower deck inside the CubeStack. A single adapter plate design can accommodate the different mounting-hole patterns for every dispenser design, as shown in Figure 4. The same plate is used for both right hand (RH) and left hand (LH) installations, with different countersinks. The interfacing joint slides laterally to facilitate

installation, and later is rigidly attached when the plates are positioned. Two plates are required for each side of the adapter (4 total), and the weight of each plate is 2.5 lb.
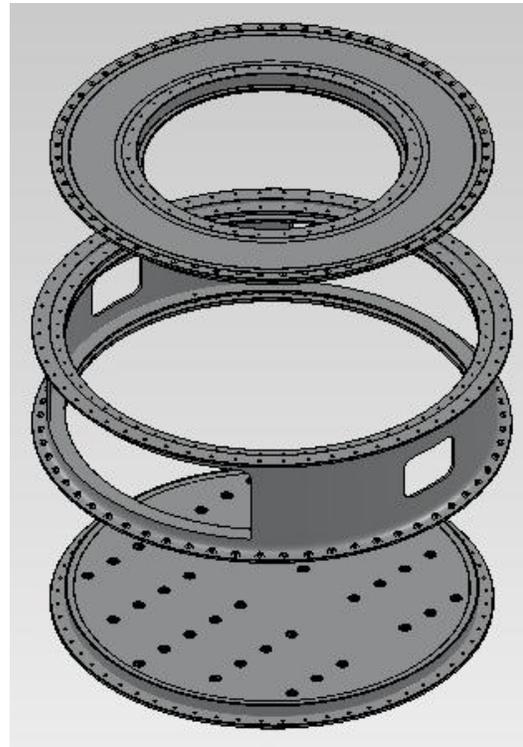

Figure 3. Top deck, cylindrical primary structure, and bottom deck
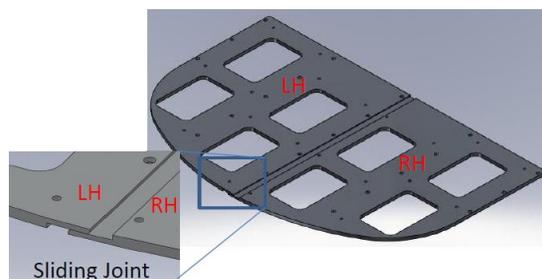

Figure 4. Dispenser adapter plates

P-PODs installed onto an adapter plate are shown in Figure 5. When the CubeSat dispensers are attached to the adapter plates, the plates are installed into the CubeStack, RH first, and then LH. Fasteners are then installed to attach the plates to the lower deck; they can be installed from the front, through the access door, or from above. The design accommodates several dispenser designs, including the standard P-PODs from Cal Poly and also new 6U dispensers from NASA Ames and Planetary Systems Corporation. Figure 5 shows an NLAS 6U dispenser mounted with two P-PODs.
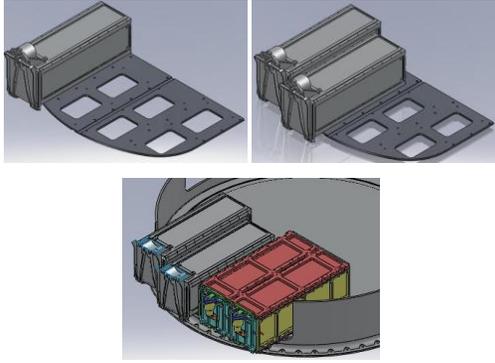
Figure 5. Dispensers installed on adapter plates

ANALYSIS

The CubeStack design was optimized and verified with a finite element model of the structure, using loading environments from candidate launch vehicles. Two launch "stack" models were used, one with a 1000-lb spacecraft mounted at the Ø38.81 inch interface, and one with a 500-lb spacecraft mounted at the Ø24.00 inch interface. Both of these stacks had a generic cylinder structure at the aft CubeStack interface to simulate the launch vehicle interface stiffness. The analysis stack with the 500-lb spacecraft simulator is shown in Figure 6. CubeSat dispensers were modeled in detail; the image in the Figure shows four P-PODs mounted through each of the two adapter doors.
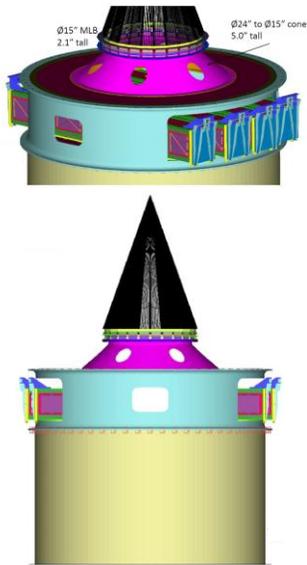

Figure 6. Analysis stack with 500-lb spacecraft simulator

Trade studies on various adapter configurations focused on minimizing weight and achieving positive strength margins while monitoring variables associated with manufacturing and assembly processes. A down-select process was performed in which candidate designs were evaluated for strength, stiffness, load peaking performance, buckling performance, and weight.

Strength analysis was based on worst-case environments from the Minotaur 1 Payload User's Guide. Three load cases were evaluated. First, a design load case with 6.6 g axial and 4.2 g lateral load factors was found to envelope the maximum predicted environment for the CubeStack with a 1000 lb primary payload. Second, a design load case of 6.6 g axial and 6.3 g lateral load factors were found to envelope the maximum predicted environment for the CubeStack with a 500 lb primary payload on the 24.00 inch interface. Third, based on mass-acceleration curves and best estimates, 30 g was chosen as the design load to be applied to the dispensers (in each axis independently). Positive margins were demonstrated in all structural components using a safety factor of 2.0. Worst-case stress contours for the primary structure components are depicted in Figure 7.
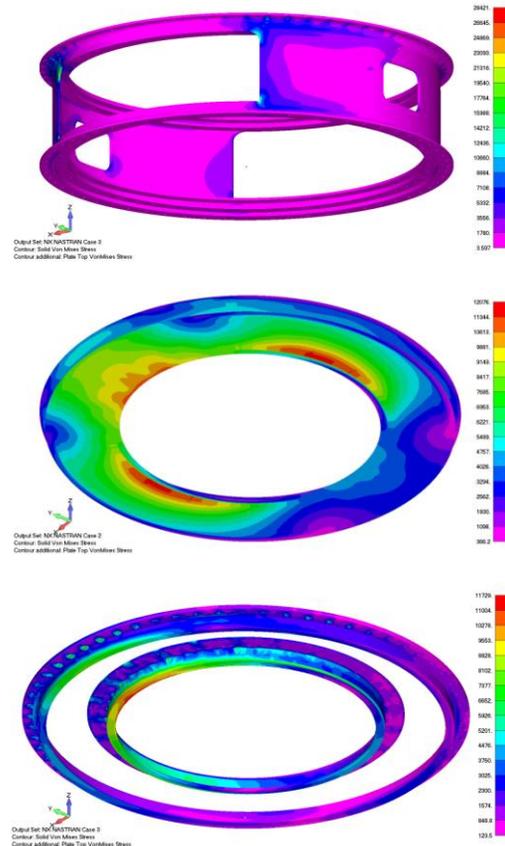
Figure 7. Stress contours in cylinder, deck, and deck rings

Buckling analysis was performed using the same models and load cases as the strength analyses. Minimum buckling factors in excess of 10.0 were computed for all cases.

Load peaking is inherent to the open-section construction of the wafer adapter design. Performance was evaluated by applying an axial load at the spacecraft CG and computing the boundary forces at the aft adapter interface. A load peaking factor for each boundary node was computed by dividing the interface force by the force computed with an evenly distributed load. Load peaking as a function of azimuth for the CubeStack final design is shown in Figure 8. Load peaking will be addressed on a mission-specific basis, since peaking can also be induced by adjacent structure design features. If necessary, the effects of load peaking can be mitigated with spacer rings or an isolation system at the adapter interface.
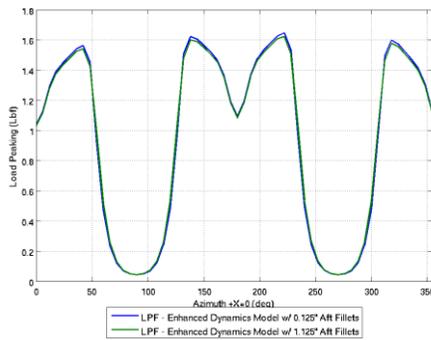
Figure 8. Load peaking performance

Normal modes analysis was performed for both primary spacecraft configurations. The primary mode of the stack with a 1000-lb primary occurs at 20.9 Hz The primary mode with a 500-lb primary spacecraft occurs at 16.3 Hz.

Panel insert and fastener load analyses were performed using the 30 g load factors on the dispenser payloads. Figure 9 shows the deformed shape of the aft deck with 30 g applied to the dispenser payloads. High positive margins were computed for bolt strength and insert pull-out, compared to allowables obtained from testing.
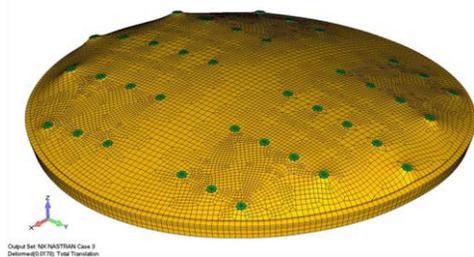
Figure 9. Deck deformed shape with axial load

FABRICATION

Fabrication of the CubeStack components, including the two removable deck components and the cylindrical primary structure will be accomplished by approved suppliers.

The cylindrical primary structure will be machined from a solid forging and will be ready for final assembly upon receipt from the supplier.

The removable honeycomb sandwich panel decks will undergo a much more process-intensive sub-assembly prior to final assembly with the cylinder. Each of the panels and rings for the removable decks will be cleaned, degreased, phosphoric acid anodized, and primed with a corrosion-resistant primer. These parts will then be ready for bonding with the honeycomb core. Bonding will be accomplished with a space qualified film adhesive that is co-cured with a foaming core splice adhesive to minimize structural voids. After curing, the lower removable deck will undergo secondary machining and potting installation of threaded inserts.

Assembly of the CubeStack is completed using NAS1102E4-12 fasteners to attach each of the removable decks to the cylindrical primary structure.

TESTING

CubeStack structural verification and flight qualification will be accomplished through a rigorous test program. A dedicated qualification unit will undergo a suite of static and dynamic load tests, while, flight articles will be subjected to a subset of static load acceptance tests on the sandwich panel decks only. A description of the coupon, qualification unit, and flight unit tests are shown in Table 1. Test levels shown are in relation to the maximum predicted environment (MPE) that the structure is subjected to during launch.

Table 1: Structural testing summary

Test Article	Test Description	Test Level
Sandwich Panel Coupons	Potted Insert Tension Pull Test	Failure
Qualification Unit	Potted Insert Tension Pull Test	1.25 * MPE
Qualification Unit	Static Load Qualification Test	1.25 * MPE
Qualification Unit	Dynamic Characterization Test	SCALED MPE
Aft Deck (Flight Units)	Potted Insert Tension Pull Test	1.1 * MPE
Aft Deck (Flight Units)	Static Load Acceptance Test	1.1 * MPE
Forward Deck (Flight Units)	Static Load Acceptance Test	1.1 * MPE

Insert Pull Tests

Initial insert pull tests will be performed to verify the sandwich panel manufacturing processes and to assess the potted insert load carrying capability. Test coupons with potted inserts will be manufactured and pulled in a standard tensile load frame as shown in Figure 10. The load will be increased gradually until failure is achieved while monitoring and recording the load cell output.
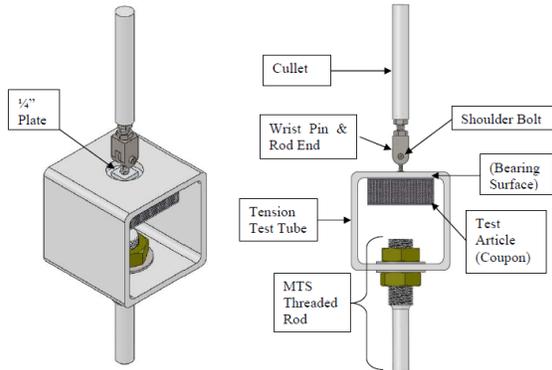
Figure 10: Coupon level insert pull test

Additional insert pull tests will be conducted on both the qualification unit and flight unit lower (aft) sandwich panel decks. The size of the full deck precludes the use of a tensile test frame, so a different approach must be taken. To accomplish the tests, each insert will be pulled via torque applied to an instrumented bolt passing through a counter-bored washer. In this configuration, the instrumented bolt will be threaded into the insert while the counter-bored washer surface reacts the load on the surrounding facesheet. This subjects the insert to the full load and does not simply compress the washer between the bolt head and insert face. Axial bolt load and applied torque will be measured and recorded until the desired axial load (tension) is achieved.

Static Testing

A full suite of static load tests will be conducted on the CubeStack qualification unit. Multi-axis loads will be applied to the test article to simulate the axial loads, shear loads, and moments witnessed during flight. These environments are consistent with those used for the finite element analyses, and are shown in Table 2. The axial load factors listed represent the maximum quasi-static acceleration of the payload along the launch vehicle axis, where a positive acceleration represents tension, or the case when the payload is being pulled away from the launch vehicle. The lateral load factor is the payload acceleration normal to the axial vector and it acts on the payload's CG. The CG above the CubeStack payload interface is the summation of the payload's CG and any associated hardware between the payload and CubeStack. For example, a 500-lb payload having a 22 inch CG on the Ø24.00 inch interface will be stacked on a 5.0-inch-tall adapter cone and a 2.1-inch-tall separation system (designated under the "MLB Offset" column), giving it a CG of 29.1 inch above the CubeStack forward interface. Having both a primary payload and secondary payloads (CubeSats), the CubeStack is subjected to several simultaneous loads of various magnitudes and load application points.

While the static test plan is still under development, the basic setup is complete. Both the Ø38.81 inch and Ø24.00 inch interfaces will be tested with similar test setups. The test stacks shown in Figure 11, will be mounted in a large reaction frame with a 5¼-inch-thick flat steel base plate and structural steel walls used to react the applied hydraulic actuator loads. Both the primary and secondary load heads will provide actuator attachment points to impart the load into the test article. This methodology was proven during the EELV Secondary Payload Adapter (ESPA) static load test, and is shown in Figure 12.

Table 2:   Qualification test loads: Payload mass, load factors and CG summary

	Primary Payload					Secondary Payloads				
	Payload Mass	Axial Load Factor	Lateral Load Factor	Payload CG	MLB Offset	Adapter Offset	Payload Mass	Axial Load Factor	Lateral Load Factor	Payload CG	Adapter Plate Offset
	lbm	g's	g's	in	in	in	lbm	g's	g's	in	in
Ø38.81" Max Compression	1000	-6.6	4.2	32.6	2.1	0.0	185	-30.0	0.0	2.0	0.25
Ø38.81" Max Tension	1000	6.6	4.2	32.6	2.1	0.0	185	-30.0	0.0	2.0	0.25
Ø24.00" Max Compression	500	-6.6	6.3	22.0	2.1	5.0	185	-30.0	0.0	2.0	0.25
Ø24.00" Max Tension	500	6.6	6.3	22.0	2.1	5.0	185	-30.0	0.0	2.0	0.25

24.00" Interface Test Stack   38.81" Interface Test Stack
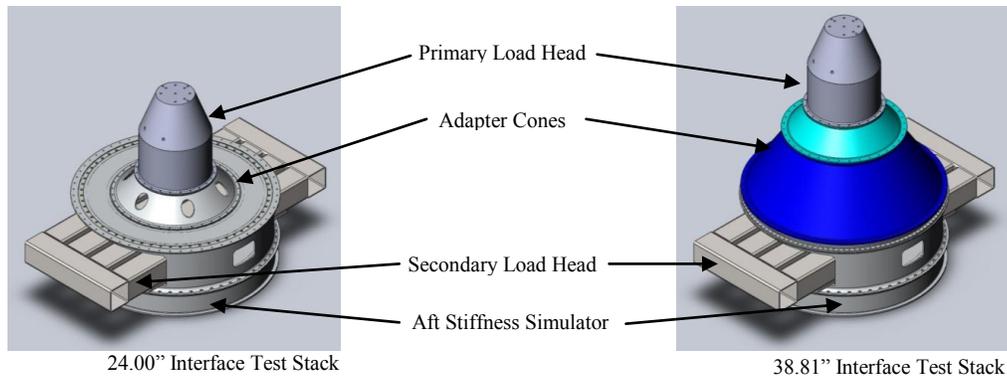
Figure 11: Static load test stacks
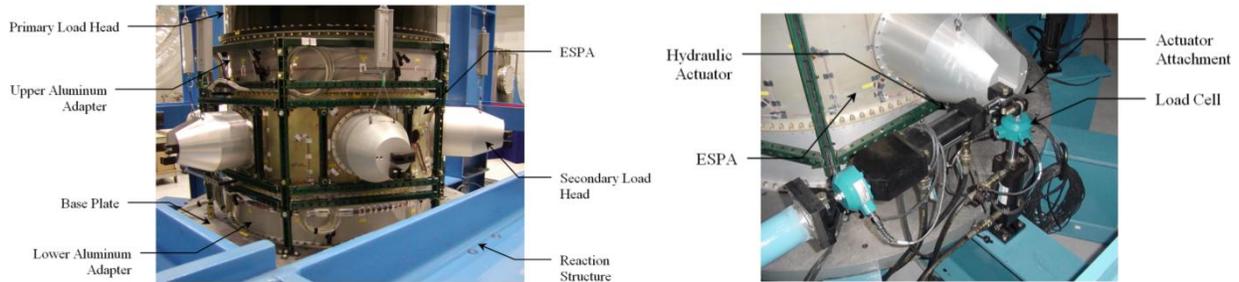
Figure 12: ESPA static load qualification test [4]

The two primary objectives of the static qualification tests are to measure the CubeStack structural stiffness and to verify the strength and structural integrity when subjected to worst-case loading scenarios. The first objective, stiffness verification, will be accomplished through the application of a unidirectional load while measuring the structure's deformation. As an axial load is applied, displacement transducers will be used to capture the CubeStack structural response, giving a displacement at a known applied load. Results of the stiffness load cases will be compared to pre-test finite element predictions.

Strength verification requires the application of the flight environments as discussed above. As the qualification unit is loaded, both displacement sensor and strain gage readings will be monitored and compared to the pre-test predictions. Strain gages will be placed in the most highly strained locations based on the finite element models. To be considered flight qualified, the structure must not exhibit any detrimental yielding at the qualification loads, 1.25 x MPE. Axial and lateral loads to be applied during stiffness and qualification testing are presented in Table 3. A total of 12 load cases will be performed, four stiffness and eight qualification. In the table, a +Z lateral load is applied directly over the large CubeSat dispenser opening at the payload CG given in the lateral offset column.

Sandwich panels used for flight, such as the CubeStack upper and lower decks, require acceptance testing equal to 1.1 x MPE [5]. To simplify these tests, each deck will be tested as an individual sub-assembly rather than in the full configuration of the qualification tests. A dedicated load frame will be constructed for timely acceptance testing. Within the frame there will be a representative interface ring that replicates the stiffness and geometry of the CubeStack deck attachment rings. Once installed in the fixture, an axial load equivalent to the combined flight conditions will be applied to the payload interfaces. No instrumentation other than direct measurement of applied load will be used during the acceptance tests.

Dynamic Testing

A dynamic test sequence is planned using a representative CubeStack configuration, including CubeSat dispenser simulators, CubeSat mass simulators and a primary payload mass simulator. The test sequence will accomplish the following objectives:

- Develop an experimental database for tuning the finite element model with estimated structural dynamic properties derived from measurements,

- Measure and characterize payload response under scaled baseline launch vehicle vibration profiles for prediction of the response when subjected to vibration profiles of alternate launch vehicles, and

- Benchmark the linearity of the test stack when subjected to varying load levels.

Table 3: Stiffness and qualification load magnitudes

		Flight Loads (100%)						Qualification Loads (125%)							
		Primary Payload			Secondary Payloads			Primary Payload			Secondary Payloads				
		Axial Load	+Y Lateral Load*	+Z Lateral Load*	Axial Load	+Y Lateral Load*	+Z Lateral Load*	Axial Load	+Y Lateral Load*	+Z Lateral Load*	Axial Load	+Y Lateral Load*	+Z Lateral Load*	Lateral Offset	Lateral Offset
Load Case	Description	lbs	in	g's	lbs	in	g's	lbs	in	g's	lbs	in	g's	in	in
1	Ø38.81" Compressive Stiffness	-5000	0	0	-2500	0	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	Ø38.81" Tensile Stiffness	5000	0	0	2500	0	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
3	Ø24.00" Copmpressive Stiffness	-2500	0	0	-2500	0	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
4	Ø24.00" Tensile Stiffness	2500	0	0	2500	0	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5	Ø38.81" Qual 1-Compression	-6600	4247	0	-5556	0	0	-8250	5309	0	-6945	0	0	34.7	2.2
6	Ø38.81" Qual 2-Compression	-6600	0	4247	-5556	0	0	-8250	0	5309	-6945	0	0	34.7	2.2
7	Ø38.81" Qual 1-Tension	6600	4200	0	-5556	0	0	8250	5250	0	-6945	0	0	34.7	2.2
8	Ø38.81" Qual 2-Tension	6600	0	4200	-5556	0	0	8250	0	5250	-6945	0	0	34.7	2.2
9	Ø24.00" Qual 1-Compression	-3300	3169	0	-5556	0	0	-4125	3961	0	-6945	0	0	29.1	2.2
10	Ø24.00" Qual 2-Compression	-3300	0	3169	-5556	0	0	-4125	0	3961	-6945	0	0	29.1	2.2
11	Ø24.00" Qual 1-Tension	3300	3169	0	-5556	0	0	4125	3961	0	-6945	0	0	29.1	2.2
12	Ø24.00" Qual 2-Tension	3300	0	3169	-5556	0	0	4125	0	3961	-6945	0	0	29.1	2.2

*Applied at payload CG

Low-level swept sine measurements will be used for estimating damping ratios and modal frequencies. Resulting measured damping data will be used to determine the structural response at resonance, and to predict loads under launch vehicle vibration environments.

A shaped random vibration acceleration power spectral density, based on the environment in the Minotaur I User's Guide, will be used to measure dynamic responses traceable to launch conditions. Acceleration transmissibility functions to predict payload response will be verified through measurements and used to determine the uncertainties in predicting dynamic response of the CubeStack when a launch vehicle other than the Minotaur I is used for a given mission.

Band-limited white noise functions, encompassing the fundamental modes of the system, and with differing power levels, will be used to characterize the load linearity. Knowing that bolted structures commonly exhibit a degree of nonlinearity that is sensitive to load level (i.e. damping ratios increase and modal frequencies decrease with increasing load level) provides insight into the behavior of the CubeStack structural dynamics at elevated base environmental levels. This allows the uncertainties in the predicted dynamics derived from the low-level swept sine data to be bounded.

FLIGHT OPPORTUNITIES

Flight adapters will be available in 2012 with a lead time of about 14 weeks. Following successful qualification testing that is planned for mid-2011, production units will be accepted with standard inspections and material certifications, except for the flight honeycomb decks which will be acceptance tested under static loads prior to delivery.

LoadPath and CSA are discussing possible missions with government and other organizations. We expect that availability of the CubeStack "wafer" to enable numerous CubeSat missions.

CONCLUSION

The CubeStack is under development as a stackable multi-payload adapter for CubeSats in support of government and commercial missions. This "wafer" adapter is similar to the NanoSat Launch Adapter System (NLAS) adapter developed at NASA Ames. The 10-inch-tall CubeStack mounts between the rocket upper stage and its primary payload and accommodates eight 3U dispensers, four 6U CubeSat dispensers, or other combinations of 3U and 6U dispensers. The modular CubeStack wafer features both Ø38.81 inch and Ø24.00 inch diameter primary spacecraft interfaces and is sized for Athena, Minotaur I, Taurus, Pegasus and Falcon 1. CubeStack features include a small part count, minimized weight, and ease of satellite dispenser integration. The CubeStack will be available in 2012.

References

1. Higgins, J.E., B.J. Arritt, E.R. Fosness, P.M. Wegner, S.J. Buckley, "Multiple Payload Adapters; Opening the Doors to Space," Proceedings of 16th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August, 2002.

2. Agasid, E., B.D. Yost, J.W. Hines, "Nanosatellite Launch Adapter System (NLAS)," Proceedings

of 8th Responsive Space Conference, Los Angeles, California, March, 2010.

3. Orbital Sciences Corporation, "Minotaur I Payload User's Guide", Release 2.1, January, 2006.

4. Sanford, G.E., and Welsh, J.S., "Structural Qualification Testing of Unique Aerospace Structures," SAMPE 2004, Long Beach, CA, May 2004

5. Department of Defense Handbook, "Test Requirements for Launch, Upper-Stage, and Space Vehicles," Mil-HDBK-340A Vol I, April 1999