1.3 GHz Cryomodule (CM1) Transport to New Muon Lab (NML)

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August 11, 2008

MSDN-ME-000076

Summary

The duration of the transport of CM1 from its support at ICB to the support at NML, spanned 4 hours, 11 minutes and 29 seconds. The CM1 assembly traveled 2.1 miles in 49 minutes and 8 seconds with an average speed of 2.6 mph. During the transport of the CM1 coldmass from MP9 to ICB on October 15th, 2007, a benchmark maximum acceleration of 2.43 g (vertical) on base frame and 0.25 g (vertical) on any cavity was measured. The goal was to limit maximum acceleration experienced by the coldmass to 0.5 g, during the CM1 assembly transport from ICB to NML.

Assembly Setup and Instrumentation

The CM1 transport assembly shown in Figure 1 consists of a cryomodule weighing 8-tons, a strong-back fixture (weighing 3.5-tons) and base frame (weighing 1.4-tons). In total, the CM1 assembly weight found above the isolators (not including the base frame) is approximately 11.5-tons. Ten helical coils in a compression-roll (45 degree) configuration attenuate shock between the base frame and isolation fixture. The isolators, manufactured by Isolator Dynamics Corp. (IDC), part # M24A-400-08 each have a static spring constant of 7,000 lb/in and dynamic constant of 3,000 lb/in[1]. The isolator design considers a frequency ratio of 3:1, providing 80% isolation between the base frame and isolation fixture.

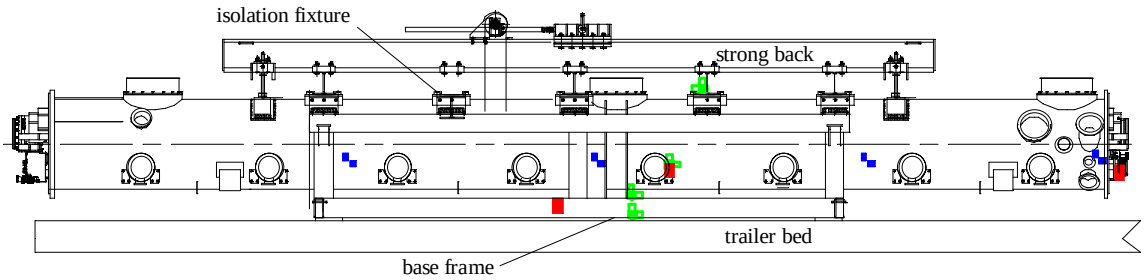

Figure 1. Elevation view of CM1 transport assembly with instrumentation locations.

In Figure 2, the center of gravity is shown, roughly in-line with the center of the isolators (therefore maximizing stability). The downstream (DS) end of the assembly is loaded slightly more due to the relative position of strong-back fixture and cryomodule. This slight off-set was necessary in order to keep the load centered or level transversely and longitudinally, when lifting with a crane.

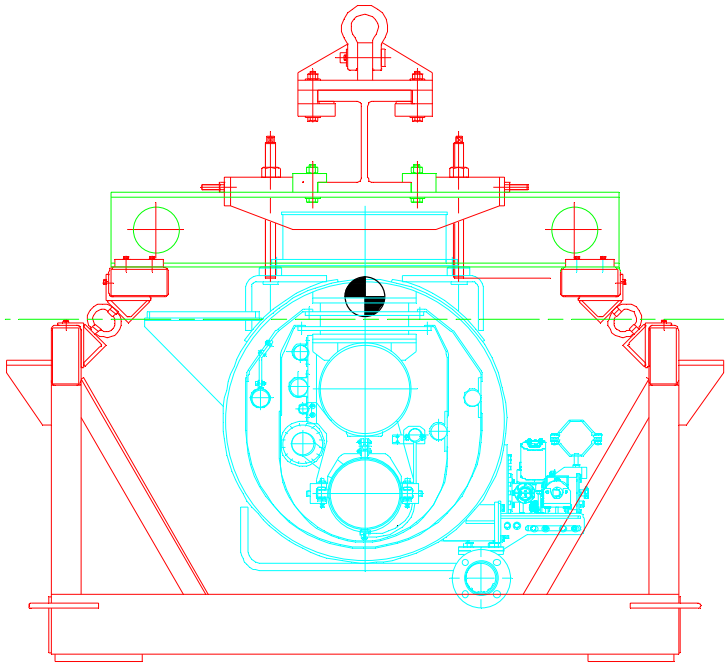

Figure 2. Center of gravity of CM1 assembly versus isolator center.

A total of (12) Geospace HS-1 geophone devices in block sets of 3 (x, y and z-direction) were attached to the isolation fixture, Cavity #5 input coupler (IC) port, base frame and trailer bed as shown in green (Figure 1)[2]. Geospace GS-14-L9 geophones were mounted just above cavities #3, #5 and #7 (one vertical and one horizontal) within CM1, shown in blue (Figure 1). Also in blue, Geospace GS-11-D geophones (one vertical and one horizontal) were mounted at the upstream (US) end on the beam-valve (BV). All geophones were connected to six National Instruments (NI) NI-9233 4-channel, 24-bit ADC modules sampled at 5K/s, and the data was recorded to a laptop hard-drive. Three GP1 Programmable Accelerometer devices shown in red (Figure 1) found at the Cavity #5 IC, US beam-valve near quad and on the base frame were used in DAQ mode to record acceleration with an epoch of 1 sec[3]. Mounting locations for the GP1 device on the CM1 assembly is shown in Figures 3(a) and 3(b).

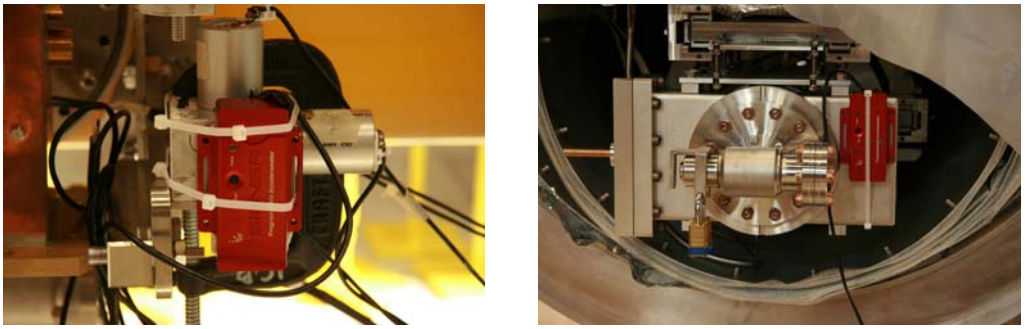

Figure 3(a) Instrumentation mounted near Cavity #5, IC. **3(b)** GP1 mounted on beam-valve.

Shock Response

The movement of CM1 from ICB to NML was divided into three phases; loading at ICB, over-the-road transport and unloading at NML.

Loading at ICB

Initially, the base frame with ten isolators attached was loaded and secured onto the air-ride trailer. All loading was completed using a 30-ton overhead crane. After activating the GP1 devices and geophones, the CM1 assembly was then carefully loaded onto the base frame as shown in Figure 4.

Figure 4. Loading CM1 assembly onto base frame at ICB.

Table 1 provides a summary of maximum acceleration loads experienced during the crane operation and subsequent attachment to the base frame. In general, differences between the geophone and GP1 device acceleration values were due to sampling rate. The geophones measured velocity at a sampling rate of 5K/sec, while the GP1 devices measured acceleration once per second. The large acceleration loads observed on the base frame were due to personnel movement during the attachment of the CM1 assembly to the base frame. Figures 5, 6 and 7 show the geophone data (noting significant events) while loading at ICB, in the vertical, transverse and longitudinal direction, respectively. The crane acceleration loads are quite low as compared to loads experienced during connection of the transport assembly. Maximum acceleration values from the cavities and quad were averaged and designated as BV/Cavity each in summary table.

Table 1. ICB summary of maximum acceleration of geophone versus GP1 device.

Location	Vertical Acceleration		Transverse Acceleration		Longitudinal Acceleration	
	Geo (g)	GP1 (g)	Geo (g)	GP1 (g)	Geo (g)	GP1 (g)
BV/Cavity	0.11	0.2	0.15	0.2	---	0.13
Base	1.85	1.73	2.11	2.14	1.41	0.68
IC	0.21	0.08	0.43	0.63	0.41	0.11

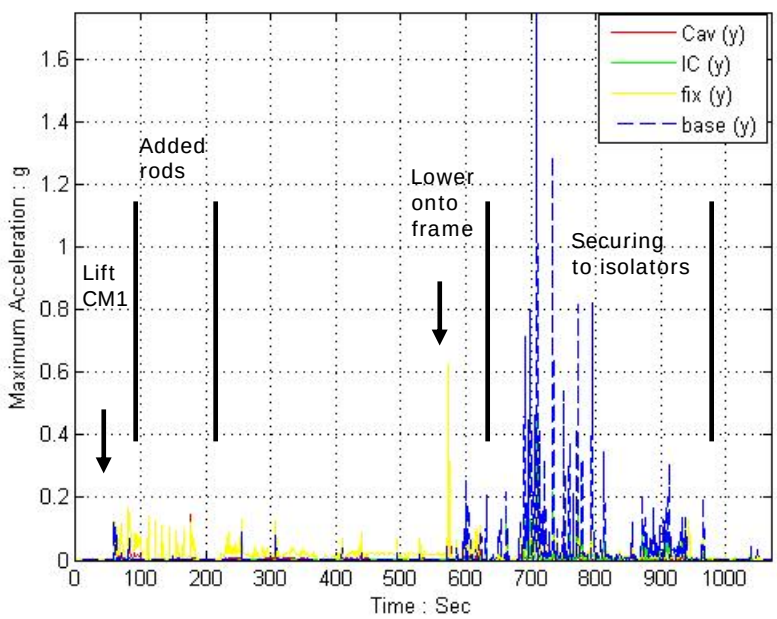

Figure 5. Vertical geophone acceleration loads at ICB.

The GP1 device acceleration data is given in a comprehensive manner over the entire transport duration in the vertical, transverse and longitudinal direction as shown in Figures 8, 9 and 10, respectively.

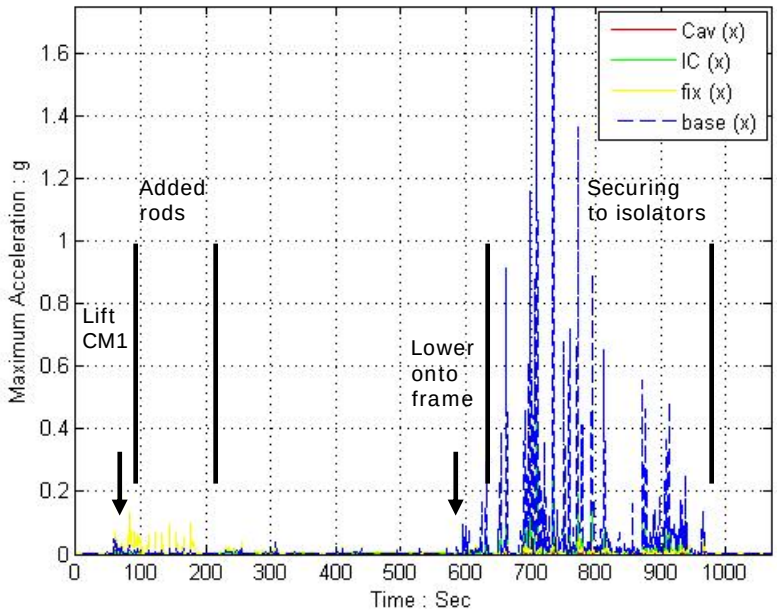

Figure 6. Transverse geophone acceleration loads at ICB.

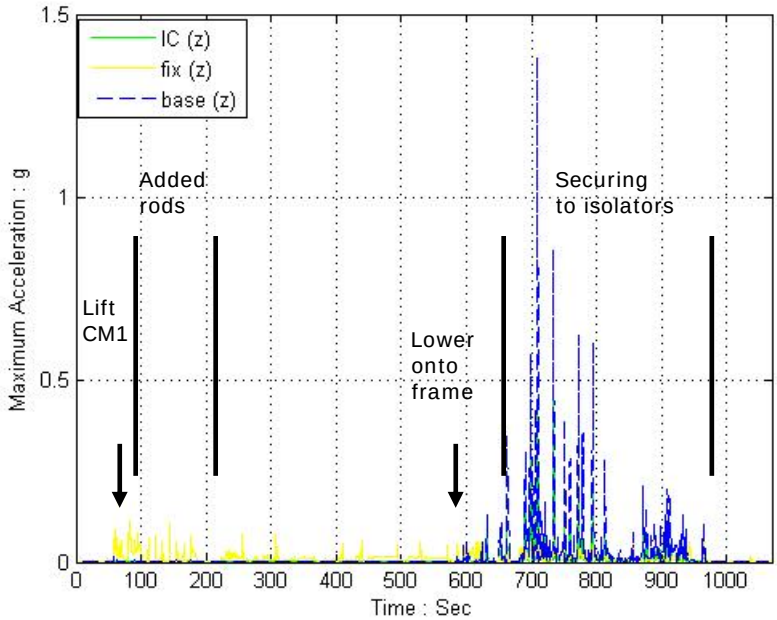

Figure 7. Longitudinal geophone acceleration loads at ICB.

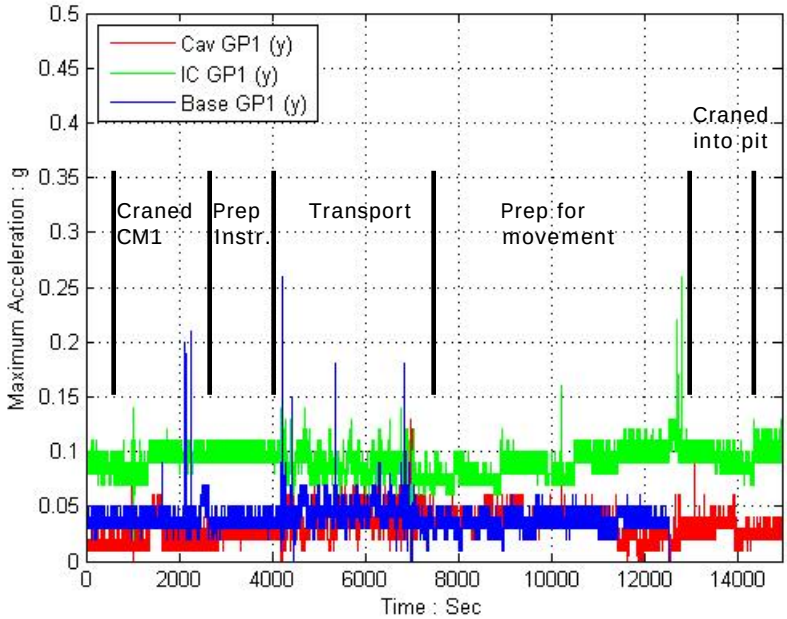

Figure 8. Vertical GP1 acceleration loads over entire transport duration.

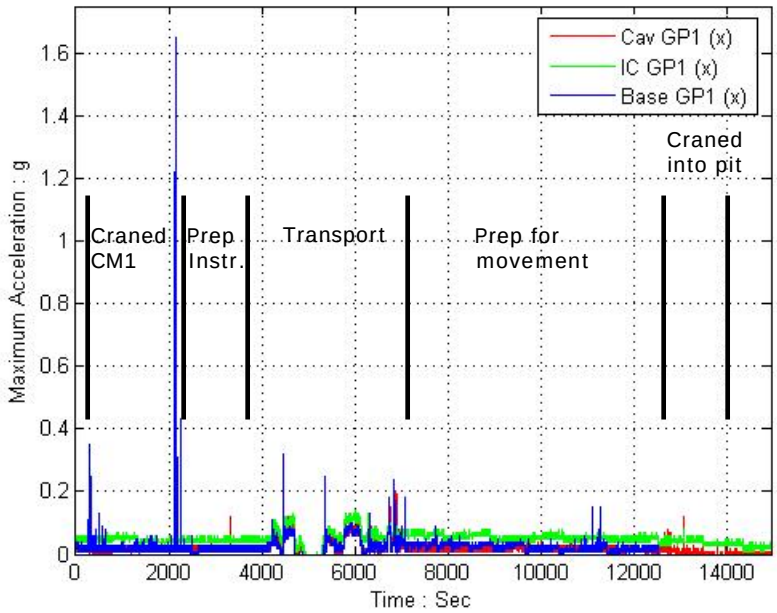

Figure 9. Transverse GP1 acceleration loads over entire transport duration.

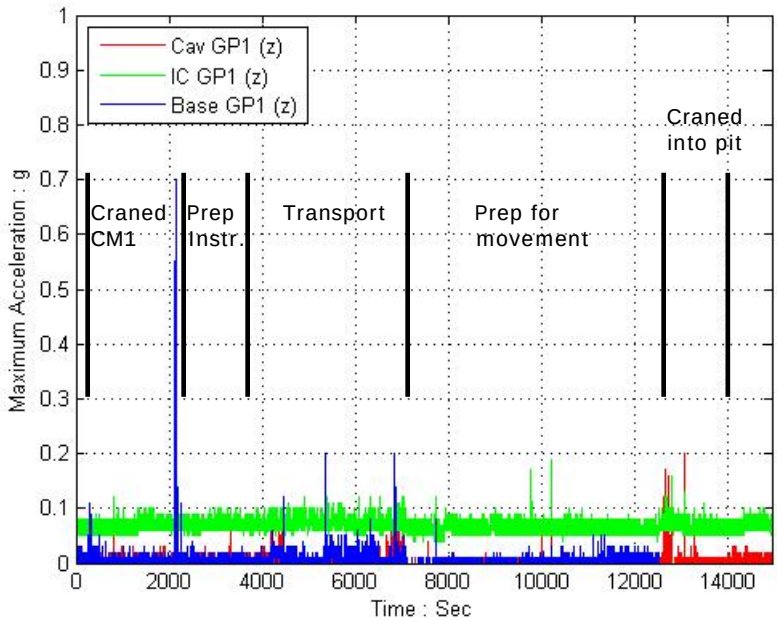

Figure 10. Longitudinal GP1 acceleration loads over entire transport duration.

Over-the-road Transport

Precautions were taken to limit longitudinal acceleration/deceleration by transporting at a continuous speed under Security escort as shown in Figure 11.

Figure 11. CM1 assembly enroute to NML.

A summary of maximum accelerations experienced during the transport phase is given in Table 2.

Table 2. Transport summary of maximum acceleration of geophone versus GP1 device.

Location	Vertical Acceleration		Transverse Acceleration		Longitudinal Acceleration	
	Geo (g)	GP1 (g)	Geo (g)	GP1 (g)	Geo (g)	GP1 (g)
BV/Cavity	**0.40**	0.20	**0.36**	0.20	---	**0.13**
Base	*1.90*	1.73	*2.40*	2.14	1.25	0.68
IC	0.10	0.08	0.38	0.63	0.10	0.11

Bold face font indicates absolute maximum acceleration of coldmass and *italic* absolute for base.

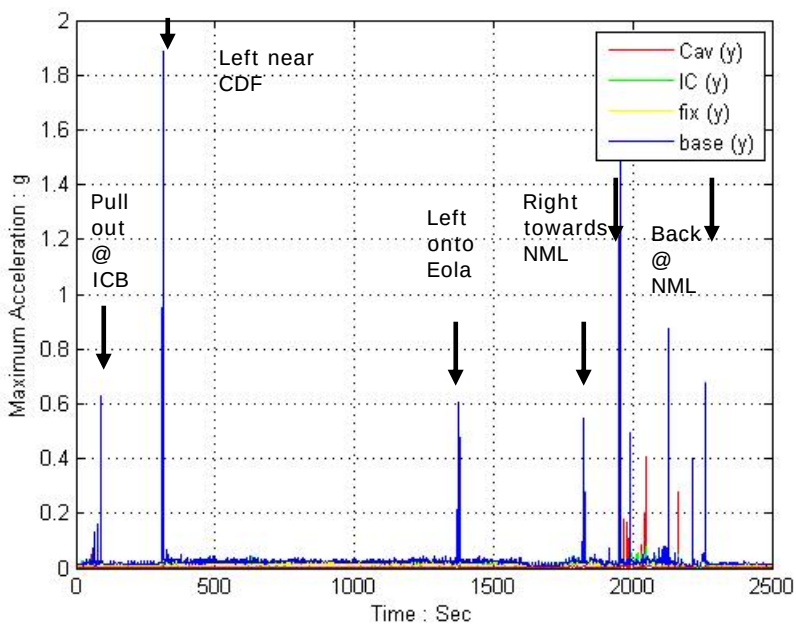

Figure 12. Vertical geophone acceleration loads during over-the-road transport.

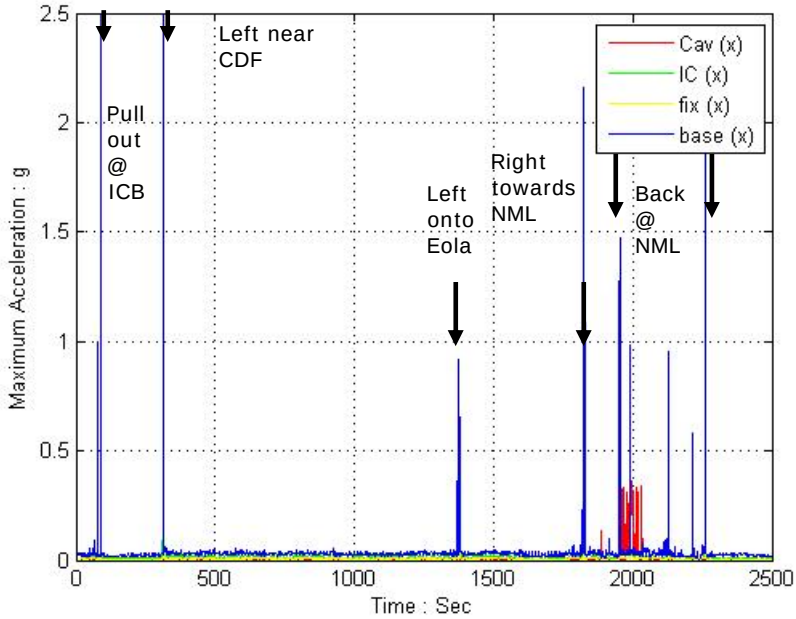

Figure 13. Transverse geophone acceleration loads during over-the-road transport.

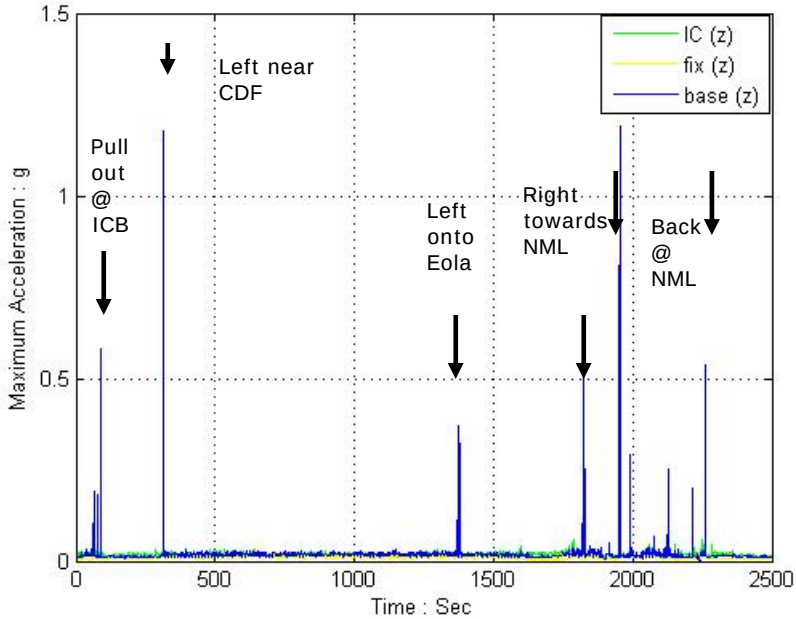

Figure 14. Longitudinal geophone acceleration loads during over-the-road transport.

Unloading at NML

After arriving within the NML highbay, the CM1 assembly was supported by the overhead crane and the isolators were disconnected as shown in Figure 15.

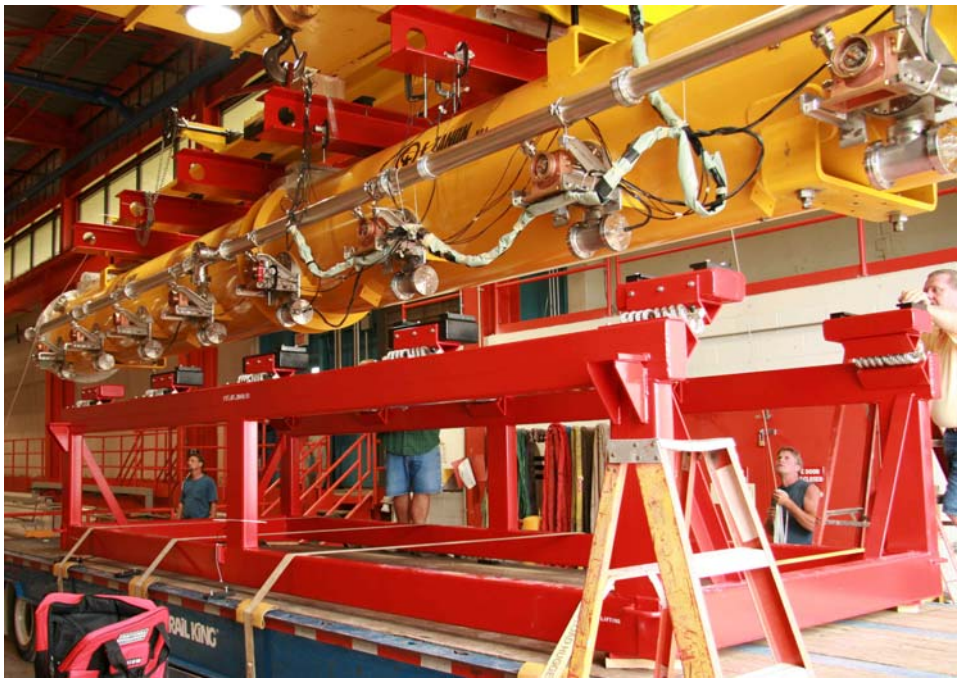

Figure 15. Unloading CM1 assembly from base frame at NML.

Table 3 provides the maximum acceleration results during unloading and crane transport into the pit at NML. A portion of the geophone data during crane operation at NML was not recorded due to a sudden loss of DAQ. However, the GP1 data covered this blackout period.

Table 3. NML summary of maximum acceleration of geophone versus GP1 device.

Location	Vertical Acceleration		Transverse Acceleration		Longitudinal Acceleration	
	Geo (g)	GP1 (g)	Geo (g)	GP1 (g)	Geo (g)	GP1 (g)
BV/Cavity	0.10*	0.2	0.10*	0.2	---	0.13
Base	---	1.73	---	2.14	---	0.68
IC	0.51*	0.08	0.20*	0.63	0.10*	0.11

* A portion of this data was lost during crane transport.

Spectral Response

Spectrograms from the geophone data reveal active frequencies on the coldmass, isolation fixture and base frame during each phase of transport.

Trailer Response

Data published by the U.S. government, shown in Figure 17 describes vibration exposure which affects trucks at the low frequency spectra[4]. Past experience has shown that the coldmass is sensitive to longitudinal low frequencies at or slightly above 5 Hz. The isolation system was pre-tuned to avoid certain low frequencies encountered while traveling over-the-road. The natural frequency of the CM1 assembly is 3.5 Hz. Road imperfections such as depressions or potholes along the route cause excitation to be transmitted through the tires and suspension system into the trailer. These imperfections were minimized prior to transport by filling depressions with crushed aggregate limestone. Also, a Security escort was provided to maintain a constant minimum speed of 2.6 mph during transport as greater vehicle speeds contribute to excitation transmission.

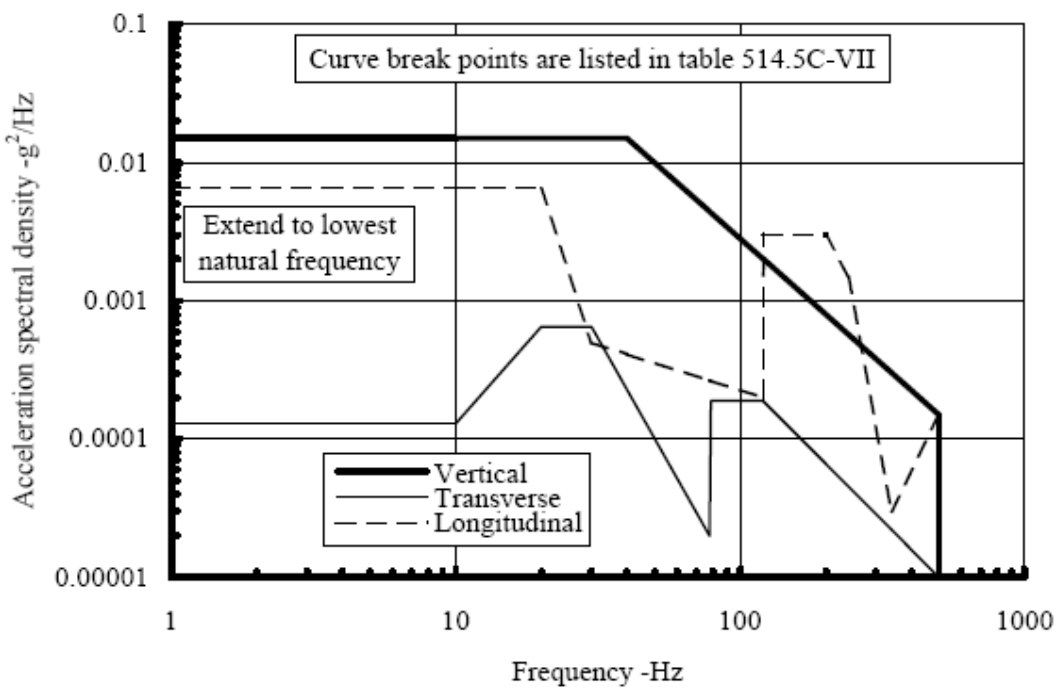

Figure 17. U. S. highway truck vibration exposure (taken from Figure 514.5C-1, MIL-STD 810F).

Sharp constant lines on a spectrogram (within the frequency domain) indicate a resonance condition. A sharp line signifies that a certain frequency (or tone in analogous to sound) continues to be active even though changes in motion, engine rotational speed and shock through the tires and suspension system has occurred. Figures 18 and 19 represent the spectral response of the quad and base vertically during the transport phase.

The red lines at low frequency show sensitivity to those frequencies. However, these lines break up when disturbances (large motion, velocity or acceleration) are encountered. Therefore they are not considered constant or lines of resonance. Similar results are shown in Figures 20 and 21 regarding the longitudinal spectral response. The maximum acceleration results indicate that the CM1 assembly was not affected by the excitation transmitted from the road into the trailer.

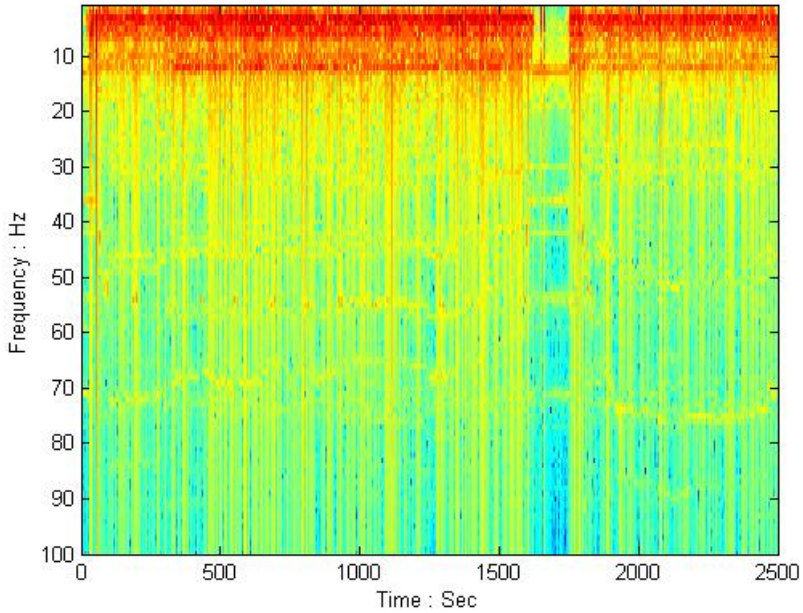

Figure 18. Spectrogram for vertical response of quad.

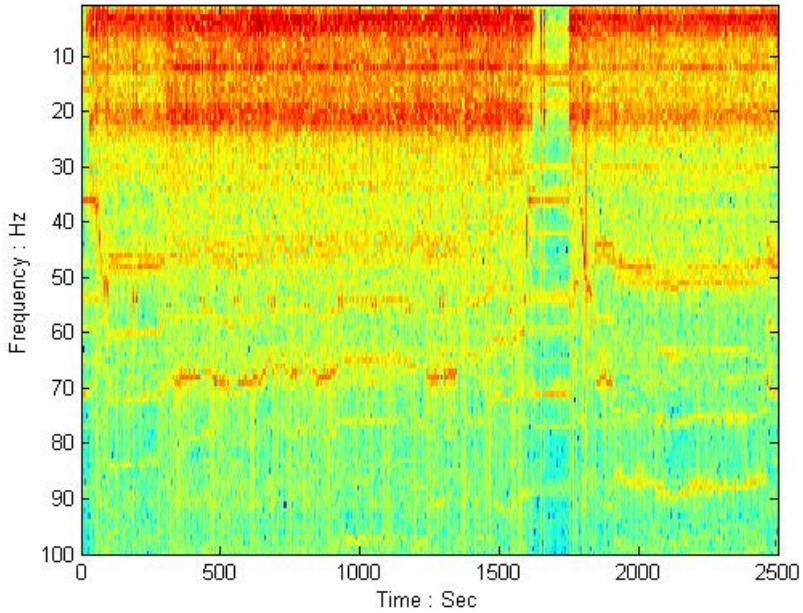

Figure 19. Spectrogram for vertical response of base.

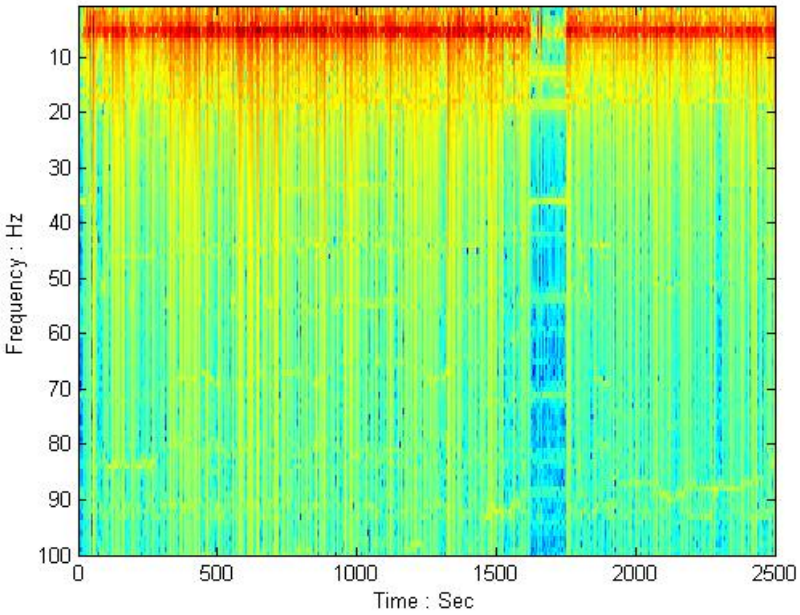

Figure 20. Spectrogram for Cavity-5 IC in longitudinal direction.

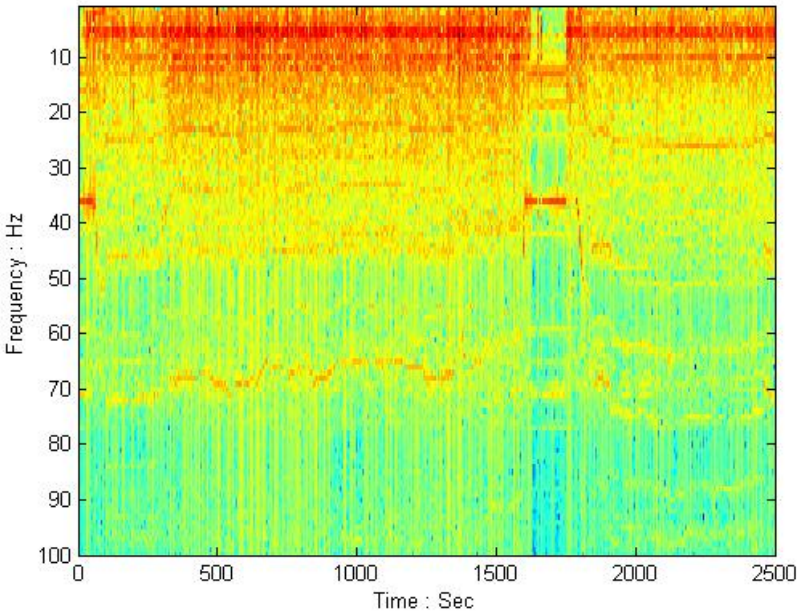

Figure 21. Spectrogram for longitudinal response of base.

Results

Maximum measured acceleration loads over all three transport phases on the cavities (or coldmass) is shown in boldface in Table 4. The maximum acceleration vertically was 0.4 g, transverse 0.36 g and longitudinal 0.13g on the coldmass. These maximum accelerations were beneath the goal value of 0.5 g. Each of these values was recorded during the over-the-road transport phase. Also, the vertical and transverse acceleration load maximum for the base (italicized in Table 4) was also measured during the transport phase. Spectral results indicate that the transport was resonance free.

Table 4 Overall Summary of maximum acceleration of geophone versus GP1 device.

Location	Vertical Acceleration		Transverse Acceleration		Longitudinal Acceleration	
	Geo (g)	GP1 (g)	Geo (g)	GP1 (g)	Geo (g)	GP1 (g)
BV/Cavity	**0.40**	0.2	**0.36**	0.2	---	**0.13**
Base	*1.90*	1.73	*2.40*	2.14	1.41	0.68
IC	0.51	0.08	0.43	0.63	0.41	0.11

References

[1] www.isolator.com

[2] www.sensr.com

[3] www.geospacelp.com

[4] U.S. Department of Defense, "MIL-STD-810F Method 516.5 VIBRATION", p 514C-1 (January 2000).