

SEISMIC QUALIFICATION OF A 4 MW EMERGENCY POWER GENERATOR SET

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Nuclear Emergency Diesel Generators

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ABSTRACT

Operation during and after a seismic event is the typical requirement for emergency equipment installed in a nuclear facility. Data from shake table testing of a large emergency generator set while operating is often not available. This paper covers the qualification process including representative static structural analysis, shake table testing and the investigation of structural data taken from mobile applications using the C175-20 engine.

INTRODUCTION

Two nuclear facilities in the Czech Republic required additional emergency diesel generators (EDGs) for station blackout (SBO) support. The site specification called for seismic qualification covering operation during and after the seismic event. NUREG/CR-0098 was the guiding regulation. The product selected for installation was the 4 MW Cat® C175-20 diesel generator set. Each nuclear facility required two units.

PROJECT DETAILS/REQUIREMENTS

The two nuclear facilities in the Czech Republic each required two 4 MW emergency diesel generator sets operating at 50 Hz.



Max Wet Weight:	37 t
Length:	8.5 m
Width:	2.5 m
Height:	2.5 m

Each unit was installed in its own enclosure mounted on a concrete base designed for the seismic loads.



The international regulation for this project was NUREG/CR-0098, with the site specific g-levels defined by the following:

- $PGA_H = 0.150\text{ g}$
- $PGA_V = 0.105\text{ g}$

To be conservative, the damping and ductility factors were selected as 7% and 1.3 respectively. The required response spectrum was derived, and it is shown in Figure 1 below.

The analysis must demonstrate the generator set’s resilience and its integrity *during* and after a seismic event.

The first step in completing the qualification was identifying the detailed requirements for both static and dynamic conditions. The dynamic conditions are defined by a required response spectrum curve, with inputs derived from the maximum g-loads listed in the project requirements and from NUREG/CR-0098.

Required Response Spectrum Curve Inputs:

- Bolted and/or riveted steel 7% critical damping
- Class I-S ductility factor 1.3
- Amplification Factors
 - Acceleration 2.36
 - Velocity 2.08
 - Displacement 1.85

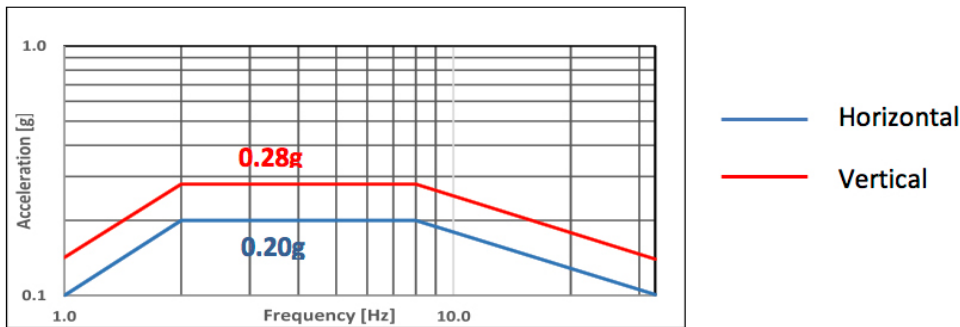


Figure 1: Required response spectrum

The requirements for static analysis were defined by the NUREG/CR-0098 regulation and the site specific maximum g-levels in Figure 2.

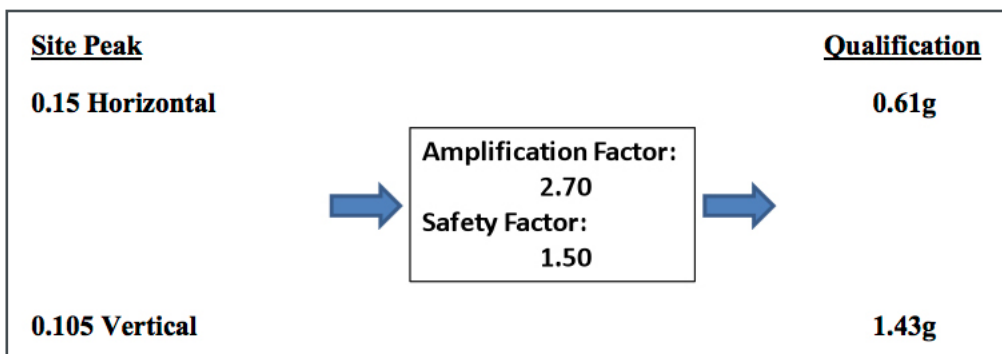


Figure 2: Requirement for static analysis

QUALIFICATION PROCESS

The process to qualify the generator set consisted of several phases; including:

- Structural analysis
- Existing previous shake table testing of similar products
- Incorporation of data from mobile applications

Structural Analysis:

The major components that were analyzed included the structural base, driveline coupling, engine flywheel, generator rotor and frame, and the remote-mounted control panel. The most important component in the generator set is the structural base, which was analyzed with the g-levels from Figure 2 and applied to the model shown in Figure 3.

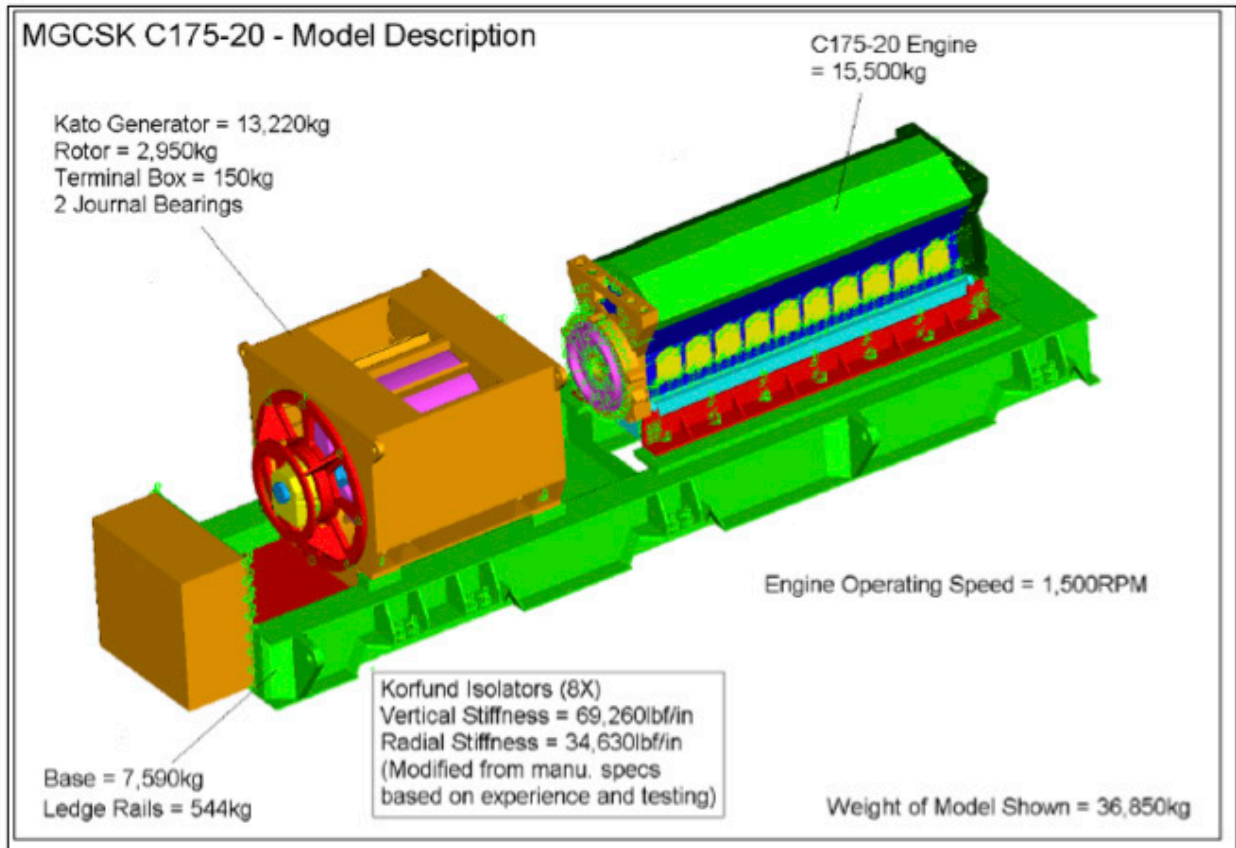


Figure 3: Cat C175-20 model description

The results were well below the minimum 50 percent design yield point, as shown in Figure 4.

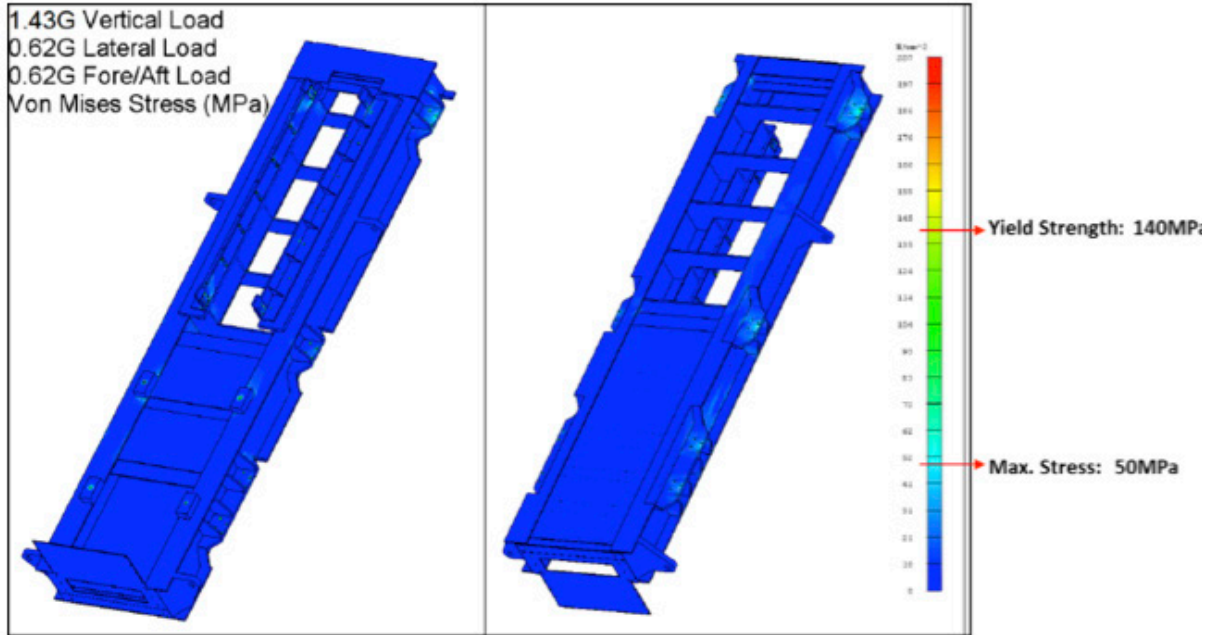


Figure 4: Cat C175-20 yield strength versus maximum stress

Another dynamic component in the driveline is the engine-generator coupling. The coupling is a rubber ring that connects the engine flywheel to the generator rotor shaft and is designed to absorb torsional vibrations. The results of this analysis are shown in Figure 5.

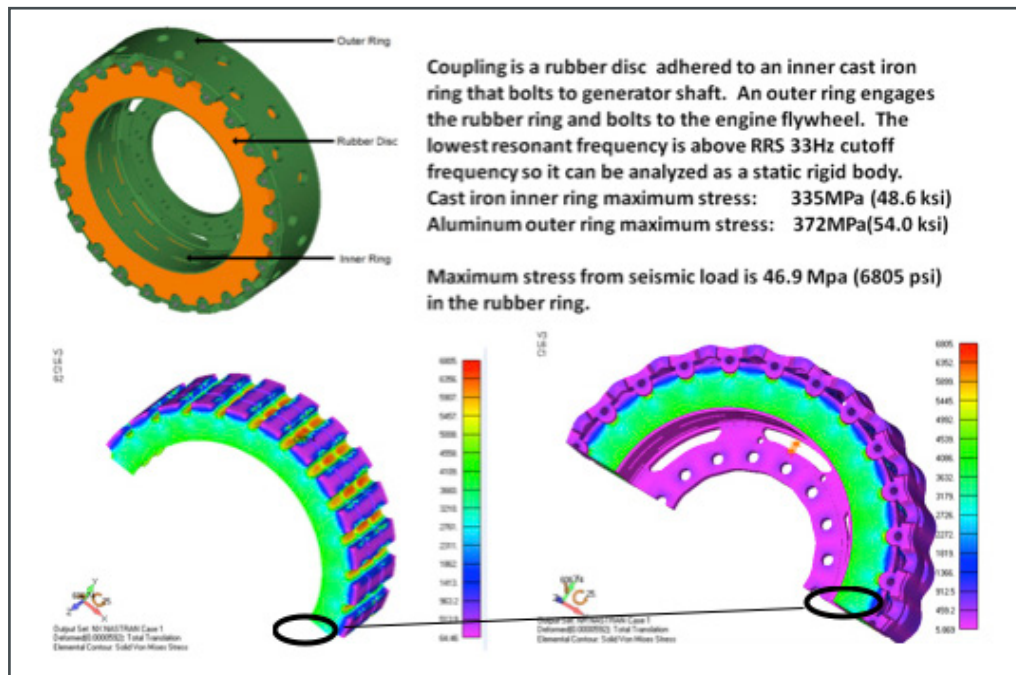


Figure 5: Engine-generator coupling analysis

Other major components were analyzed in a similar fashion and found to meet the seismic requirements.

Previous Shake Table Testing

Over the past several years, shake table testing of Cat generator sets and related generator set components has been performed to achieve certification for meeting the seismic provisions of all published editions of the International Building Code (IBC). The g-levels required in the IBC certification process are typically greater than 2.0, which is higher than the g-level required for the Czech Republic project.



Figure 6 shows the combined plots from these similar products. The site requirements are plotted in blue for each direction:

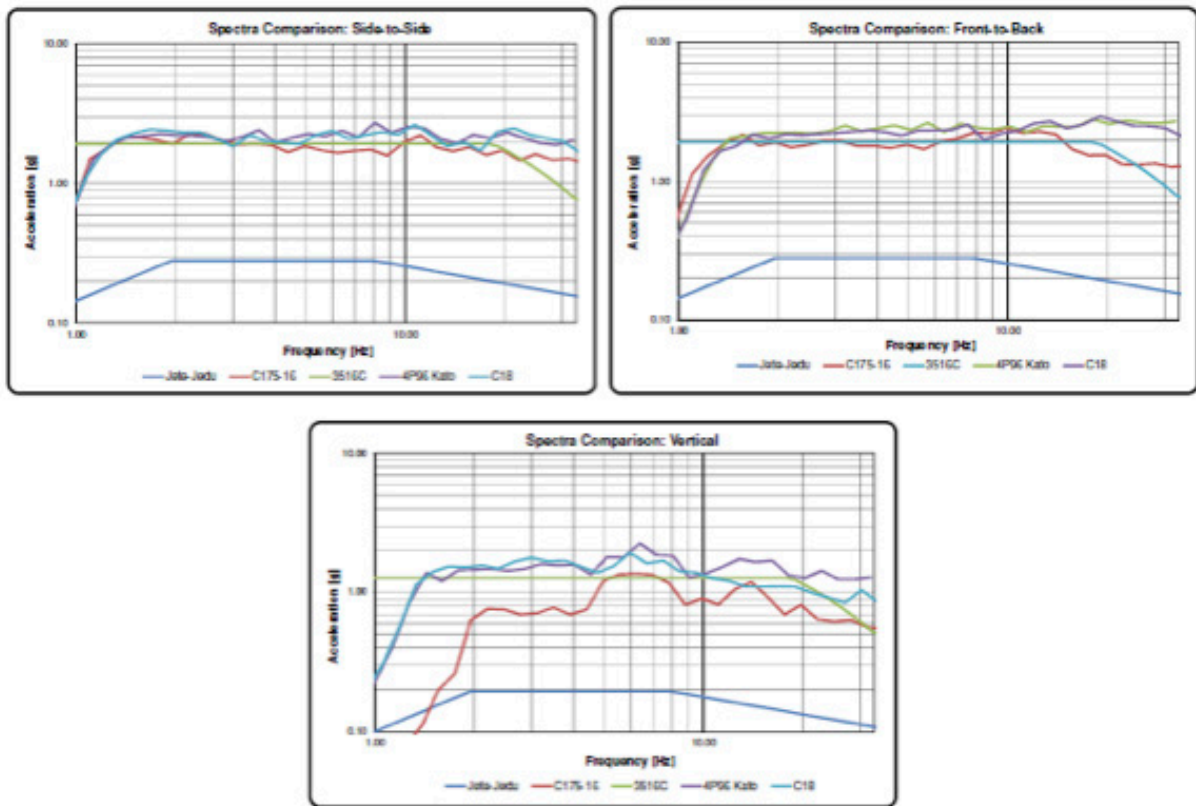


Figure 6: Combined g-level plots for Cat generator sets

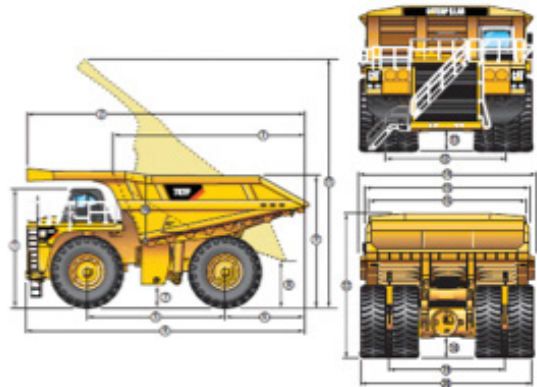
The test plot shown in red is significant, as it is a 16-cylinder version of the Cat C175-20 generator set under review. The major components for the Cat C175-16 – cylinder heads, pistons, connecting rods, rod and main bearings, valves and valve train, intake and exhaust system, basic cylinder block and crankshaft design – are the same as the Cat C175-20. The peak g-levels tested are approximately 8 times the level required, which indicates the Cat C175-20 generator set is robust and would withstand the seismic events defined.

Mobile Application Data

The Cat engine used on the 4 MW Cat C175-20 diesel generator set is applied in many different markets, including electric power, marine, industrial and petroleum. One notable application is the Cat 797F truck for off-highway and mining applications. It is the largest truck Caterpillar produces and one of the largest trucks in the world. It is designed to carry 400 tons (363 megagrams) of material out of a mine or large quarry.



~700 t Loaded



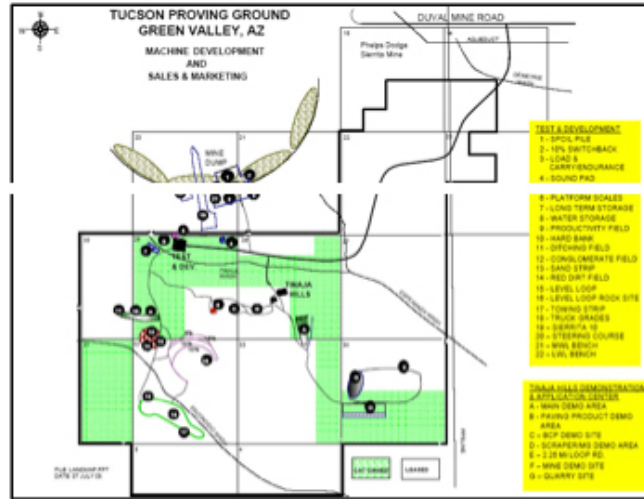
- Overall Length:** 15 m
- Width:** 10 m
- Height (bed down)** 10 m
- Top Speed:** 70 km/h

The 797F truck is an extremely high-hour, high load-factor application, and it is considered one of the most severe applications of a Cat engine. Typically, a mining shovel bucket fills the truck in no more than three loads, meaning the truck experiences 133 tons (121 megagrams) dropped into it three times for each truck load. The truck then hauls that load to a dumping location.

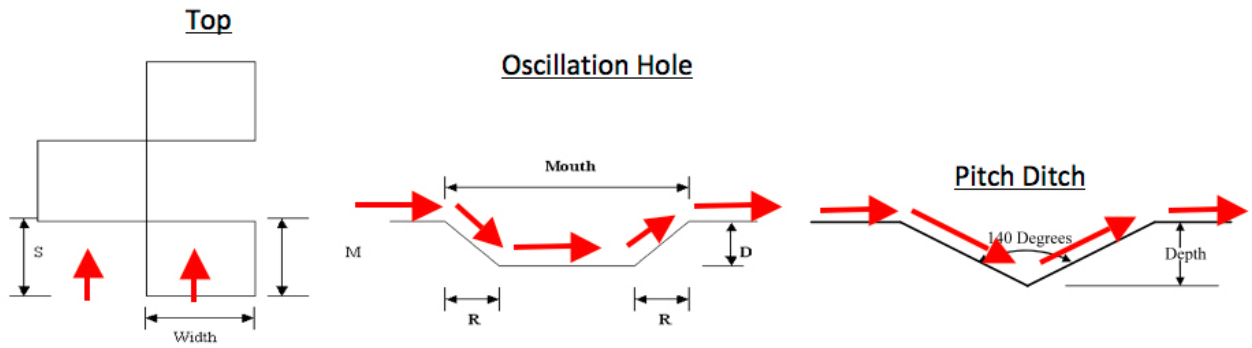
It may take several hours to climb out of the mine on each trip, and the temporary roads on a mining site change as the mining process progresses. This creates very difficult operating conditions and loads on the truck structure.

In the product development process at the Tucson Proving Grounds, Caterpillar engineers captured accelerometer data as they ran the trucks through a simulated operational course.



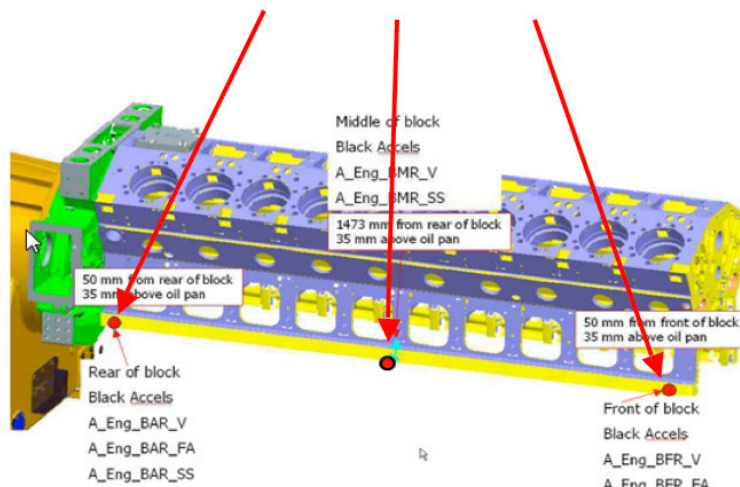


The truck traversed a defined course of ditches, pot holes, washboard-shaped inclines and rocks dropped from excessive heights, in addition to being subjected to numerous severe-duty tests, such as backing into a rock wall.



The engine was instrumented with accelerometers at the front, middle and rear of the cylinder block.

Instrumented Cylinder Block



The data from all of the tests were combined and plotted in Figure 7 against the ratio of response spectra (RRS) curve for the project. The lower frequencies show g-levels significantly higher than the RRS curve, and the higher frequencies are generally lower than the RRS. The frequency where the g-levels start to decrease are in the 8-10 Hz range. These results may be attributed to the various speeds the vehicle travels through the obstacles and the frequencies at which the engine mounting system starts to attenuate the displacement. The lower frequencies represent the vehicle's overall displacement as it travels through the test course being lifted and rolling to the right and left.

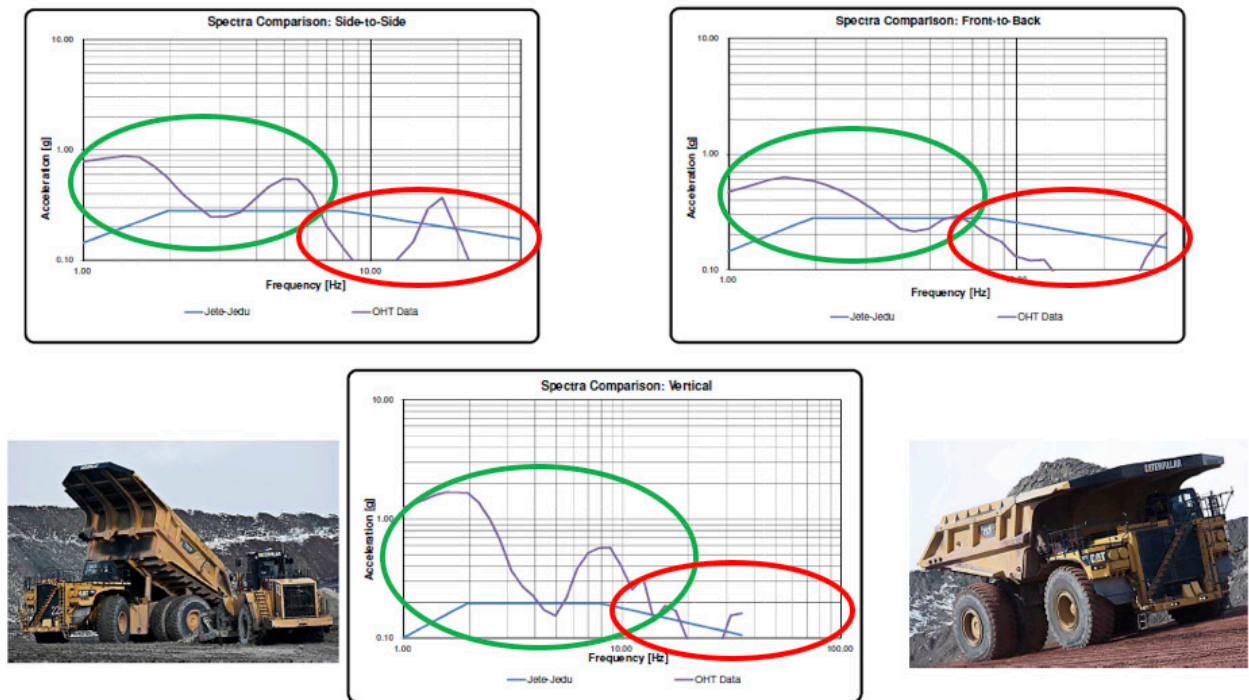


Figure 7: 797F accelerometer data analysis

A total of 228 off-highway 797F trucks with the C175-20 engine have combined for over 1 million hours of duty without a major engine component failure, including 20 units with more than 10,000 hours of operation each. This is significant because the loads carried by these trucks exert a high degree of stress over thousands of hours of operation, while a seismic event experienced by a generator set configured with the same engine lasts only seconds.

CONCLUSION

Based on structural analysis work, previous shake table testing and the experience of the Cat C175-20 engine in off-highway and mining trucks in a high-hour, high operation mobile application, the Cat C175-20 diesel generator set can be considered seismically qualified for nuclear applications.

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