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Using Fatigue Damage Spectrum for Accelerated Testing with Correlation to End-Use Environment

Tom Achatz, PE
Global Technical Integration Engineer,
General Motors Company
John VanBaren, PE
President, Vibration Research Corporation

ABSTRACT:

The accumulated damage that a product experiences in the field due to the variety of vibration stresses placed upon it will eventually cause failures in the product. The failure modes resulting from these dynamic stresses can be replicated in the laboratory and correlated to end use environment to validate target reliability requirements. This presentation addresses three fundamental questions about developing accelerated random vibration stress tests.

Question #1:

What random profile is needed (and for how much time) to accurately simulate the end use environment over the life-cycle of my product?

Question #2:

My product operates in many different vibration environments, how can I confidently combine them into one accelerated test?

Question #3:

How can I use the FDS to accelerate my test?

BACKGROUND:

Products in the field experience a wide range of vibratory environments. Test engineers want to incorporate a product's many different experiences into one test. One way of trying to take all of these environments and experiences into consideration is to use a new tool called the Fatigue Damage Spectrum (FDS).

The Fatigue Damage Spectrum is based on Miner's Rule of Damage, which teaches that fatigue damage will accumulate over time until it reaches a level that causes a crack or other deformation of a product. So, regardless of how a product arrives at its life-dose of fatigue damage (ie: quickly or slowly), the product will experience a failure mode when it reaches its life-dose of fatigue damage.

A Fatigue Damage Spectrum is produced in the following way (Figure 1).

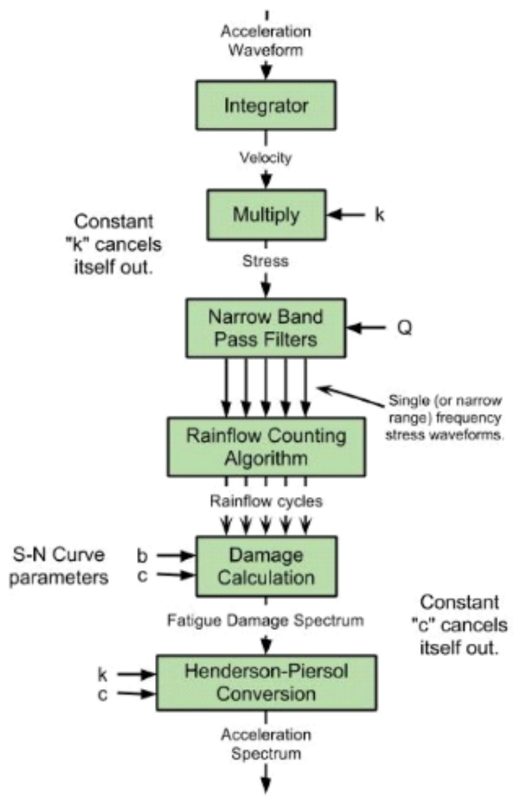

Figure 1: Fatigue Damage Spectrum Calculation Flowchart

First, a PSD data file (acceleration waveform) is converted to a velocity waveform by an integration process. The original acceleration waveform is converted to a velocity waveform because the Henderson-Piersol method of calculating fatigue originally based their calculations on using a velocity waveform. They did so because it had been argued that stress (causing fatigue) is proportional to velocity[1]. As true as that may be, Vibration Research Corporation has recently demonstrated that the PSD produced from the Fatigue Damage Spectrum calculation will be the same whether the Fatigue calculation is made based on acceleration, velocity, or displacement (See Figure 2, 3). The reason this is true is because the final PSD is ultimately an equivalency of two waveforms. So whether the two waveforms during the process of calculating the PSD are acceleration waveforms or not, the plot showing the equivalency of the two acceleration units would be the same as if the plot was showing the equivalency of two displacement or two velocity waveforms.

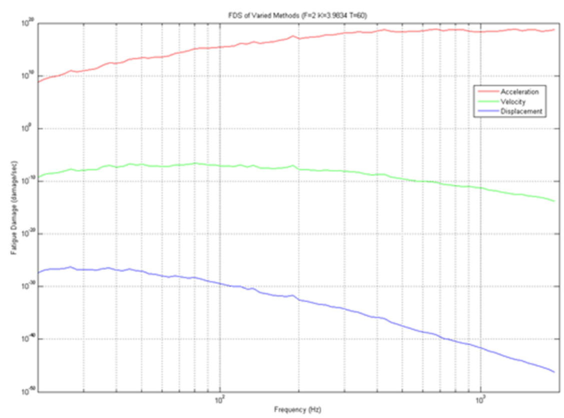

Figure 2: Fatigue Damage Spectrum calculated based on Acceleration, Velocity, and Displacement waveforms

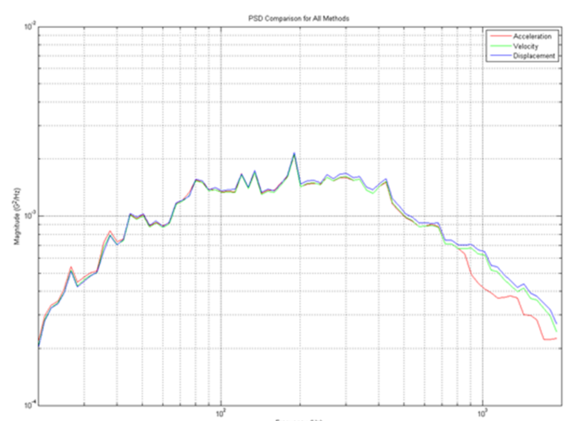

Figure 3: PSD calculated based on Acceleration, Velocity, and Displacement FDS calculations. No matter what FDS method was used the final PSD was the same.

Secondly, the converted PSD data is run through a narrowband filter, utilizing a specific Q value. Then a specialized calculation tool is used to determine the fatigue damage for the data filtered for each frequency band. This is accomplished by using a Rainflow counting algorithm to count the stress peak-valley cycles[2] (Figure 4).

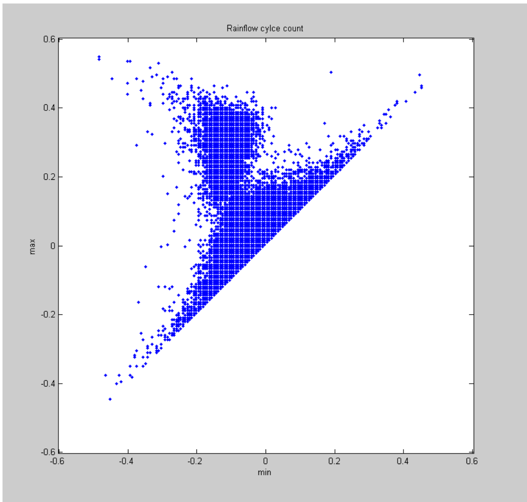

Figure 4: Rainflow Cycle Count for a data file from GM (E_01).

The stress cycle amplitudes are weighted non-linearly, because of the power law function found in Miner's rule ($N = cS^{-b}$). "The most commonly used method for calculating a reduction in test duration is the Miner-Palmgren hypothesis that uses a fatigue-based power law relationship to relate exposure time and amplitude" (MIL-STD-810 G; Method 514.6, Annex A). These cycles are accumulated to get the accumulated fatigue at that specific frequency, according to Henderson-Piersol's fatigue calculation method. At this point, since the "Q" of the resonance has been specified, as well as the "b" value (assumed to be the slope of the S-N curve for the material composing the UUT), the fatigue damage value for each frequency can be calculated. These fatigue damage values are plotted (Figure 5). The collective plot of all of these fatigue damage values is the Fatigue Damage Spectrum (Figure 6).

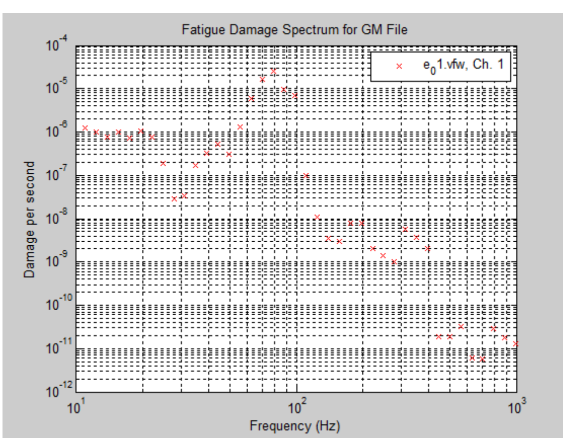

Figure 5: FDS plotted (one fatigue value per frequency bin

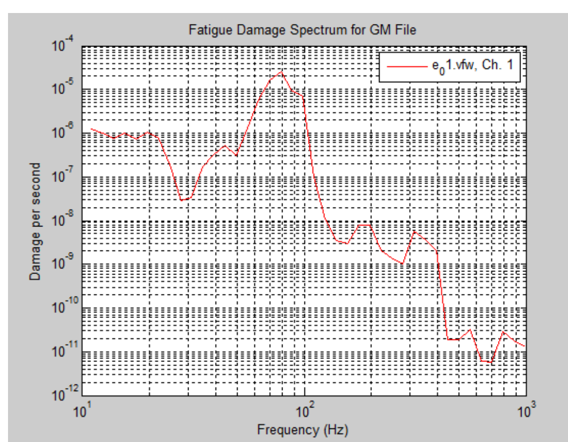

Figure 6: Collective FDS plot for GM data file (E_01)

(QA #1): Creating a Random Profile to Simulate End-Use Environment

One goal of test engineers is to create test profiles that will simulate the kind of vibrations experienced by a produce in its real-life environment. Random profiles that simulate end-use environments can be produced using the Fatigue Damage Import.

To illustrate how to create a random profile we utilize a data set from GM. If the data set is imported into the Random Fatigue Damage Import with specified m and Q values, then a PSD and break-table can be created – generating a Random profile (Figure 7).

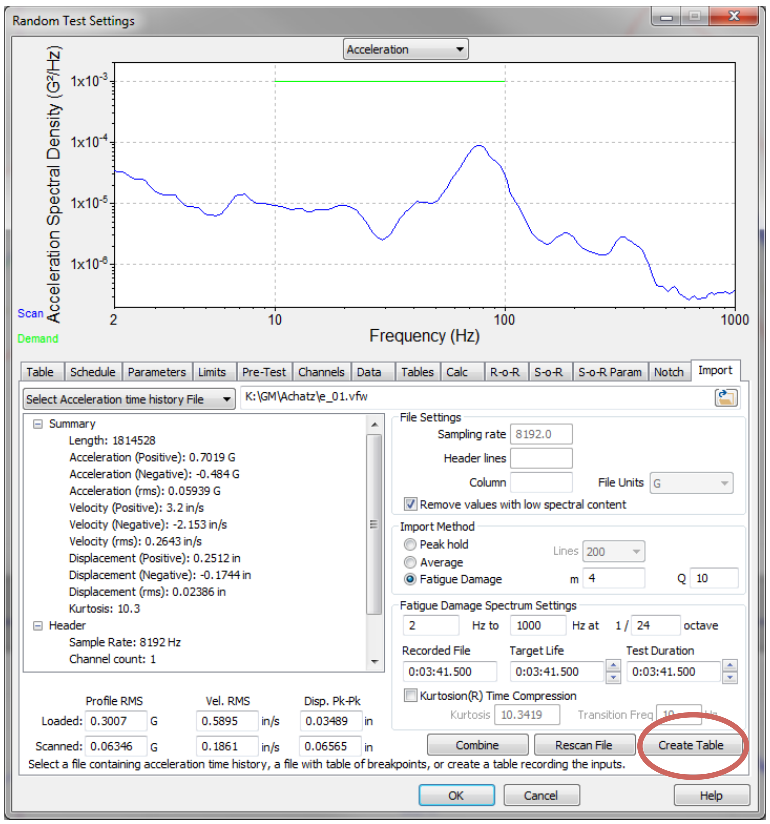

Figure 7: GM recording of a sample of real-life data imported into Fatigue Damage Import using m of 4 and Q of 10. Note the PSD and GRMS value (0.06346 G). Clicking the Create Table button will generate the break-table for this imported file – generating a Random profile.

To illustrate that this new Random profile (generated from the imported recording using the Fatigue Damage import) simulates the end-use environment, the new random test is run and recorded for the same amount of time as the original recorded file. When the Fatigue Damage Spectrum of the originally imported GM file is compared to the Fatigue Damage Spectrum of the recording of the new Random profile, it is clear that the FDS plots are the same (Figure 8 and 9). This is similarly shown on another plot as the original and simulated FDS plots of GM file D_01 are overlaid (Figure 10). These plots show that a new Random profile produced using Fatigue Damage import can simulate the end-use environment (original GM file).

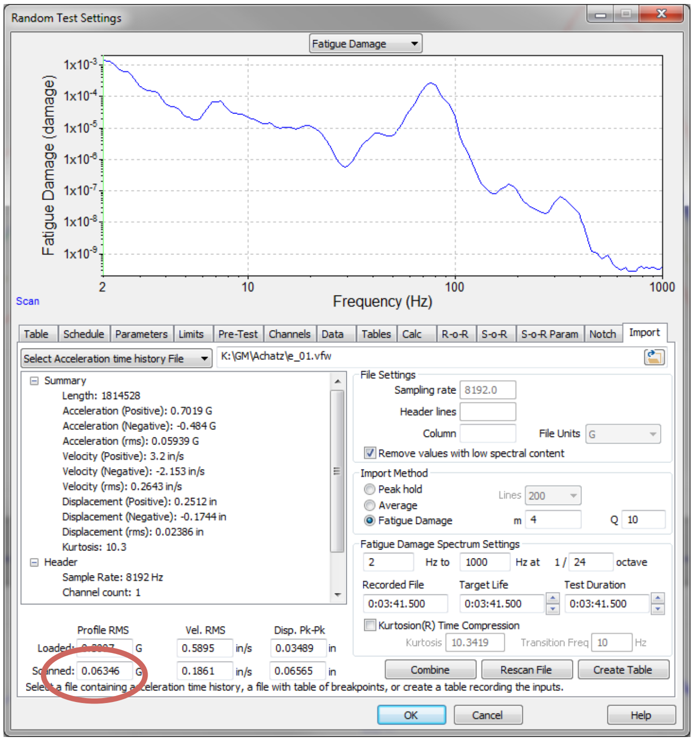

Figure 8: FDS of original GM e01 data. Note the GRMS value (0.06346 G).

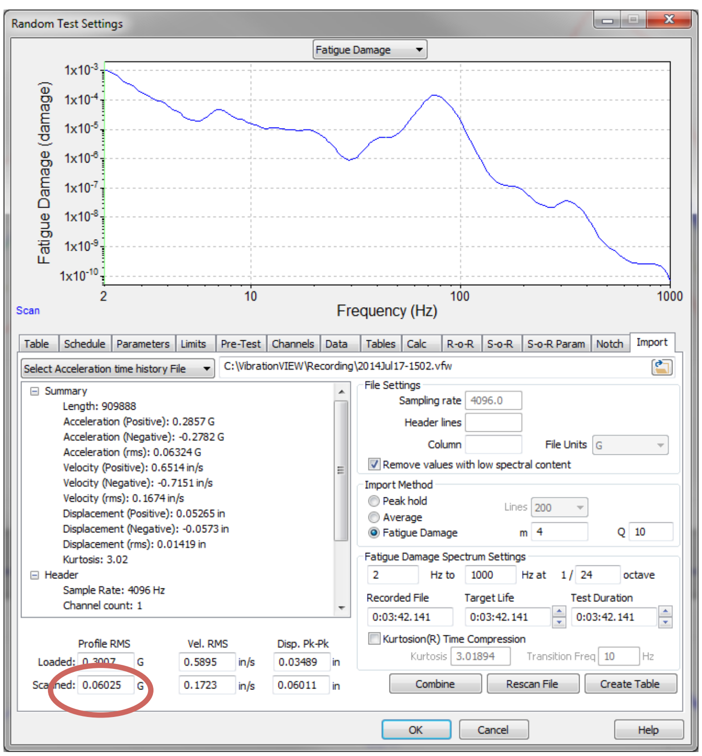

Figure 9: FDS of a recording of the Random Profile generated from an end-use environment. Note the GRMS value (0.06025 G). Also note the similarity of the FDS plot with the FDS plot of the original GM e01 data in Figure 3.

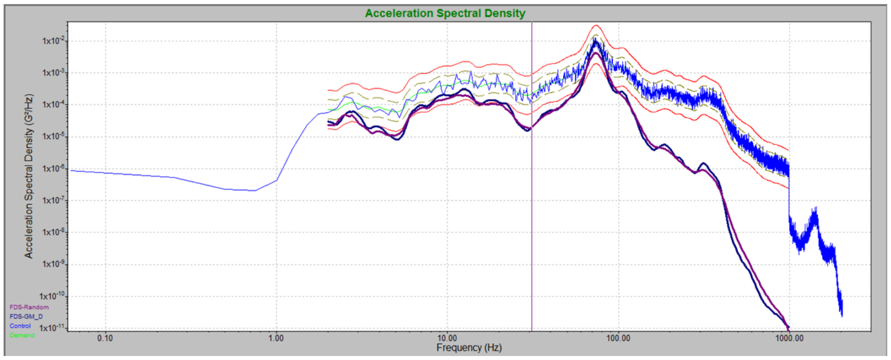

Figure 10: FDS of original GM file (D_01) and FDS of recording of the Random Profile generated from D_01. Note that the FDS plots are very similar, indicating the ability to simulate an end-use environment.

(QA #2): Combining Different Vibration Environments into One Accelerated Test

As previously demonstrated, a random profile can be generated to simulate the end-use environment of a product. However, a product often will experience vibrations in a ***variety*** of settings. ***It may be desirable to combine all of these experiences into one simple test.*** This can be done quite easily with VRC's Fatigue Damage Spectrum Import Tab. To illustrate how this can be accomplished, a set of 13 recordings from GM are used. Each one of the 13 recorded files was individually imported into the same Fatigue Damage Spectrum Import profile (Figure 11).

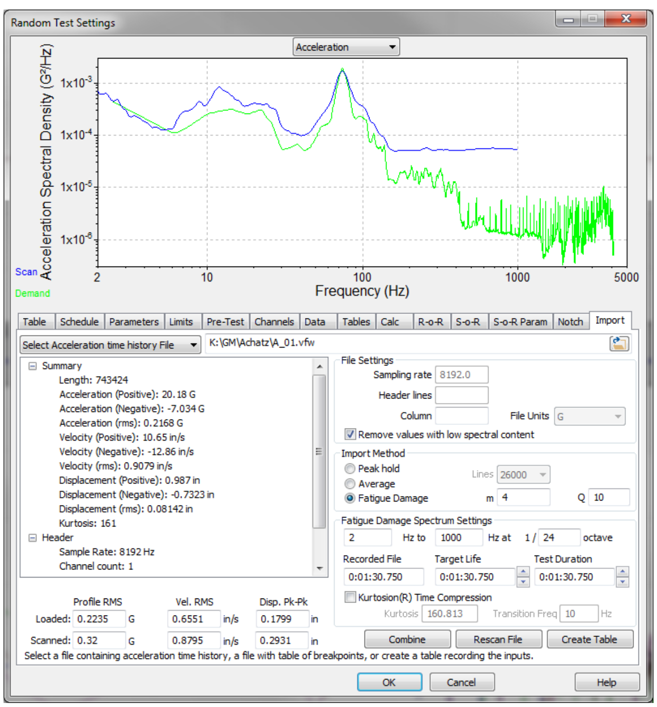

Figure 11: GM recorded file A_01 imported into a Random Test using Fatigue Damage Import with m=4 and Q=10 for a 2 Hz to 1000 Hz range. The PSD is plotted for the Fatigue Damage import (blue) and it is compared to the Average import (green) for comparison purposes.

Once all the files are imported, the "Combine" tab will indicate that all 13 files are actually loaded into the random test (Figure 12).

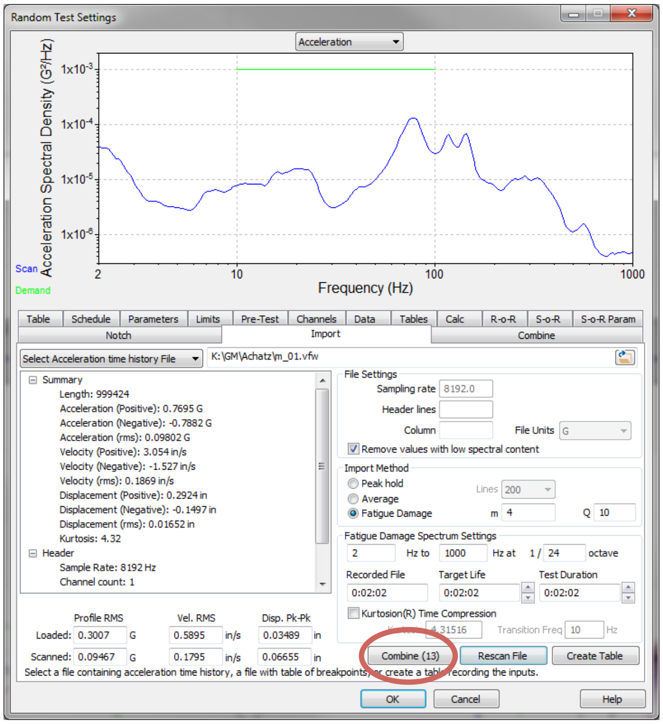

Figure 12: All 13 GM recorded files have been imported into a Random Test using Fatigue Damage Import with m=4 and Q=10 for a 2 Hz to 1000 Hz range. Notice the tab that shows all 13 files are available to be combined.

With the files loaded, they can be combined to form a single PSD spectrum and break-table. In order to do this each loaded file must be given a Target Life. The Target Life values given in this example are pre-ordained values provided from GM based on their experience of how often such vibrations occur in the field (Figure 13). The combined value of all the Target Life values is approximately 603 hours (Figure 14). GM did not want to run 603 hours of testing; therefore, a Test Duration was set for 16 hours (Figure 15). Then the "Create Table" tab was clicked and the new PSD spectrum and break-table were generated – representing the combination of the 13 tests (Figure 16).

INPUTS		
FILENAME	REPETITIONS	Dyanmic amplification, Q = 10
A	400	Spring stiffness, K = 1
B	90	SN coefficient, A = 1
C	100	SN coefficient, C = 1
D	2000	SN exponent, b = 4
E	4000	
F	16	
G	200	
H	200	
I	8	
J	1800	
K	1200	
L	1800	
M	1600	

Figure 13: GM's 13 files with specified number of repetitions needed to simulate life-dose of vibrations.

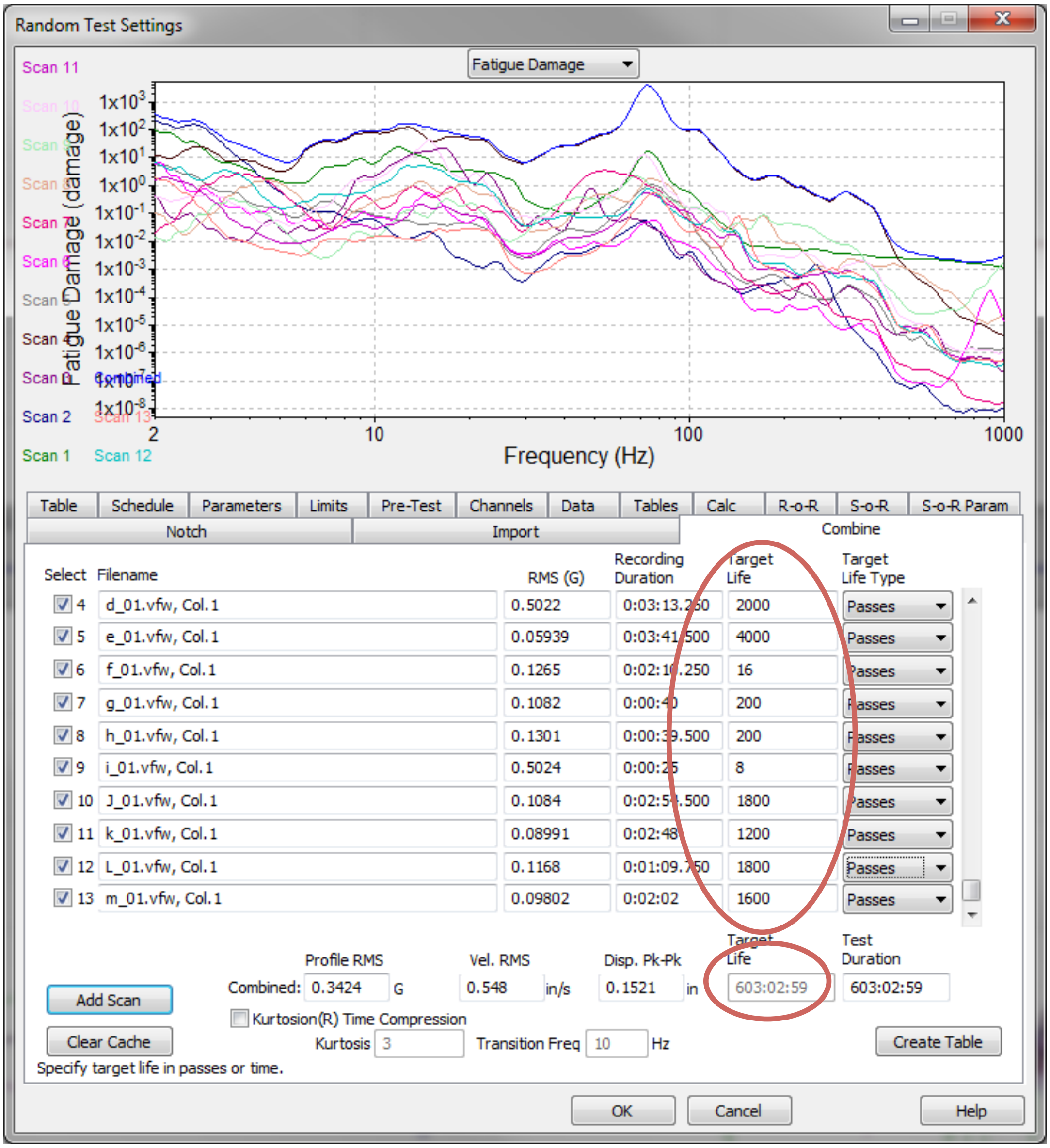

Figure 14: The Fatigue Damage Spectrum for each of the 13 GM files is adjusted for GM's Target Life for that file. Notice the sum of the Target Life values is 603 hours. The Combined RMS for 603 hours is 0.3424 G.

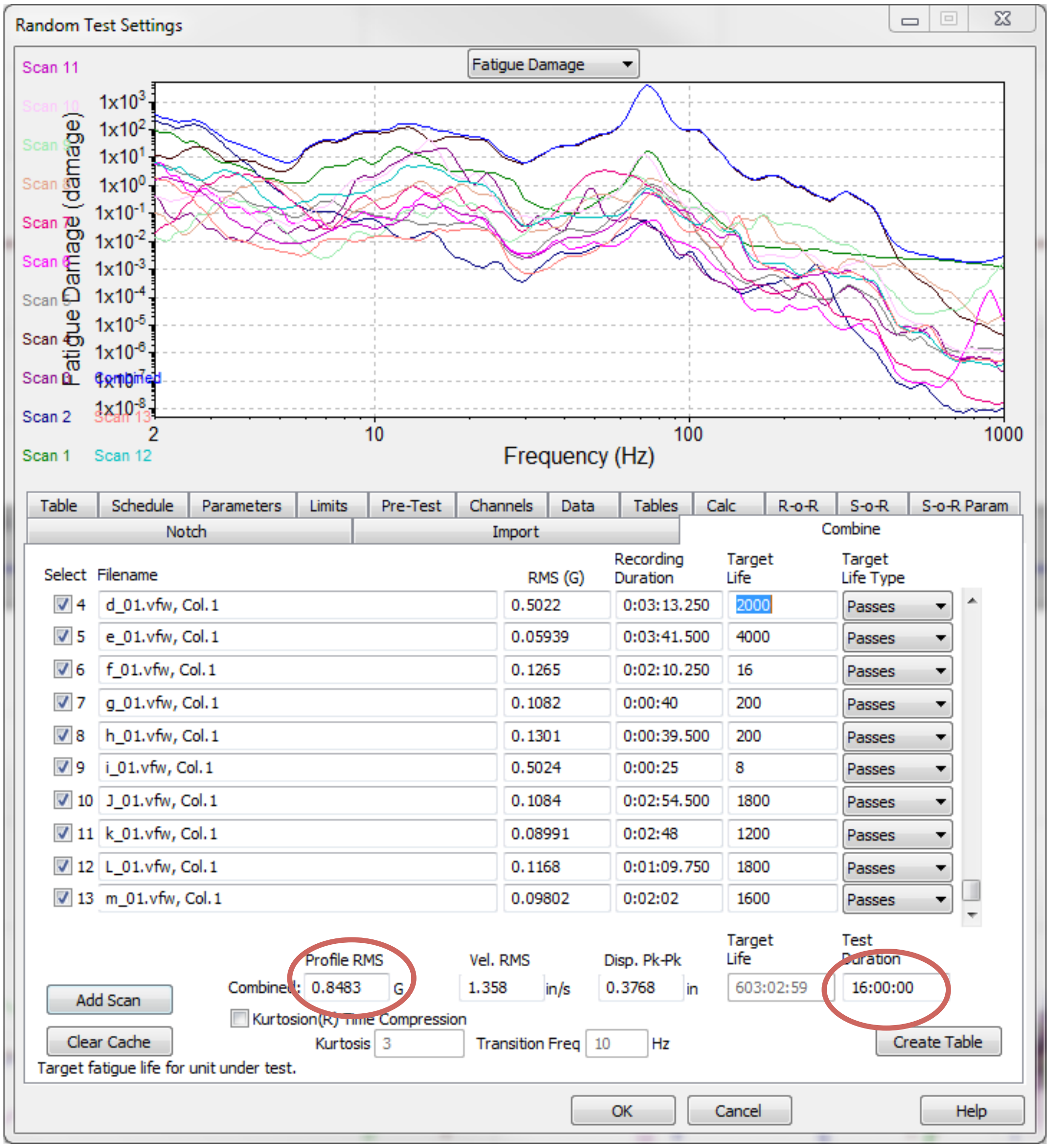

Figure 15: The Test Duration for the combined 13 files is set for 16 hrs. Note the increase in RMS to 0.8483 G.

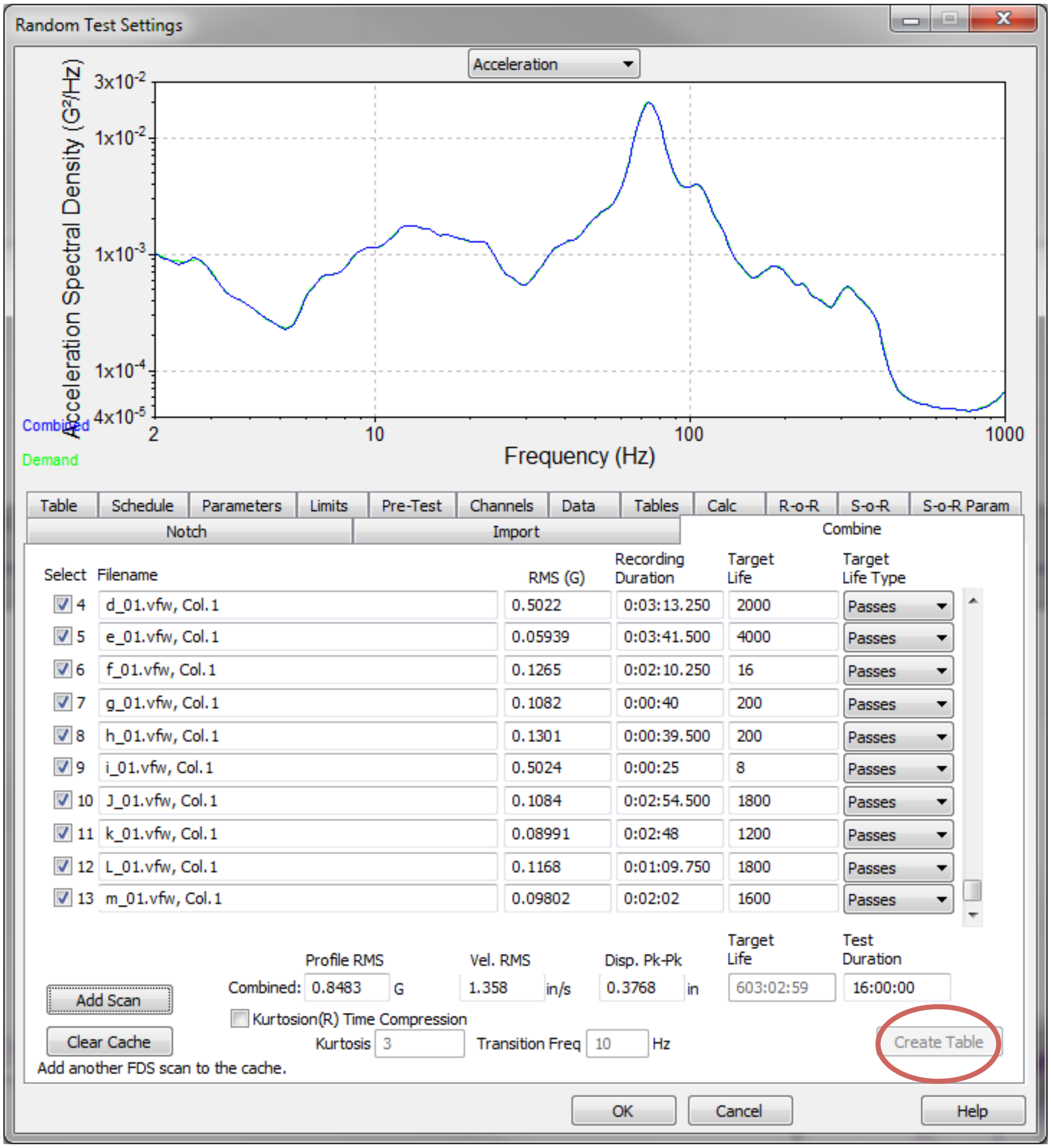

Figure 16: The 13 files have been successfully combined into one test, with one PSD and appropriate break-table.

From this example, using GM's 13 files of different end-use environments, it can be clearly seen that with VRC's new Fatigue Damage Import tab, test engineers can seamlessly combine many different test environments into one random vibration test.

(QA #3): Using FDS and Kurtosion® to Accelerate Vibration Tests

Not only do test engineers want to create random vibration tests that simulate the end-use environment, including the combination of many different end-use environments, but test engineers also want to be able to accelerate their vibration tests using by including Kurtosion® with the Fatigue Damage import.

i.) Using FDS to Accelerate a Vibration Test:

In the following example we use a GM recorded file from a particular vibration environment. The recording was approximately 3.5 minutes of data (Figure 17). This particular vibration is quite common so GM chose a typical test life for this vibration of 246 hours.

To accelerate the test, the test engineer needs to adjust the test duration to a reasonable value. In this example, the test duration was set for approximately 6.5 hours (Figure 18). Decreasing the test duration results in a higher GRMS value for the test. This will bring about a life-time dose of fatigue for that particular test more quickly than if the test ran for the 246 hours.

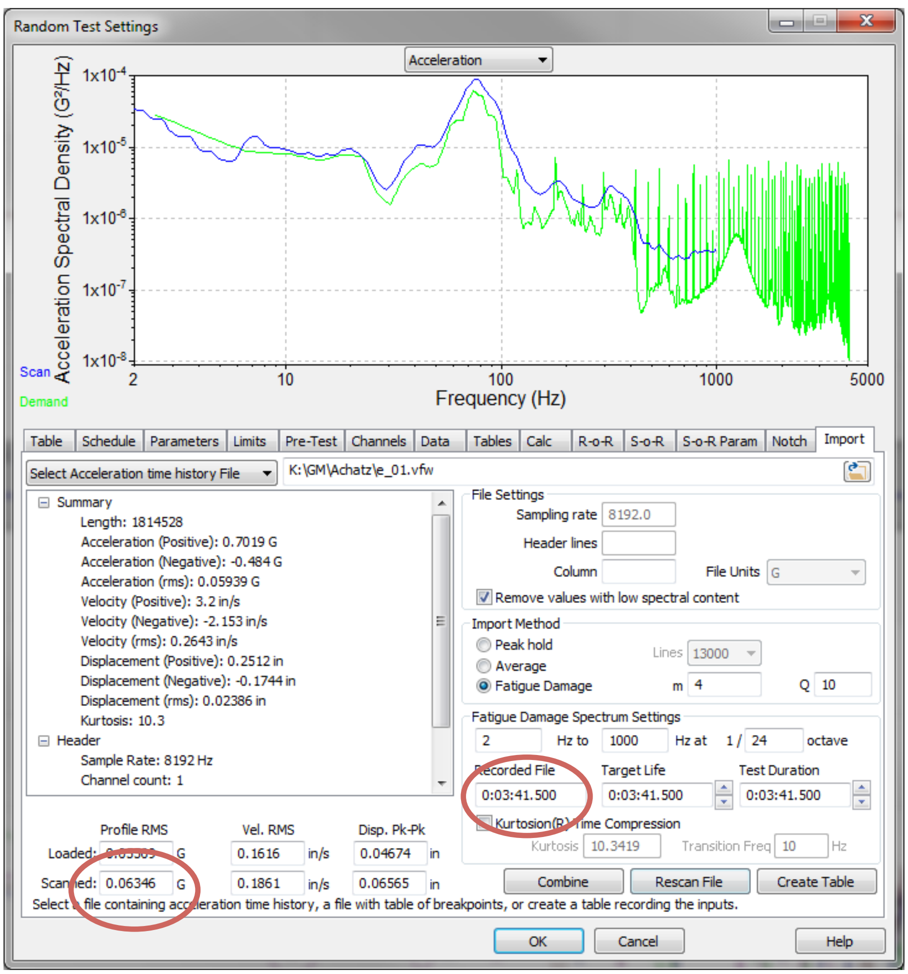

Figure 17: The PSD and GRMS of the imported GM E_01 file using the FDS import.

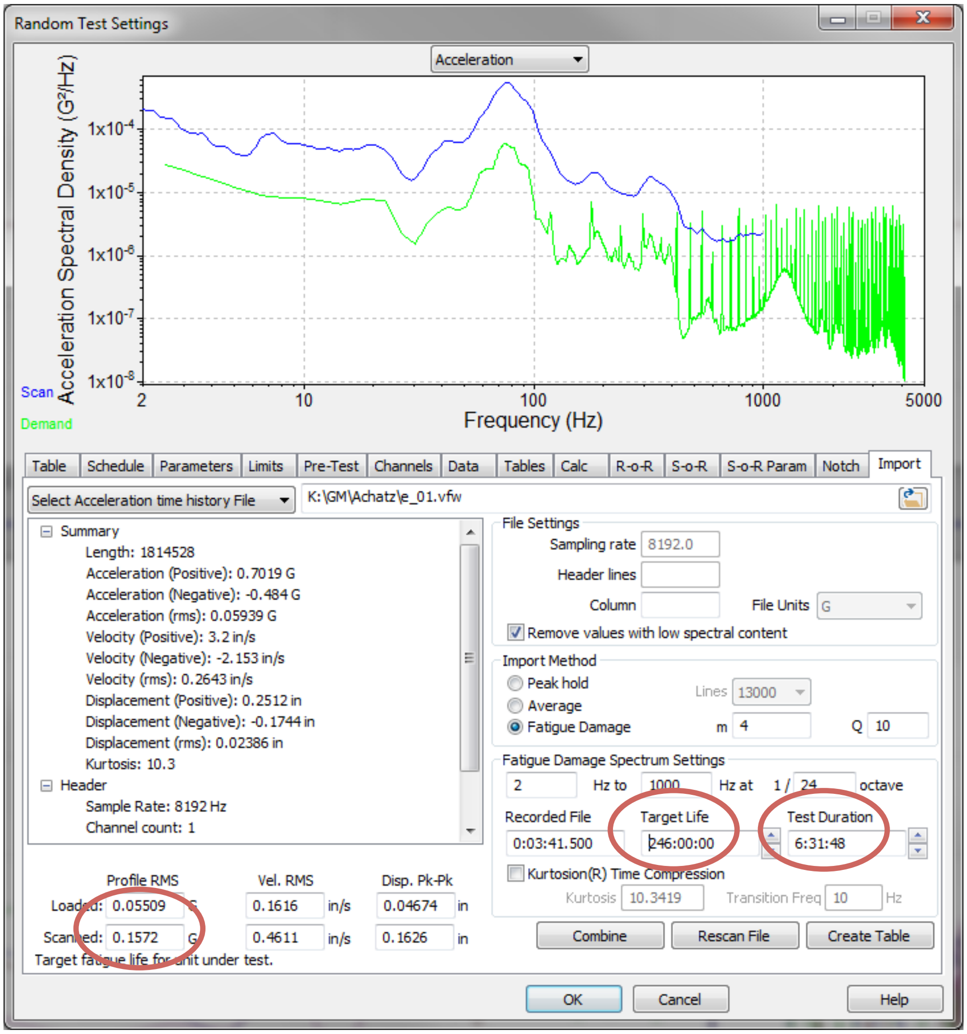

Figure 18: The PSD and GRMS of the imported GM E_01 file using the FDS import, when Target Life is set for 246 hrs and the Test Duration is set for approximately 6.5 hrs. Note how the GRMS value increased.

ii.) Using Kurtosion® with FDS to Accelerate a Vibration Test:

The original Fatigue Damage Import of a file assumes a Gaussian distribution of the data. This is because the Henderson-Piersol method of computing Fatigue converts the FDS back into a PSD using a Gaussian distribution. By doing so, some of the large peaks that cause fatigue damage are removed from the test. Kurtosion® restores those large peaks to the test, making the distribution of the data to be non-Gaussian. The presence of the large peaks will cause the fatigue damage to accumulate more quickly. The total life-dose of fatigue is not increased (Figures 19)! The total life-dose of fatigue is simply accumulated more quickly.

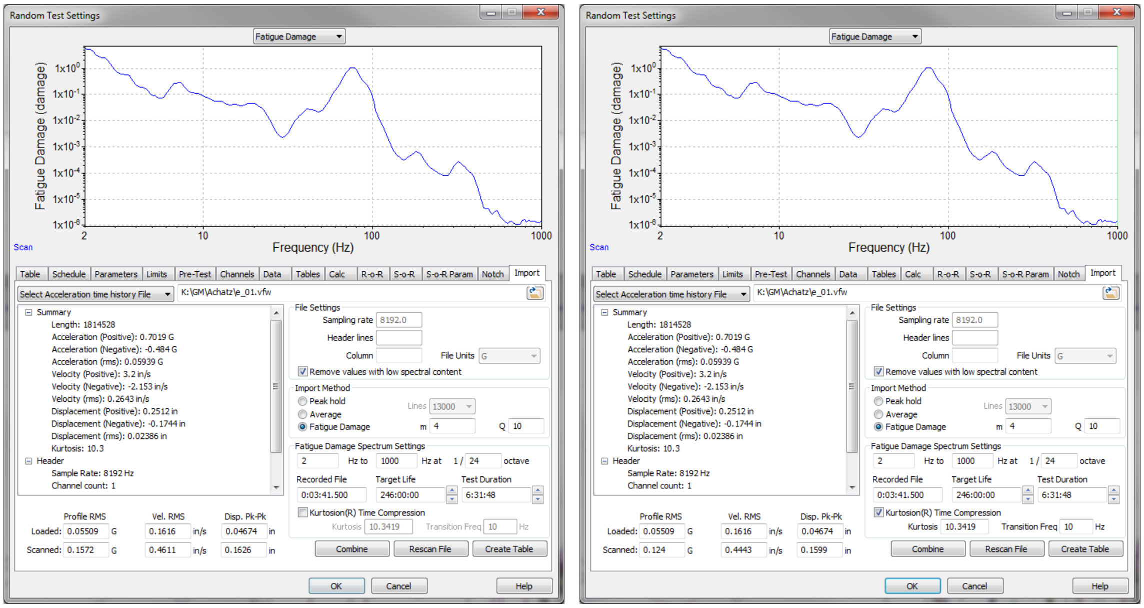

Figure 19: The PSD and GRMS of the imported GM E_01 file using the FDS import, when Target Life is set for 246 hrs and the Test Duration is set for approximately 6.5 hrs. The figure on the left is FDS import without Kurtosion®. The figure on the right is the FDS with Kurtosion®. Note how the FDS plots are identical – indicating that the total life-dose of fatigue remains the same whether or not Kurtosion® is enabled. Note also, that the GRMS value actually decreased with Kurtosion® enabled.

CONCLUSION:

Test engineers want to test a sample product to simulate a life-dose of fatigue. But to do so, using traditional methods can be long and tedious. But with Vibration Research Corporation's Fatigue Damage Import for Random vibration testing, the life-dose of fatigue for a product can be accurately simulated and rapidly accelerated.

This paper has shown that a ***realistic simulation of an original waveform can be successfully generated*** with random vibration's Fatigue Damage Import feature.

In addition, the ***multiple environments that a product experiences on the field can be combined*** into a single fatigue damage test. In this way, the life-dose of fatigue of all possible environments can be combined and synthesized to produce a single random vibration test profile.

Finally, using the Fatigue Damage Import feature the life-dose of fatigue for a UUT can be achieved in a faster test time. In other words, ***random vibration tests can be accelerated using the Fatigue Damage Import***. In addition, since the regular Fatigue Damage Import produces a Gaussian random vibration test, Kurtosion® can be added to the test to make a test have a non-Gaussian distribution. Adding Kurtosion® to a test does not increase the total fatigue damage experienced by the UUT, but simply causes the fatigue damage to accumulate more rapidly.

The Fatigue Damage Import feature of a random vibration test is a valid and innovative method to achieve a life-dose of fatigue test and to accelerate random vibration tests.

References

[1]Henderson, George R., and Piersol, Allan G., "Fatigue Damage Related Descriptor for Random Vibration Test Environments," *Sound & Vibration*, p. 21, October 1995.

[2]VanBaren, John, and VanBaren, Philip VanBaren, "The Fatigue Damage Spectrum and Kurtosis Control," *Sound & Vibration*, p. 10, October 2012.