Proceedings of the 18th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2016
September 18-23, 2016, Kobe, Japan

Paper No. 1002

Accelerations Acting on a Nuclear Transport Package During a Routine Transport

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Abstract

According to the IAEA Regulations (SSR-6[i]) packages shall be capable of withstanding the effects of accelerations arising from routine conditions of transport. We present the results of a measurement campaign (road and rail transport) with a package in the lower mass range of about 10 tons and propose covering acceleration factors and load collectives for future safety analysis.

Introduction

The IAEA Advisory Guide (SSG-26[ii]) Appendix IV gives an indication of the magnitude of the acceleration factors which might be used in the general stress analysis. However, SSG-26 also states that the acceleration factors recommended by the competent authorities may differ from one country to another. Thus, the package designer has to justify the validity of the acceleration factors to the relevant competent authority. In addition, the package designer should also account for the effects of cyclic loads in order to prevent the package from failure due to fatigue. The load collective in terms of acceleration values and number of cycles used in fatigue analysis should be agreed with the relevant competent authorities, too.

The GNS product portfolio comprises packages for intermediate and high level waste (i. e. MOSAIK®, CASTOR®) with a mass between approx. 10 and 150 tons. The applied acceleration factors for routine conditions of road and rail transports used in the general stress analysis are conservatively in accordance with national and international regulations (CTU Guideline[iii], UIC Guideline[iv], and VDI[v]). An adequate justification only based on these regulations is difficult because of the poor information situation regarding the scope and derivation of these values. Furthermore, national or international regulations provide only limited information on load collectives.

Measurement campaigns are necessary to facilitate the justification about the applied acceleration factors and load collectives. Looking into available results from published measurement campaigns of nuclear transport packages, there is a lack of experimental data. On that account, GNS has already performed a measurement campaign (road and rail transport) in 2005 with an empty CASTOR® package which has a mass of approx. 98 tons. To determine the level of acceleration (maximum loads and load collective) which is experienced by packages for radioactive material in the lower mass range of about 10 tons during routine transport and to confirm the assumptions made in the safety analysis, GNS has performed additional measurement campaigns in 2014/2015 with an empty CASTOR® package (road transport) and an empty MOSAIK® package (rail transport).

This paper focusses on the results of the recent measurement campaign. GNS has analyzed the time signal in the frequency and amplitude domain (FFT- and PSD-analysis) to receive proper acceleration factors. To obtain accurate load collectives the rainflow counting method has been used. The results we obtain mostly are in accordance with national and international regulations. For future safety analysis of packages for radioactive material in the lower mass range of about 10 tons we propose covering acceleration factors and load collectives based on the measurement.

The Measurement Campaign

The first part of the measurement campaign by GNS was a road transport with an empty CASTOR® package with a mass of approx. 17 tons. It was performed in September 2014. The empty CASTOR® package was arranged in a 20' container loaded onto a semi-trailer (see Figure 1). For the measurement campaign the empty CASTOR® package was transported by road including inner-city traffic, roundabouts, bridges, federal roads and motorways so that the distance profile represented typical road excitations during routine road transport (see Figure 2). The overall distance was 236 km; the maximum speed was 85 km/h. 3 hours 36 minutes of data were recorded.

Figure 1: CASTOR® package in 20' container

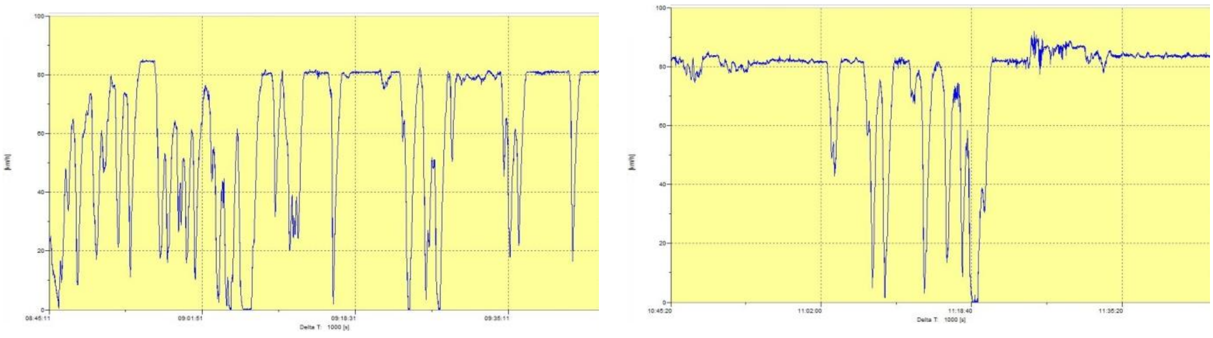

Figure 2: Velocity profiles for two sections of the driving route

The second part of the measurement campaign was a rail transport with an empty MOSAIK® package with a mass of approx. 8 tons. It was performed in October 2015. The empty MOSAIK® package was arranged in a 20’ container loaded onto a wagon used in combined transport trains with containers (see Figure 3). For the measurement campaign the empty MOSAIK® package was transported in a combined transport train on a route which not only included a wide range of frequently used line sections for freight transports but also several shunting stations. Additionally, hump and fly shunting was prohibited for a part of the line. Therefore, the distance profile represented typical rail excitations during routine rail transport (see Figure 4). The overall distance was 887 km; the maximum speed was 97 km/h. 115 hours of data were recorded.

Figure 3: 20' container with MOSAIK® package

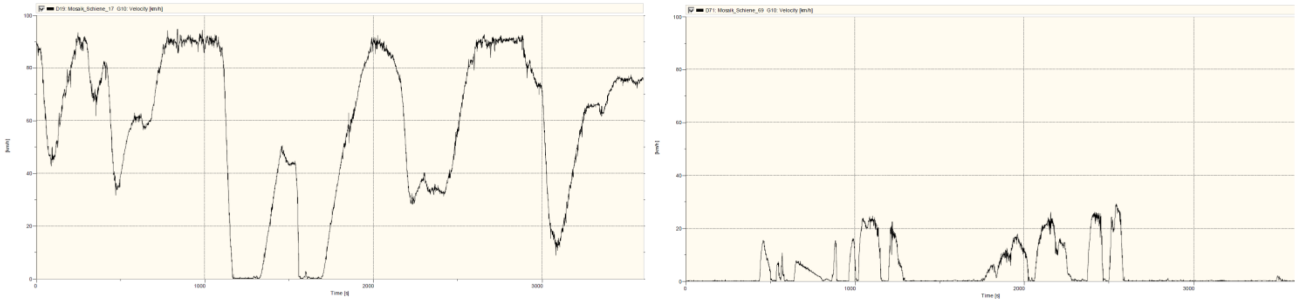

Figure 4: Velocity profiles for two line sections: transit (left) and shunting (right)

Data Acquisition

For the measurement campaign, package and container were equipped with accelerometers. This was done in the same way for both the road and the rail transport. A total of 21 acceleration channels were recorded. The accelerometers were placed as close as possible to the center of gravity of the package: the top and bottom impact limiter, on the cask itself and the container floor in front, sideways and behind the package. The accelerometers used were high precision uni-axial sensors type 622B01 produced by IMI-Sensors with a measuring range of ± 50 g and a frequency range of up to 10 kHz. Furthermore, each sensor was calibrated individually with a calibration accuracy of ± 2 % and a transverse sensitivity of ± 2.1 %. To ensure an exact alignment in all three spatial dimensions, the accelerometers were mounted on stiff adapters made of aluminum. Additionally, a GPS signal was recorded so that location and velocity were logged, too.

Figure 5: CASTOR® package (left) and accelerometers on the cask (right)

The data acquisition system (DAQ) used was a LMS SCADAS Recorder and V8-II analogue to digital transducer modules with up to 102.4 kHz sampling frequency and alias free bandwidth of 46 kHz (anti-alias filter). The sampling frequency was set to 5 kHz. According to the Nyquist-Shannon Theorem, the digital signal with a certain sampling rate only contains unambiguous information about frequencies below the so-called Nyquist frequency that is half of the sampling frequency[vi]. With respect to a sampling frequency of 5 kHz and an oversampling factor of 2.5, the available frequency range is up to 2 kHz. The DAQ itself has an accuracy of ± 0.2 % and a residual offset of ± 0.1 %, so that taking the acceleration sensors' accuracy into account the overall accuracy amounts to less than ± 3 %.

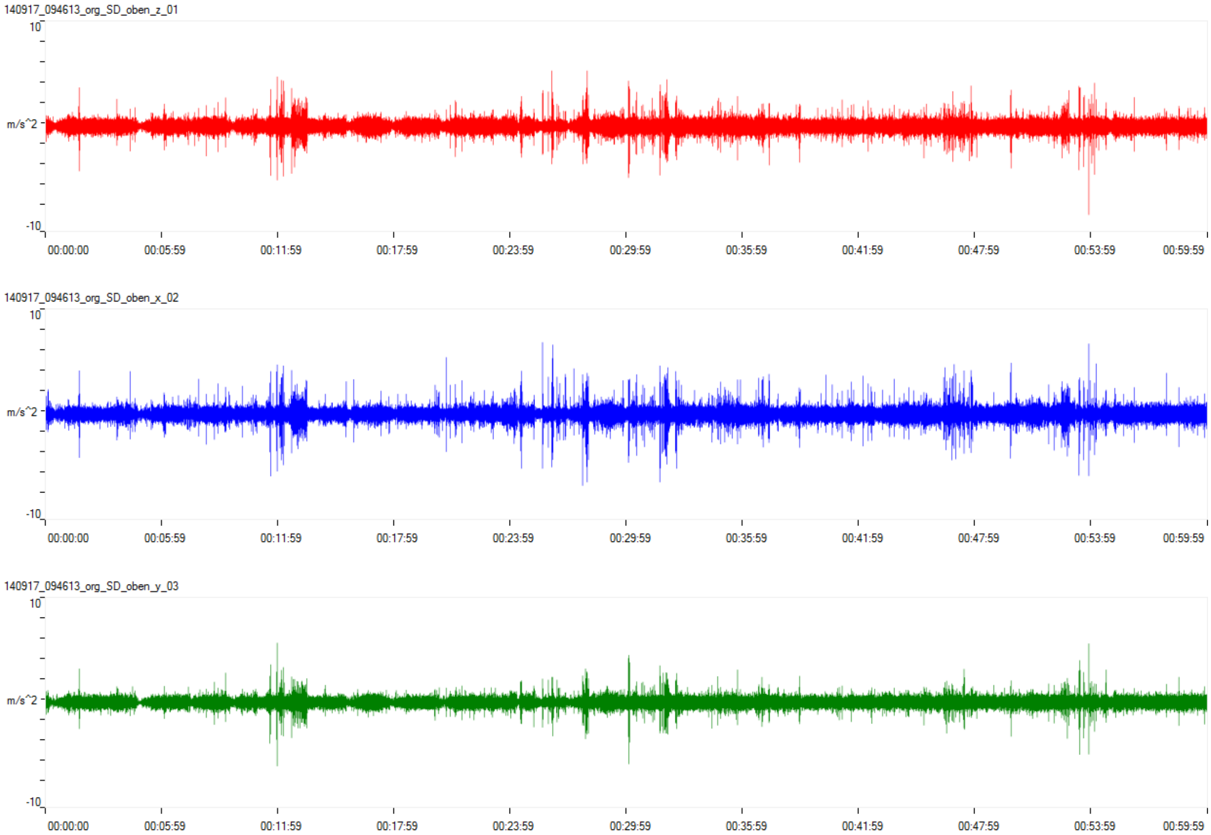

Figure 6: Example of acceleration time signal (top impact limiter), red (x), blue (y), green (z)

Data analysis

Data analysis was done with Matlab[vii] and the WAFO-toolbox for Matlab.[viii] Regarding loads imparted to the package during routine transport a distinction is made between quasi-static loads and cyclic loads[ii].

For a general stress analysis, only quasi-static loads have to be considered. They are generally slowly applied and therefore appear in the lower frequency range. The IAEA Advisory Guide (SSG-26[ii])

Appendix IV contains instructions on how to filter time signals as shown in Figure 6 to obtain quasi-static loads, more precisely, on how to select a suitable cut-off frequency considering the mass of the package. According to the IAEA Advisory Guide the cut-off frequency for a package with a mass of 100 tons should be of the order of 10 to 20 Hz. For a smaller package with a mass m the cut-off frequency should be adjusted by multiplying by a factor of $(100/m)^{1/3}$. Thus, the relevant frequency range should be between 18 and 36 Hz for a CASTOR® package with a mass of approx. 17 tons and between 23 and 46 Hz for a MOSAIK® package with a mass of approx. 8 tons. GNS has performed an extensive analysis of the time signal in the frequency domain to obtain a suitable cut-off frequency and with that quasi-static loads (acceleration factors). More specifically, Fourier transformation and power spectral density analyses (PSD) were applied for this purpose.

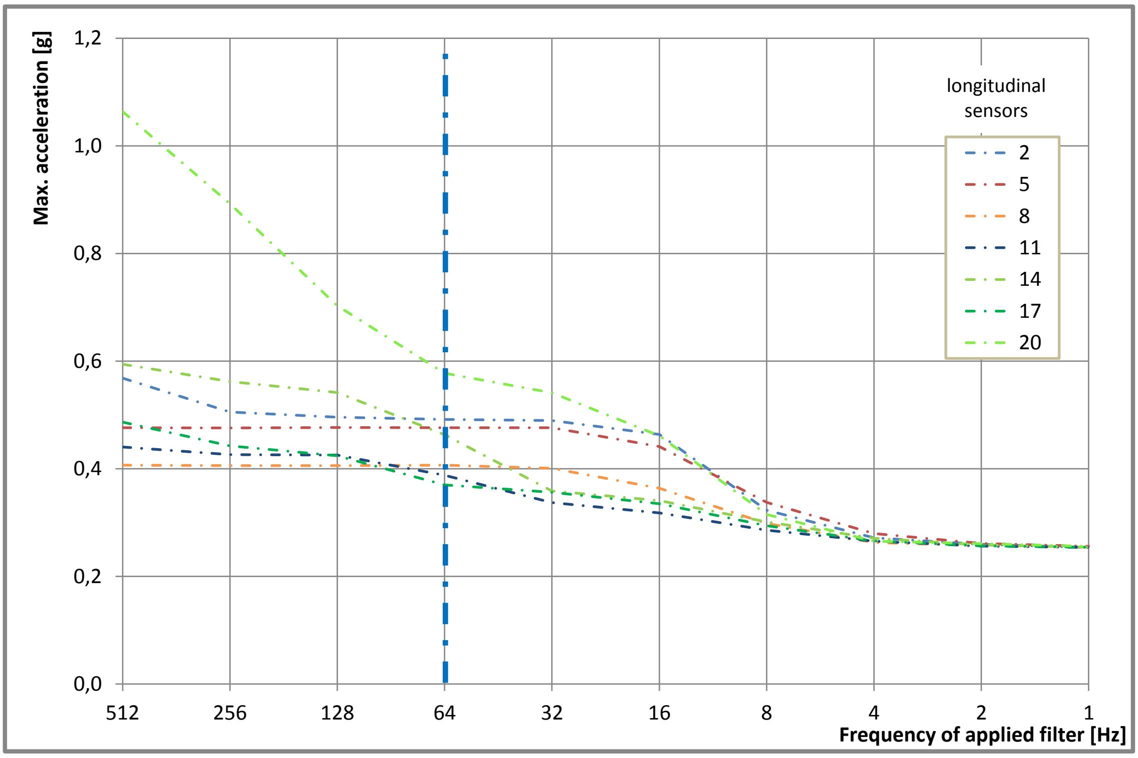

Figure 7: Maximum acceleration factors at different filter frequencies on the road
(Lengthways, sensor 5 and 8: cask, 2 and 11: container, 20: impact limiter)

Comparing the maximum acceleration values measured at the cask (see Figure 7, sensors 5 and 8) for different filter frequencies during the road transport we find identical values between 512 Hz and 64 Hz and a decrease below 64 Hz. An analogue behavior can be observed in the other directions and also for the rail transport. Therefore, the frequency of 64 Hz is suitable for the determination of quasi-static loads covering both road and rail transport and considering all relevant impacts. Furthermore, it is well above the relevant frequency range calculated from the IAEA Advisory Guide.

Concerning fatigue strength, cyclic loads occurring in the higher frequency range have to be considered, too. We set the frequency to 128 Hz which is in the range of a typical damage frequency. Commonly, a frequency of 100 Hz is used for the determination of cyclic loads[ix]. The filtering is done by a 2nd order Butterworth filter resulting in a decrease of energy in the measured signal of less than 5%. This is moderat and ensures that high-frequency accelerations do not manipulate the resulting load collectives.

To obtain proper load collectives the so called rainflow counting method is used. The rainflow counting method is generally accepted as being the best cycle counting procedure to date. It has become a de facto industrial standard[vi] and is required as cycle counting procedure by FKM guideline[x] when defining load collectives and doing fatigue analysis.

The idea behind the rainflow cycles is to count hysteresis loops.[vi] In a first step the amplitudes of the cycles are classified and then counted per class. The result can be depicted in form of a rainflow-matrix, an example is given in Figure 8.

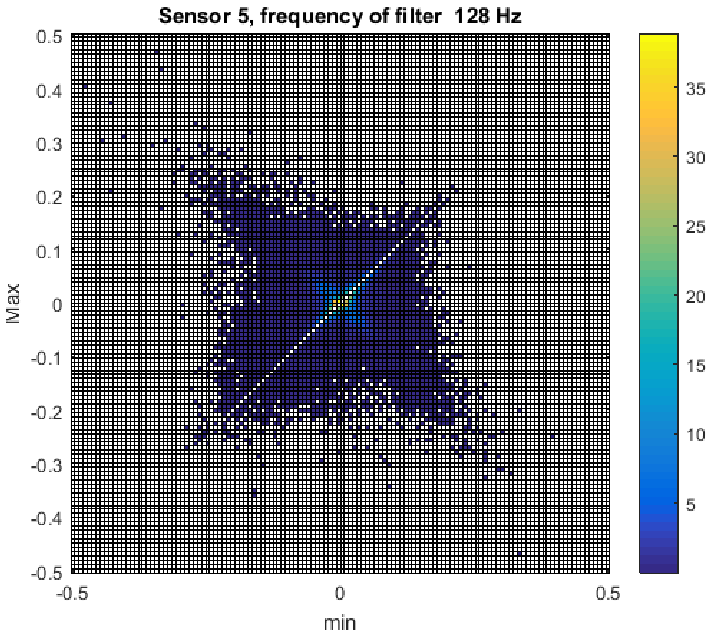

Figure 8: **Rainflow-matrix counting the measured accelerations on the cask (CASTOR, road transport)**

The rainflow matrix allows the derivation of load collectives based on the assumption of a linear correlation between the strains and the measured accelerations. It is possible to define a so called pseudo damage which is a simple measure describing the severity of the damage and very helpful for comparisons. It is based on the concepts of the Wöhler curve and the Palmgren-Miner rule.[vi]

With S_i the amplitude of cycle i and β the damage exponent (slope of the Wöhler curve), the pseudo damage is defined as

$$d = \sum_i S_i^\beta$$

and the sum runs over all counted cycles.[vi] The concept is independent of a special component, but several slopes of the Wöhler curve are considered. In this case, the damage exponents for welded and non-welded components as well as for screws according to the regulations of FKM and VDI[v,x] are considered. After calculating the pseudo damage from the rainflow matrix of a specific set of data (e. g. cask, road transport) a load collective is fitted to the set of data by minimizing the difference of the pseudo damage calculated from the rainflow matrix of the data and from the load collective respectively. This is feasible under the condition that all cycles contribute to the damage accumulation (Palmgren-Miner rule). The result is a load collective that resembles the measured damage.

Results

Acceleration factors for general stress analysis

Using the methods described before, we identified the accelerations factors for the road transport given in Table 1. The values shown are maximum values for a filter frequency of 64 Hz and result from the signals of the accelerometers at the cask. For comparison, in Table 1 we also give the values specified in the regulations[iii].

Table 1: Acceleration factors during road transport

	lengthways	crosswise	vertical
Regulations	1 g	0.5 g	---
GNS measurement	**0.5 g**	**0.35 g**	**0.4 g**

For the rail transport we distinguish between the range of transit or shunting and furthermore between the range with or without the prohibition of hump and fly shunting. The values given in the regulations[iv] are the same in all these cases, therefore, we did not expect major differences. The given values in Table 2 are maximum values for a filter frequency of 64 Hz and result from the signals of the accelerometers at the cask. For comparison, in Table 2 we also give the values specified in the regulations.

Table 2: Acceleration factors during rail transport

	lengthways	crosswise	vertical
Regulations	1 g	0.5 g	0.3 g
GNS measurement			
transit, without prohibition	0.3 g	**0.2 g**	**0.75 g**
transit, with prohibition	0.2 g	**0.2 g**	0.7 g
shunting, without prohibition	**0.75 g**	0.1 g	0.4 g
shunting, with prohibition	0.5 g	0.15 g	0.25 g

The relevant impact during transit occurs in the vertical direction whereas during shunting the lengthways direction is relevant. This reflects the routine transport conditions and is to be expected. Note the acceleration in the vertical direction during transit which is well above the value given in the regulations.

To summarize, the frequency based filtered time signals of both road and rail transport indicate that the quasi-static loads occurring during the measurement campaign are below 1 g in each direction. This value also covers the accelerations given in the regulations. We therefore propose to use an acceleration factor of 1 g in each direction for future safety analysis.

Load collectives for fatigue analysis

We calculated the pseudo damages from the rainflow matrices of the measurement data using a filter frequency of 128 Hz. As before we used the data collected by the sensors at the trunnions for the analysis of the road transport and at the cask for the rail transport, respectively. For the analysis of the rail transport the range of the shunting is not considered. Strong impacts and high accelerations occur during shunting, however, the frequency is low and therefore the contribution to the damage is neglectable. The calculation of the pseudo damage uses slope 3 of the Wöhler curve, the results are given in Table 3.

Table 3: Measured pseudo damages

	ROAD	RAIL
Direction	Pseudo damage [1/km]	Pseudo damage [1/km]
lengthways	0.04	0.17
crosswise	0.01	0.01
vertical	0.03	0.20

Considering these pseudo damages we calculate load collectives in the way described in the section before. We propose to use the load collectives given in Table 4 for future safety analysis.

Table 4: Load collectives

ROAD	Load collective		
Direction	Acceleration	Frequency [1/km]	Pseudo damage [1/km]
lengthways	0.4 g	0.650	0.04
crosswise	0.4 g	0.138	0.01
vertical	0.3 g	1.092	0.03

RAIL	Load collective		
Direction	Acceleration	Frequency [1/km]	Pseudo damage [1/km]
lengthways	0.4 g	2.611	0.17
crosswise	0.4 g	0.191	0.01
vertical	0.3 g	19.814	0.54

Conclusion

By performance of a series of acceleration measurements and appropriate data analysis we find a maximum acceleration factor of 0.75 g. To cover all relevant regulations, we propose to use a factor of 1 g in each direction for future safety analysis. By using the rainflow counting method we define load collectives for fatigue stress analysis based on the measurement data. These collectives are very accurate as the method allows a precise counting of the acceleration cycles. The results complete the data basis for packages in the lower mass range and facilitate the justification about the applied acceleration factors and load collectives.

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