

## Rail Transportation of Wind Turbine Main Shaft Assembly

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Many Wind Turbines have a main shaft assembly, consisting of the main shaft, rolling bearing, and a housing attached, Figure 1. The principal dimensions of the main shaft assembly are given by the general drawing of Figure 2, and a cut away view of the rolling bearing is shown in Figure 3.

A number of these main shaft assemblies arrive by ship to the United States, and they are sent to their destination in railroad cars. As is well known, rail transport is the usual means of transportation for heavy and bulky cargo, but in this case some concerns arise on the damage that rail transport may have inflicted to the rolling bearing. According to certain criteria, such damage does not occur during truck transportation.

The purpose of this article is to analyze the shocks involved in truck and rail transportation in the United States, and compare them with the shock strength of the main shaft rolling bearings, in order to clarify the real possibilities of damage during the above mentioned transportation.

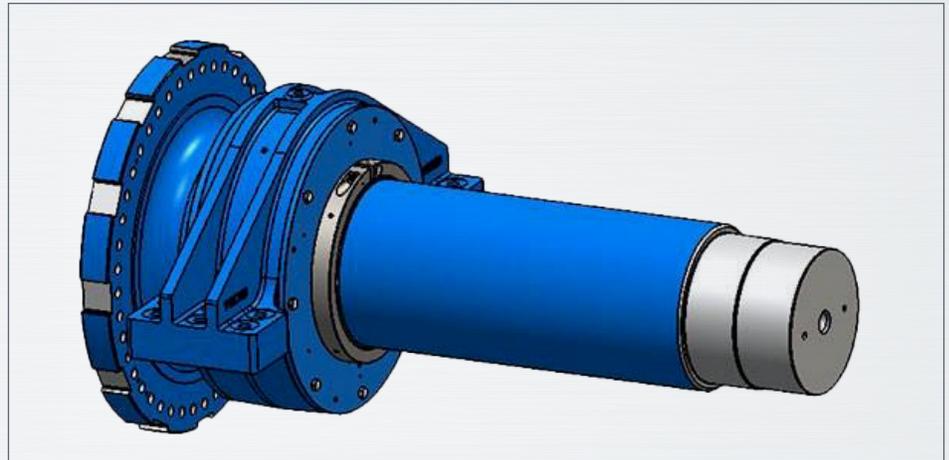


Figure 1. Typical wind turbine main shaft assembly

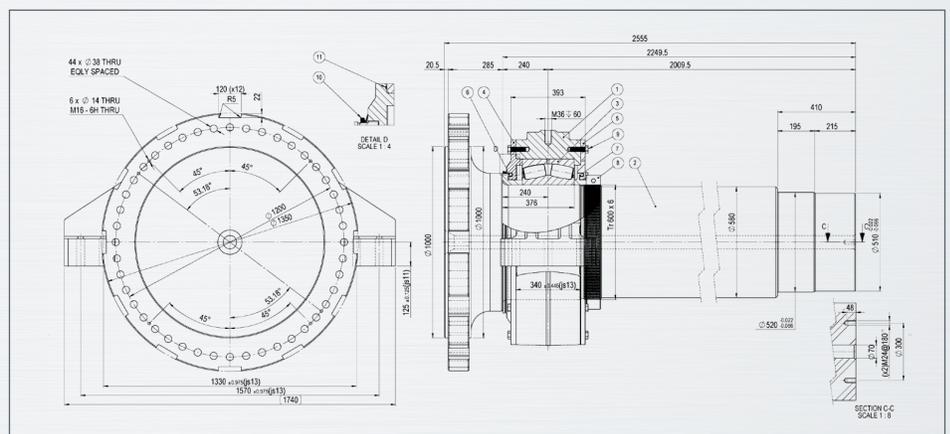


Figure 2. General drawing of main shaft assembly

### Vibration and Shocks During Truck and Rail Transportation

The Sandia National Laboratories (SNL), managed and operated by the National Technology and Engineering Solutions of Sandia, is one of three United States National Nuclear Security Administration (U.S.NRC) research and development laboratories.

Located in Albuquerque, New Mexico, and Livermore, California, the SNL has been involved since 1970 in the study of the shock and vibration environments of truck and rail transportation of nuclear fuel shipping casks, with the aim of assuring its safety.

The dynamic environments of cargo under land transportation are a mixture of vibration, occasional shock superimposed on the vibration and isolated shock which occurs in single events.

Vibration is the excitation which occurs whenever the carrier is in motion and is produced when the carrier suspension system and carrier frame members react to surface irregularities in highways or railroads under the effects of the carrier motive system. Conventionally, the acceleration of the carrier due to vibration is limited to a maximum of 2 g, and usually envelopes 99 % of all acceleration measurements.

Superimposed shock produces a cargo motion response stronger than 2 g, and envelopes about 1 % of all acceleration measurements. These shocks consist of decaying transient pulses superposed and intermixed with vibration. For trucks, superimposed shocks appear when crossing bridge approaches, railroad tracks, and by striking potholes. For rail cars, superimposed shocks are produced by run-in, run-out and by crossing

bridges, switches, and other track intersections.

Isolated shocks occur during car coupling operations. These shocks are significantly more severe than the superimposed ones; however,

they occur only during train formation, which is a less frequent event. In trucks moving normally on highways, no similar isolated strong shocks happen.

The work of J.T. Foley and M.B. Gens, published in 1971, opened this research front [1], including data obtained from sources back since 1960. Afterwards, a group of reports by teams headed by C.F. Magnuson were published during the period 1977/1982 [2, 3, 4, 5, 6, 7].

In these early works, the data collection was not continuous and covered only some characteristic events and operating parameters. Besides, several results about shock caused by rail coupling were obtained from simulations with mathematical models.

Over-the-road truck tests on superimposed shock were initially developed with cargo masses essentially from no-load to 14 000 kg (30 000 lb). Later, casks of 20 000 kg

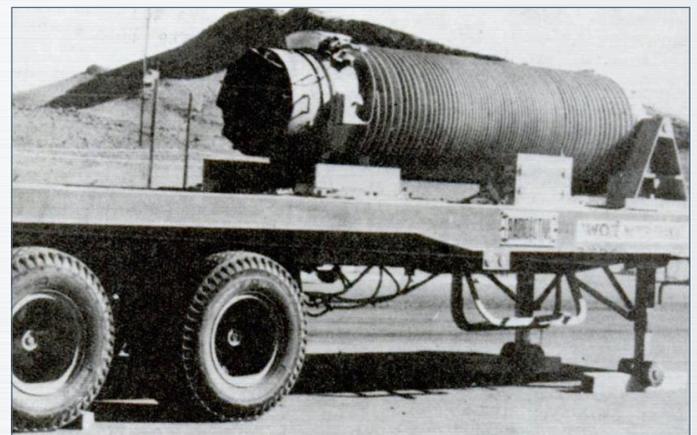
(44 000 lb) and 25 000 kg (56 000 lb) were used. An image of the 11 m (35 foot) tandem axle trailer [7] for the 20 000 kg cask is shown in Figure 4.

Superimposed shock tests in rail cars were developed with a cask of 45 000 kg (100 000 lb), Figure 5, along a typical route of 160 km (100 mile).



< Figure 3 . Typical main shaft roller bearing 240/600 type shown for example

Figure 4. Tandem axle trailer with 20 000 kg cask for superimposed shock test [7]



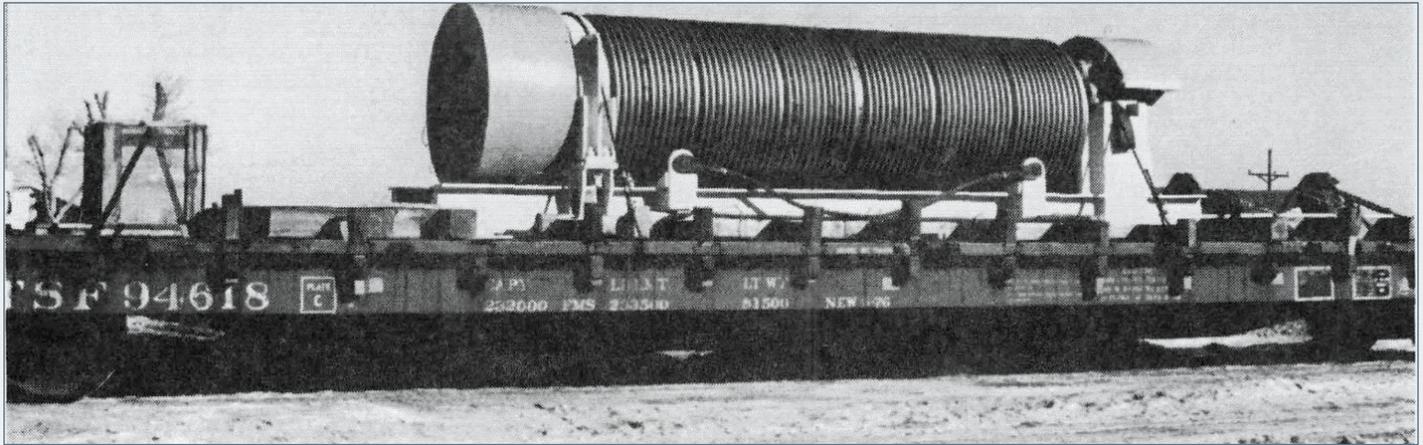


Figure 5. Rail car loaded with 45 000 kg cask for superimposed shock test [

Initially, railcar coupling tests used light casks of 4 500 kg (10 000 lb) at impact velocities in the interval 1.23–4.99 m/s (2.76–11.2 mile/h). Afterwards, these tests used casks of 36 000 kg (80 000 lb), and 63 500 kg (140 000 lb). However, speeds over 3.58 m/s (8.00 mile/h) are no longer allowed in US and Canadian railway yards [8]. Since kinetic energy of a rail car and its load are proportional to the square of their speed, coupling shock accelerations are now lower. This fact has been shown in current tests [9, 10].

Data yielded from test projects developed during the period 1960/1982 has been the main source of information for scientific research and engineering applications on shock and vibration environments for land transport along 35 years.

However, technical progress never stops. New nuclear fuel casks are bigger and weightier, heavy transportation means have evolved in both land and sea, measurement instruments are smaller, stronger, need less energy and are more precise. Last, but not least, GPS systems allow an unprecedented link between measurements taken and the locations where they happened in real time.

Accordingly, the same question has been posed once more: Can current nuclear casks withstand the shocks and vibrations experienced during normal conditions of transport? This recurrent question was the motivation for the multi-modal transportation [9, 10, 11] test conducted in the period June–October of 2017. In this project the US Department of energy (DOE)—through Sandia National Laboratories and Pacific Northwest National Laboratory—collaborated with the Equipos Nucleares SA, SME (ENSA), Empresa Nacional de Residuos Radiactivos S.A. (ENRESA), and ENUSA Industrias Avanzadas,

SA SME (ENUSA) of Spain, and Korea Radioactive Waste Agency (KORAD), Korea Atomic Energy Research Institute (KAERI), and Korea Electric Power Corporation Nuclear Fuel (KEPCO NF).

The ENSA UNIVERSAL (ENUN) 32P 120 000 kg (264 000 lb) dual-purpose rail cask was the test load. The accelerations and strains were measured during:

1. On-travel heavy-haul truck, ship, and rail transport;
2. Handling operations between these means;
3. Controlled rail tests at the Transportation Technology Center, Inc. (TTCI), a railroad testing and training facility in Pueblo, Colorado.

During the multi-modal test, 40 accelerometers, 37 strain gauges, and three Global Positioning System channels were used to collect 6 terabytes of data over the 54- day, 7-country, 12-state, and 13 700 km (8 500 mile) of travel.

The greatest strains and accelerations were observed during the testing at TTCI, specifically during the coupling tests. Water transport strains and accelerations were the lowest. Truck heavy haul, Figure 6, and rail transport, Figure 7, strains, and accelerations were comparable. The handling tests were somewhat higher than the most extreme rail tests, except coupling. The observed strains were—in all cases—well below the yield points for nuclear fuel cladding.

The dedicated rail transport covers a 3 140 km (1 950 miles) route from the Port of Baltimore, Maryland, to Pueblo, Colorado. The trip, code-named Rail 1, took approximately six days, during which the train was moving 59 hours. A total of 2 939 shock events were identified along the rail route.

The major events of Rail 1 trip were related to track switches (629 events) and grade crossings (1 029 events). Only one coupling event was observed on the route from Baltimore to Pueblo, Colorado.

As previously noted, the return rail shipment—code-named Rail 2—was a non-dedicated train. Due to battery exhaustion, data collection stopped after 18 days near East St. Louis, Illinois, yielding a 1 800 km (1 125 mile) test route. This route provided a valuable opportunity for considering coupling events, since 30 of them were identified and analyzed.

The new multi-modal test has enhanced and clarified many previous truck and rail data and extended their scope to heavier casks. In every case, this ABS Technical Report will take into account the new data as far as they are available, jointly with the old reliable data, in order to apply the best applicable data at hand to evaluate the vibration and shock environments for the main shaft assembly transportation by truck and train in the United States. This Report data selection is shown in the following three Sections of this Chapter.

### Truck and Rail Car Vibration

According to [2, 6], vibration data for truck and rail car shows the highest levels given in Table 1. These long-established values are not contradicted by later tests. It is quite clear that vibration acceleration levels in trucks are higher than in rail cars, reaching the top values for this phenomenon in the vertical axis.



Figure 6. Truck heavy haul in Spain of ENUN 32P cask



Figure 7. The tested ENUN 32P cask on a rail car in the United States

Carrier	Axis	0 to Peak Maximum Acceleration, g	Frequency Range, Hz
Truck	Longitudinal	1.50	<b>0 – 1 900</b>
	Traverse	1.17	
	Vertical	2.00	
Rail Car	Longitudinal	0-750	<b>0-750</b>
	Traverse	0.19	
	Vertical	0.52	

Table 1. Truck and rail car highest vibration levels

### Truck Superimposed Shocks

According to [2], superimposed shock data for trucks shows the highest levels given in Table 2. Cargo weight were from zero to 14 000 kg (30 000 lb), spring and suspension systems, moving at speeds up to 88 km/h (55 mile/h) on a road trip from Mercury, Nevada, to Albuquerque, New Mexico. These values are compatible with earlier [2] or later [11] test data.

### Rail Car Superimposed Shocks

According to [6], cargo weight was a 45 000 kg (100 000 lb) cask, installed on a 21 m (68 foot) flat car, with a 38 cm (15 in) end of car coupling device. Travel speeds were up to 80 km/h (50 mile/h) on a trip from Denver, Colorado, to Socorro, New Mexico. Superimposed shock data for this rail car shows the highest levels given in Table 3. These values are not contradicted by earlier tests [2]. Nevertheless, the maximum vertical acceleration of 20.0 g from [6] seems to be an extraordinary exception to be taken into account. Recent test [11] data recorded during the much longer Rail 1 trip show a sole absolute maximum peak acceleration of 8.68 g over a diamond-crossing in Jacksonville, Illinois, that seems to be a value compatible with other axes results. The statistics of Rail 1 superimposed shock events shows that the probability of a vertical acceleration value over 3.71 g is less than 5 %.

Carrier	Axis	Maximum Acceleration, g	Pulse Duration, ms
Truck	Longitudinal	2.8	20
	Traverse	2.3	19
	Vertical	7.0	77

Table 2. Truck highest superimposed shock levels

Carrier	Axis	Maximum Acceleration, g	Pulse Duration, ms
Rail Car	Longitudinal	9.0	10
	Traverse	4.9	4.0
	Vertical	8.68 (20.0)	3.2(2.4)

Table 3. Rail car highest superimposed shock levels

Carrier	Axis	Maximum Acceleration, g	Pulse Duration, ms
Rail Car	Longitudinal	51 (39.0)	12 (18)
	Vertical	20 (26.0)	10 (9.0)

Table 4. Lightly loaded rail car highest coupling shock levels [2]

Carrier	Axis	Axis	Maximum Acceleration, g
	Front End	Longitudinal	7.5
		Traverse	3.9
		Vertical	23
Rail Car	Middle	Longitudinal	4.0
		Traverse	2.5
		Vertical	7.5
	Back End	Longitudinal	7.0
		Traverse	8.0
		Vertical	26

Table 5. Heavily loaded rail car highest coupling shock levels [9]

## Main Shaft Assembly Shock Strength

Obviously, rail car coupling shocks are the main loads on the roller bearing of the Main Shaft Assembly. Specifically, the highest values of acceleration happened in the back end of the rail car platform, Table 6. Traverse and vertical accelerations are vectorially added to become the radial acceleration, as follows.

Accelerations on bearing & housing	Symbol	Unit	Value
Longitudinal	$a_L$		7.0
Traverse	$a_T$	g	8.0
Vertical	$a_V$		26
Gravity	$a_G$		1

Table 6. Values of acceleration acting on main shaft

These accelerations can be vectorially added to obtain the radial acceleration applied to the main shaft bearing and housing, Equation 1.

$$Eq 1. \quad a_r = \sqrt{(a_V - a_G)^2 + a_T^2}$$

On the other hand, the longitudinal acceleration becomes the axial acceleration applied to the main shaft bearing, Equation 2.

$$Eq 2. \quad a_a = a_L$$

The masses of the bearing and its housing are given in Table 7.

Mass	Symbol	Unit	Value
Bearing		kg	540
Housing			1530

Table 7. Masses of the bearing and its housing

The maximum radial and axial forces acting on the bearing are, according to Equation 3 and Equation 4,

$$Eq 3. \quad F_r = (m_B + m_H) * a_r$$

$$Eq 4. \quad F_a = (m_B + m_H) * a_a$$

The radial equivalent static bearing load, according to Equation 5, is:

$$Eq 5. \quad P_o = F_r + Y_o * F_a$$

Where  $Y_o$  is the bearing static axial factor.

The safety factor of the bearing to static load is, according to Equation 6, is:

$$Eq 6. \quad S_o = C_o / P_o$$

The results of the calculation of the bearing strength to the rail car coupling shock loads are shown in Table 8.

Denomination	Symbol	Unit	Value
Radial acceleration on bearing and housing	$a_r$	g	26.2
Axial acceleration on bearing and housing	$a_a$	g	7
Radial static force on bearing	$F_r$	kN	533
Axial static force on bearing	$F_a$	kN	142
Radial equivalent static bearing load	$P_o$	kN	846
Bearing static axial factor	$Y_o$	1	2.2
Bearing basic static load rating	$C_o$	kN	17 000
Bearing safety factor to static load	$S_o$	1	20.1
Minimum bearing safety factor to static load when bearing is stationary and there are impact loads	$S_{o\_min}$	1	2

Table 8. Results of the calculation of the bearing strength

## Conclusions

The current article has posed the following problem: **Is it safe to send the main shaft assembly normally packed by train, without suffering damage due to the vibration and shock environment of standard rail cars?**

This article has shown that the answer to this problem is YES. Truck and railcar vibration and shock environments are compared through the corresponding accelerations. It is shown that vibration and superimposed shocks of train travel are comparable to those of trucks, and the only difference relies in the coupling shocks of rail cars, that may reach higher values during the process of train formation. It is shown in the report that coupling shocks of standard current US trains are aptly supported by the main shaft assembly bearing, with a safety factor of 20, well above the recommended minimum of 2, for the case load at hand.

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