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Impact Analysis of RAM Packages under Kinematic Aspects

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Abstract

BAM is the German Federal Institute for Materials Research and Testing and the competent authority for mechanical and thermal safety assessment of transport packages for spent fuel and high level waste. In context with safety assessment of RAM packages BAM performed numerous drop tests in the last decades. The tests were mostly accompanied by extensive and various measurement techniques especially by instrumented measurements with strain gages and accelerometers.

The procedure of drop testing and the resulting measurement analysis are the main methods to evaluate the safety against mechanical test conditions. Measurement techniques are dedicated to answer questions in regard to the structural integrity of a RAM package, the mechanical behavior of the prototype as well as of its content under impact conditions.

Test results like deceleration-time functions constitute a main basis for the validation of assumptions in the safety analysis and for the evaluation of numerical calculations. In this context the adequate selection of accelerometers and measurement systems for the performance of drop tests is important. Therefore it is not only necessary to find suitable positions for the accelerometers at the test specimens, but also to consider technical boundary conditions as e.g. temperature.

Introduction

Acceleration measurements as well as their analysis are often very complex and extensive also because they are in turn embedded in complex drop test experiments having to consider difficult boundary conditions as for example very low specimen temperatures, large drop heights and sophisticated drop orientations of the specimen. In every case special instruments and adequate technical equipment is required to accelerations under these and transient shock conditions which are characterized in our case by impact times in the range of a few milliseconds up to perhaps 100 Milliseconds naturally depending on container design and drop test conditions as drop height and target.

The paper gives an overview of drop tests under kinematic aspects performed with RAM packages. Furthermore, experimental advancements of accelerometer instrumentation within drop testing, e.g. the characteristics and possibilities of accelerometers, behavior of accelerometers and various influence factors are shown.

Experimental background

The experimental context for instrumented measurements within container drop testing will be shown exemplary by the drop test arrangement of a full jacketed shock absorber container for transportation and storage of radioactive waste which was tested at the BAM 200-tons drop test facility in Berlin, Germany. The related drop test program comprised three 9-m drop tests with two specimens each loaded with a content simulating mass (maximum container mass including content 18,300 kg) at different impact orientation onto the IAEA-target. Figure 1 shows one of the tree drop test setup with a drop positioned specimen at the final drop height attached with nylon slings to the release system.

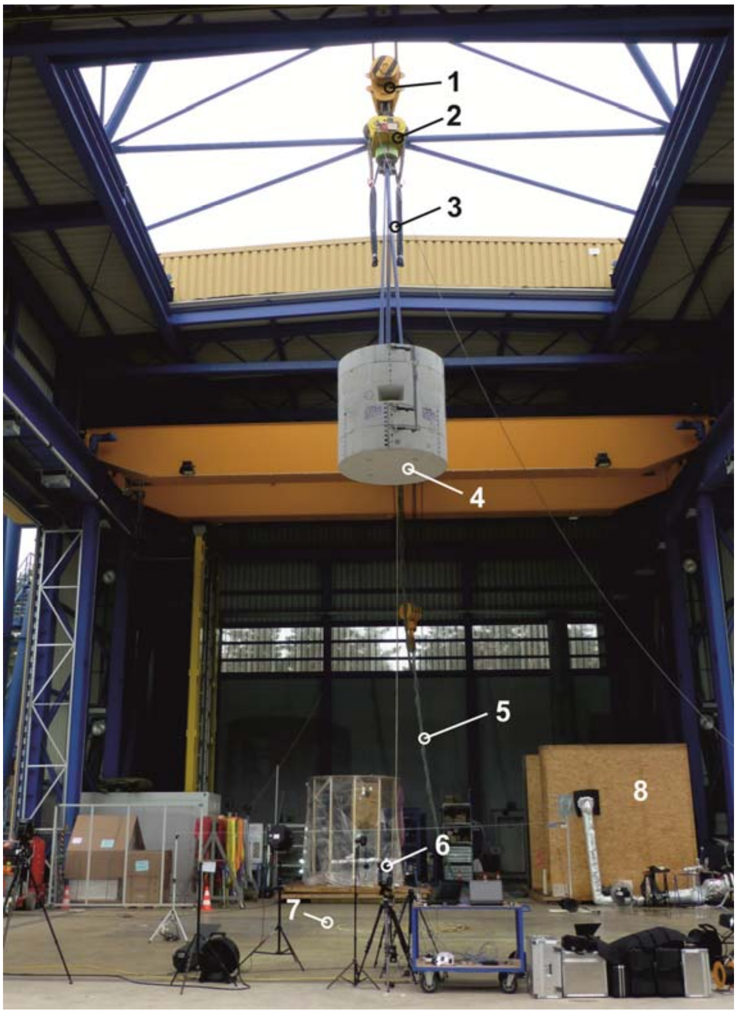

Figure 1 Drop test setup

(1) hoists crane hook, (2) momentum free release system,

(3) nylon slings for the specimen attachment to the release system, (4) specimen in drop orientation, (5) measuring cables,

(6) high-speed video camera, (7) impact target, (8) cool box.

The BAM's drop test facility is mainly characterized by the big drop tower with hoist, the assembling hall with movable roof and the impact target [1]. The drop tower, a 36-meter high steel frame construction, is placed over the assembling hall. The hoist is located in a height of 33 meter. The lifting capacity is limited to a mass of 200,000 kg, the maximum lifting height belongs to 30 meters. The impact target is built according to the IAEA Regulations [2], [3] as an unyielding target for specimens up to 200,000 kg [4]. It consists of a concrete block (German concrete quality B25/B35) with the geometrical dimensions 14 m x 14 m x 5 m and an embedded steel plate as impact pad. This 220 mm thick, 4.5 m wide and 10 m long steel plate is form- and force-fitted fixed with 40 pieces of M36 anchor bolts to the concrete block. The total mass of the target is 2,600,000 kg.

The instrumentation of the specimens was done with uni-axial (range ±5,000 g) and tri-axial (range: ±10,000 g) piezoresistive accelerometers as well as with strain gauges. The accelerometers were connected in a six-wire Wheatstone Full-Bridge circuit with sense wiring of the power supply. At the top side of the cask a central soldering terminal merges all ribbon cables coming from measurement sensors. The terminal is connected to the data acquisition units by means of 40 m long and shielded measuring cables.

Instrumented measurement

The continuous measurement of accelerations at selected locations on a container during a drop test can provide significant information about the container's mechanical response due to impact.[5] These transient measurements require special instruments and technical equipment. Figure 2 shows a typical measurement chain for acceleration measurements. Basically it is the procedure of an electrical signal processing which can be subdivided into an analog and digital stage.

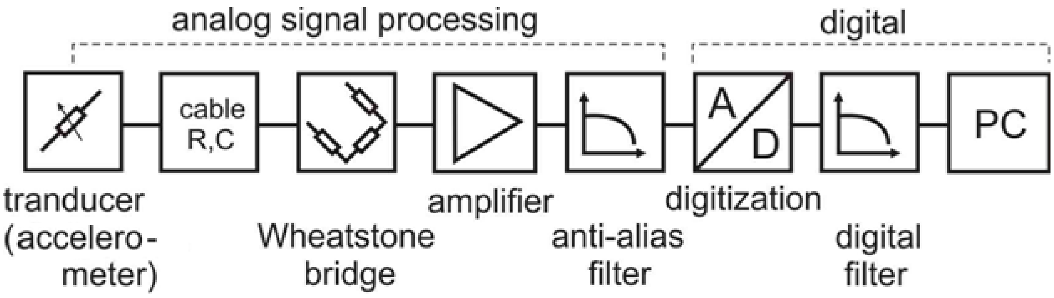

Figure 2: Typical measurement chain for acceleration measurements

The transducer – accelerometer (piezoresistive or piezoelectric with integrated electronics, e.g. ICP®) – which is applicated or mounted on the container at defined points of interest converts the mechanical transient impact response (acceleration) into an electrical voltage change, which can be regarded as the output signal of the transducer.

In container drop testing the signal transmission between transducer and measurement device can be realized in the majority of cases only by long distance measuring cables – BAM performs the measurements mostly with 40-meter cables. But, with extended cable lengths the influence of the cables' electrical characteristics to the transmission of the transducers output signal increase. In general measuring cables contain several wires, one or more shieldings and isolation material in between. Wires have ohmic resistances and build among each other and the shielding capacitors. Ohmic resistance and capacity could build electrical circuits, e.g. RC-elements with frequency depending amplitude and phase response, which could influence higher frequency signals to be transmitted.

As signal conditioner for acceleration measurements with piezoresistive accelerometers high quality DC-amplifiers are used. Amplifiers with analogues bandwidths of 100 kHz, 200 kHz, 300 kHz or up to 1 MHz are commercially available depending on use and requirements.

The data acquisition i.e. the analog to digital conversion of the analog measuring signal and its transient recording is provided by A/D-cards. Commercial cards offer sample rates up to 500 Megasamples/s per channel, 16-bit resolution or more, high fast on-board memory and trigger functions. The sampling of all input channels must be simultaneously performed by one A/D converter for each channel in order to avoid time delays between the channels and therewith misinterpretations in signal analysis of container drop testing. In order to avoid aliasing-effects a low-pass filter with very steep characteristics is located upstream of the A/D converter to ensure that the analog signal does not contain frequency components above the half sample frequency [6].

Acceleration measurement

Acceleration measurement is also one of the accepted standard measurement methods in container drop testing. The acceleration measurement can provide amongst others following important information for the impact behavior analysis of a package:

- at first, continuous acceleration-time histories at the monitored locations of the container and target
- rigid-body impact acceleration or force
- rigid-body impact kinematics of the container during impact (velocity- and displacement history)
- impact duration
- vibration frequencies
- response spectra

Figure 3 shows some examples of available commercial accelerometers for drop testing.

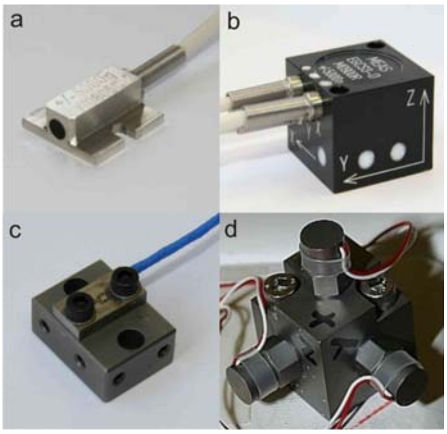

Figure 3: Examples and characteristics of some commercial piezoresistive and piezoelectric accelerometers for drop test

(a) Piezoresistive, uni-axial, oil-damped, ±5000 g, 0 to 2 kHz

(b) Piezoresistive, three-axial, oil-damped, ±5000 g, 0 to 2 kHz

(c) Piezoresistive, uni-axial, undamped, ±10,000g/ ±50,000 g, 0 Hz to 10 kHz, -54°C to 120°C, mounting bloc

(d) Piezoelectric, uni-axial, built-in mechanical filter, ± 10,000 g, 0.4 Hz to 10 kHz, -18°C to 66°C.

Types and characteristics

In principal, an accelerometer can be described as a single-degree-of-freedom mass-spring-system consisting of a small mass suspended from the sensor case by a spring with a high stiffness. The motion of the mass within the case maybe damped by a viscous fluid or another built-in mechanical filter. The base of the mass-spring-system and of the accelerometer respectively is attached to the moving part (test object) with its measuring axis oriented towards the acceleration to be measured. The relative displacement between mass and sensor case is a measure for the acceleration of the moving part. The mechanical characteristics of accelerometers can be described mathematically by Newton's second equation of motion [6, 7].

At high frequencies, the response of an accelerometer follows consistently the time history of an applied shock pulse (input excitation) if the natural period of the accelerometer τn with $\tau n=1/fn$ is smallest relative to the pulse duration τ ($\tau n<<\tau$). The natural frequency fn of the accelerometer should be significantly higher than the frequencies of the accelerations to be measured. For example, an un-damped accelerometer should be typically used for vibration frequencies only up to approximately one-fifth of its natural frequency fn (see Figure 4).

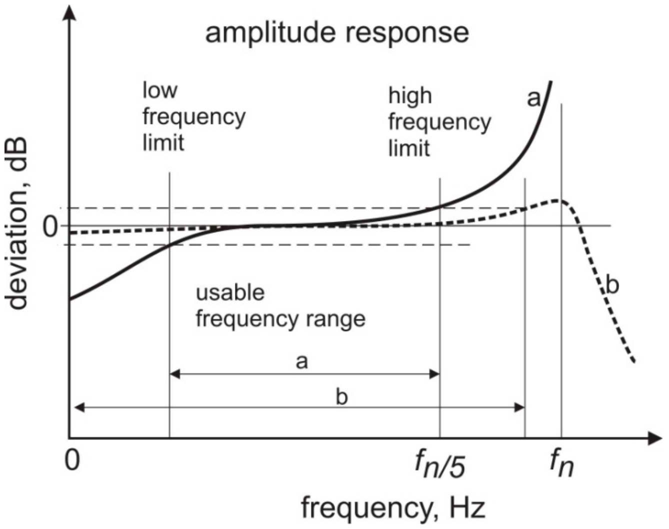

Figure 4: Schematically amplitude responses of an un-damped piezoelectric (a) and a damped piezoresistive accelerometer (b) with their usable frequency range within a flat amplitude response

However, damping, e.g. achieved by built-in mechanical filter, extends the usable frequency range of an accelerometer, reduces the amplitude of the resonance frequency and blocks out high frequency input spikes protecting the sensing element from overstress and reduces vibrations overlaying the pulse which is referred to as ‘ringing’. Then the high frequency limit of the accelerometer depends on its natural frequency and mechanical damping characteristics [6]. In this context also the mounting technique has a considerable influence to the accelerometers natural frequency fn (see paragraph ‘mounting’).

A good response at low frequencies down to a frequency of zero Hertz is important when acceleration data i.e. acceleration time histories a(t) are integrated to obtain e.g. velocity $v(t)=\int a(t)dt + C1$ or displacement $d(t)=\iint a(t)dt +C2$ time histories concerning the rigid body motion of a container during impact.

Apart from the mentioned mechanical characteristics of an accelerometer it must be naturally considered that the performance of an accelerometer significantly depends as well from its electrical characteristics and the subsequent electrical signal processing.

In container drop testing with measuring of accelerations mostly piezoresistive transducers are common but also piezoelectric transducers are applied. Both designs consist in principal of two basic components – a mass and a load measuring element.

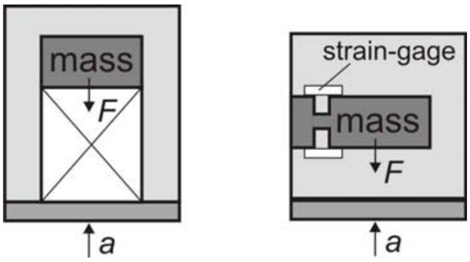

Figure 5: Working principle of the piezoelectric and piezoresistive accelerometer

The piezoelectric accelerometer [6, 7] has a piezoelectric material (quartz, ceramic) as load measuring element (see Figure 5). The inertial force of the mass causes strain in the piezoelectric material (‘the spring’) producing an electrical charge proportional to the acceleration applied to the base of the transducer. In field conditions of container drop testing transducers are exclusively adequate when having built-in signal-conditioning electronics converting the charge signal into a usable low-impedance voltage signal output. In this way the signal can be transmitted over ordinary e.g. two-wire cables and over long cable distances to the measuring device.

The decrease in response at low frequencies (see Figure 3) depends primarily on the characteristics of the electronic preamplifier. But commercial sensors already achieve low frequency limits down to e.g. 1 Hz (±1dB) or several Hertz.

Most piezoelectric accelerometers are essentially undamped which may result in zero-shifting(s) of the acceleration signal when higher frequency input spikes occur during impact. This effect has to be considered using undamped piezoelectric accelerometers in container drop testing. But available commercial types with built-in mechanical filter avoid this effect optimally. In return the widely usable temperature range decreases, depending on the temperature characteristics of the damping material.

Further characteristics are the small size and light weight design, the available resonance frequencies up to 100,000 Hz and amplitudes up to 100,000 g’s.

Summarized, the piezoelectric accelerometer when used in container drop testing should have integrated electronics (e.g. ICP®), a built-in mechanical filter but also considering the low frequency limit for good measuring results.

The piezoresistive accelerometer [6, 7] has as load measuring element a strain-sensing element today mostly made of semiconductor material usually silicon (see Figure 4). In principle the transducer consists of a cantilever beam (‘the spring’) loaded at the end with a mass. The inertial force F of the mass causes bending of the beam which produces a resistance change of the strain-sensing elements proportional to the acceleration a applied to the base of the transducer. Often two pairs of elements are used – two on the upper side (tension) and two on the corresponding lower side (compression) of the beam – all together electrically connected in a Wheatstone full-bridge. Piezoresistive transducers require an external and very stable power supply to provide the necessary voltage excitation which is commonly 10 Volts DC. It should be operated with the same excitation as used during calibration. For operating piezoresistive accelerometers usually wide bandwidth bridge-amplifiers which provide e.g.

the necessary excitation voltage and the signal conditioning are used. Because of long distance measuring cables in container drop testing the electrical connection between accelerometer and amplifier is ideally realized by a six-wire Wheatstone Full-Bridge circuit with sense wiring of the excitation supply – 2 wires additional to the current voltage supply (2 wires) and signal output (2 wires).

The major advance of piezoresistive accelerometers is that they have a frequency response extending down to DC (0 Hz) or to steady state accelerations for measurements of long duration transients, respectively, along with a relatively good high-frequency response.

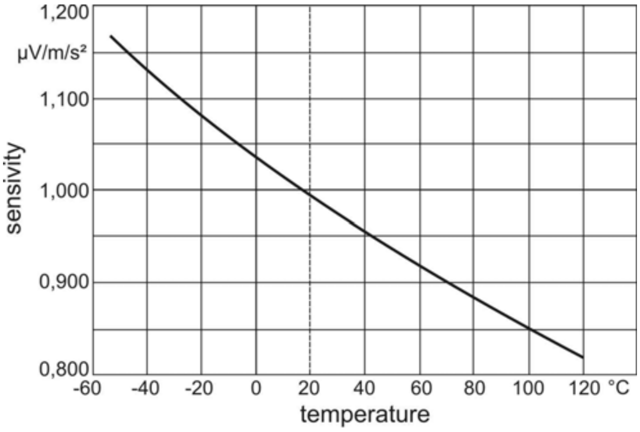

Figure 6: Temperature response of an un-damped, piezoresistive accelerometer with a specified operation temperature of between -54°C and 120°C

At temperature test conditions differing from room temperature the associated changes of specified sensitivity and damping properties (affects only mechanical damped types) of the piezoresistive accelerometer should be considered. The sensitivity, defined as the ratio of its electrical output to the acceleration input (e.g. mV/g) at a defined excitation (e.g. 10 VDC), varies as a function of temperature due to the fact that the properties of the strain-sensing element material are temperature dependent. Figure 6 shows exemplarily the sensitivity-temperature function of a commercial accelerometer. The function was determined at BAM laboratories using a Hopkins-bar calibration facility with climatic chamber. The accelerometer's sensitivity varies approximately ± 17% with regard to the sensitivity specified at a temperature of 20°C within the specified transducer operation temperature of between -54°C and +120°C.

Mechanical damping of piezoresistive accelerometers is typically performed as viscous damping, having silicon oil pressed between the mass and its casing. Damping is usually adjusted to 0.7 or less of the critical damping namely at room temperature. With this damping factor, the output signal is undistorted because of a linear phase shift and the accelerometer's amplitude response is flat – means that amplitudes are transmitted one-to-one within typically ±0.5dB – to greater than one-fifth (fn/5) of its natural frequency fn. Viscosity of the damping oil and therewith damping changes with temperature. At higher temperatures the viscosity of the oil decreases, resulting in low damping – at low temperatures the viscosity increases causing higher damping. Due to this fact, frequency and phase response of the transducer changes: phase response becomes non-linear, which causes distortion of the signal. This effect results in a limited temperature range for damped piezoresistive transducers.

Mechanical damping test of piezoresistive accelerometers

The Hopkinon Bar is a laboratory device, which is used for testing and calibration investigations of high dynamic impact processes. BAM uses a Hopkinson bar to characterize accelerometers for their application in drop tests corresponding to ISO 16063-13:2001 [7]. Its mode of operation is based on the propagation of an elastic shock wave in a long and thin bar. The used Hopkinson bar consists of a ball pendulum, which is dropped against the rear end of the bar to excite the shock wave. The impact generates a bell-shaped compression impulse, which propagates as an elastic wave in the bar [8]. Thus the accelerometer mounted at the opposing front end of the bar receives a defined acceleration. As reference a laser vibrometer measures the displacement of the accelerometer. The acceleration is determined by double integration of the displacement time signal. Comparing the result with the measured signal of the accelerometer enables calculation of the sensitivity and standard deviation. With using the laser vibrometer as a highly exact reference method, an absolute calibration method is constituted [9]. Additionally, frequency and phase resolution allows a comprehensive characterization of accelerometers under shock impact.

For systematical investigation of the temperature influence, it is essential to not only perform an experiment at a defined temperature, but also to take the temperature history of the accelerometer into account [10]. Integration of the front end of the Hopkinson Bar into a temperature chamber enables to adjust a full temperature progression according to application conditions. Figure 7 displays the front bar end with a mounted accelerometer and a connected thermocouple for direct temperature measurement at the sensor.

Figure 7: Piezoresistive accelerometer on the Hopkins-bar

The used temperature chamber (Weiss WTL 34/70, Weiss Umwelttechnik GmbH, Germany) allows a nominal temperature range between -70 and +180 °C, which can be applied almost completely, due to effective isolation measures.

To prepare drop tests at low temperatures, e.g., -40 °C, it is an established procedure to cool down the whole drop test specimen inclusive all sensors in a wooden enclosure using liquid nitrogen. Because of the specimen's generally high mass and large dimensions, cooling durations of several hours, respectively days, are necessary to ensure a complete temperature penetration. Hence, a temperature below the drop test temperature must be applied before the cooling equipment is removed, subsequently the temperature increases, and the drop is triggered at the defined target temperature.

Figure 8 shows the temperature time course used for Hopkinson Bar experiments to characterize an accelerometer for application in a drop test at -40 °C with a comparable temperature progression to application conditions. The red curve displays the temperature of the sensor, while the dark blue curve displays the chambers programmed temperature. The light blue bars indicate the time points of Hopkinson Bar measurements. Measurements were performed at specified temperature steps of 5 °C.

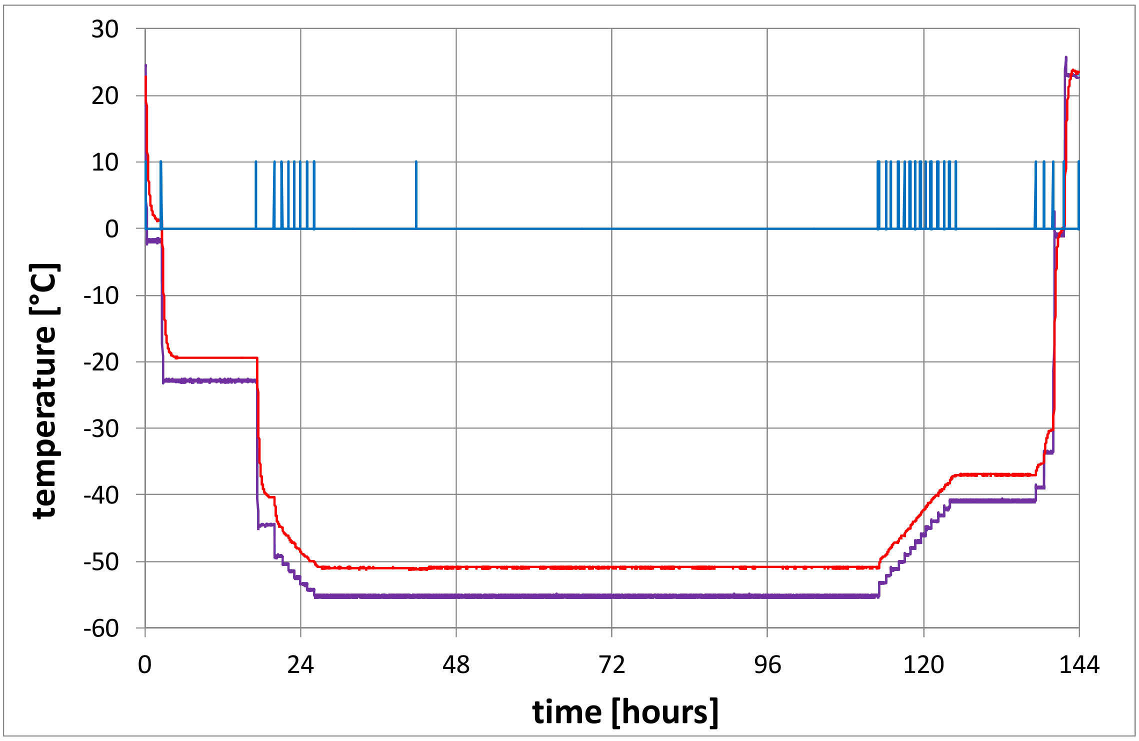

Figure 8: Temperature vs. time of piezoresistive accelerometer

Figure 9 displays the measurement results in means of sensitivity versus temperature. The red curve presents the sensitivity progression at decreasing temperatures, while the blue curve presents the sensitivity progression at increasing temperatures. Decreasing sensitivity at decreasing temperatures indicates the typical behaviour of damped piezoresistive accelerometers, mainly caused by viscosity increase of its damping oil. Up to a temperature of -48 °C the accelerometer was principally functioning despite a sensitivity decrease of over 30 %. At lower temperature the sensitivity dropped rapidly to 0. After a steady cooling of more than 72 h at -51 °C a stepwise warming was initiated. Remarkably, instead of following the sensitivity course at decreasing temperatures, the accelerometer shows a different behaviour by remaining at a sensitivity of 0 up to the temperature of -35 °C and jumping back to normal results at -30 °C. This hysteresis can be attributed to the specific system components of the accelerometer and their characteristics, e.g., the viscosity properties of the damping oil. What means, that every type of accelerometer, particularly those with oil damping, can provide a different temperature behaviour. Typically, such kind of information is not available in the manufacturer's data sheet and demands in critical applications for individual testing.

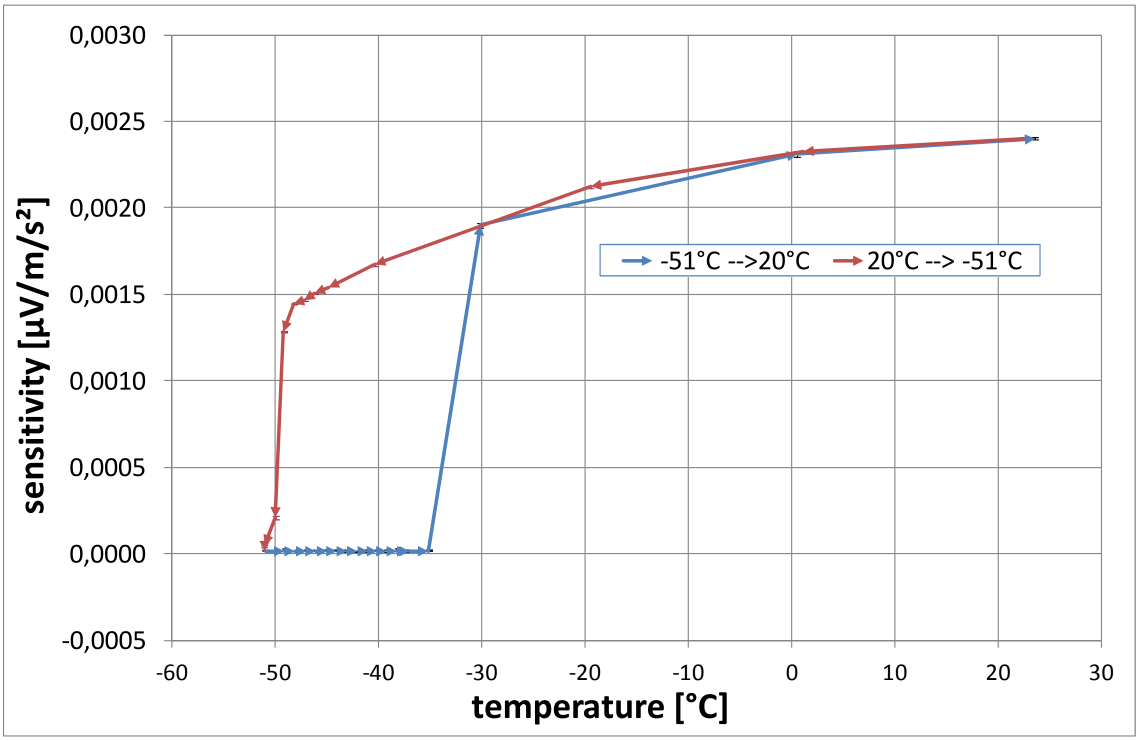

Figure 9: Sensitivity vs. temperature of piezoresistive accelerometer

Accelerometer mounting

The optimum mounting technique of an accelerometer is by means of a threaded stud or screw immediate onto an absolutely flat and fine finish surface part of the specimen considering the required mounting torque of the manufacturer [11]. Under this condition the amplitude frequency response of the accelerometer is flat within a few percent. In actual drop testing practice of heavy containers the bolted connection is the mostly feasible. Due to the fact that in a container drop test an accelerometer can be mounted to heavy and stiff structures (container wall, lid) the small mass and geometry of the accelerometer does not influence the mechanical behavior at the measuring location of the specimen. Variations from that mounting technique e.g. adhesive mounting or the use of a mounting block, etc.

tend to change the amplitude frequency response above 1 kHz – 2 kHz. Therefore measurements with focus on higher signal frequencies should consider this fact by calibration of the accelerometer including its specific mounting technique. For measuring lower frequency signals e.g. all rigid body relevant signals in context with impact duration times in a range from 5 - 100 Milliseconds these effects normally do not have to be considered.

Under high shock conditions as with package drop testing the sensor cables should be securely fastened by e.g. adhesive or tape to the mounting structure near the sensor as well as over the whole cable laying along the container in order to minimize cable whip. Cable whip can introduce electrical noise – this phenomenon is known as triboelectric effect. Also, it is recommended to perform all electrical connections at the container side, e.g. connection between sensor and cable, by soldering. Plug-in-connections shall be avoided because the impact introduced shock waves and vibrations may cause a change or interruption of the mechanical plug-in-contact causing unfeasible signals.

Selected drop test results

Exemplarily, from the numerous results of acceleration measurement signals of drop tests the results of one selected drop test shall be presented.

The cask was dropped from a height of 9 m in a 20° declined position with primary impact onto the base end of the cask. Figure 10 (left) schematically shows the drop test configuration of the container and the measuring direction of the acceleration sensor.

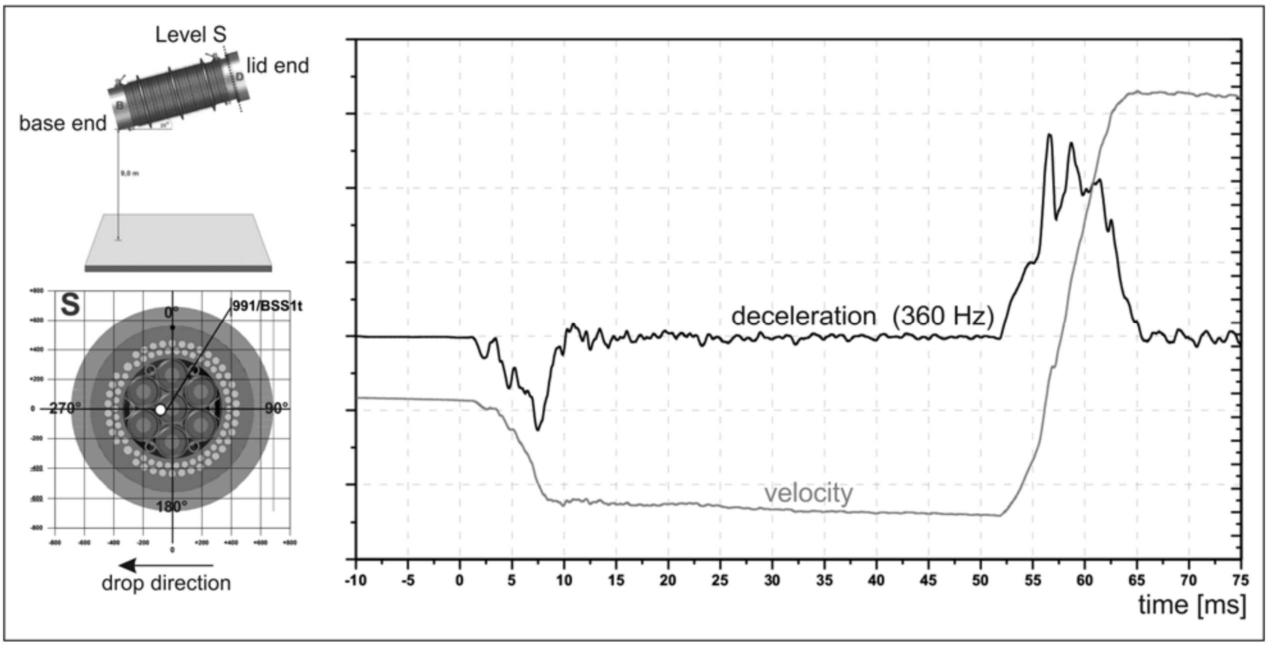

Figure 10. 9m slap-down with primary impact onto base end; deceleration and velocity vs. time measured at lid end

[Quantitative deceleration and velocity values are not displayed because of confidentiality.]

The deceleration signals on the primary lid were analyzed, measuring point level S in Figure 10, to determine impact kinematics of the cask. The curve (Figure 10) shows a typical accelerometer signal of the package, as typical for most slap-down impacts [12]. Filtering was done by a Bessel-filter of second order with a 360 Hz threshold [3]. Impact duration according to both acceleration sensors was about 12 ms. The lid end impacted around 50 ms later than the bottom end. The resulting velocity-time curve obtained by integration is shown in Figure 10. The bottom end of the prototype hit the unyielding target with an impact velocity of 13.3 m/s. Due to the rotational acceleration, the impact velocity of the lid end was 18.2 m/s.

Conclusions

Instrumented measurements especially acceleration measurements are one of the accepted standard methods in drop testing of packages for radioactive materials. This method is dedicated to answer questions in regard to the structural integrity of a package, the behavior of a package's components as well as of the content's behavior under impact conditions. In this context the adequate selection of accelerometers and their behavior under temperature fluctuations and other factors influencing for the performance of drop tests is important.

BAM recommends strain and acceleration measurements, high-speed video for kinematic analysis and the comparison with acceleration measurements and photogrammetry for evaluation of the lid movement and projected fringe methods for quantitative package analysis. The combined application of these methods provides a good knowledge on the package behavior, and a useful basis for a state-of-the-art transport package safety case.

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