Transactions, SMiRT-26
Berlin/Potsdam, Germany, July 10-15, 2022
Special Session

Vibration monitoring of cooling tower collapse

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ABSTRACT

In the present paper the methods for vibration monitoring during the blast demolition of cooling towers in nuclear power plants are described. Beginning with the methods for conventional buildings, the main focus of this paper are the additional efforts in nuclear environment. The assessment of the measured vibrations with regard to the safety related buildings of a nuclear power plant is described. Examples are given.

INTRODUCTION

The phase out of nuclear power in Germany is decided and shall be conducted until December 2022. This brings many challenges concerning the decommissioning and deconstruction of the nuclear power plants. The cooling towers – one of the most prominent parts of a NPP – can either be deconstructed by a remote controlled excavator on the top of the tower or by blasting. Whereas the deconstruction by excavator causes less ground vibrations, the deconstruction by blasting brings advantages such as less cost and time efforts or a shorter period of noise and dust pollution.

Anyway, nuclear safety regulations still have to be considered during demolition of the cooling towers if the decommissioning of nuclear parts at the site is not finished. Especially the ground vibrations have to be limited and observed in the neighboured buildings. This requires a special concept for vibration monitoring during the cooling tower collapse, which differs from typical vibration measuring concepts in conventional environment.

VIBRATION MONITORING IN CONVENTIONAL ENVIRONMENT

Monitoring the vibrations during a blast demolition provides information about possible damages to nearby buildings or plants caused by blasting. Therefore it is already common to measure the ground vibrations during blasting.

A common scope of monitoring the ground vibrations is the preservation of evidence that the blast demolition did not cause any damages in neighboured buildings or plants and the assessment of stability of endangered buildings near the demolition object. The ground vibrations are measured at endangered buildings to directly assess the vibrations of the concerning buildings. Furthermore, the vibrations can be measured at free-field measuring points (MP) in different distances to assess the decrease of vibration amplitudes with increasing distance.

Typical objects, that have to be monitored during blast demolitions in conventional environment are the nearest buildings, very sensitive buildings (such as old buildings) or plants, critical infrastructure and further more.

Assessment of vibrations during blasts and important guidelines

Depending on the type of the monitored object, different methods for the assessment may be used. For buildings, the DIN 4150-3 indicates reference values for the vibration velocities of short period exposition to vibrations. These velocities, measured on the foundation or at the top floor level respectively, are depicted in table 1. If these values are not exceeded, there are no damages in terms of serviceability to be expected. Otherwise, it is not necessarily the case that damages occur, if the values are exceeded. Damage in this sense is the consequence of an impact, which reduces the serviceability of the structure. In buildings according to line 2 and 3 of table 1 (e.g. residential buildings) even slight damages like cracks in the plaster are damages in terms of serviceability.

Values, that are more specific, may be necessary for plants (for example electrical plants). A possible assessment is the comparison with vibrations caused by the operation of the plant itself or values given by the manufacturer for specific components. Another possibility is the comparison with calculated limits for specific buildings. Calculations of the structural integrity of special buildings or plants can be carried out based on the predicted vibrations. The measured vibrations should be compared with the predicted vibrations. The criteria and the consequences of an exceedance of the limits always have to be specified for this case.

Table 1: Reference values from DIN 4150-3 for assessment of the effects of short-term vibrations on buildings

line	type of building	reference values for velocity $v_{i,\max}$ in mm/s			
		foundation frequencies			upper level, horizontal
		1 Hz to 10 Hz	10 Hz to 50 Hz	50 Hz to 100 Hz	all frequencies
1	industrial buildings and comparable	20	20 to 40	40 to 50	40
2	residence buildings	5	5 to 15	15 to 20	15
3	Buildings which, due to their particular sensitivity to vibrations, do not comply with those in line 1 and line 2 and are particularly worthy of preservation (e.g. listed buildings).	3	3 to 8	8 to 10	8

Measuring Equipment

The requirements on the measuring equipment are described in DIN 45669-1. Measuring the velocities is preferred, since there is approximately a linear correlation between the velocities and the stresses in components and buildings. Alternatively, accelerations may be measured and the velocities can be calculated from the measured signals by integration. For practical aspects, devices with integrated sensor, recorder and battery have become state of the art.

The sensor installation is described in DIN 45669-2. In many cases, when only the lower frequency content is relevant and the expected accelerations are lower than 3 m/s^2, a loose installation of the sensors is sufficient. When a coupling to the soil is needed, ground spikes have been established as a suitable compromise between accuracy and effort. Further methods are described in DIN 45669-2. Two examples of sensor installation are depicted in figure 1.

Figure 1. typical sensor installations (left: free-field measuring point, coupling to soil by ground spike according to DIN 45669-2; right: measuring point on foundation, loose installation)

Example: Free-field measurements during a blast of a cooling tower

During the blast demolition of a cooling tower a measurement of the ground vibrations has been conducted at ten free-field measuring points to analyse the propagation of the vibrations. Therefore two chains of sensors in different distance have been built up (figure 2). The sensors have been coupled to the soil by ground spikes according to DIN 45669-2 and measured the velocities in vertical and horizontal directions. The horizontal measuring axes have been aligned to radial and tangential direction with respect to the cooling tower.

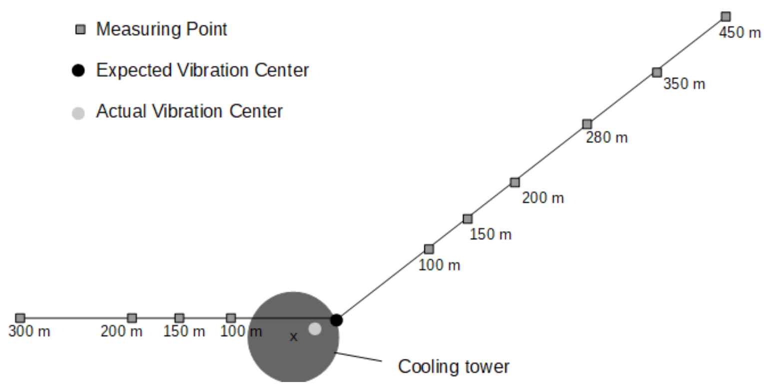

Figure 2. Measuring Points

The measured velocities at distance 100 m are depicted in figure 3 as time history signal and its spectrum gained by fast fourier transformation (FFT). The vibrations have a duration of about 10 s. The velocities are characterized by a typical low frequency content below 10 Hz. The maximum velocity is $v_{\max} = 5.5\ \mathrm{mm/s}$. The maximum velocities, related to the value at a distance of 100 m, are depicted in figure 4. A comparison of the measured maximum velocities with the description of the spreading of vibrations from DIN 4150-1 shows a good accordance. The spreading of vibrations in vertical direction can be described by the formula for a point source, impact excitation and shear wave (see “PQ/I/R”-line in figure 1 of DIN 4150-1), whereas the spreading of horizontal vibrations could also be described by a Rayleigh wave (see “PQ/I/O”-line in figure 1 of DIN 4150-1).

The comparison of the maximum values of the left and the right measuring chain also shows, that the vibration center is not – as expected in advance at the edge of the cooling tower – it seems to be further directed to the center. This correlates to the visual impression of the individual collapse of the considered cooling tower. The distances used for figure 4 are the corrected distances related to the actual center of vibrations in figure 2.

The reference values from DIN 4150-3 for residence buildings (5 mm/s for frequencies below 10 Hz) have been complied in all directions at a distance of about 150 m from the actual vibration center at the free-field measuring points. Due to an estimated coupling factor of the buildings to the soil of about 0.5, the maximum velocities on their foundations are even lower. This factor is based on empirical values from past blast demolitions.

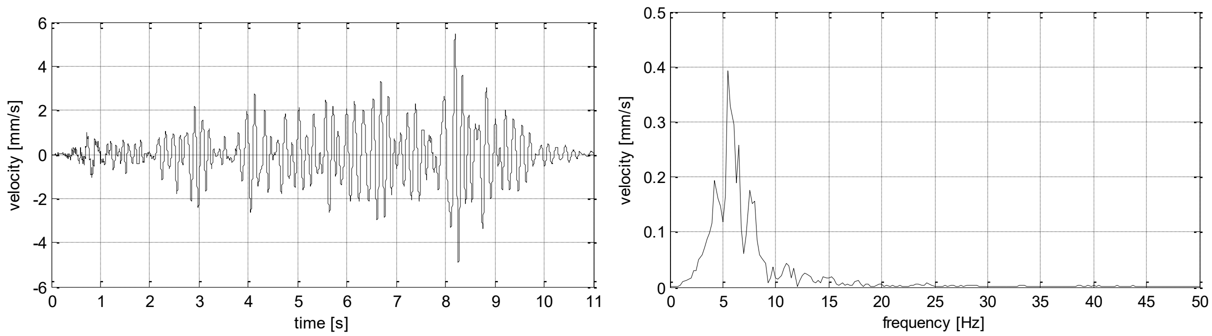

Figure 3. Velocity measured at 100 m distance in vertical direction (left: time history, right: spectrum of measured velocity by FFT)

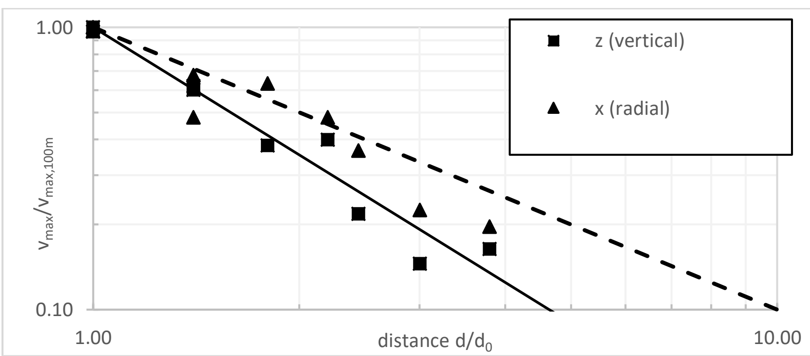

Figure 4. Reduction of maximum velocities with increasing distance (related to MP at d = 100 m)

Example: Vibration monitoring during blasting several buildings of power plant "Lünen"

Vibrations due to the blast demolition of a cooling tower, a chimney and further buildings of the coal-fired power plant "Lünen" had to be measured and to be assessed with regard to possible damaging effects in accordance with DIN 4150-3. Therefore in total 22 measuring points at nearby buildings have been installed. Since the vibrations at some of the measuring points did not exceed the trigger values of the sensor, the number of measured values differs from the number of measuring points. The measurements proofed, that the reference values from DIN 4150-3 have not been exceeded (see figure 5). No damages to surrounded buildings are to be suspected.

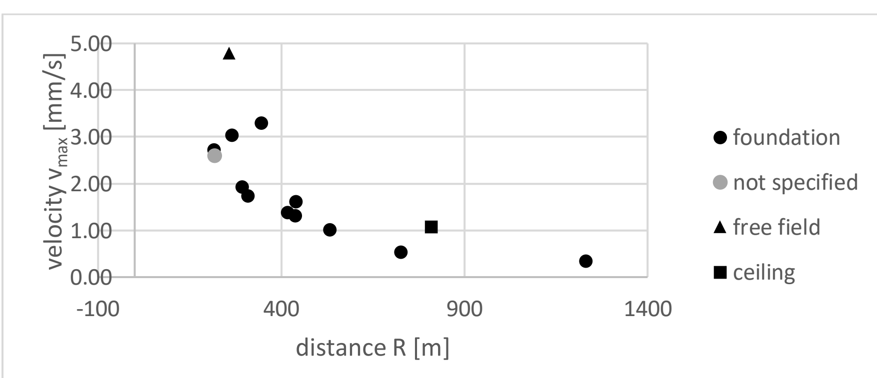

Figure 5. Maximum velocities during blast demolition of a cooling tower of power plant Lünen

ADDITIONAL CHALLENGES IN NUCLEAR ENVIRONMENT

The preceding chapters described the tasks of vibrations measurements due to blast demolition of cooling towers or other objects in conventional environment. This approach can also be applied to conventional buildings in nuclear power plants (NPP) like administration buildings. For buildings necessary for a safe operation of the nuclear parts of the NPP (safety related buildings) advanced approaches have to be applied since the reference values from DIN 4150-3 are not sufficient. In the following chapters, these additional approaches are sketched up.

The seismic design of the NPP is a good basis for the evaluation of the ground vibrations due to the blast demolition of the cooling towers. For the design of the NPP site specific free-field response spectra of the design bases earthquake (DBE) have been defined. The measured vibrations can be compared with the site specific response spectra used during the design of the NPP. In contrast to the assessment according to DIN 4150-3, accelerations are used instead of velocities.

KTA 2201.6 describes the actions that have to be done after an seismic event depending on the level of vibrations. Safety related buildings and components are designed to withstand the design bases earthquake (DBE), which is defined for the free-field of the NPP. Depending on the three levels trigger threshold, inspection level (0.4 x DBE) and shutdown level (f x 0.4 x DBE, with a typical value f = 1.5), actions like plant walk-down inspection, shutdown inspection are defined after an seismic event. Based on the free-field response spectra, these levels are also defined for the floor response spectra of the buildings.

For the monitoring of seismic events, each NPP is equipped with a seismic instrumentation. The requirements on the seismic instrumentation of a NPP are defined in KTA 2201.5. Acceleration sensors have to be used, whereas measuring the velocity is recommended in DIN 45669-1. Since the amplitudes during an earthquake can be assumed the same on the total free-field area of the NPP, usually one free-field measuring point exists in the seismic instrumentation. According to KTA 2201.5 at least three measuring points are placed in the reactor building, two in the lowest building level and one in an upper level. In contrast to seismic events, the vibrations due to the blast demolition of the cooling towers strongly depend on the distance to the center of vibrations, which is typically assumed to be on the edge of the collecting basin of the cooling tower (see figure 2). This makes additional monitoring equipment necessary. The requirements on the measuring equipment and the installation can be based on the requirements for seismic instrumentation for NPPs in KTA 2201.5 and/or the requirements for measuring vibration immissions from DIN 45669-1 and DIN 45669-2.

Since there are free-field response spectra and floor response spectra for each building, there are also two ways to compare the measured vibrations with the seismic design levels:

1. Monitor at free-field measuring points at the distance of the closest safety related building/component and compare with the free-field response spectrum of the NPP
2. Monitor on the foundations of the buildings and compare with the floor response spectra that have been calculated close to the measuring point.

Whereas monitoring on the foundations also considers the coupling to the soil of each building, the free-field measuring points can be used for a global assessment of the vibrations in relation to the distance to the vibration centers.

Example: Vibration monitoring during blasting two cooling towers of a nuclear power plant

In figure 6, a simplified site plan of a NPP with its corresponding cooling towers that have to be blasted and the buildings that had to be monitored are drawn. Since the decommissioning of the nuclear parts of the NPP had not been finished at the time of the blast, nuclear safety regulations had also to be considered for the safety related buildings and components. The safety related buildings had been e.g. the reactor buildings of block 1+2, emergency power diesel building, temporary storage buildings and the 110 kV transformer with a mass of about 100 t. The emergency power diesel building and the 110 kV transformer have been the closest safety related building/component to the vibration centers with a distance of about 315 m.

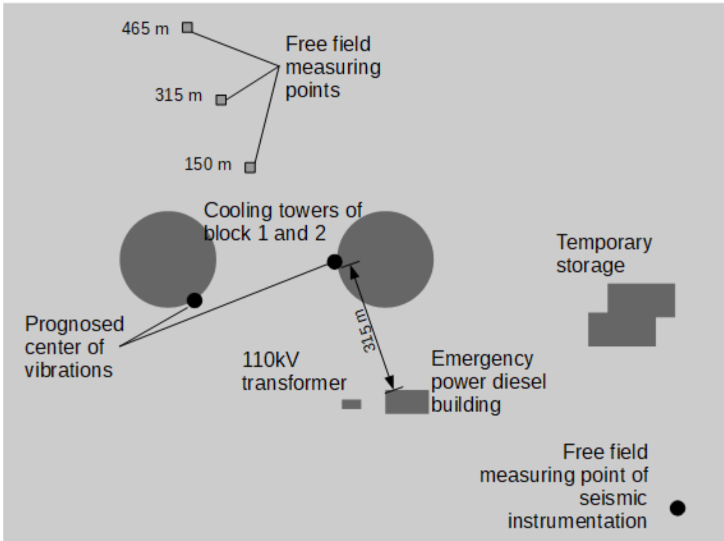

Figure 6. Schematic site plan of critical buildings/components of NPP

Monitoring the vibrations in the free-field

A chain of several measuring points in different distances is useful to evaluate the reduction of vibrations with increasing distance. One sensor at the distance of the closest safety related building (315 m), one closer and one further away to the vibration centers. The free-field measuring points have been placed on the centerline of both vibration centers. The measured response spectrum at the same distance of the nearest safety related building should lie below the inspection level, otherwise additional actions are necessary. In the example in figure 7 the vibrations at a distance of 315 m and more lie below the inspection level. Thus there are no further actions required in safety related buildings. Since the DBE in horizontal direction is a resultant spectrum and the vibrations have been measured in three directions, the DBE has been converted into a component spectrum by the factor 1/1.2.

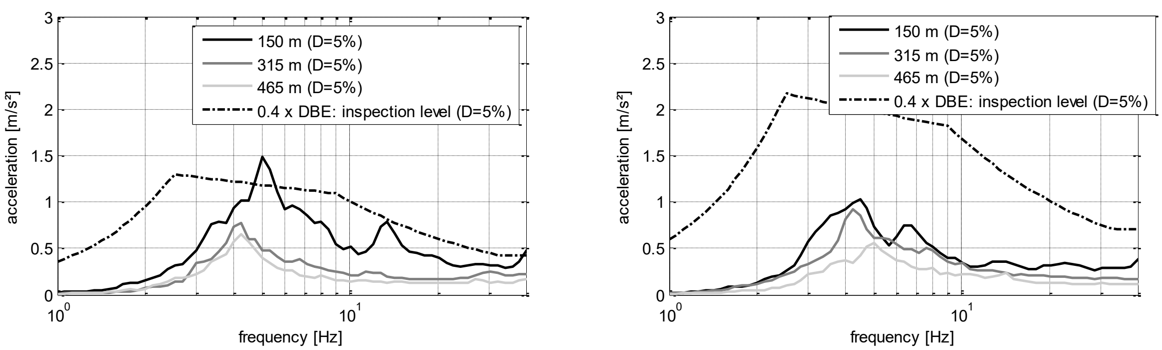

Figure 7. Comparison of free-field response spectra with inspection level, D = 5 % (left: vertical direction, right: horizontal direction – spreading direction)

For the 110 kV transformer no seismic design existed in advance. Since other components of the power supply had to be taken out of operation during the blast demolition, it became safety related for that time. Calculations have been carried out, to proof the stability of the transformer during the blast demolition with the vibration prognosis. The prognosis method is described in Karapetrou et al. (2022) and the concept of the proof of stability of the transformer is described in Ries et al. (2022). The distance of the

110 kV transformer to the vibration center is also about 315 m. With the comparison of the 315 m free-field measuring point against the inspection level, the transformer is also assessed without any exceedances.

Monitoring the vibrations on foundations of the safety related buildings

In addition, the most critical safety related buildings have been equipped with at least one measuring point on their foundation in the direction of the closest cooling tower. These buildings have been the reactor buildings, emergency power diesel building and temporary storage buildings. The measured response spectra of the reactor buildings and the emergency power diesel building have been compared with the floor response spectra that have been calculated for a location close to the measuring points during the design of the NPP. As an example, this comparison is depicted in figure 8 for the emergency power diesel building, measured with a geophone with loose installation on the foundation. No exceedances of the inspection level occurred during the blast demolition of the two cooling towers.

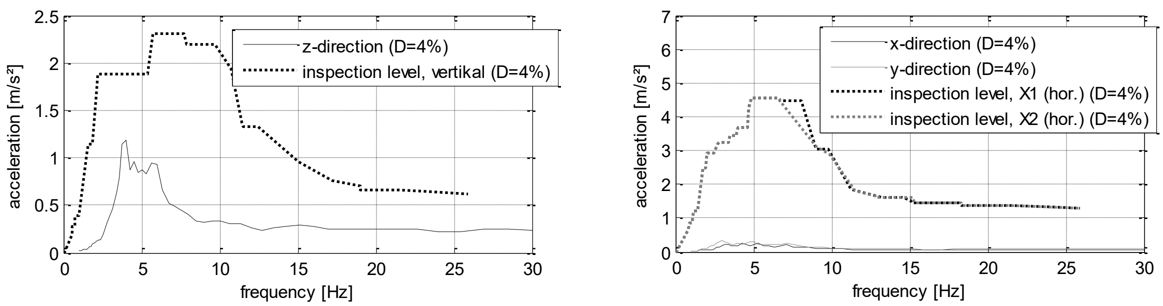

Figure 8. Comparison of vibration response spectra with inspection level at foundation of emergency power diesel building, D = 4 % (left: vertical direction, right: horizontal direction)

Validation of the vibration prognosis

A vibration prognosis has been carried out in advance to the blast demolition of the two cooling towers. The procedure and results of the prognosis are described in Karapetrou et al. (2022). Response spectra for free-field at 315 m distance to the cooling towers have been gained. The predicted response spectra did not exceed the inspection level. In figure 9 the measured response spectra and the prognoses are compared. There is a good agreement in vertical direction, in horizontal direction the prognosis is on the conservative side. Overall, the prognosis method could be validated by the measurements. The results can also be used to adjust the prognosis model for future blast demolitions, by increasing the number of time histories from past events and improving the statistical basis.

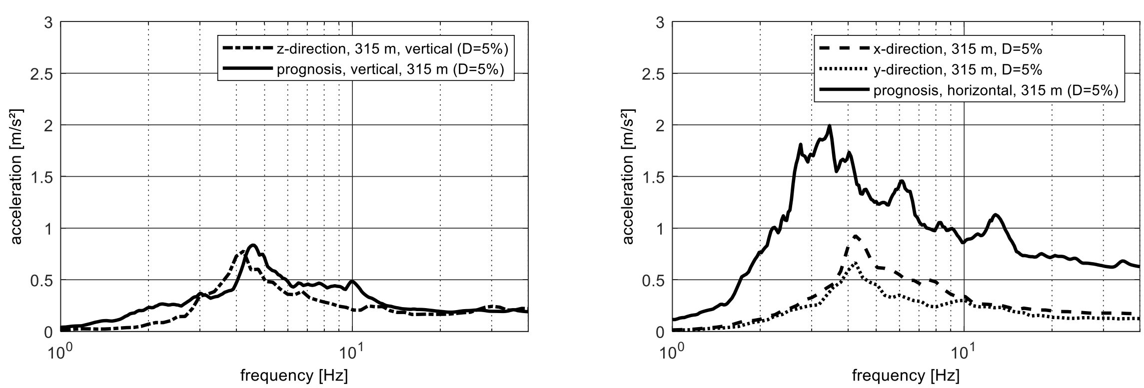

Figure 9. Comparison of vibration response spectra with vibration prognosis and inspection level of NPP, D = 5 % (left: vertical direction, right: horizontal direction)

CONCLUSION

Starting from the goals and assessment methods of vibration measurements during blast demolition of cooling towers in conventional environment like coal-fired power plants the additional requirements and assessment methods for safety related buildings and components in a nuclear plant are described.

Whereas a comparison of the maximum velocities with reference values from DIN 4150-3 is sufficient in most cases, the assessment for safety related buildings in NPPs is based on the response spectra for the seismic design of the plant. Response spectra measured at free-field measuring points or on the foundations of the buildings are compared with the inspection level of the design bases earthquake (DBE). This comparison is shown in a case study of the blast demolition of two cooling towers in a nuclear power plant. All limit values were complied. No additional events have become necessary. Furthermore the prognosis method of vibrations has been validated by the measurements.

REFERENCES

Karapetrou, S., Rapps, C., Henkel, F.-O., Gündel, M. (2022). *Prognosis and Assessment of Vibration Propagation due to Blast Demolition*, Transactions, 26th SMiRT, Berlin/Potsdam, Germany, to be published

Ries, M., Feulner, M., Rapps, C., Henkel, F.-O. (2022). *Assessment of electrical components under ground vibration Loading*, Transactions, 26th SMiRT, Berlin/Potsdam, Germany, to be published

DIN 4150-1 (2001). *Vibrations in buildings - Part 1: Prediction of vibration parameters*

DIN 4150-3 (2016). *Vibrations in buildings - Part 3: Effects on structures*

DIN 45669-1 (2020). *Measurement of vibration immissions - Part 1: Vibration meters - Requirements and tests*

DIN 45669-2 (2005). *Measurement of vibration immission - Part 2: Measuring method*

KTA 2201.5 (2015). *Design of Nuclear Power Plants against Seismic Events; Part 5: Seismic Instrumentation*

KTA 2201.6 (2015). *Design of Nuclear Power Plants against Seismic Events; Part 6: Post-Seismic Measures*