TRANSPORT OF LARGE NUCLEAR POWER PLANT COMPONENTS - EXPERIENCES IN MECHANICAL DESIGN ASSESSMENT

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ABSTRACT

In the course of decommissioning of nuclear power plants in Germany large nuclear components must be transported over public traffic routes to interim storage facilities.
In dependence of classification of the package it is necessary to subject the package to different mechanical tests according to the transport regulations.
Since it concerns surface contaminated objects (SCO) or low specific activity materials (LSA), a safety evaluation considering the IAEA transport regulations mainly for industrial packages (Type IP-2) is necessary.
For Type IP-2 packages the mechanical assessment under normal conditions of transport is required - a free drop of the package onto an unyielding target and a stacking test has to be investigated.
Large components are unique packages, therefore it is not possible to choose experimental testing as assessment method. The application of a complex numerical analysis for mechanical proof is necessary.
The assessment of the loads takes place on the basis of local stress distributions, also with consideration of radiation-induced brittleness of the material and with consideration of current scientific investigation results.
The large nuclear components have typically been transported in an unpackaged manner, so that the external shell of the component provides the packaging wall.
According to the present IAEA regulations the drop position is to be examined, which causes the maximum damage to the package.
In case of a transport under special arrangement a drop only in an attitude representing the usual handling position is necessary.
The paper will represent the methods, which are used for the evaluation of the mechanical integrity of the package for transport approval and will present recent transports of a reactor pressure vessel and of steam generators in Germany.

INTRODUCTION

In the course of decommissioning of power plants in Germany large nuclear components (steam generator, reactor pressure vessel) must be transported over public traffic routes to interim storage facilities, where they are dismantled or stored temporarily.
In dependence of classification of the package it is necessary to subject the package to different mechanical tests according to the transport regulations [1].
The paper will represent the methods, which are used for the evaluation of mechanical integrity of the package for transport approval. Examples of recent large component transports in Germany (NPP Stade - steam generators transport by sea ship to Sweden, NPP Rheinsberg - reactor pressure vessel transport to ZLN interim storage) will also be presented.

PACKAGE AND CLASSIFICATION

The packages are large components of nuclear installations like e.g. reactor pressure vessels or steam generators. Due to the mass and the geometrical dimensions it is generally not possible to pack these items separately. The large nuclear components have typically been transported in an unpackaged manner, so that the external shell of the component provides the packaging wall, which have to comply with the requirements according [1]. Exemplarily the geometrical dimensions and masses of some large components and packages are shown in Table 1. These components are from early nuclear installations, therefore a bit smaller than new NPP generation components.

Table 1. Geometrical dimensions and masses of transported components

	Steam generator (NPP Stade)	Steam generator (NPP Obrigheim)	Reactor pressure vessel (NPP Rheinsberg)
Mass [Mg]	165	177	170 (incl. shielding)
Diameter [mm]	3500	3600	3250
Length [mm]	16110	15700	11163

Figure 1 shows the package of the reactor vessel from the nuclear power plant Rheinsberg which was transported by rail over appr. 300 km to the interim storage of EWN in Lubmin.

Figure 1. Reactor pressure vessel (white) including additional shielding elements and transport frame (blue) - NPP Rheinsberg (Picture: EWN)

At first the radioactive material has to be classified according [1]. The steam generators are surface contaminated objects (SCO). The reactor pressure vessels are to be classified both in the group of surface contaminated objects (SCO) and in the group of low specific activity material (LSA). Due to the available but inaccessible surfaces of the large components an exact definition of the surface contamination and thus the classification in the group of the surface contaminated objects SCO II is not reliably possible, according by [1] the transport under special arrangement has to be chosen. Competent Authority approval can be granted under these conditions when the required safety

standards can be demonstrated through alternative means. For the case, that the classification in the group of surface contaminated subjects SCO II can be shown, an industrial package of Type IP-2 [1] is required.
If dose rate values of the package are higher than maximum allowable values for a public transport, then it is necessary that additional shielding construction units are attached to the large component.

REQUIREMENTS OF THE PACKAGE FOR MECHANICAL ASSESSMENT

A package to be qualified as Type IP-2 shall be designed to meet the requirements for Typ IP-1 as specified in para. 621 [1] and, in addition, if it is subjected to the test specified in paras. 722 and 723, it should be prevent:

(a) loss or dispersal of the radioactive contents; and

(b) a more than 20% increase in the maximum radiation level at any external surface of the package.

The examinations in accordance with the paras. 722 and 723 are valid for the proof of the integrity of the package under normal transport conditions.
The examination according the para. 722 contains the drop test onto an unyielding foundation; which must meet the requirements in accordance with para. 717 [1]. The specimen shall drop onto the target so as to suffer maximum damage in respect of the safety features to be tested. For a package transport under special arrangement the drop position which results from the handling position is examined concerning the mechanical evaluation of the integrity of the package. Furthermore is to be guaranteed, that nozzles, manholes or handholes do not impact the target during drop test. This would lead to high local loadings (e.g. stresses and strains) in the package, which have to be prevently by additional constructional measures (e.g. shock absorbers around the nozzle). The free drop height of the package to be covered is dependent on the mass and is presented in Table 2 (Table 14 in [1]).

Table 2. Free drop distance for testing packages to normal conditions of transport

Package mass [kg]					Free drop distance [m]
		Package mass	<	5 000	1.2
5 000	≤	Package mass	<	10 000	0.9
10 000	≤	Package mass	<	15 000	0.6
15 000	≤	Package mass			0.3

The stacking test in accordance with para. 723 is not to be regarded for large components usually, since the size and form of these packages reliably exclude stacking. To assess the reduction of the shielding and/or a rise of the radiation level due to deformations and/or ovalization of the component, these aspects are explicitly to be determined and evaluated.

MECHANICAL ASSESSMENT

The mechanical integrity must be proved. Large components are unique packages, therefore it is not possible to choose experimental testing as assessment method.
A computational proof with analytical calculations and an evaluation of nominal stresses is not possible because of the complex geometry of the package. Approaches with simplified assumptions

do not correspond to the current state of the art. The determination of mechanical loads currently is carried out by dynamical numerical calculations e.g. application of the explicit Finite-Element-Code LS-DYNA.

Figure 2 shows an example of a numerical model simulating a reactor pressure vessel (NPP Rheinsberg). An initial velocity is applied to this numerical model, resulting from the drop height. According to the regulations [1] the drop position which causes the maximum damage at the package is to be assumed. The drop position resulting from handling position, due to the transport under special arrangement, can be assumed.

The position of the package during the transport is defined as a result of the mechanical examination. Nozzles, manholes or handholes with high local stresses must be adjusted in a manner that they do not impact the foundation.

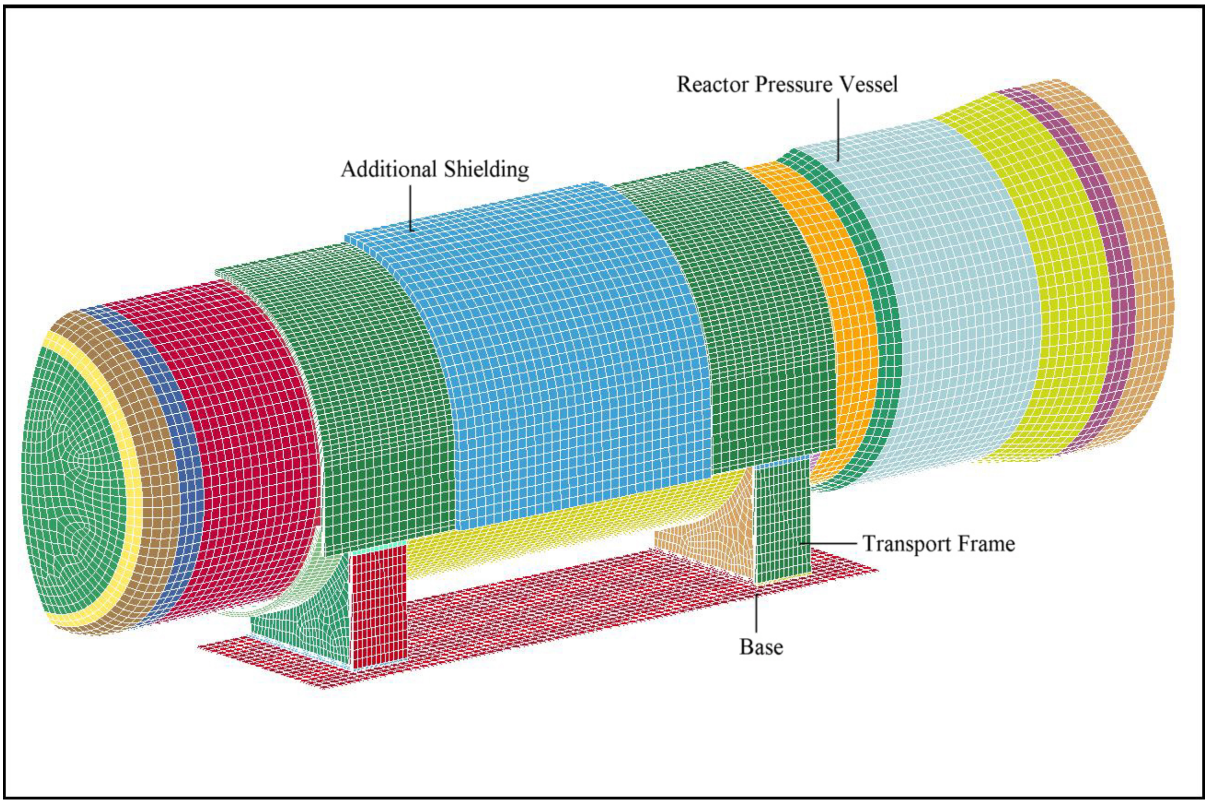

Figure 2. Finite-Element-Model of the Reactor Pressure Vessel – NPP Rheinsberg (Model created by WTI)

Since there are not any results determined from experiments in order to verify the numerical calculations is necessary to establish conservatively all physically or material parameters for the Finite-Element-Analysis used. The assessment of the determined stresses is carried out for local areas, i.e. the local stresses and strains has to be evaluated in view to maximum stresses in the wall. Global deformations are relevant for shielding assessment. Since the exact material behaviour is not known in general, elastic-plastic material behaviour with consideration of the hardening is to be considered in the Finite-Element-Analysis for stress maximizing. If the occurring plastic strains represent the decisive loading to be evaluated, the assumption of an elastic-ideally plastic material law covers. If necessary is additionally the influence of the neutron embrittlement on the current material condition is to be considered (e.g. for reactor pressure vessels). This depends on the neutron fluence and the temperature during operation time of the component. A permissible stress intensity factor is determined considering the lowest temperature of transport and the material embrittlement. This factor is compared with the stress intensity factor, which is determined from stresses of the 0.3m drop test under the assumption of an artificial flaw in the construction unit [2]. Components of the package, which are not explicitly modelled in the numerical analysis are to be considered by additional equipollent masses distribution. These components could have a substantial influence on the dynamical behaviour of the package during the 0.3m drop test. In Figures 3 and 4 the equivalent stress distribution and plastic strain distribution resulting from BAM calculations are shown for the reactor pressure vessel assessment.

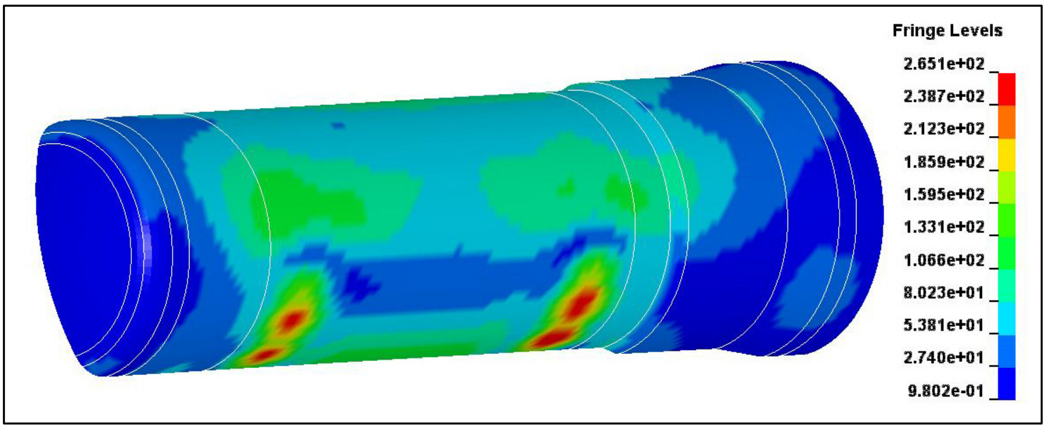

Figure 3. Von-Mises stress distribution in the outer shell of the reactor pressure vessel [MPa] – NPP Rheinsberg

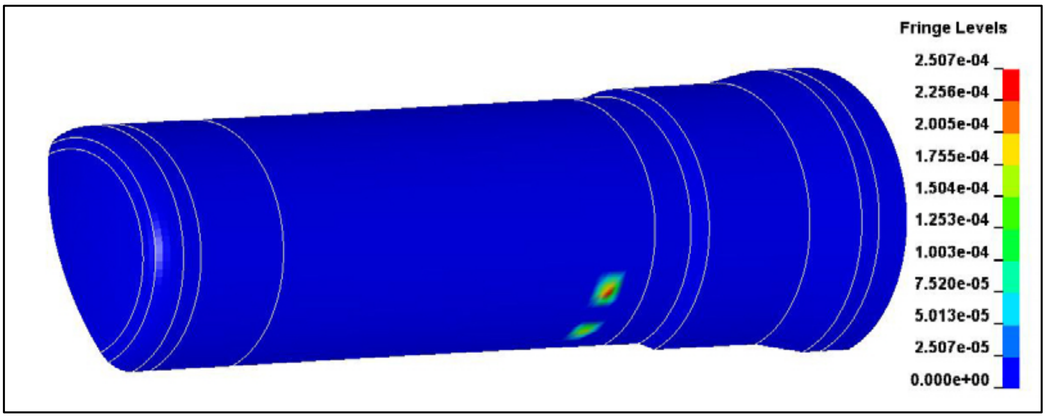

Figure 4. Plastic strain distribution in the outer shell of the reactor pressure vessel [-] – NPP Rheinsberg

During the approval process the applicant provided appropriate documents including input datas of models and calculation results to BAM. BAM assessed the numerical analysis and own parameter studies conducted.
If the component stresses are in the plastic range, the strains are to be evaluated with respect to their influence on the integrity of the package. Considering new scientific investigation results of materials for pressure vessels [3] it is possible to evaluate occurring local plastic strains. If external construction parts of the package (e.g. nozzles, manholes, handholes) are in contact with the foundation during 0.3 m drop test, high local stresses can occur. This situation should be avoided. Plastic strain distribution appearing by impact of a nozzle onto the unyielding target, is presented in Figure 5.
Plastic strains around the nozzle that occur outside of the closure plates are uncritical for the package, provided that these is no a risk for the package integrity and only large deformations of the nozzle occur. The plastic strains at the contact area between nozzle and outer shell of the vessel occur on a high level difficult to evaluate. Such a drop position must be excluded or constructive protectors (e.g. shock-absorbing components) are to be attached to the package.

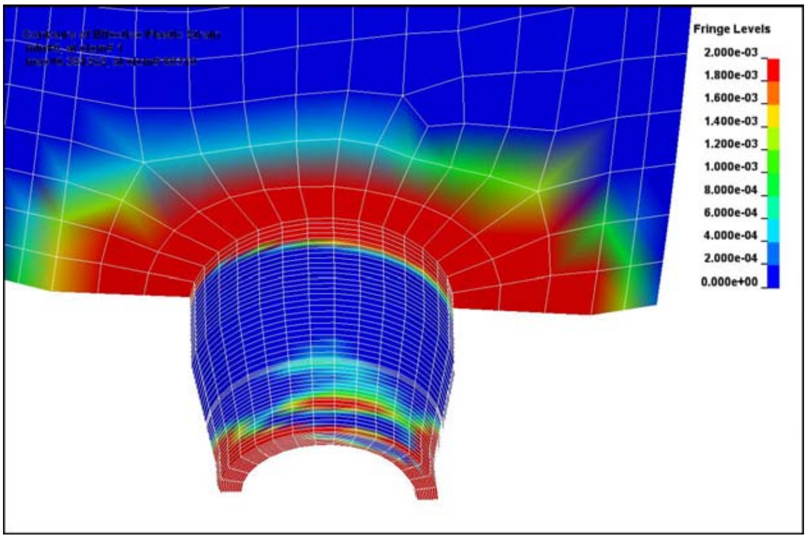

Figure 5. Plastic strain distribution at a nozzle after impact onto unyielding target [-] – NPP Stade

In the regulations [1] it is required that a loss or a dispersal of the radioactive contents must be excluded. Thus all openings such as nozzles, man-holes or hand-holes are covered with closure plates. If necessary additional shielding units are to be installed above the openings.
The proof of these components is carried out by analytically calculations with maximum acceleration values determined from Finite-Element-Analysis. The welding seams in the “package” are not explicitly modelled in the numerical calculations generally. A separated modelling of the weld is carried out depending on necessary degree of accuracy. However it is difficult to define the realistic material behaviour.
If dose rate values of the package are higher than maximum allowable values for a public transport [1], it is necessary that additional shielding construction units are attached to the large component (Figure 1). These shielding construction units have to withstand the requirements from the routine

transport conditions and/or the normal transport conditions. Occuring plastic deformations are therefore permissible, if they do not impair the shielding efficiency e.g. by large distortion.
If the package is fixed on a transport frame during transport, there is a need for evaluation, whether the package is handled with or without the frame (e.g. during reloadings). If the package is handled with the transport frame, the transport frame belongs to the package and has to be considered as package part during the 0.3m drop test. The occurring high local stresses and strains in the transport frame (plastic deformations) can be tolerated from case to case (Figure 6). Special attention must be put on the interface between the package and the transport frame. These are high local stresses.
Additionally to the numerical calculations for the 0.3m drop test and for the assessment of the resulting plastic strains, the BAM calculated the ultimate load.
With this calculation it is checked whether plastic failure of the decisive component can occur. In order to guarantee the calculation assumptions are conservative during the numerical analysis, it becomes necessary to carry out parameter studies. Thus the influence of certain parameters can be examined and evaluated.

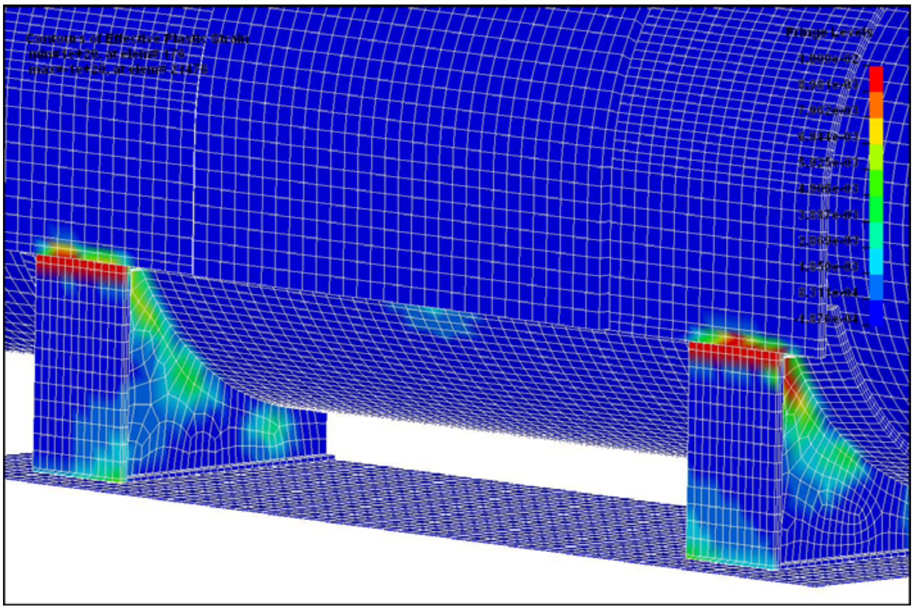

Figure 6. Plastic strain distribution at a transport frame [-]
– Reactor pressure vessel (NPP Rheinsberg)

LARGE COMPONENT TRANSPORT EXAMPLES

In the last years in Germany three large component transports over public traffic routes were realized. In the course of decommissioning of NPP Stade four steam generators must be transported over public traffic routes to interim storage facilities in Sweden by sea ship, where they are dismantled or stored temporarily (Figure 7). At the nuclear power plant site the steam generators were transported to the river Elbe by truck and loaded onto a sea ship.
During the second transport a reactor pressure vessel was transported from the nuclear power plant Rheinsberg (in the north of Berlin) to the interim storage facility in Lubmin (Figure 1). The reactor

pressure vessel was shipped from the area of the nuclear power plant by railway to storage facility. At the area of storage facility the transport was carried out by a truck.

In a third transport two steam generators were transported from NPP Obrigheim to the storage facility in Lubmin by an inland waterway vessel.

CONCLUSIONS

The number of transport of contaminated large components of nuclear installations over public traffic routes will increase in the future due to the dismantling of nuclear installations.

Since physical drop tests are impossible generally due to the uniqueness of such "packages", a calculation has to be performed, preferably by a complex numerical analysis. This procedure corresponds to the current state of the art of technology. Since there are not any results determined from experiments in order to verify the numerical calculations is necessary to establish conservatively all physical and/or material parameters in Finite-Element-Analysis. An assessment of the occurring mechanical loadings is carried out in view to local stress and/or strain distributions, of the material state and the limiting operation conditions. Since due to inaccessible surfaces the limiting dose rate values cannot be exactly determined for a classification in SCO and the examined drop position corresponds to the handling position of the package, therefore these large components are transported under special arrangement [1].

Figure 7. Steam generators (NPP Stade) inside the hold of SIGYN sea ship

REFERENCES

[1] International Atomic Energy Agency (IAEA), Regulations for the Safe Transport of Radioactive Material, 2009 Edition, Safety Standard Series No. TS-R-1, Vienna, 2009

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[3] Forschungszentrum Karlsruhe, Wissenschaftliche Berichte, FZKA 6854, Limit Strains for Severe Accident Conditions, Final Report of the EU-Project LISSAC, Contract No. FIKS-CT1999-00012, October 2003