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Research

A Model Study of Costs Estimates of Decontamination and Decommissioning with an Emphasis to Derive Cost Functions for Alpha-Contaminated Material Using OMEGA Code

Kristina Kristofova
Vladimir Daniska
Frantisek Ondra
Ivan Rehak
Marek Vasko

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SKi

SKI perspective

Background

The nuclear power utilities in Sweden must under the so-called "Studsvik Act" [1]contribute with 0,15 öre (approximately 0,02 European cents) per kWh produced by nuclear power to the Swedish Nuclear Waste Fund. This part of the financing system was resolved by the Swedish parliament for the future expenses of decontamination and decommissioning of older Swedish research nuclear reactors and certain objects at the Studsvik site. The task to accrue and fund appropriate capital is based on the reliability, objectivity and long term sustainability of cost estimates for decontamination and decommissioning of individual facilities.

The validation of cost estimates must therefore be done on a continually basis so that contemporary comparative costs is derived. This mode of analysis may be regarded as a consistency test of the appropriateness of the cost estimates.

Purpose of the project

The aim of this applied study has been to describe and derive cost function for alpha-contaminated parts with the application of an analytical model, i.e. the OMEGA code.

Results

The presented results of decommissioning cost calculation for the decommissioning planning phase using OMEGA code can be summarised into inter alia the following four statements.

- The comparative calculation shows that nuclide vectors with non-alpha contaminants and no fission products gives significantly lower decommissioning and dismantling costs. Besides, this cost tends to decline progressively over time.
- Successively higher levels of contaminations has a tendency to an increased ratio of remote controlled dismantling to hands-on dismantling, which in turn will enhance the overall decommissioning costs and manpower.
- The general assumption that an application of pre-dismantling decontamination leads to the decrease of collective dose equivalent and to extension of hands-on dismantling instead of remote one was supported by the calculations. Consequently it can lead depending on the level of contamination to the decrease of costs and total manpower-time by as much as one ¼. However, there is an exception for pre-dismantling decontamination application in very high dose ambient (especially during preparatory activities for pre-dismantling decontamination) that can lead to significant increase in the total collective dose equivalent.
- The calculations has demonstrated that the more materials released into environment the more out-spelled is the need for post-dismantling decontamination or melting respectively.

This study demonstrates how a systematic comparative analysis of cost estimates can be done, in order to increase the traceability and reliability, to derive the shape of cost functions for dismantling and decommissioning of older nuclear facilities.

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[1] The complete name is the Act on the Financing of the Management of Certain Radioactive Waste etc. (1988:1597).

The report clearly demonstrates that it is possible to enhance and extend the present knowledge basis for cost functions by using feedback of experience in a learning loop were successful outcome will depend on the quality of the original data as well as the model used.

This report shall be seen as a contribution to active learning in the field of nuclear waste economics; that ultimately will help to improve the quality of estimates of decontamination and decommissioning cost so that a more reliable estimate can be presented on successive higher confidence levels in the early planning stages of decommissioning projects.

Continued work

This study indicates that there exists a need to develop a more comprehensive platform for systematic procedures for how decommission cost data can be analysed and compared in a clearer and more traceable manner. It is generally accepted that neutral and appropriate estimates must be based on a comprehensive and clear method and it therefore beneficial to further evaluation of the accuracy of the OMEGA code by an authentic study of one Swedish nuclear facility.

Effects on SKI work

SKI will be able to draw inferences from this study in the annual monitoring of cost estimates which are presented by the company AB SVAFO in late April every year.

Project information

At SKI Staffan Lindskog has been responsible to supervise and co-ordinate the project. Kristina Kristofova, Vladimir Daniska, Frantisek Ondra, Ivan Rehak and Marek Vasko at DECOM, Slovakia, have mastered to accomplished the research task.

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Frantisek Ondra
Ivan Rehak
Marek Vasko

DECOM SLOVAKIA spol. s r.o.
J. Bottu 2
917 01 Trnava
Slovakia

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ABSTRACT

The presented study is focused on model decommissioning cost calculations for primary circuit of A-1 nuclear power plant in Jaslovske Bohunice. In addition, the survey of advanced decommissioning costing is included together with impact analyses of contamination on particular decommissioning parameters.

OMEGA code decommissioning cost calculations for primary circuit of A-1 NPP presented in the study are performed and evaluated under the following conditions:

- different contamination level of inner and outer surfaces
- different waste management scenarios
- application and non-application of pre-dismantling decontamination
- different start of decommissioning: 2004, 2010, 2020, 2030, 2040
- radionuclide composition of primary circuit contamination in A-1 NPP with occurrence of alpha radionuclides and fission products as a consequence of operational accident with damaged fuel cladding
- radionuclide composition of primary circuit contamination in V-2 NPP in Jaslovske Bohunice as a representative NPP with an operation without accidents and therefore neither non-alpha contaminants nor fission products are included.

The results of all the above mentioned conditions impacts on calculated costs, manpower, exposure and distribution of materials arisen from decommissioning are evaluated in detail within the calculation sensitivity analysis.

ABSTRAKT

Predkladaná štúdia je zameraná na modelové výpočty parametrov vyraďovania primárneho okruhu jadrovej elektrárne A-1 v Jaslovských Bohuniciach. Okrem toho, v štúdii sú uvádzané princípy súčasných metód oceňovania nákladov na vyraďovanie a hodnotený je vplyv kontaminácie na jednotlivé parametre vyraďovania.

Pomocou kódu OMEGA boli vypočítané a analyzované rôzne kombinácie variantov vyraďovania primárneho okruhu JE A-1, pričom bola uvažovaná:

- rôzna úroveň kontaminácie vnútorných a vonkajších povrchov,
- rôzne scenáre spracovania odpadov,
- aplikácia resp. neaplikácia preddemontážnej dekontaminácie,
- rôzny začiatok vyraďovania: 2004, 2010, 2020, 2030, 2040,
- rádionuklidové zloženie kontaminácie primárneho okruhu JE A-1 s výskytom alfa rádionuklidov a štiepnych produktov ako dôsledok prevádzkovej havárie s porušením pokrytia paliva,
- rádionuklidové zloženie kontaminácie primárneho okruhu JE V-2 v Jaslovských Bohuniciach reprezentujúcej elektráreň s bezporuchovou prevádzkovou a teda neobsahujúcou medzi kontaminantami ani alfa rádionuklidy ani štiepne produkty.

V rámci citlivostnej analýzy výpočtov vyraďovania boli pre všetky uvedené zmeny vstupných parametrov podrobne zhodnotené náklady, prácnosť, ožiarenie a distribúcia materiálov z vyraďovania.

1. ABBREVIATIONS

CDE	-	Collective dose equivalent
FRC	-	Fibre reinforced concrete
HWGCR	-	Heavy water moderated gas cooled reactor
NPP	-	Nuclear power plant
PSL	-	Proposed Standardised List of Items For Costing Purposes in the Decommissioning of Nuclear Installations
RAW	-	Radioactive waste
SKI	-	Swedish Nuclear Power Inspectorate
WBS	-	Working breakdown structure
WWER	-	Water moderated water cooled power reactor

2. INTRODUCTION

A presented „Model study of cost estimates of decontamination and decommissioning with an emphasis to derive cost functions for alpha contaminated material using OMEGA code“ is the result of pilot project on decommissioning costing between Swedish Nuclear Power Inspectorate (thereinafter SKI) and DECOM Slovakia. The primary objective of the study is to provide information on cost structures for decommissioning and decontamination of older nuclear facilities.

The study is focused on decommissioning cost calculations for A-1 nuclear power plant (NPP) primary circuit in Jaslovske Bohunice. In addition, the survey of advanced decommissioning costing is included together with qualitative and quantitative impact analyses of contamination on decommissioning parameters.

A-1 NPP in Jaslovske Bohunice is an example of NPP with a non-standard radiological situation, as it was finally shutdown after an accident. Therefore, selected primary circuit of A-1 NPP as a subject of decommissioning cost calculations, is characterised mainly by alpha-contaminated material.

In order to perform and evaluate a set decommissioning calculations for primary circuit of A-1 NPP in Jaslovske Bohunice, an OMEGA code was applied - a decommissioning planning tool, developed by DECOM Slovakia in the frame of the technical support for project management of NPP A-1 decommissioning. The main purpose of OMEGA (Oracle Multicriterial General Assessment of Decommissioning) code applications for decommissioning planning of nuclear facilities is to find an optimal mode of decommissioning activities. Analysing various waste treatment scenarios and time structure of decommissioning under the same input inventory conditions can be done effectively using an instrument based on linking of decommissioning material flow items in calculation process together with radiological parameters of these material items.

OMEGA code decommissioning cost calculations for primary circuit of A-1 NPP presented in the study are performed and evaluated under the following conditions:

- different contamination level of inner and outer surfaces
- different waste management scenarios
- application and non-application of pre-dismantling decontamination
- different start of decommissioning: 2004, 2010, 2020, 2030, 2040
- different radionuclide composition of contaminated material, so called nuclide vectors: alpha or non-alpha contaminated surfaces.

The results of all the above mentioned conditions impacts on calculated costs, manpower, collective dose equivalent and distribution of materials arisen from decommissioning are subsequently analysed and discussed within the calculation sensitivity analysis.

3. ADVANCED DECOMMISSIONING COSTING (A SURVEY)

Principles of current costing methods in decommissioning are briefly described and survey of advanced costing methods based on standardised costs structure for decommissioning, on calculation modelling of material and radioactivity flow in decommissioning process and on dynamical radiological calculation are presented. The advanced decommissioning costing methods were used in this study.

3.1 CURRENT COSTING METHODS IN DECOMMISSIONING

Estimating of parameters of decommissioning is one of the main issues in preparatory phases of decommissioning. The main aim of these activities is to prepare a file of qualified data like costs, exposure, duration, amount of waste, manpower, personnel and equipment needed, etc. Based on this qualified data, the decommissioning process can be planned to be performed:

- Safely - with minimal influence on personnel and environment
- Economically - with costs and resources optimized option of decommissioning
- In due time - according to time optimized option of decommissioning

Typical current decommissioning costs estimation methods are based on unit cost factors approach which has following main steps [8]:

1. Definition of cost categories. In typical decommissioning projects, costs are classified into three categories:
    - Activity-dependent costs which are directly related to the extent of “hands-on” work involved, e.g. dismantling, decontamination, processing of waste, etc. (proportional to the extent of if input parameter - mass, surface, volume, ...)
    - Period-dependent costs which are proportional to the duration of individual activities, phases of project or whole project
    - Collateral costs and costs for special items which can be characterized mostly by a fixed cost value
2. Identification of decommissioning activities in a technical plan with identified discrete elementary activities for which unit costs are defined. The list of activities must be completed with a plant buildings and equipment inventory in order to define the extent of each activity.
3. Definition of unit cost factors in accordance to the detail of the items considered in the plant inventory and in the activity listing of the decommissioning project. Cost unit factors can be defined for ideal working conditions and a set of various coefficients or correction factors are assessed that reflect the specific working conditions (radiation, working height, etc.).
4. Project scheduling with calculated duration of individual work phases in a decommissioning project, based on the plant inventory and critical path identification. The time schedule is produced for different phases of the decommissioning project as well as for the entire project which may be used as a basis for estimating the period-dependent decommissioning costs. An additional estimate is required to define the size of the staff involved in management, administration and other supporting activities. The relation between period-dependent costs and activity-dependent costs may give rise to a need for optimisation.
5. Collateral costs and costs for special items definition which are not dependent neither on the level of activities, nor on the duration, like cost for heavy equipment for site support, health physics equipment and supplies, licenses and permits, costs for lighting, heating or cooling, income from sold equipment or scrap, etc.
6. Total costs estimate obtained as a sum of the costs estimated in the three categories. In general, the activity-dependent costs are calculated on the basis of activity lists, plant inventories and unit cost factors. The period-dependent costs are calculated on the basis of estimates, project schedules and staff requirements, while the collateral costs are assessed separately for each item. Before summing up, the cost estimates may be adjusted to include a contingency that reflects the level of uncertainty in the estimates. A general contingency expressed in some special cost items may be applied to the total cost estimate in this phase.

3.2 ADVANCED DECOMMISSIONING COSTING - A REVIEW OF PRINCIPLES

The structure of calculated costs in current costing methods is in general country specific, company specific or even decommissioning project specific. Therefore the comparison of total costs and costs sub-items may cause problems which give rise to request for unification of the cost structure. The first and most important feature of the advanced costing is the implementation of standardised cost structure for decommissioning This could improve the uniformity of presenting the costs for decommissioning and clear many inconsistencies or contradiction of results of costs evaluations.

Other features of advanced costing refer to effort to achieve higher accuracy of cost calculation. One of the main part of the decommissioning cost are the costs for complete management of radioactive waste for decommissioning. New methods of calculation modelling of material and radioactivity flow in decommissioning process and methods of dynamical radiological calculation can improve substantially the accuracy of cost calculation and at the same time they can be used for optimisation of management of radioactive waste.

Effective optimisation of overall option of decommissioning or their sub-parts requires the on-line data link between the cost calculation code and the tool for optimisation so the advanced costing refers also to methods of on-line optimalisation. The selection of the most optimal option of decommissioning can be supported by sensitivity analysis for finding the margins of costs under various input conditions like contamination, start date of decommissioning, technology available etc.

Generally, the advanced decommissioning costing refers to following main issues:

- Standaridsed decommissioning cost calculation methods and other aspect of standardisation
- Algorithmisation of material and radiological aspects of decommissioning
- The decommissioning working breakdown structure and methods of on-line optimisation
- Sensitivity analysis

This four listed issues of advanced decommissioning costing which have to relevance to this study will be discussed in following chapters. To the aspects of advanced decommissioning costing also other issues like management of contingencies and uncertainties in calculation results or implementation of cost tracking system could be assigned but they will not be discussed here.

3.3 STANDARDISED DECOMMISSIONING COST CALCULATION

3.3.1 Proposed Standardised List of Items for Costing Purposes

Three dominant European organisations in decommissioning - OECD/NEA, IAEA, EC agreed on common effort in definition of cost items of decommissioning. The main reason for this step were significant inconsistencies in presented costs of various decommissioning projects, caused by different definition of extent of decommissioning, technical factors, time structure, waste management systems, local working force factors, financial factors, etc. The result of this common effort is the document “A Proposed Standardised List of Items for Decommissioning Purposes” [2], which represents a list of categorized decommissioning activities. The main purpose of the Proposed Standardised List (PSL) is:

- To facilitate communication
- To promote uniformity
- To encourage common usage
- To avoid inconsistency or contradiction of results of costs evaluations
- To be of world wide interests to all decommissioners

The structure of standardized structure of cost items at the first numbered level is following:

01 Pre-decommissioning actions
02 Facility shutdown activities

03 Procurement of general equipment and material
04 Dismantling activities
05 Waste processing, storage and disposal
06 Site security, surveillance and maintenance
07 Site restoration, cleanup and landscaping
08 Project management, engineering and site support
09 Research and development
10 Fuel and nuclear material
11 Other costs.

The structure is numerically categorized up to the third level and for the lowest level the content of each item is defined, it means the relevant decommissioning activities are listed. From this level lower, the structure is open for supplement numerical categorization which was also used in the calculation code Omega. The standardized structure defines also four costs groups:

- Labour costs
- Capital, equipment and material costs
- Expenses
- Contingency.

3.3.2 Principles of implementation of standardised decommissioning cost calculation structure

The decommissioning activities identified in Proposed Standardised List (PSL) of Items for Costing Purposes [2] are the base for constructing the structure of decommissioning calculation options. The lowest numerical level in PSL is further extended according to the list of activities defined at the lowest level. This structure can be defined as static PSL structure and has a typical tree structure. At the lowest numbered level are allocated relevant calculation procedures which are used for calculation. For homogeneous decommissioning activities are defined modes for further extending of the calculation structure, for example dismantling calculation items according to the number of database inventory items in the room. This sub-trees extensions are based on inventory data and generally they have the structure building object - floor - room - equipment. Other types of sub-trees extensions could be defined, for example based on inventory items marked by PSL identification number.

The static calculation structure of a decommissioning option can be created by the user based on set of template PSL static structures. The user can modify, extend or shorten the selected template structure depending on extent of the decommissioning option.

The structure used for calculation, the executive PSL calculation structure is created based on static calculation structure of the calculation options completed with a plant buildings and equipment inventory in order to define the extent of each activity (see point 2 of the chap. 3.1). In this calculation structure are generated also input data points from which the user can manually enter user defined calculation parameters (for example definition of personnel for time dependent activities) or modify the input calculation parameters which are calculated (for example manpower correction coefficients).

The extent of calculation should be defined in the executive calculation structure. This can be achieved by including the individual calculation items or groups of calculation items into the executive calculation run.

3.4 ALGORITHMISATION OF MATERIAL AND RADIOLOGICAL ASPECTS IN DECOMMISSIONING COSTING

The flow of materials and radioactivity in decommissioning process and calculation of relevant costs for management of radioactive waste up to their final disposal can be typified for the same types of NPP's based on analysis of decommissioning projects already completed. Total costs for management of waste represent a significant part of total decommissioning costs. When calculating the decommissioning parameters for a NPP with non-typified situation, significant inaccuracy could be introduced into the final costs, because the input conditions are not sufficiently algorithmised in the calculation process. The accuracy of calculated costs for management of waste can be enhanced by calculation modelling of material and radioactivity flow throughout whole decommissioning process. This modelling results in creating a direct calculation link between the input inventory parameters and calculated parameters.

This case is for example the situation of a NPP shutdown after an accident when it is required to find an optimal mode of decommissioning. Analysing various waste treatment scenarios or time structure of decommissioning under the same input inventory conditions can be done effectively using an instrument based on linking of decommissioning material flow items in calculation process together with radiological parameters of these material items.

3.4.1 Material aspects of decommissioning costing

Qualitative and quantitative characteristics of input inventory material items to be decommissioned have influence on output parameters of the decommissioning process. Weight/volume/surface and radioactivity are those input inventory material parameters, that effect on output parameters such as costs, duration, personnel needed, collective dose, production of secondary radioactive waste, spent material, etc. Time of execution of each elementary decommissioning process has influence on above mentioned output parameters too, because of time decrease of radioactivity.

Two ways of output parameters calculation exist in general. The first one takes into account elementary decommissioning process input parameters of weight/volume/surface of input inventory item. The level of input inventory item radioactivity is taken into account in the case of material sorting after dismantling only. Dismantled material is sorted according to the level of activity into the few groups related to the proposed way of processing (material to be released directly or decontaminated and subsequently released or disposed). In the case of secondary radioactive waste processing input parameters of weight/volume are take into account only. No serious interactions between elementary decommissioning processes exist from the point of view of radioactivity of processed material, so the calculation can be called off-line calculation. Decommissioning parameters calculated by this method have in general lower accuracy, but on the other hand they are satisfactory in the case of overview decommissioning study estimation.

The second way of the output parameters calculation is based on the fact, that parameters of weight/volume/surface and radioactivity of various nuclides are calculated and stored for each decommissioned material item in each elementary decommissioning process. Time dependent radioactivity decrease, decontamination factors and nuclide resolved limits are taken into account for each material item during the process calculation. This calculation process models the decommissioning process close to reality and results with higher accuracy can be obtained. Moreover, collective dose and volume aerosol activity in each process is calculated due to nuclide resolved calculation. Time development of the decommissioning processes is registered and stored, so the time dependence graphs of various output parameters can be visualised. This type of calculation is based on interactions between elementary decommissioning processes via decommissioned elementary material item parameters of weight/volume/surface and activity. The calculation process can be called on-line calculation. The principle mentioned above and applied in the second way of calculation is called integral material and radioactivity flow control in decommissioning process.

3.4.2 Radiological aspects of decommissioning costing

Composition and level of radioactivity (contamination, induced activity) can vary from building to building, from equipment to equipment within the same nuclear installation. Character and level of radioactivity can have essential influence on decommissioning work to be done (dose rate, radiation protection measures, technology used, etc.), on amount and category of resulting radioactive waste, on choice of technology for waste treatment and conditioning, on demand of volume in repository, etc. Sufficient data on contamination/induced radioactivity, on amount and categories of radioactive waste for NPP’s shutdown after normal operation can be based on radiological measurements, activation calculation and data from evaluated decommissioning projects of similar or of the same reactor type. Together with material and building inventory of the NPP to be decommissioned, more or less accurate calculation of costs and other calculation parameters can be done even without a direct calculation link between the contamination/activation and calculated parameter, because the amounts and categories of waste can be established as input parameters before the calculation.

The situation can be different in the case of a NPP which was shutdown after a non-standard situation or an accident during the operation. The costs of decommissioning can then depend strongly on the character and level of contamination. The amounts and categories of resulting waste can be difficult to estimate. In this case it is desired to have a direct calculation link between the input radiological parameters and calculated parameter. This link can be done by calculation modelling of radioactivity distribution in individual decommissioning activities up to the disposal of conditioned radioactive waste.

The important points of radioactivity and material flow in decommissioning activities like generation of waste during dismantling, input of waste into the treatment or conditioning processes, disposal of conditioned waste, release of material, etc., can be characterized by a set of data resolved according to individual nuclides. Together with character of nuclide distribution in a partial decommissioning activity/process considered, it is possible to define the calculation link between the original contamination and calculated parameter.

This direct calculation link can be also used in optimising/choice of most suitable technology for treatment and conditioning of waste and other contamination dependent decommissioning activities.

Another radiological aspect of decommissioning is the time decay of radioactivity in the case of decommissioning options with deferred dismantling. In this case the direct calculation link between the radiological parameters as input variables and calculated parameters together with on-line calculation of radioactivity decay in individual calculation steps, can be used for optimisation of duration/extent of safe storage.

Radiological parameters are bounded to material items and unambiguous material linking enables to follow the radioactivity distribution and decay in whole decommissioning process. When radioactivity decays, radioactivity distribution coefficients (based for example on decontamination factors) and nuclide resolved limits are taken into account for each material item considered during the calculation process, models of decommissioning process close to the reality can be created.

3.4.3 Tools for algorithmisation of material and radioactivity flow in decommissioning and for dynamical radiological calculations in costing

Main tools for organizing the material and accompanied radioactivity flow in calculation process are following:

- Tools for material decomposition
- Tools for material procedure input/output definition
- Definition of material procedures calculation sequence
- Scenarios for treatment and conditioning

Tools for material decomposition provide decomposition of technological equipment/building inventory data into elementary material items according to category of inventory equipment/building database item in the frame of a calculation procedure for dismantling or demolition. Technological equipment/building database items are described by physical parameters (weight, inner/outer surface, inner/outer surface contamination, induced activity and nuclide vectors representing nuclidic content of the contamination/induced activity) and by a material category which defines set of elementary material items, which the category consists of, material types of these items, ratio of elementary material item physical parameter to equipment/construction physical parameter for each item.

Tool for material procedure input/output is based on the fact, that each procedure representing radwaste processing has a default set of material inputs and outputs, i.e. input material items acceptable to the procedure and output radwaste material items as a product of processing.

Definition of material procedures sequence is based on the principle, that each output material item is input material item of just one procedure at all. Thus unambiguous material sequence can be created for modelling material flow in decommissioning process from pre-dismantling decontamination up to the material release or radwaste disposal. The prescribed calculation sequence which respects this material flow is defined in static calculation structures. Based on this, alternative scenarios were defined according to available radwaste processing technologies. Proper scenario can be selected by the user in the calculation process.

Main tools for dynamical radiological calculations in costing - processing of radiological parameters linked to material flow items and for dynamical radiological calculation are:

- Nuclide vectors
- Distribution coefficients
- Limits and sorters
- Time decay.

Composition of input material inventory contamination, induced activity and dose rate in the facility database of the code are characterized by nuclide vectors which describe the relative contribution of individual radionuclides on total contamination, induced/mass radioactivity or dose rate. Together with total value of contamination, induced radioactivity or dose rate (facility inventory database or interim data for processed waste items) and the actual date of creating the nuclide vector it is possible to recover the actual radiological data of individual radionuclides. These kinds of data are in the calculation used for check of limits defined for nuclides and for calculation of radioactivity/dose rate decrease in time.

Distribution coefficients (based for example on decontamination factors) realise the distribution of radioactivity within actual decommissioning calculation procedure, i.e. distribution of radioactivity of the input material type into the radioactivity of the primary/secondary output material type(s). Distribution coefficients take into consideration:

- Type and properties of the material procedure
- Properties and nature of the primary/secondary output material type
- Type and properties of individual radio nuclide - gaseous, volatile, insoluble etc.

Limits and sorters realise the distribution of radioactivity among the individual decommissioning calculation procedures. Two basic types of nuclide resolved limits are used in calculation code:

- Limits for material release/radioactive waste disposal:
    - surface contamination of released solid materials
    - mass radioactivity of released solid materials
    - volume radioactivity of released liquids
    - volume radioactivity of the inner content of disposal containers
- Technological limits which define the radiological properties of materials entering the technological equipment (surface contamination or volume radioactivity limits)
- Radioactivity sorters sort the material items in a material calculation stream on the basis of the compliance with radioactivity limits in two steps:
- Update of radioactivity of the material to the time of radioactivity check - actual date of the calculated procedure (for example when material enters the technological processing) or date of check in other calculation items (for example time of future releasing of the material)
- Comparison of radioactivity of material (recovered to the time of radioactivity check) with limits. If the radioactivity of material is in compliance with limits, material is transferred into first output material stream, otherwise material is transferred into second output material stream
- Calculation recovery of nuclide resolved radiological parameters in relevant calculation procedures, due to natural decay, is a general tool which enables to asses and optimise on-line the quantity of radioactive waste in individual waste categories (interim categories and disposal categories), quantity of materials released into environment, method of dismantling, duration of long term periods in the case of deferred dismantling, etc.

3.5 THE DECOMMISSIONING WORKING BREAKDOWN STRUCTURE AND METHODS OF ON-LINE OPTIMISATION

3.5.1 The project specific working breakdown structure

The real sequence and structure of decommissioning activities in the working breakdown structure (WBS) of a decommissioning project is different from the PSL structure. The PSL structure is a structure with fixed items while the WBS can be project specific, option specific or facility specific and can vary significantly from one decommissioning project the other. The WBS reflects the real sequence of decommissioning activities and therefore the optimisation of a decommissioning option refers to the optimisation of resulting WBS.

The PSL executive calculation structure is generated based on template PSL structure and on the inventory of the decommissioned facility. The decommissioning activities in the executive calculation structure are repeated in accordance with the inventory, for example the dismantling activities are repeated for each inventory item in the room. The number of calculation items in the resulting executive calculation structure can reach the level of 10^5 to 10^6 items and even more, depending on the extent of the inventory of the facility. It is practically impossible to manage such a huge extent of calculation items manually. Therefore the grouping of the items of the standardised calculation structure and converting them into another structure reflecting the real sequence of decommissioning activities is inevitable from two points:

- to manage the calculation items, at least in the definition of the start dates of individual calculation items on the most detailed level
- to create a user defined project specific working breakdown structure to enable the project scheduling and time optimisation of the working breakdown structure of the calculation option.

WBS has in general the building object – floor - room oriented structure. The main decommissioning activities like dismantling, decontamination of building surface, radiation survey are organised generally according the room structure of the facility. The lowest level of the WBS can then group all relevant activities related to the room. For example in the case of dismantling the grouping into one item of the WBS covers all individual preparatory activities in the room, calculation items for dismantling for all individual inventory item in the room and all activities after the dismantling in the room. The duration of such an item of the WBS is constructed as the sum of all individual items of the calculation structure, grouped into the item of the WBS. The grouping of items of the calculation structure should therefore reflects this fact it means that only that items should be grouped which are in reality additive in time sequence.

The using the WBS is effective under the assumption that there is a direct calculation link between the data calculated during the main calculation run in the standardised calculation structure and a direct link to the inventory database. The tool in which the WBS is created should be the standard software like Microsoft Project tool for optimising of project structures.

The creation of the WBS is similar like in the case of the calculation structure. It has two basic steps - in the first step is defined the static WBS and in the second the executive WBS is created based on static WBS, inventory database and on calculated data.

3.5.2 Optimisation of the decommissioning calculation options using the working breakdown structure

Optimisation of the WBS is a process with more steps starting with definition of calculation structure:

- Definition of calculation structure - definition of calculation structure, generation of executive calculation structure, definition of extent of calculation.
- Definition of the static WBS of the calculation option
- Definition of input calculation parameters for the generated calculation structure. The parameters can be generated as default values during generation of the executive calculation structure, or can be inputted by the user or the generated default values can be modified by the user
- Definition of scenarios for management of the RA waste

- Definition of the datum for start of all decommissioning activities
- Calculation of decommissioning parameters (first calculation run). The starting date is the same for calculated items.
- Evaluation of calculation results
- Creation of the WBS of the option
- Time scheduling of the of the WBS, construction of critical path in the WBS based on decommissioning activities for which the duration is the calculated parameter (e.g. dismantling). The construction of critical path represents linking of the decommissioning activities in a sequence which correspondence with planned sequence of activities.
- Management of period-dependent activities like management, administration and other supporting activities (see chap.3.1., point 4). The management represents linking these activities to the activities on the critical path, modification of duration of these activities and modification of staff parameters involved.
- Modification of optimalisation parameters like number of working groups, number of working shifts. These parameters are modified as the input parameters of the calculation structure. The effect of this step is modifying the length of the decommissioning activities on the critical path. Other input parameters of the executive calculation structure can be modified at this step.

The end result of these steps is the WBS with defined time structure (sequence) and optimised hand-on and period-dependent decommissioning activities (chap.3.1). This WBS is then the base for defining the starting dates for individual items of the calculation structure during the second calculation run. In the second calculation run are the radiological parameters, relevant for each calculation item, recalculated for the actual stating date defined in the WBS. In this way, the decay of individual radio-nuclides is respected with all consequences on calculated parameters, so the effect of time in optimising the decommissioning option if fully implemented.

After the second calculation run, the calculated data are again evaluated and the WBS is again generated based on the new calculated data. The user has the possibility to optimise the WBS again and to repeat the recalculation and re-optimisation of the WBS up the point when the WBS has the final required structure.

3.6 METHODS OF SENSITIVITY ANALYSES IN ADVANCED COSTING

The principles of advanced costing discussed in previous chapters enable a wide and comprehensive extent of sensitivity analysis of decommissioning costs and of other decommissioning parameters. The sensitivity analysis in decommissioning costing represent the analysis of variation of selected calculation parameters when changing the input parameters. The subject of the sensitivity analysis are the main decommissioning parameters like:

- Costs in total value or costs in detailed structure
- Manpower in total value or in detailed structure of individual professions involved
- Exposure in total value or in detailed structure of individual professions involved or in detailed structure of items of the working time
- Material items of the decommissioning process – individual items during the decommissioning or materials released to the environment
- Radioactivity items on nuclide resolved level – individual radio-nuclides linked to the material items
- Disposal packages resolved for surface repository and for deep geological repository
- Effluents from the process, gaseous or liquid
- Material consumption items as input materials for decommissioning technologies applied in the processes

The input parameters varied during the sensitivity analysis could be following:

- contamination level of the equipment as defined in the inventory database for analysing the influence of contamination on total costs or on costs for individual technologies for treatment, conditioning or disposal, etc.

- start of decommissioning activities for analysing the effectiveness of deferred decommissioning activities or analysing the effect of time generally
- nuclide composition of the contamination of the equipment for analysing the effectiveness of deferred decommissioning activities combined with the deferred start of decommissioning activities
- scenarios of management of radioactive waste which reflects the real or planed technologies for treatment, conditioning and disposal for analysis of effectiveness of individual technologies for management of the radioactive waste
- application of pre-dismantling decontamination for selected parts of the technology equipment to be dismantled for analysis of effectiveness of application of the pre-dismantling from the point of view of costs, exposure or overall management of the decommissioning radioactive waste

The role of individual discussed principles of advanced decommissioning costing is then evident. The breakdown of the standardised calculation structure enables to “visualise” the cost in their inner structure related to individual items of the decommissioning technologies applied in the process. The tools of material and radioactivity flow control system and tools of dynamical radiological calculation are the prerequisite for sensitivity analysis because they create a direct link through whole decommissioning process from the first waste generating technologies like pre-dismantling decontamination up to the final disposal of conditioned waste and these tools reflects the decay of individual radio-nuclide.

The main purpose of the sensitivity analyses can be achieved by these tools it means to find out the margins of costs and to find out the behaviour of the cost under various input conditions like contamination, start date of decommissioning, technology available etc.

4. OMEGA CODE FOR DECOMMISSIONING PLANNING

The computer code OMEGA, developed at DECOM Slovakia, is an option oriented calculation and optimization code which is intended to be used in decommissioning planning phases of NPPs in Slovakia for the following tasks:

- Generating of decommissioning calculation options according to the standardised structure
- Calculation of costs and other decommissioning parameters in standardised format, evaluation and of calculated data
- Time and parametric optimization of individual calculation options
- Comparison of options and choice of the optimal one based on multi attribute analysis
- Data processing and optimization of parallel decommissioning projects which use common equipment or other resources.

Basic principles applied in the code [1]:

- The elementary activities of decommissioning options are identified and configured according to the Proposed Standardised List of Items for Costing Purposes (PSL) [2] issued commonly by OECD, IAEA and EC. A set of default calculation structures is available. Therefore, the costs and other parameters are calculated in true PSL format and no additional data reformatting or recalculation for presenting in PSL structure is needed.
- The calculation structure is generated automatically based on actual building, technology and radiological inventory database and prescribed conditions for generating introduced by the user. The generated calculation structure at the calculation level has wide range of local input calculation parameters with default values, which can be modified by the user.
- The principles of dynamical radiological calculation are applied, i.e. the recovery of the actual radiological state of the relevant inventory items related to the actual date of performance of the elementary decommissioning activity (time decay calculation for individual radionuclides).
- The code implements the nuclide resolved material and radioactivity flow control system. Together with nuclide resolved time recovery of radiological inventory items, nuclide resolved limits for disposal / treatment technologies / releasing of materials, default scenarios of treatment and conditioning of waste, a tool was created which enables the modelling the flow of materials in decommissioning process and radioactivity bounded to this materials from pre-dismantling decontamination up to disposal of conditioned waste.
- The user defined working breakdown structure (WBS) which in general is option specific, is generated automatically based on user defined grouping of individual calculation items of the standardised calculation structure and based on building inventory structure. The WBS can be transported to the standard Microsoft Project software for its optimisation and after optimisation can be transported back to the calculation code for recalculation of parameters based on WBS optimised structure.
- The multi attribute analysis tool is used for choice of the optimal decommissioning option from a set of options, based on criteria defined by the user and on total calculated parameters for each option. A set of default criteria is available.

The basic calculated parameters :

- Costs in standardised structure
- Manpower and exposure items - total values and profession resolved items
- Material items and nuclide resolved radioactivity items linked to these material items
- Time parameters - starts and duration of elementary activities and of phases of the process
- Equipment planning items.

The code implements mathematical explanation for all groups of decommissioning activities defined in the standardised structure and is continuously extended. The database of the code contains data needed for period-dependent procedures and for technological procedures like:

- pre-/post-dismantling decontamination
- dismantling (hands on, remote)

- decontamination of building surfaces
- radiological survey of building surfaces
- building demolition and landscaping
- treatment, conditioning, storage, transport and disposal of waste
- radiological measurements (technological check, releasing, waste for disposal).

During the calculation process, the computer code controls material and radioactivity flows on individual nuclide basis based on principles presented in chap. 3.4. This in-built radionuclide resolved system for material and radioactivity flow control during the calculation enables a direct calculation link between input radiological/material parameters and calculated decommissioning parameters. The tools for dynamical radiological calculation respect the time decay of individual radionuclides and a distribution of radioactivity in all essential decommissioning processes. A set of built-in waste management scenarios with pre-defined material routes is available for optimisation of waste management. This can increase the accuracy of calculated decommissioning parameters especially for NPP with a non-standard radiological situation, shutdown after an accident. The actual number of radionuclides taken into account in the calculation process is 27.

The principles of generation and optimisation of the working breakdown structure presented in chap.3.5 are implemented. The WBS can be optimised in a standard planning software Miscrosoft Project. The direct data link between the code Omega and Microsoft Project was developed which enable effective WBS optimisation.

The principle applied in the code Omega can be summarised following:

- What to do - definition of decommissioning activities in the calculation structure and definition of extent of calculation
- How to do - definition of calculation procedures and conditions for calculation (input data, correction factors, …)
- In what sequence - definition of sequence of calculation procedures for material and radioactivity flow modelling
- At what time - definition of executing time of decommissioning activities enabling the time decay implementation into calculation process (first calculation run and second calculation run, chap. 3.5).

The principles of overall work for calculation and optimisation of decommissioning calculation option, as presented in chap. 3.5 and implemented in the code Omega are summarised on Figure 1):

The principles of the sensitivity analysis presented in chap. 3.6 are fully implemented in the code, so the sensitivity analysis for various decommissioning cases can be performed effectively.

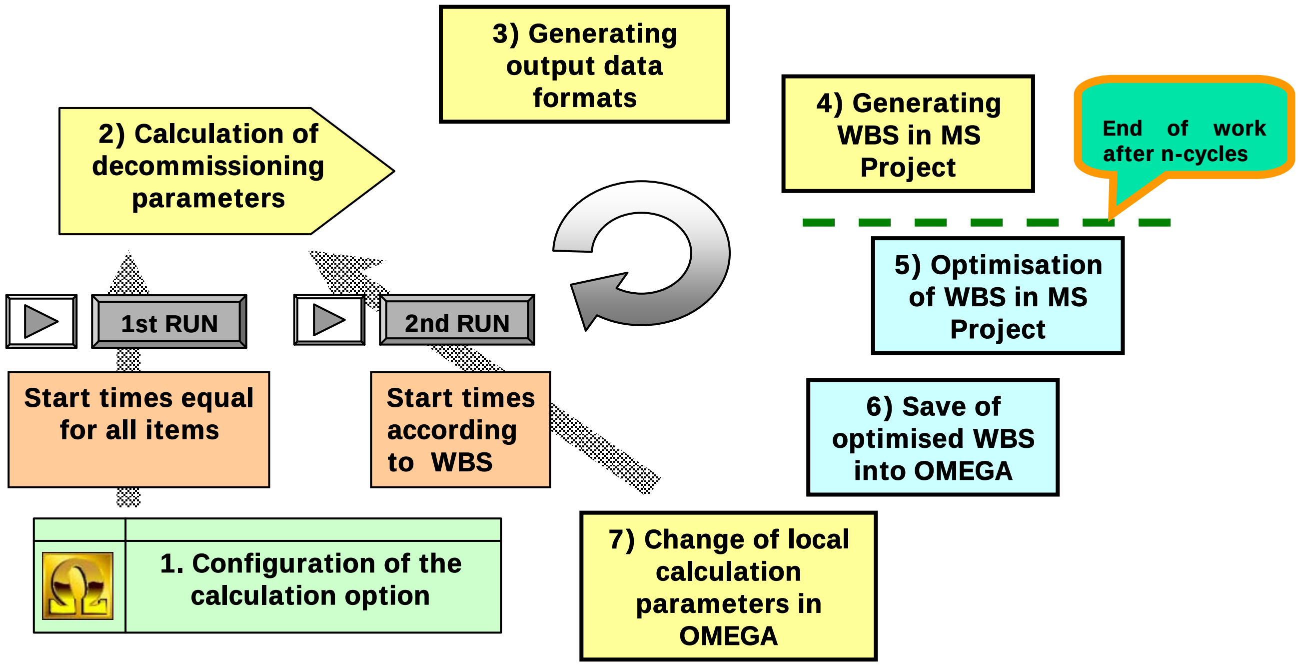


Figure 1: Schematic set of OMEGA code operations

5. IMPACT OF CONTAMINATION ON DECOMMISSIONING PARAMETERS (A QUALITATIVE ANALYSIS)

The level and nature of contamination is influenced by operational history of nuclear facility and especially by occurred incidents or accidents. Contamination of technological equipment is directly reflected in dose equivalent values and is the main source of internal exposure for decommissioning personnel. The higher surface contamination, the more expensive technological procedures and equipment for pre- and post-dismantling decontamination, dismantling, radioactive waste treatment and conditioning is necessary. At the same time, the higher contamination level, the bigger amount of radioactive waste destined for disposal that influences upon decommissioning costs. A brief analysis of contamination impacts on selected decommissioning parameters is described below:

Costs – integral parameter, sensitive to any change of input decommissioning parameters. In respect to contamination, costs are directly proportional to the level of contamination. The reason is, that the higher contamination requires in most cases application of remote controlled dismantling methods and subsequently strict safety precautions which have an impact on decommissioning cost increase. In addition, the higher contamination means the longer period of decommissioning process and more expensive waste management. When the contamination level is higher or the composition on radio-nuclides is shifted toward long-lived nuclides or alpha-nuclides then it can be expected that ratio of conditioned waste disposed at the geological repository will increase which essentially increase the costs because the costs for geological disposing are more the one order higher in comparison with the surface disposing.

Manpower – reflects overall work intensity during the decommissioning process and is influenced mainly by radiation situation and working conditions. Manpower needs are proportional to the level of contamination, as higher contamination requires enhanced safety precautions and more demanding working procedures especially for remote controlled operations.

Collective dose equivalent – basic parameter representing impact of internal and external exposure on decommissioning personnel regarding the radiation safety. In connection with the increase of contamination, the dose equivalent from external exposure is growing due to the increase of dose rate and/or time of the process. In addition, the higher contamination, the higher aerosol generation and possible higher probability of inhalation. Of course, used protective clothing and masks can significantly decrease internal exposure, however in general prolong the duration of decommissioning activities, such as dismantling. Using the remote controlled techniques reduce the exposure essentially, but the higher cost should be expected.

Duration of the process – integral decommissioning parameter influenced by partial duration of individual decommissioning activities. In general, the higher contamination, the longer duration of the process because of the more sophisticated technologies/procedures application.

Number of workers - basic parameter characterizing personal assurance of decommissioning process. Regarding the level of contamination, the number of workers is effected by applied dismantling and radioactive waste treatment technology. However, this parameter is estimated only for individual decommissioning activities and not for the whole decommissioning option.

Effluents – express the impact of decommissioning of activities on environment. The range of decommissioning activities is changing with the increase of contamination, mainly used waste treatment and conditioning technologies. Therefore, dependency of gas and liquid effluents on contamination can be different for each particular decommissioning option.

No. of containers with radioactive waste – The increase of contamination and the shift of the nuclide composition toward long-lived nuclides or alpha-nuclides causes the growth of radioactive amount, which has to be treated, conditioned, not possible to release to environment and so has to be disposed.

Amount of radioactive waste generated from decommissioning - parameter which is generally proportional to the level of contamination. The lower contamination, the higher possibility of environmental release for given material. However the amount of radioactive waste generated from decommissioning is dependent on applied methods for decontamination, radioactive waste treatment and conditioning.

6. CALCULATION SENSITIVITY ANALYSIS OF INFLUENCE OF ALFA CONTAMINATION ON DECOMMISSIONING PARAMETERS

The key chapter introducing input conditions, structure and range of selected decommissioning options in decommissioning cost calculations using OMEGA code for contaminated parts of A-1 NPP primary circuit excluding the reactor pressure vessel. OMEGA code decommissioning cost calculations presented in this chapter are performed and evaluated for:

- different contamination level of inner and outer surfaces
- different waste management scenarios
- application and non-application of pre-dismantling decontamination
- different start of decommissioning: 2004, 2010, 2020, 2030, 2040
- different radionuclide composition of contaminated material, so called nuclide vectors: alpha or non-alpha contaminated surfaces

Documented and analysed cases of sensitivity analyses and a set of decommissioning option combinations are listed in section 6.3 for the following calculated output parameters: costs, manpower collective dose equivalent, distribution of materials arisen from decommissioning and the number of containers destined to deep geological repository or surface repository.

In order to evaluate an influence of alpha contamination on decommissioning parameters, described decommissioning options were divided into two categories:

1. decommissioning options using contamination levels based on radionuclide composition typical for A-1 NPP alpha contaminated primary circuit surfaces containing fission products (Cs-137) and actinides (Pu, Am) coming from operational accident
2. decommissioning options using contamination levels based on radionuclide composition typical for V-2 NPP non-alpha contaminated primary circuit surfaces containing basic contaminants (Co-60) arisen from non-accident operation.

6.1 NUCLEAR POWER PLANT A-1

This chapter provides an information on A-1 NPP primary circuit which is subject to decommissioning cost calculations and describes the circumstances of A-1 NPP operation and final shutdown that affected its subsequent decommissioning approach.

6.1.1 Description of A-1 NPP primary circuit

NPP A-1, with the reactor KS-150 (HWGCR - natural uranium as fuel, heavy water moderated, CO_2 cooled reactor, 150 MWe - nominal electrical power output) had been the first nuclear power plant under operation in the Slovak Republic, former Czechoslovakia respectively. The sketch of A-1 NPP main operation building is displayed on **Figure 2**.

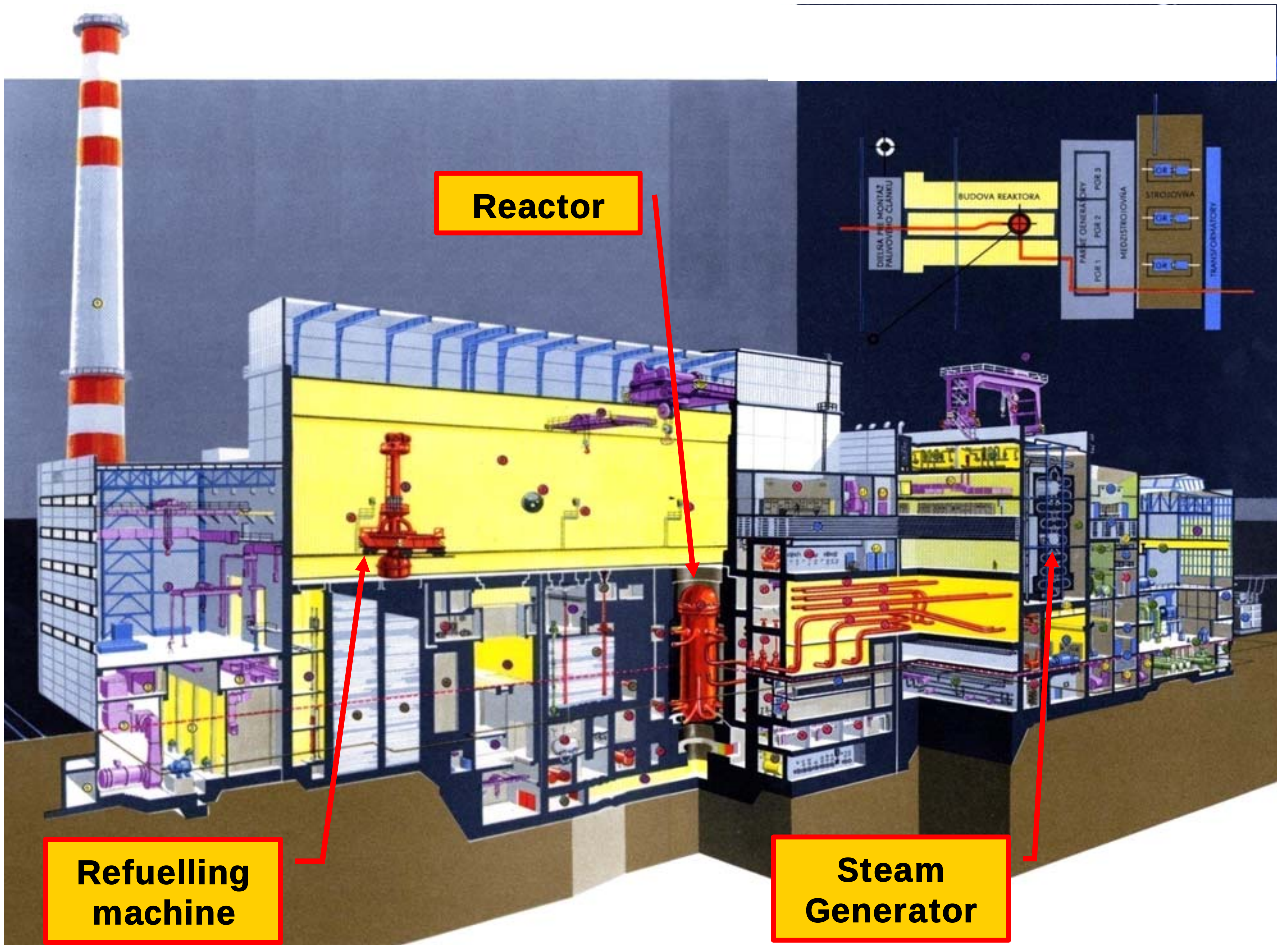


Figure 2: A-1 NPP main operation building

The primary circuit consisted of the reactor and 6 loops ensuring heat removal. The main technological parts of primary loop equipment are shortly described below as follows:

Reactor

Reactor consists of steel pressure vessel and internals. Core of reactor is formed by aluminium-magnesium-silicon alloy vessel for heavy water (D_2O) as a moderator, placed in the pressure vessel. Inlet and outlet coolant chambers, neutron and biological shielding were also located in the reactor vessel. Each fuel assembly consisted of a bundle of rods made of metallic uranium inserted in protective zirconium alloy pipe. Individual fuel assemblies were located in an independent technological channel allowing flow of carbon dioxide coolant. Refuelling of fresh fuel was secured by special refuelling machine during full reactor operation. Compensation for burn-up, fission poisoning and emergency protection were secured by cluster of control rods with cadmium as absorber. Emergency rods were hung on electromagnets and they were automatically dropped into reactor core by free fall in the case of emergency signal.

Reactor auxiliary systems

– Cooling of moderator circuit: moderator (D_2O) temperature, max. 90°C, in the reactor core was maintained by heat exchangers cooled by water from primary circuit cooling towers.
– Clean-up of moderator: continuous removal of corrosion and eventual fission products by condensation and re-evaporation.
– Incineration of explosive mixture: recombination of $D_2 + O_2$ mixture by platinum catalyst.
– D_2O system: storage and refilling of moderator to the reactor
– CO_2 system: storage and refilling of coolant to the reactor

Summary weight of D_2O and CO_2 system equipment is estimated to 55 t and inner volume to 36 m^3.

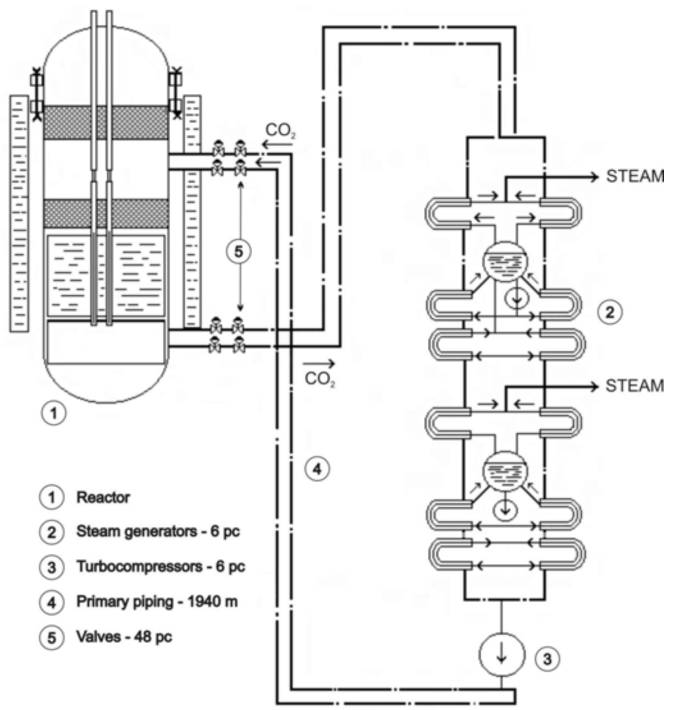
Cooling loop
The piping of each loop consisted of two seamless pipes with inner diameter 500 mm. There was one steam generator and one turbo-compressor connected to each loop. Hot gas leaving through piping from the lower nozzles of the reactor passed through main primary valves and continued to steam generator. Cooled gas was led to the turbo-compressor suction and through the turbo-compressor it was pressed to main primary valves and through upper nozzles of pressure vessel back into cold gas chamber and to the reactor core. Overall length of primary loops piping is to be about 1940 m with total weight 376 400 kg. It is thermally isolated by glass wool and covered by zinc-coated plates. Inner area of primary piping is about $3x10^7$ cm^2 and inner volume about 360 m^3. Overall weight of glass wool is estimated about 90 265 kg with 600 m^3 volume. Overall weight of zinc-coated plates is about 30 921 kg with area of 4800 m^2.

Steam generators
The steam generators were of a vertical type, composed of a huge number of U-shaped sections made by pipe-in-pipe system. The external pipe with 159 mm diameter contained 19 inner pipes of diameter 20 mm. Coolant flowed in space among these inner pipes. Internal pipes served for heating and evaporation of secondary circuit water, or for superheating of secondary steam. A two pressure system on the secondary side was selected to improve the cycle thermal efficiency. The design of steam generator enabled production of sections in series, the possibility of their exchange after accidents, assembly in blocks and transportation by railway. There are six stem generators with overall weight of 2910 t, volume of 480 m^3 and inner area $4,4x10^8$ cm^2. They are made of carbon steel.

Turbo-compressors
There are six turbo-compressors one in each primary loop. Turbo-compressors ensured gas circulation in the reactor primary circuit. They were centrifugal single-stage, with overhung impeller. Swiveling blades for regulation of the flowing amount of CO_2 were placed in the inlet orifice. The shaft was sealed by means of oil stuffing boxes. Weight of one turbo-compressor is about 20 t and it is made of carbon steel.

The above mentioned primary circuit equipment are displayed on **Figure 3**.

Figure 3: Schematic drawing of A-1 NPP primary circuit



Contaminated parts of A-1 NPP primary circuit shown in **Figure 3** excluding reactor pressure vessel are subject to OMEGA code decommissioning cost calculation, that is introduced in the following chapters.

6.1.2 A-1 NPP final shutdown

As a pilot power reactor project in Jaslovske Bohunice, A-1 NPP had been under operation from 1972 to 1977 with an average power output of 35% from nominal value. However there were relatively frequent problems during operation of A-1 NPP (mainly problems with steam generator tightness) and also two serious accidents occurred. Owing to the second accident NPP had to be shut down.

The first serious operational incident occurred in January 1976 after a refuelling procedure, when a fresh fuel assembly was ejected from the reactor and caused coolant to leak into the reactor hall. The reactor core was not damaged during the accident and NPP started to operate again after refurbishment of the damaged technological channel in September 1976.

Second serious accident happened in February 1977, when the rest of silicon absorber had been left in a fresh fuel assembly and inserted into the reactor. The silica gel reduced the gas flow rate in the fuel channel and caused a local overheating and local damage of the given technological channel. The moderator (heavy water) penetrated into the gas cooling circuit and caused large fuel cladding damage. As a result, there was an extensive contamination of the primary circuit by fission products. The accident was classified as level 4 according to an International Nuclear Event Scale (INES).

Damaged fuel cladding and also some incorrect technical procedures in manipulation with spent fuel had become the source of complicated radiological situation of the manipulation equipment and also of the spent fuel storage pond. Large volumes of liquid radioactive waste with sludge phases with activities ranging up to 10^{11} Bq/l and high transuranic content were created. Also, the partial chemical decontamination of steam generators in 1977 added to this large liquid waste volume. In addition, a typical feature of NPP A-1 was that after shutdown, there were high contamination levels on building surfaces in selected rooms plus the fact that various solid and liquid radioactive wastes from the operation were stored in many places [3]. Some of these liquid waste containers were plagued by leakage.

Restoring NPP operation meant repairing the reactor, replacing the steam generators and some other damaged equipment and systems. It demanded high investment costs. At the same time, WWER reactors were already being built. As a result of these reasons it was decided to shut down A-1 NPP in 1977.

A-1 entered the decommissioning phase in May 1979.

6.1.3 NPP A-1 decommissioning approach

Based on the technical and economic analysis results of NPP A-1 status after the accident, the government of former Czechoslovakia decided to begin decommissioning in 1979. The decommissioning process in the following 20 years had been influenced by [4]:

- unavailability of preliminary plans for NPP A-1 decommissioning
- accident during it's operation
- financial and technical constraints, mainly lack of methods and equipment for radioactive waste (RAW) treatment and conditioning, no repository available for RAW
- no decommissioning fund
- insufficient legislative background
- no decommissioning experience.

Therefore, during the period from 1979 to 1994 activities were carried out to solve the situation with spent fuel, selected radioactive wastes, selected equipment and establishing a decommissioning infrastructure - mainly development of treatment technologies and construction of a surface repository. Partial decommissioning of auxiliary systems and building objects was also achieved.

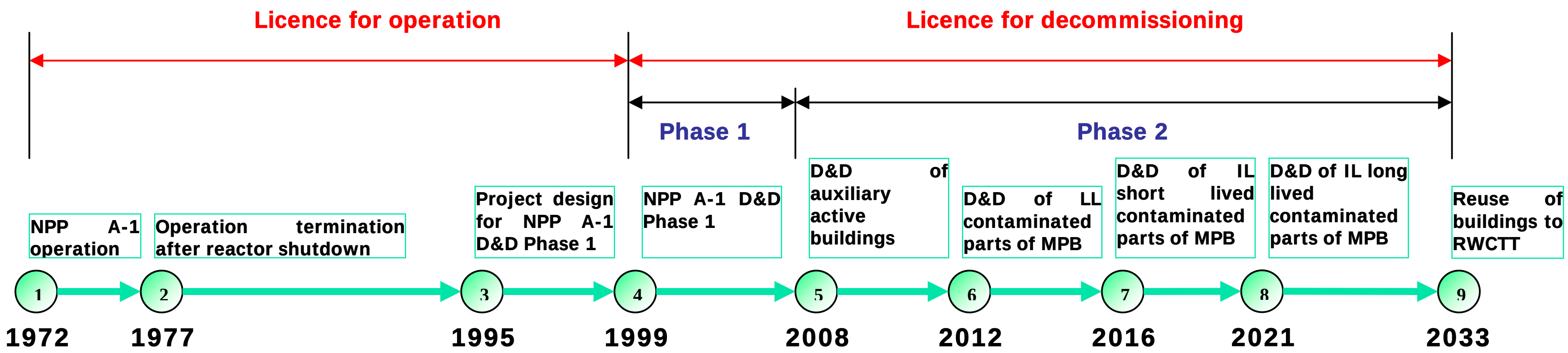
In 1994 the Project for the NPP A-1 decommissioning I. stage was developed and approved. The purpose of the project is to achieve the radiological status of NPP A-1 comparable with standard (non-accident) NPPs at final shutdown by the end of 2007.

Important milestones within the frame of the I. stage of decommissioning were achieved by the year 2000, when all spent fuel was successfully transported to the Russian Federation, a surface repository was put into operation, all main radioactive waste treatment technologies for producing final disposal packages were available, and funding and legislative framework was established.

Final decommissioning of NPP A-1 will start after 2007 using more or less standard methods and procedures based on worldwide experience and on specific conditions of NPP A-1. Within the frame of technical support of NPP A-1decommissioning (1999 – 2002) there was developed a universal computer code OMEGA (described in chapter 4) for calculating the costs and other decommissioning parameters. The code OMEGA is intended to be used for final decommissioning planning.

According to recent analysis [5], “Continuous decommissioning” is considered to be the preferred decommissioning option for A-1 nuclear power plant at present. The process of decommissioning activities within the “Continuous decommissioning” option is characterized by continuous production of radioactive waste and its subsequent treatment and conditioning to the final waste form in Fibre Reinforced Concrete (FRC) containers. The completion of “Continuous decommissioning” option is estimated in 2033, the duration of decommissioning Phase 2 is estimated to 26 years (2008 – 2033). Schematic decommissioning schedule for A-1 NPP continuous decommissioning is displayed in **Figure 4** taken from document [6]. At present, decommissioning Phase 1 is in progress (from 1999 to 2007) aiming to achieve the radiological status of A-1 NPP comparable with standard (non-accident) NPPs at final shutdown. Final decommissioning of NPP A-1 will start after 2007 using more or less standard methods and procedures based on worldwide experience and on specific conditions of NPP A-1.Since 2008, the estimated beginning of decommissioning Phase 2 (2008 – 2033), the final decommissioning of all contaminated buildings will be carried out: from less to high contaminated parts.

Figure 4: Decommissioning schedule for „Continuous decommissioning" of A-1 nuclear power plant



where:

D&D - decommissioning
LL - low level
IL - intermediate level
MPB - main production building
RWCTT - radioactive waste conditioning and treatment technologies

6.2 SUBJECT OF DECOMMISSIONING COST CALCULATIONS

Decommissioning cost calculations by OMEGA code were executed for contaminated parts of A-1 NPP primary circuit excluding the reactor pressure vessel. For these calculations, an input database of primary circuit technological equipment has been created together with its typical alpha-radionuclide composition of inner and outer contamination represented mainly by fission products and actinides coming from fuel damage accident. In order to compare the impact of alpha-contamination on calculated decommissioning costs, there were also included radionuclide characteristics of typical non-accident nuclear power plant (for this case it was V-2 NPP in Jaslovske Bohunice - WWER type 440 MWe reactor), which does not contain alpha contaminants and fission products.

This chapter also describes the range of OMEGA decommissioning cost calculations and especially considered decommissioning options with its inner structure of included decommissioning activities and the characteristics of calculated output decommissioning parameters.

6.2.1 Input technological database for OMEGA calculations

For the purpose of decommissioning cost calculations using OMEGA code, an input database of A-1 NPP primary circuit excluding reactor pressure vessel has been created. Each particular primary circuit technological or building equipment is assigned to given room, floor and building objects. At the same time, each room is characterized by several parameters, such as: identification number of the room (referring to the floor and building object), dimensions of the room and average dose rate inside the room.

In most cases, individual technological equipment located in the room correspond to particular database items. However, some technological equipment, mainly primary piping, is divided into several database items. Reason is, the different elevation position of the primary piping inside the room, which influences on calculated decommissioning parameters. Therefore the number of database items for primary piping is higher in comparison to other technological equipment. Each database item within A-1 NPP primary circuit is characterized by the following parameters:

- Identification number of technological or building equipment – identification of database item within the database
- Name of technological or building equipment
- Number of room to which technological or building equipment is assigned
- Weight of technological or building equipment [kg]
- Inner surface of technological equipment [m^2]
- Outer surface of technological or building equipment [m^2]
- Inner surface contamination of technological equipment [Bq/m^2]
- Outer surface contamination of technological or building equipment [Bq/m^2]
- Nuclide vector of inner surface contamination – represent an average isotopic composition of inner surface contamination source [%]
- Reference date for inner contamination and nuclide vector of inner surface contamination [DD.MM.YYYY]
- Nuclide vector of outer surface contamination – represent an average isotopic composition of outer surface contamination source [%]
- Reference date for outer contamination and nuclide vector of outer surface contamination [DD.MM.YYYY]
- Dose rate nearby technological or building equipment – dose rate 0,5 m from the surface of the technological or building equipment [μGy/h]
- Nuclide vector of dose rate – represent an average isotopic composition of dose rate source [%]
- Reference date for dose rate and nuclide vector of dose rate [DD.MM.YYYY]
- Inner volume of technological equipment – parameter used only for pre-dismantling decontamination by autonomous circuits

- Category of technological or building equipment – characterizes type, shape, dimensions and material composition of technological or building equipment. This parameter is used for assignment of default dismantling and demolition procedures.

Input technological database of contaminated parts of A-1 NPP primary circuit for OMEGA code decommissioning calculations includes the following typical 4 type equipment categories: piping, valves, steel construction and tanks and containers. Complete table of equipment categories used in A-1 NPP primary circuit input database is listed in **Table 1**. This input database includes carbon steel (CS) as well as stainless steel (SS) equipment, which in total represent approximately 1000 database items.

Table 1: Equipment categories in A-1 NPP primary circuit input database for OMEGA calculations

	Technological equipment	
	Category of equipment	**Number of database items**
Pipes	POT2N - Piping (SS), D25 mm < diameter <= D100 mm	23
	POT3N - Piping (SS), D101 mm =< diameter <= D499 mm	64
	POT1C - Piping (CS), diameter =< D25 mm	52
	POT2C - Piping (CS), D25 mm < diameter <= D100 mm	96
	POT3C - Piping (CS), D100 mm < diameter < D500 mm	89
	POT4C - Piping (CS), D501 mm =< diameter (typical diameter D1200 mm)	4
	POTA1 - A1 NPP primary piping CO_2, (CS)	108
	TRUBC - Pipe heat exchangers (CS)	36
Valves	ARM1C - Valves (CS), mass <= 50 kg	194
	ARM2C - Valves (CS), mass > 50 kg, any dimension <= 1m	108
	ARM3C - Valves (CS), mass > 50 kg, dimension => 1m	37
Steel constructions	TOK1C - Steel constructions, (CS), hangings of piping, general hangings	136
Tanks and containers	NDK2C - Tanks and containers (CS), diameter >= D 1 m, typical wall thickness 12 mm	24
Total		**971**

A-1 NPP primary circuit input database includes 3 nuclides vectors that represent radionuclide composition of activity source: inner, outer contamination and dose rate source. Mentioned nuclide vectors with the reference date 01.12.2003 are listed in **Table 2** below.

Table 2: Nuclide vector of inner and outer surface contamination of NPP A1 primary circuit

Nuclide	**Half - life [year]**	**Nuclide vector of inner surface contamination of NPP A1 primary circuit (1.12.2003)**	**Nuclide vector of outer surface contamination of NPP A1 primary circuit (1.12.2003)**
		Percentage representation [%]	**Percentage representation [%]**
Am-241	431,90	0,8898903255	0,0000002599
Cl-36	300793,98	0,0000000355	0,0021512666
Co-60	5,27	11,2546502908	0,0000276622
Cs-137	30,17	45,1441081119	99,0209725550
Eu-152	13,49	1,0360248684	0,0000022948
H-3	12,29	0,0796504456	0,3132131766
I-129	15689271,00	0,0252704573	0,0000000015
Mo-93	3497,60	0,0006853566	0,0000000376
Nb-94	19986,31	0,0166780376	0,0000001845
Ni-59	75947,98	0,0937735654	0,0000179874
Ni-63	99,93	9,8242222937	0,0000001242
Pu-238	87,68	0,1214628692	0,0000003843

Nuclide	Half - life [year]	Nuclide vector of inner surface contamination of NPP A1 primary circuit (1.12.2003)	Nuclide vector of outer surface contamination of NPP A1 primary circuit (1.12.2003)
		Percentage representation [%]	Percentage representation [%]
Pu-239	24093,50	0,4092708786	0,6282078387
Sm-151	92,94	0,2853992839	0,0013119467
Sn-126	99931,55	0,0005954190	0,0302733062
Sr-90	28,62	30,8047995082	0,0000361306
Tc-99	212854,21	0,0118008554	0,0037848432
Zr-93	1498972,82	0,0017173975	0

Radionuclide composition of inner and outer surfaces of A-1 NPP primary circuit is a typical example of equipment contaminated by fission products and actinides coming from fuel damage accident described in chapter 6.1.2. As it is clearly seen from Table 2, the main gamma radiation source that influences dose rate from contaminated NPP A1 primary circuit equipment is Cs-137. This radionuclide represent the radiation source considered in dose rate calculations.

However, for evaluating an impact of alpha contamination on decommissioning costs and other parameters there were included nuclide vectors of contamination typical for non-accident V-2 NPP in Jaslovske Bohunice (WWER type 440 MWe reactor). V-2 NPP nuclide vectors of contamination do not contain alpha contaminants and fission products and their radionuclide composition is listed in **Table 3**. The representing radiation source considered in NPP V-2 dose rate calculation is Co-60.

Table 3: Nuclide vectors of NPP V2 inner and outer surface contamination

Nuclide	Half - life [year]	Nuclid vector of inner surface contamination of NPP V2 primary circuit (1.12.2003)	Nuclid vector of outer surface contamination of NPP V2 primary circuit (1.12.2003)
		Percentual representation [%]	Percentual representation [%]
Ag-110m	0,68	9,365	9,365
Co-60	5,27	58,45	58,45
Mn-54	0,86	29,39	29,39
Zn-65	0,67	2,799	2,799

Except of mentioned input data there were several group of technical-economical parameters used in OMEGA calculations:

- Unit factors for decommissioning technologies (specific costs, manpower, energy and media consumptions, specific capacity of given technology…)
- Parameters of working groups
- Parameters of working time
- Parameters for personnel exposure calculations
- Radiological parameters
- Other economical parameters.

These parameters are available for discussions at DECOM Slovakia.

6.2.2 Range of OMEGA decommissioning cost calculations

Within the decommissioning cost calculation using OMEGA code for A-1 NPP primary circuit there were numerous decommissioning options considered. Total number of calculated sensitivity analysis cases is 10 whereas each case is a combination of changed input parameters such as: level of contamination, applied waste management scenario, application or non-application of pre-dismantling decontamination, direct or deferred dismantling and applied alpha- or non-alpha-contaminated nuclide vectors. The principle of sensitivity analysis is clearly described in the following chapter.

Each calculated case includes several decommissioning activities that were taken into account. Each calculated sensitivity analysis is characterised by the following set of output parameters: cost, manpower, collective dose equivalent, mass distribution of steel from decommissioning (either released into environment or disposed in repositories) and the number of disposed radioactive waste containers.

6.2.2.1 Decommissioning options

Calculations were performed under the following combination of input conditions displayed in **Table 4**:

- Various inner/outer surface contamination of technological equipment
- Various scenarios of radwaste treatment
- Application / Non-application of pre-dismantling decontamination on some of technological equipment
- Various decommissioning start times
- Various nuclide vectors representing isotopic content of inner/outer surface contamination of technological equipment.

Table 4: Sensitivity analysis cases – combination of calculated decommissioning options

Sensitivity analysis No.	**Input parameters**				
	Levels of contamination	**Scenarios**	**Pre-dismantling decontamination**	**Start time of decommissioning**	**Nuclide vectors**
1.	K1, K2, K3, K4	S1	N, P	2004	A-1
2.	K2, K3	S1, S2, S3, S4	N	2004	A-1
3.	K2, K3	S1, S2, S3, S4	P	2004	A-1
4.	K2	S1, S2, S3, S4	N	2004, 2040	A-1
5.	K2	S1, S2, S3, S4	P	2004, 2040	A-1
6.	K3	S1, S2, S3, S4	P	2004, 2040	A-1
7.	K2	S1, S2, S3, S4	N	2004, 2040	V-2
8.	K2	S1, S2, S3, S4	P	2004, 2040	V-2
9.	K3	S1, S2, S3, S4	P	2004, 2040	V-2
10.	K2	S1	P	2004,2010, 2020, 2030,2040	V-2

The legend of **Table 4** explains a principle of input parameters sensitivity analysis used in calculation:

Levels of contamination: Radionuclide composition of inner/outer surface contamination of technological equipment items are shown in Table 2 for A-1 NPP and in Table 3 respectively for V-2 NPP. These contamination levels given in Table 2 and Table 3 (different levels for accident and non-accident NPP's) are called basic contamination level K2 hereinafter. Calculations were also performed for the cases when the inner/outer surface contamination levels of technological equipment items mentioned in Table 2 and Table 3 were increased ten times (contamination level K1), decreased ten times (contamination level K3), decreased one hundred times (contamination level K4), respectively, in comparison to basic contamination level K2. That means:

- Contamination level K1 = K2 * 10 (basic contamination level K2 increased ten times)
- Contamination level K2 is basic contamination level and it represents inner/outer surface contamination levels of technological equipment items mentioned in **Table 2** and **Table 3** respectively.
- Contamination level K3 = K2 / 10 (basic contamination level K2 decreased ten times)
- Contamination level K4 = K2 / 100 (basic contamination level K2 decreased hundred times).

Scenarios: The calculations were performed for the following radioactive waste treatment scenarios (rarely called decommissioning scenarios):

- Scenario S1: Wet bath post-dismantling decontamination equipment for iron/steel radwaste and melting equipment for iron/steel radwaste are available at decommissioning site.
- Scenario S2: Wet bath post-dismantling decontamination equipment for iron/steel radwaste is available at the site.
- Scenario S3: Melting equipment for iron/steel radwaste is available at the site.
- Scenario S4: Neither wet bath post-dismantling decontamination equipment for iron/steel radwaste nor melting equipment for iron/steel radwaste are available at the site.

Pre-dismantling decontamination: Calculations were performed for these input conditions:

- Pre-dismantling decontamination was not applied on technological equipment surfaces (sign of “N“ is used in this case)
- Pre-dismantling decontamination was applied on selected technological equipment surfaces. In the following text the sign of “P“ is used in this case.

Decommissioning start time: There were following decommissioning start time: 2004 (as a basic start time – immediate dismantling), 2040 (deferred dismantling option) and also 2010, 2020 a 2030 in one case. Decommissioning start date was January 1 for relevant year.

Nuclide vectors: Following two sets of nuclide vectors representing isotopic content of inner/outer surface contamination were used as input parameters for calculation of NPP A-1 primary circuit decommissioning:

- The first set is nuclide vector of inner and outer surface contamination of NPP A-1 primary circuit, respectively. This set is typical for NPP A-1 primary circuit and represent primary circuit contamination after accident with multifarious isotopic content including alpha nuclides and a dominant representation of Cs-137. Detailed radiological composition of A-1 NPP primary circuit contamination is given in **Table 2**
- The second set is a nuclide vector of inner and outer surface contamination of NPP V-2 primary circuit. This set is typical for non-accident power plants and represent the primary circuit contamination without fission products and actinides when the fuel elements cover tightness is very good. No important levels of alpha contamination is present, Co-60 is a dominant nuclide. Detailed radiological composition of V-2 NPP primary circuit contamination is given in **Table 3**.

Isotopic content sensitivity analyses related to the amount of repository containers was the main aim of using these different nuclide vectors.

6.2.2.2 Decommissioning activities included in calculation options

Activities included in calculations of A-1 primary circuit decommissioning are divided into following categories:

- Pre-dismantling decontamination activities
- Dismantling activities
- Radiation control and sorting of dismantled material
- Treatment and conditioning activities of dismantled material
- Packaging, transportation and disposal activities.

Main individual activities are described in more detail below:

Pre-dismantling decontamination

In primary circuit is an overwhelming majority of radioactivity deposited onto inner surfaces of equipments (piping, turbo-compressor internals, steam generator heat exchangers). Primary circuit creates enclosed area which can be easily regulated by valves and fittings. Due to these facts decontamination by autonomous circuits is considered as most appropriate pre-decommissioning decontamination method in calculations. During this decontamination a needed amount of decontamination solution with appropriate chemicals is filled into a prior prepared primary circuit loop (or its part). This decontamination solution circulates through individual parts of autonomous circuit and dissolves upper (corrosion) layers of inner equipment surfaces containing radioactivity. Period of solution circulation depends on variety of parameters: requested decontamination factor, size of decontaminated circuit, saturation of decontamination solution, etc.

Dismantling

Dismantling is provided by oxy-acetylene flame or plasma arc cutting. These techniques are very suitable for segmenting especially for primary piping due to its cutting speed, ease of transportation, not high costs and universal usage in variety of thicknesses, shapes and geometries of steel materials.

During oxy-acetylene cutting, the heating flame heats the workpiece locally to its ignition temperature. The flame then keeps the workpiece at this temperature. After the ignition of temperature is reached, the cutting oxygen is added and workpiece is cut by exothermal combustion process.

Conventional plasma arc cutting with a transferred arc is a pure fusion cutting process by means of which any conductive material can be cut. The plasma arc, created by highly heated gas or its mixture which is conductive and consists of ions, electrons, neutral atoms or molecules, has high energy density, melts or partially evaporates the workpiece. The high kinetic energy gas jet blows the molten material out of the kerf.

Treatment and conditioning of dismantled material

There is a variety of RAW generated during activities of dismantling and decontaminations. We considered follow technologies for material treatment and conditioning in our calculations:

- fragmentation of metals with overall radioactivity up to 3kBq/cm^2
- fragmentation of metals with overall radioactivity over 3kBq/cm^2
- post-dismantling decontamination
- low-pressure compaction
- high-pressure compaction
- incineration
- melting of metal RAW
- evaporation and bituminization
- vitrification
- cementation of solid RAW into drums
- final cementation into FRC containers for near surface repository disposal
- final cementation into containers for deep geological repository disposal.

Fragmentation of metals with radioactivity up to 3kBq/cm^2

This workplace includes fragmentation by air plasma cutting, hydraulic shears and circular saws. Dismantled material is transported to the fragmentation workplace in standardized ISO containers (1,6 x 1,2 x 1,4 m) with weight capacity 1,5 t. Material is fragmented to pieces with maximal dimensions up to 200 mm and filled into 200 l drums. Maximal allowed dose rate is 2 mGy/h at the surface of a drum. Capacity of fragmentation is considered about 2000 kg/shift.

Fragmentation of metals with radioactivity over 3kBq/cm^2

This fragmentation workplace is remotely controlled due to higher radioactivity of dismantled material. The dismantled material is cut by hydraulic shears. Material is fragmented into 200 l drums. Capacity of fragmentation is considered about 200 kg/shift.

Post-dismantling decontamination

Post-dismantling decontamination is used to obtain larger amount of material for unconditional or conditional release or decreasing of material amount destined to deep geological repository disposal.

The chemical post-dismantling decontamination by means of ultrasound is considered in calculations. Dismantled material is immersed into the tank filled with chemical decontamination solution and its contaminated surface layer is removed by means of ultrasound action. Afterwards, material is transferred into rinsing tank where it is rinsed by detergent and dematerialized water. Assumed capacity of such post-dismantling decontamination is around 3 m^2/h.

Low-pressure compaction

Low pressure compactor is hydraulic equipment designed for noncombustible solid material compaction (PVC, glass, isolation glass wool, brash metal material). The RAW is compacted directly in 200 l drum. Drums with compacted RAW are intended for high-pressure compaction. Considered capacity of low-pressure compaction is 1,6 m^3/h.

High-pressure compaction

High-pressure compactor is designed for drums with low-pressure compacted materials, drums with small pieces of fragmented metals or debris. In this process the whole drum is compacted. Dimensions of output product depend on compressibility of compacted waste. It can be pellets or only partially compressed drums. These products are destined to final cementation cementation into FRC containers for near surface repository. Capacity of low-pressure compaction is 3 drums/h with average weight of drum 330 kg.

Incineration

There are burnable solid wastes, packed in bags (3-10 kg) and transported in 200 l drums, processed in the incinerator. Incineration of a burnable liquid waste (oils, lubricant and grease) is also possible. Washing liquids for exhaust gases cleaning are generated as a secondary RAW. They can be used for active cement filler in cementation process. The same is usage of generated ash, it is mixed with cement filler. We suppose capacity 50 kg/h of input RAW with volume reduction factor around 15 and generation of 200 l of washing liquid per 1t of RAW.

Melting of metal RAW

Melting is used for, in combination with post-dismantling decontamination, increasing of amount of material for conditional and unconditional release. It means that melting is not intended for volume reduction for non releasable materials.

Individual radionuclides can have different behavior in the process of melting. Some migrate from metal (or its surface) to exhaust gases or slag, some migrate only a little and mostly stay in metal volume. For example Cs-137: around 96 % evaporates and is caught by filters and remain (4 %) migrates to slag. On the other side major part of Co-60 remains in metal (90,5 %), 7,2 % is migrating to sludge and 2,3 % to exhaust gases as a dust [[7]]. This behavior of radionuclides is also taken into account in calculation. Supposed capacity of melting furnace is 125 kg/h.

Evaporation and bituminization

Bituminization line is intended for processing and fixation of liquid concentrates, sludge or used ion exchangers. Firstly, waste waters are concentrated by evaporator with natural circulation. Thicken liquid is consequently fixed into bitumen by rotary evaporator and filled into 200 l drums. Spent ion exchangers and condensate are generated as a secondary waste during the process of bituminization. Limit salinity of evaporated concentrates is intended to be about 180 kg/m^3. Capacity of bituminization line is 1drum of bitumen product per hour.

Cementation of solid RAW into drums

This cementation line is designed for remotely fragmented solid materials which radioactivity level doesn't allow high-pressure compaction. Fragmented material is grouted with cement mixture directly in drum. Capacity of drum cementation is 0,56 m^3/h.

Vitrification
Liquid RAW with high level of overall radioactivity and especially with significant alpha radioactivity are treated by vitrification. Liquid RAW is concentrated in evaporator and generated concentrate is mixed with glass frit, dried and incorporated into glass matrix during melting of glass frit. Glass product is filled into metal shells with 7 liters volume and they are destined for cementing into containers for deep geological disposal. Assumed capacity of vitrification line is 0,002m^3/h.

Final cementation into FRC containers destined to near surface repository
Cementation into FRC containers is used for final disposal of RAW that can't be released and its radioactivity enables disposal at surface repository.

The FRC (fiber reinforced concrete) container is a container designed for disposal of RAW at near surface repository. It is made of concrete reinforced by metal fibers (mixed together with concrete). Its inner volume is 3 m^3 and payload 10 t.

There are solid radioactive wastes placed into FRC containers such as high-pressure compaction products, drums filled with bitumen, cement product or pressured RAW, stand alone RAW (e.g. debris). These solid wastes are consequently fixed in the FRC container by cementation mixture grouting.

Capacity of cementation is 1 FRC container per day.

Final cementation into FRC containers destined to deep geological repository
Radioactive waste which can't be disposed at near surface repository has to be cemented into containers and destined to future deep geological repository. Disposal at deep geological repository is needed mainly for high alpha level contaminated materials or for high level activated reactor core materials.

Pieces of a high level irradiated or contaminated material and products of vitrification are put into containers and consequently grouted by cement mixture.

Payload of container is 4,5t and capacity of cementation is 1 container per day.

There are some other activities, such as preparing and ending activities of decontamination and dismantling (covering with foil, preparing and dismantling of scaffolding, preparing of tools, etc.). These activities not affect material flow during decommissioning process and therefore they are not included in calculations.

6.2.2.3 Output calculated decommissioning parameters

Output parameters are chosen in range that allows comparing influence of selected input parameters on decommissioning process and to carry out sensitivity analysis. They are divided into 2 main categories:

1. **Main general decommissioning parameters -** these parameters characterize decommissioning option from the overall manager point of view. Costs, manpower and collective dose equivalent are included in this category.
   - *Costs* - integral parameter, sensitive to any change of input decommissioning parameters. Summarize subtotal costs items connected with decommissioning activities - labour costs, investment costs, expenses and contingency.
   - *Manpower* – represents the sum of overall work carried out during the decommissioning process and is influenced mainly by radiation situation and working conditions.
   - *Collective dose equivalent* - represents the sum of all individual dose equivalents for all decommissioning personnel. Depends on individual dose rates at workplaces during work execution and manpower needs of individual work processes.

2. **Distribution of materials arisen from decommissioning** - these parameters characterize decommissioning option from the dismantled material distribution point of view. This category contains mass distribution of steel destined to repositories, released into environment respectively, and distribution of disposed radioactive waste containers.

   Mass distribution of steel – this parameter represents mass distribution (kg) of steel as a result of primary circuit decommissioning process into categories as follows:

   - *Steel released to environment after dismantling* – directly released steel without application of post-dismantling decontamination.
   - *Steel released to environment after decontamination* – dismantled steel released after post-dismantling decontamination without melting.
   - *Steel released to environment after melting* - dismantled steel released after post-dismantling decontamination and consequent melting or direct melting.
   - *Steel destined to near-surface repository* – non-releasable steel placed in FRC containers for near-surface repository disposal
   - *Steel destined to deep geological repository* - non-releasable steel placed in containers for deep geological repository disposal

   Distribution of disposed radioactive waste containers - this parameter represents numbers of containers with RAW destined to disposal at repositories:

   - *Containers destined to deep geological repository with vitrified packages* – containers contain vitrified packages that are products of high radioactivity (especially alpha radioactivity) liquid RAW vitrification process.
   - *Containers destined to deep geological repository with metals* - containers contain dismantled steel with higher radioactivity then near-surface repository limits
   - *Containers destined to near-surface repository with metals* - containers contain dismantled steel that meets near-surface repository limits

6.3 CALCULATION RESULTS

Since decommissioning cost calculations by OMEGA code for contaminated parts of A-1 NPP primary circuit were executed for numerous decommissioning options with several evaluated decommissioning parameters, the obtained results are grouped into 2 categories:

- Calculated results of main decommissioning parameters, such as costs, manpower and collective dose equivalent characterizing each decommissioning option.
- Results characterizing distribution of materials arisen from decommissioning, such as mass distribution of steel destined to repositories or released into environment and number of disposed radioactive waste containers.

6.3.1 Main calculated decommissioning parameters

As it was mentioned in chapter 6.2.2.1, decommissioning cost calculations were performed for 10 sensitivity cases whereas each case is a combination of several decommissioning options with changed input parameters. For easier identification of calculated main decommissioning parameters, representing manpower, collective dose equivalent and costs, the table below summarizes a set of output figures belonging to each particular sensitivity analysis case. Naturally, used symbols for input parameters remain unchanged and are described in mentioned chapter 6.2.2.1.

Table 5: Sensitivity analysis cases – calculated main decommissioning parameters

Sensitivity analysis No.	Output parameter figures			Input parameters				
	Manpower	Collective dose equivalent	Costs	Levels of contamination	Scenarios	Pre-dismantling decontamination	Start time of decommissioning	Nuclide vectors
1.	**Figure 5**	**Figure 6**	**Figure 7**	K1, K2, K3, K4	S1	N, P	2004	A-1
2.	**Figure 8**	**Figure 9**	**Figure 10**	K2, K3	S1, S2, S3, S4	N	2004	A-1
3.	**Figure 11**	**Figure 12**	**Figure 13**	K2, K3	S1, S2, S3, S4	P	2004	A-1
4.	**Figure 14**	**Figure 15**	**Figure 16**	K2	S1, S2, S3, S4	N	2004, 2040	A-1
5.	**Figure 17**	**Figure 18**	**Figure 19**	K2	S1, S2, S3, S4	P	2004, 2040	A-1
6.	**Figure 20**	**Figure 21**	**Figure 22**	K3	S1, S2, S3, S4	P	2004, 2040	A-1
7.	**Figure 23**	**Figure 24**	**Figure 25**	K2	S1, S2, S3, S4	N	2004, 2040	V-2
8.	**Figure 26**	**Figure 27**	**Figure 28**	K2	S1, S2, S3, S4	P	2004, 2040	V-2
9.	**Figure 29**	**Figure 30**	**Figure 31**	K3	S1, S2, S3, S4	P	2004, 2040	V-2
10.	**Figure 32**	**Figure 33**	**Figure 34**	K2	S1	P	2004,2010, 2020, 2030,2040	V-2

In order to clear presentation of calculated results, each sensitivity analysis case is introduced by relevant table with calculated values of manpower, CDE and costs for given decommissioning option. Decommissioning costs are presented in EUR with used exchange rate 1 EUR = 38.739 SKK.

Calculated results of main decommissioning parameters in all sensitivity analysis cases: manpower, collective dose equivalent and costs, documented by set of tables and graphs below, are influenced by the following factors:

In case on changing the level of contamination, manpower needs (see **Figure 5** left part) are influenced by two opposite processes: Generally the lower contamination level, the lower manpower needs (the influence of decreased remote dismantling and increased of hands-on dismantling). However manpower decreases to a so called local minimum and increases again due the influence of significantly increased ratio of released materials into environment after post-dismantling decontamination and melting. Application of these decontamination methods increases the manpower needs. In case of pre-dismantling decontamination application (see **Figure 5** right part), there can be noticed the same U-shape curve for manpower with lower values. CDE on **Figure 6** is growing with the increase of hands-on dismantling in comparison with remote dismantling. However the lower contamination level, the lower influence of this “dismantling” (transformation of remote dismantling to hands-on one) factor. The application of pre-dismantling decontamination decreases costs and for higher contamination levels on the contrary increases CDE. Approved decreasing of costs with decreasing of contamination level is displayed on **Figure 7**.

Figure 8 through **Figure 13** represent the calculated cases for application of various radwaste treatment scenarios and for application or non-application of pre-dismantling decontamination performed on alpha contaminated surfaces (used A-1 NPP nuclide vectors). In generally, changing of radwaste treatment scenario has no significant impact on manpower, costs and CDE because scenarios do not influence the distribution of dismantled materials (especially for highly alpha contaminated materials which are mainly destined to geological repository). The values of all main decommissioning parameters are lower in case of contamination level K3 which is 10-times lower than basic level K2. The application of pre-dismantling decontamination causes decreasing of manpower and costs. However CDE in this case is increased (**Figure 12** in comparison with **Figure 9**) along of remote dismantling transformation to hands-on dismantling.

Calculated results of sensitivity analysis for changing decommissioning start time from 2004 to 2040 are displayed on **Figure 14** through **Figure 31**. For deferred dismantling in 2040, the values of costs, manpower and CDE are lower than dismantling in 2004. However the impact of alpha contamination for both decommissioning start times remains constant (in case the pre-dismantling decontamination is not applied) and therefore the distribution of materials destined to repositories is almost unchanged. Deferral of dismantling causes a soft dose rate decrease (coming from Cs-137) and simultaneously only a partial transformation of remote dismantling to hands-on one which has just low impact on cost decrease (see **Figure 16**). Small differences between immediate and deferred dismantling are caused by the present alpha contaminants and fission products (Cs-137) with long half life that are destined to repositories and cannot be released into environment. In case of pre-dismantling decontamination application manpower decreases (**Figure 17** in comparison with **Figure 14**). The only exception is a decommissioning option S1(’40) on

Figure 17 where the manpower is increased by application of post-dismantling decontamination and melting leading to a increased amount of released materials into environment. For lower contamination level K3 (**Figure 20**), the manpower profile is in compliance with the distribution trend of released materials. A soft increased CDE values for pre-dismantling decontamination application in 2004 (**Figure 18** in comparison with **Figure 15**) are caused by the remote dismantling partial transformation to hands-on dismantling. The situation is different for deferred dismantling in 2040 and pre-dismantling decontamination application when CDE decreases significantly by remarkable usage of hands-on dismantling methods. For lower contamination level and pre-dismantling decontamination application cases are costs and CDE the lowest in comparison with previous analysed cases.

The above mentioned analysis is valid also for V-2 NPP nuclide vectors (**Figure 23** through **Figure 31**) but the costs, manpower and CDE values are significantly lower. Non-alpha contaminated treated materials (dominant Co-60 nuclide) are mainly released into environment especially in case if deferred dismantling. There are no highly alpha contaminated materials that have to be disposed either in geological or in surface repository as in case of A-1 NPP.

The last sensitivity analysis case No.10, was the deferral of decommissioning start time from 2004, to 2010, 2020, 2030 through 2040 applied for specific contamination level K2 and pre-dismantling decontamination on non-alpha contaminated surfaces. Costs and CDE profile are decreasing (**Figure 33** and **Figure 34**). However the profile of manpower (**Figure 32 -** S-shape curve) is given by remote dismantling transformation to hands-on dismantling on one side (decreasing manpower trend) and on the contrary increased manpower needs for radwaste treatment destined first to surface repository and later on released into environment.

Table 6: Sensitivity analysis No. 1 – calculated decommissioning options

Sensitivity analysis No. 1			
Decommissioning option	**Manpower [manhour]**	**CDE [manmicroSv]**	**Costs [EUR]**
N-K1-S1-04-A1	1 831 665	8 745 884	254 445 291
N-K2-S1-04-A1	1 437 322	13 060 585	144 051 641
N-K3-S1-04-A1	890 088	4 309 873	39 548 170
N-K4-S1-04-A1	936 966	2 222 082	31 348 747
P-K1-S1-04-A1	917 473	117 710 478	172 598 724
P-K2-S1-04-A1	912 270	14 188 801	41 330 628
P-K3-S1-04-A1	975 359	3 304 170	34 191 262
P-K4-S1-04-A1	1 064 034	2 353 823	30 388 642

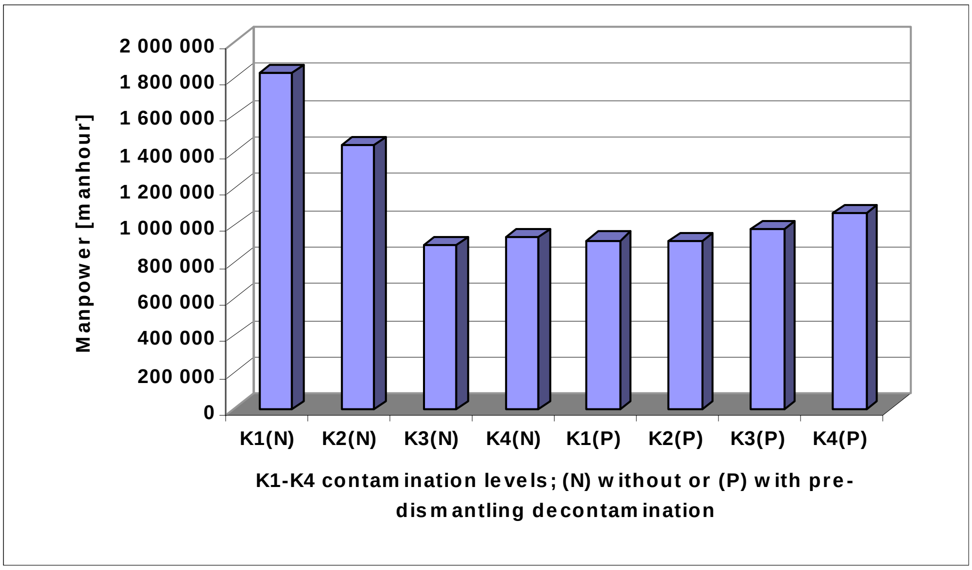


Figure 5: Manpower for different calculated options. These options differ in level of contamination of decommissioned technology equipment (with typical radionuclide composition for NPP A-1, decommissioning scenario S1) without (N) or with (P) pre-dismantling decontamination.

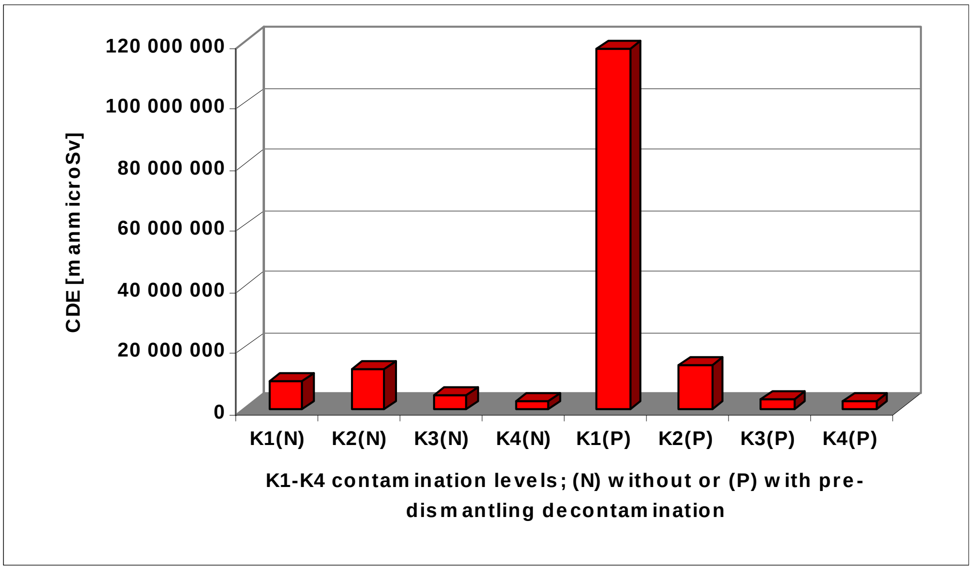


Figure 6: Collective dose equivalent for different calculated options. These options differ in level of contamination of decommissioned technology equipment (with typical radionuclide composition for NPP A-1, decommissioning scenario S1) without (N) or with (P) pre-dismantling decontamination.

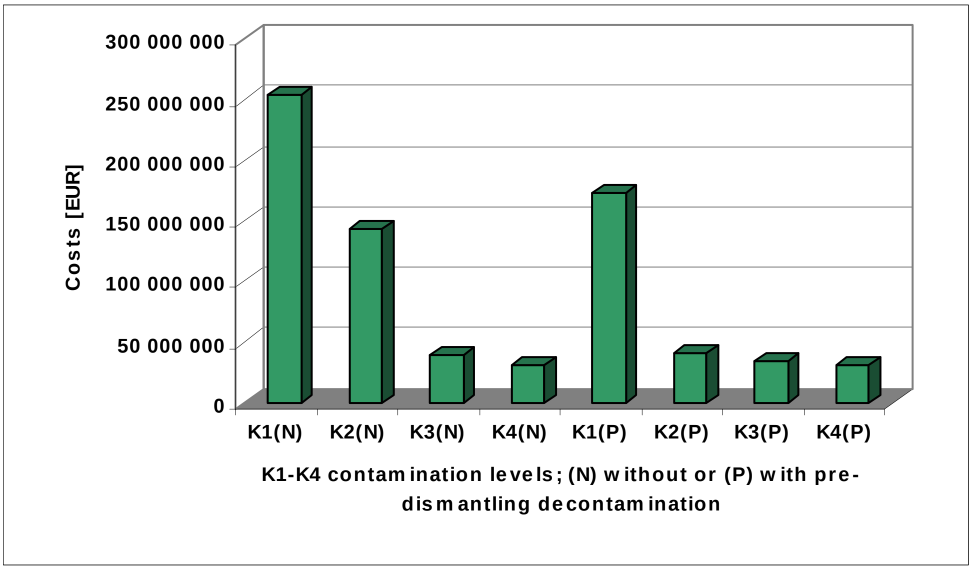


Figure 7: Costs for different calculated options. These options differ in level of contamination of decommissioned technology equipment (with typical radionuclide composition for NPP A-1, decommissioning scenario S1) without (N) or with (P) pre-dismantling decontamination.

Table 7: Sensitivity analysis No. 2 – calculated decommissioning options

Sensitivity analysis No. 2			
Decommissioning option	**Manpower [manhour]**	**CDE [manmicroSv]**	**Costs [EUR]**
N-K2-S1-04-A1	1 437 322	13 060 585	144 051 641
N-K2-S2-04-A1	1 426 992	13 033 259	144 030 954
N-K2-S3-04-A1	1 434 135	13 053 385	143 955 915
N-K2-S4-04-A1	1 426 992	13 033 259	144 030 954
N-K3-S1-04-A1	890 088	4 309 873	39 548 170
N-K3-S2-04-A1	859 785	4 235 824	39 014 510
N-K3-S3-04-A1	865 890	4 252 534	39 394 286
N-K3-S4-04-A1	858 653	4 231 916	39 472 597

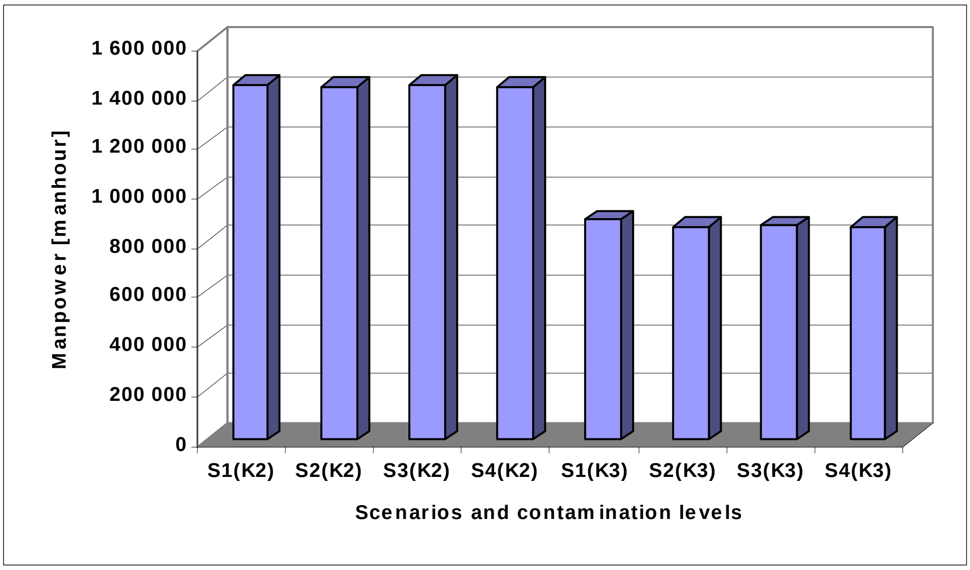


Figure 8: Manpower for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and level of contamination of decommissioned technology equipment (either K2 or K3 level with typical radionuclide composition for NPP A-1). No pre-dismantling decontamination applied.

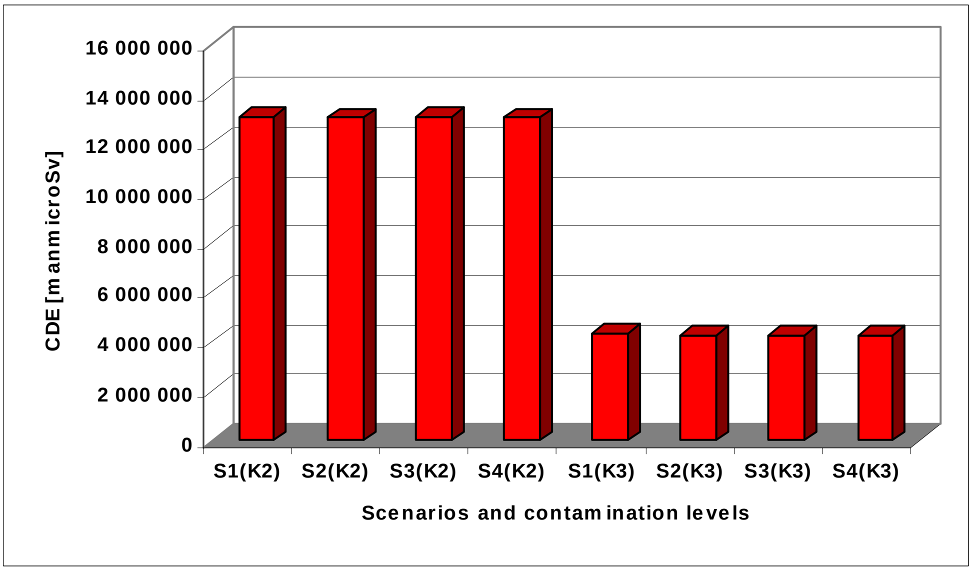


Figure 9: Collective dose equivalent for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and level of contamination of decommissioned technology equipment (either K2 or K3 level with typical radionuclide composition for NPP A-1). No pre-dismantling decontamination applied.

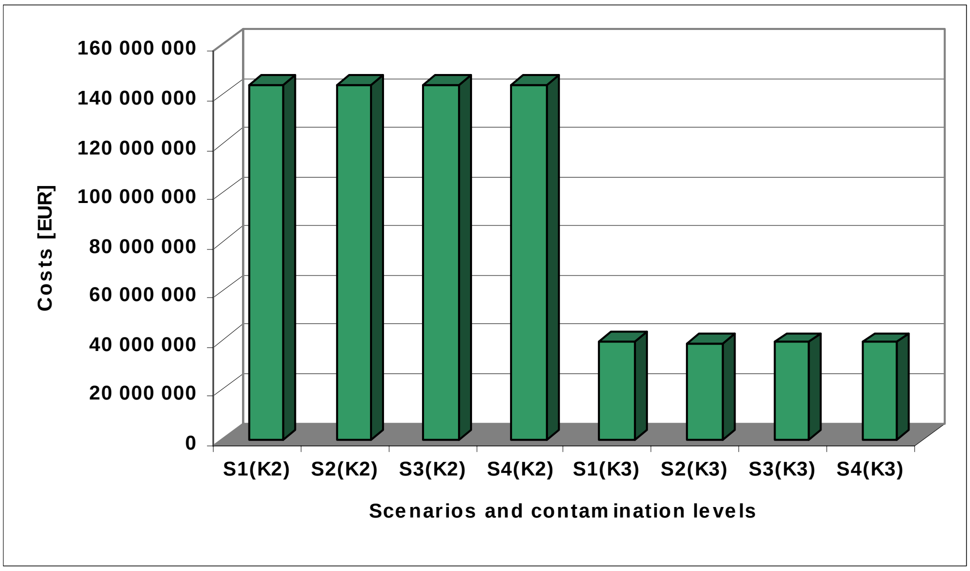


Figure 10: Costs for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and level of contamination of decommissioned technology equipment (either K2 or K3 level with typical radionuclide composition for NPP A-1). No pre-dismantling decontamination applied.

Table 8: Sensitivity analysis No. 3 – calculated decommissioning options

Sensitivity analysis No. 3			
Decommissioning option	**Manpower [manhour]**	**CDE [manmicroSv]**	**Costs [EUR]**
P-K2-S1-04-A1	912 270	14 188 801	41 330 628
P-K2-S2-04-A1	871 669	14 087 554	40 775 949
P-K2-S3-04-A1	878 566	14 106 881	40 870 874
P-K2-S4-04-A1	871 249	14 086 132	40 935 770
P-K3-S1-04-A1	975 359	3 304 170	34 191 262
P-K3-S2-04-A1	671 618	2 570 705	28 580 472
P-K3-S3-04-A1	618 306	2 453 402	28 396 359
P-K3-S4-04-A1	604 225	2 413 691	2 705 591

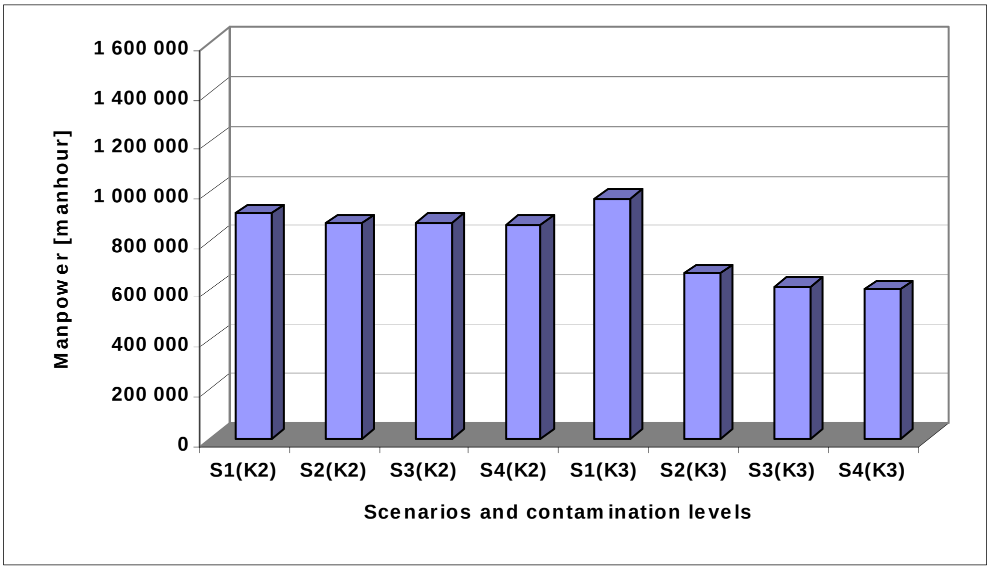


Figure 11: Manpower for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and level of contamination of decommissioned technology equipment (either K2 or K3 level with typical radionuclide composition for NPP A-1). Applied pre-dismantling decontamination.

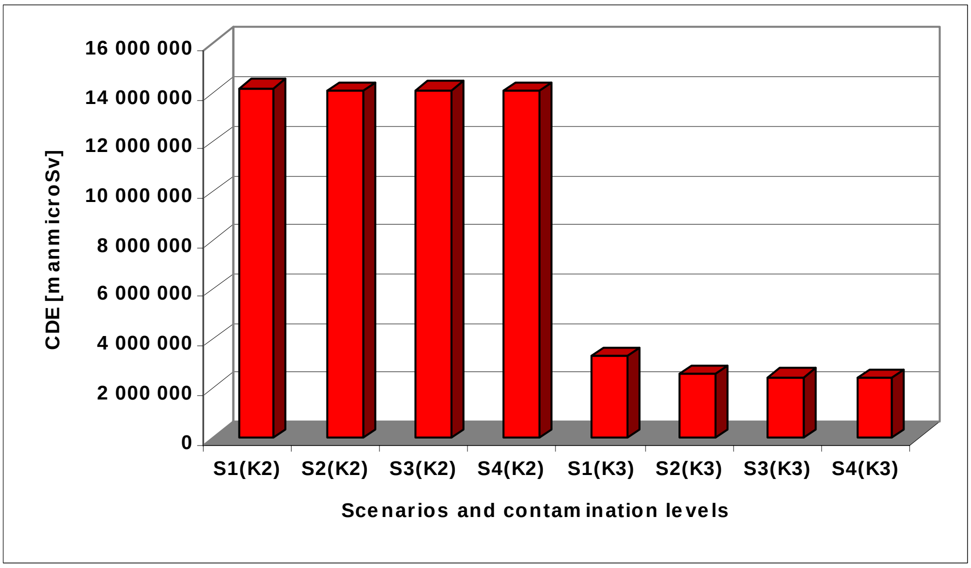


Figure 12: Collective dose equivalent distribution for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and level of contamination of decommissioned technology equipment (either K2 or K3 level with typical radionuclide composition for NPP A-1). Applied pre-dismantling decontamination.

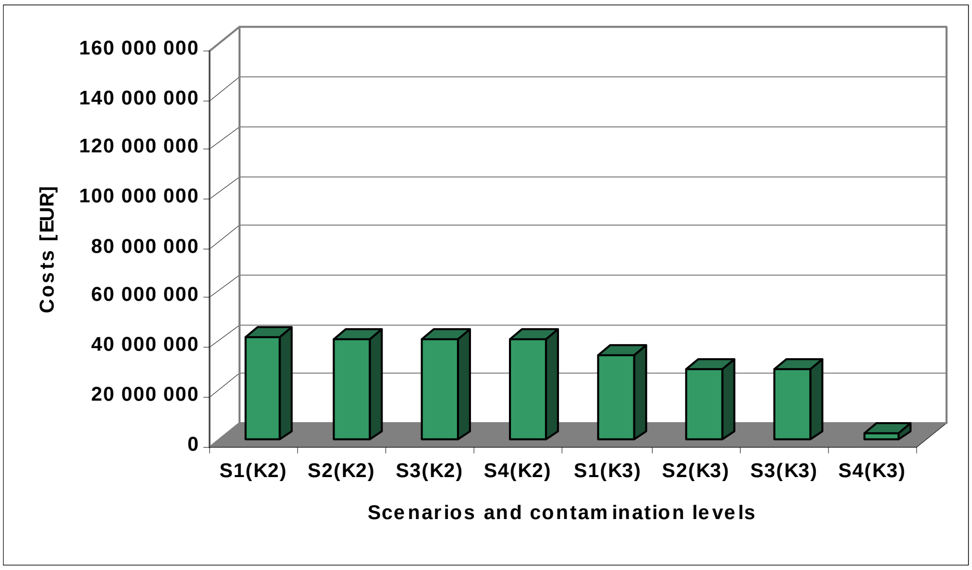


Figure 13: Costs for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and level of contamination of decommissioned technology equipment (either K2 or K3 level with typical radionuclide composition for NPP A-1). Applied pre-dismantling decontamination.

Table 9: Sensitivity analysis No. 4 – calculated decommissioning options

Sensitivity analysis No. 4			
Decommissioning option	**Manpower [manhour]**	**CDE [manmicroSv]**	**Costs [EUR]**
N-K2-S1-04-A1	1 437 322	13 060 585	144 051 641
N-K2-S2-04-A1	1 426 992	13 033 259	144 030 954
N-K2-S3-04-A1	1 434 135	13 053 385	143 955 915
N-K2-S4-04-A1	1 426 992	13 033 259	144 030 954
N-K2-S1-40-A1	857 097	11 598 939	132 853 399
N-K2-S2-40-A1	733 898	11 287 224	133 342 133
N-K2-S3-40-A1	741 086	11 307 671	133 266 084
N-K2-S4-40-A1	733 898	11 287 224	133 342 133

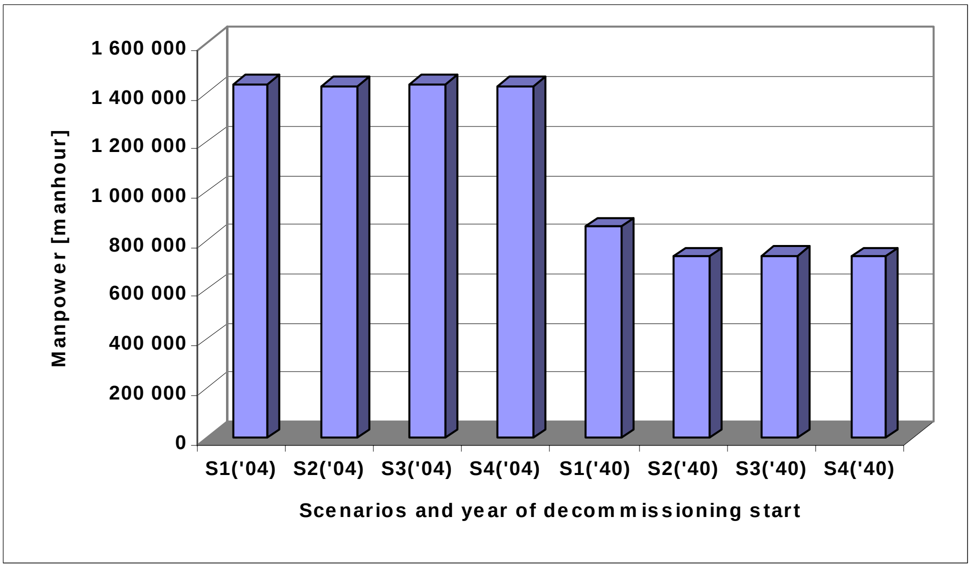


Figure 14: Manpower for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for NPP A-1. No pre-dismantling decontamination applied.

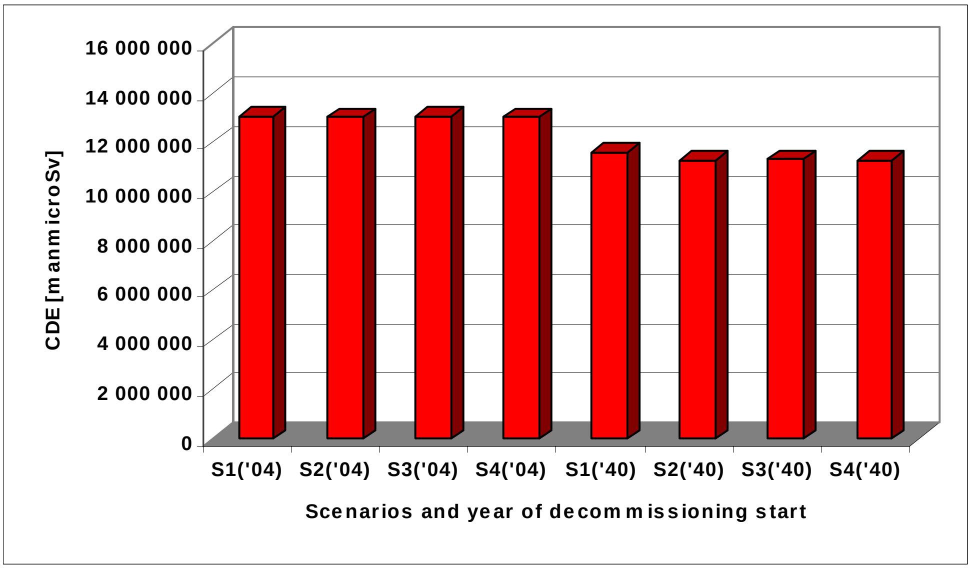


Figure 15: Collective dose equivalent for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for NPP A-1. No pre-dismantling decontamination applied.

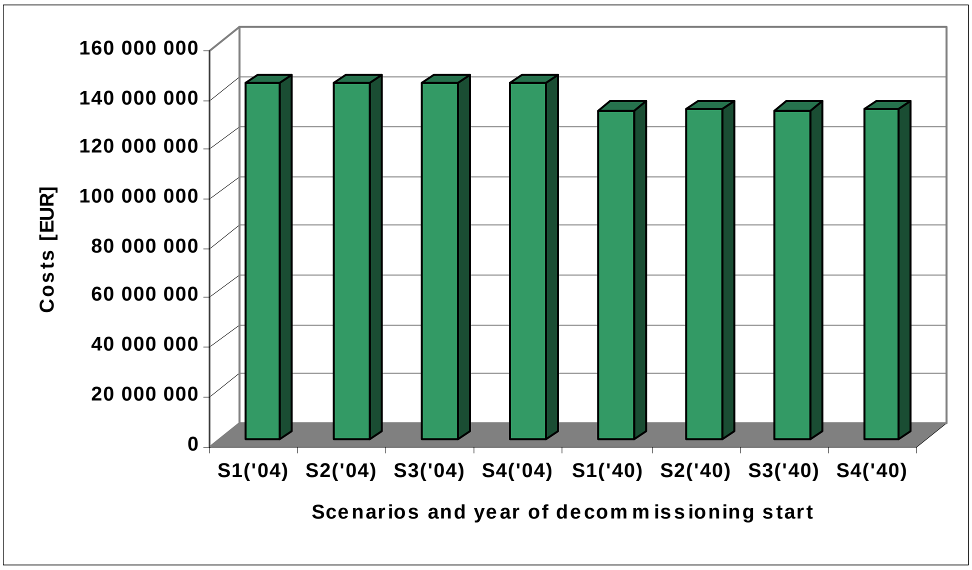


Figure 16: Costs for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for NPP A-1. No pre-dismantling decontamination applied.

Table 10: Sensitivity analysis No. 5 – calculated decommissioning options

Sensitivity analysis No. 5			
Decommissioning option	**Manpower [manhour]**	**CDE [manmicroSv]**	**Costs [EUR]**
P-K2-S1-04-A1	912 270	14 188 801	41 330 628
P-K2-S2-04-A1	871 669	14 087 554	40 775 949
P-K2-S3-04-A1	878 566	14 106 881	40 870 874
P-K2-S4-04-A1	871 249	14 086 132	40 935 770
P-K2-S1-40-A1	1 208 110	8 124 821	43 645 210
P-K2-S2-40-A1	777 428	7 080 625	37 042 715
P-K2-S3-40-A1	835 726	7 244 244	36 636 569
P-K2-S4-40-A1	776 990	7 079 140	37 210 299

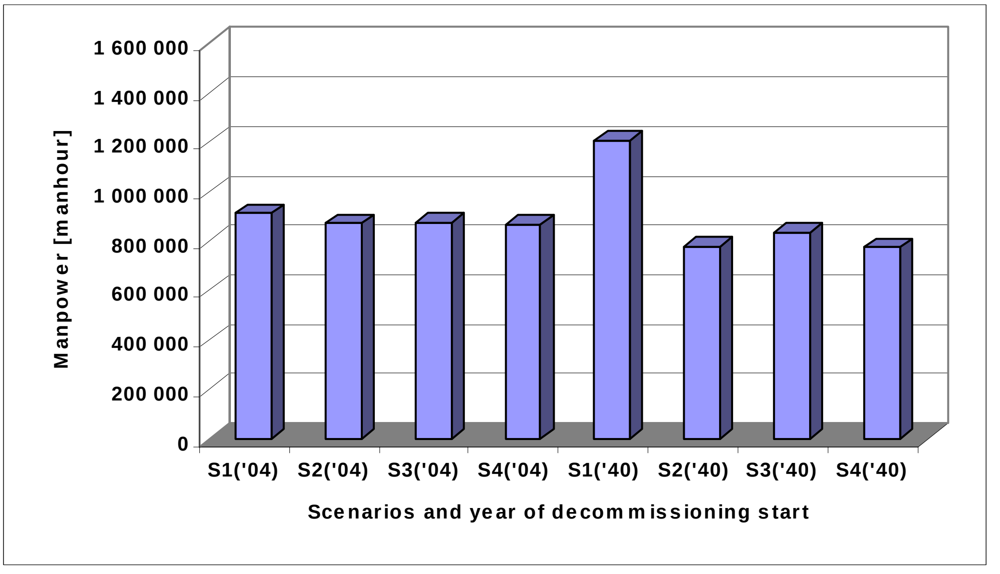


Figure 17: Manpower for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for NPP A-1. Applied pre-dismantling decontamination.

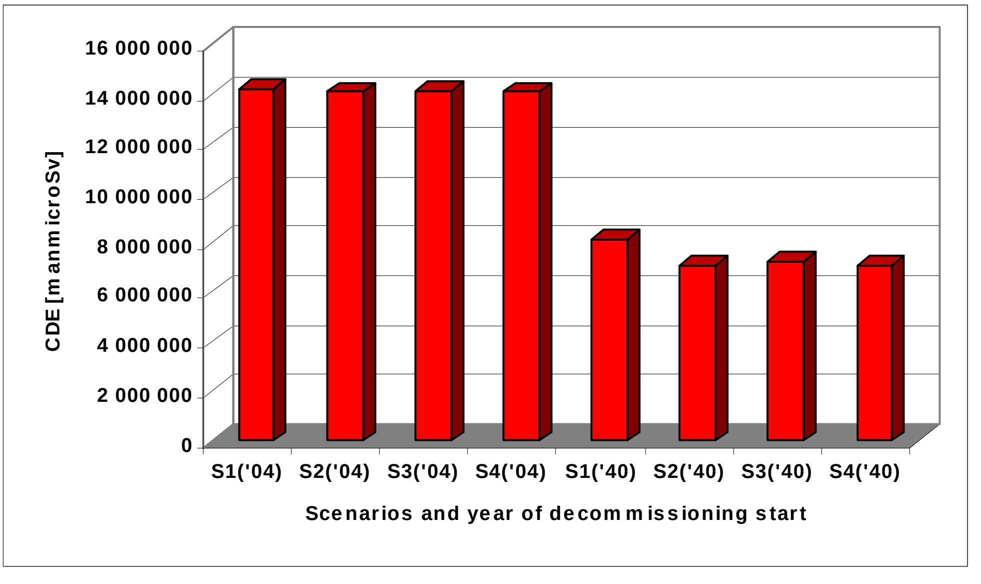


Figure 18: Collective dose equivalent for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for NPP A-1. Applied pre-dismantling decontamination.

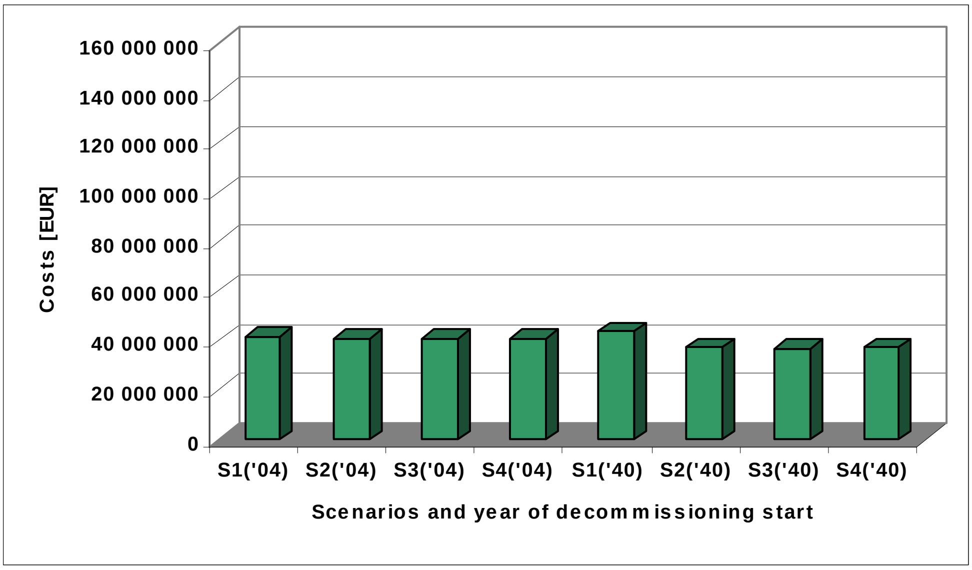


Figure 19: Costs for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for NPP A-1. Applied pre-dismantling decontamination.

Table 11: Sensitivity analysis No. 6 – calculated decommissioning options

Sensitivity analysis No. 6			
Decommissioning option	**Manpower [manhour]**	**CDE [manmicroSv]**	**Costs [EUR]**
P-K3-S1-04-A1	975 359	3 304 170	34 191 262
P-K3-S2-04-A1	671 618	2 570 705	28 580 472
P-K3-S3-04-A1	618 306	2 453 402	28 396 359
P-K3-S4-04-A1	604 225	2 413 691	2 705 591
P-K3-S1-40-A1	1 125 205	2 968 340	32 626 964
P-K3-S2-40-A1	773 828	2 120 474	26 104 416
P-K3-S3-40-A1	712 082	2 055 981	22 608 002
P-K3-S4-40-A1	556 276	1 618 506	24 149 085

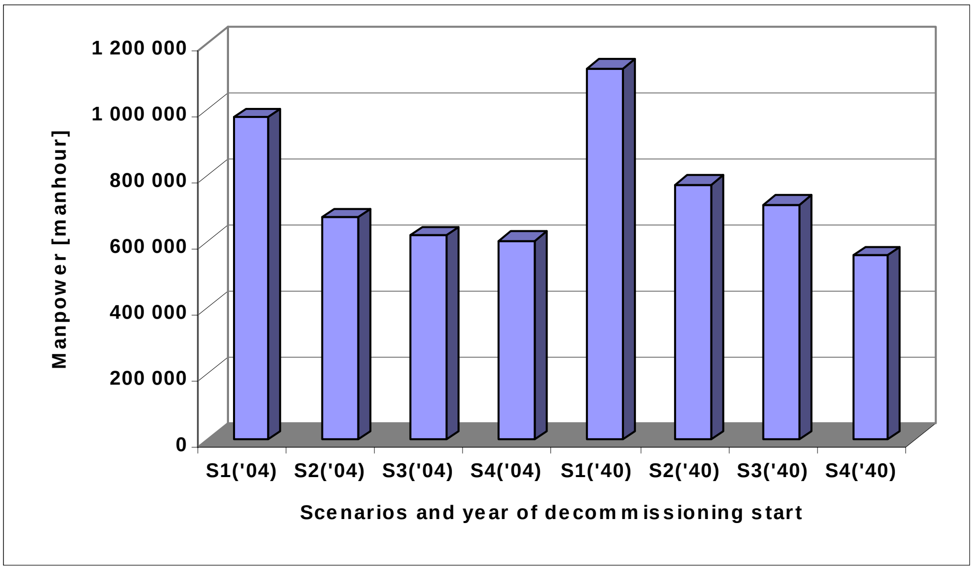


Figure 20: Manpower for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for NPP A-1 with 10-times lower contamination level. Applied pre-dismantling decontamination.

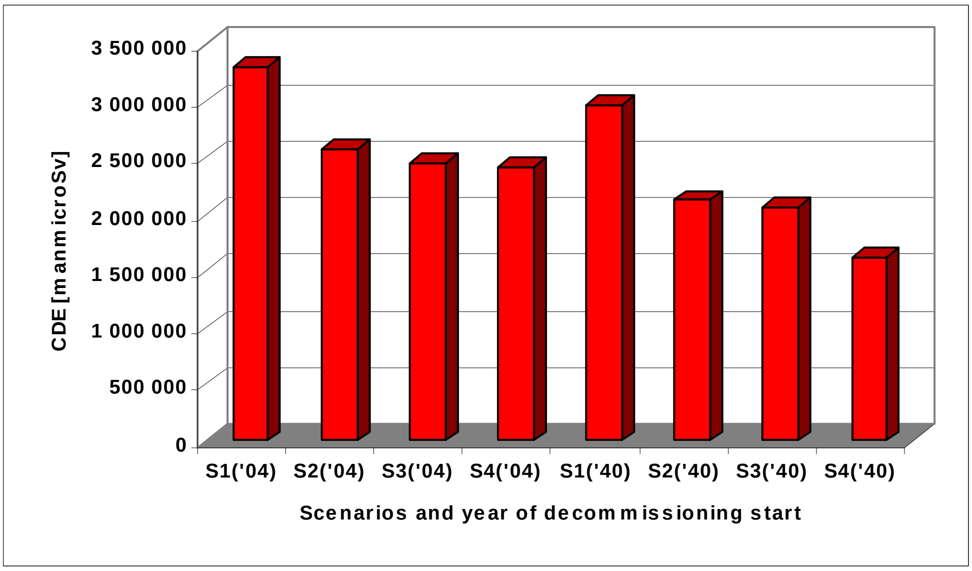


Figure 21: Collective dose equivalent for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for NPP A-1 with 10-times lower contamination level. Applied pre-dismantling decontamination.

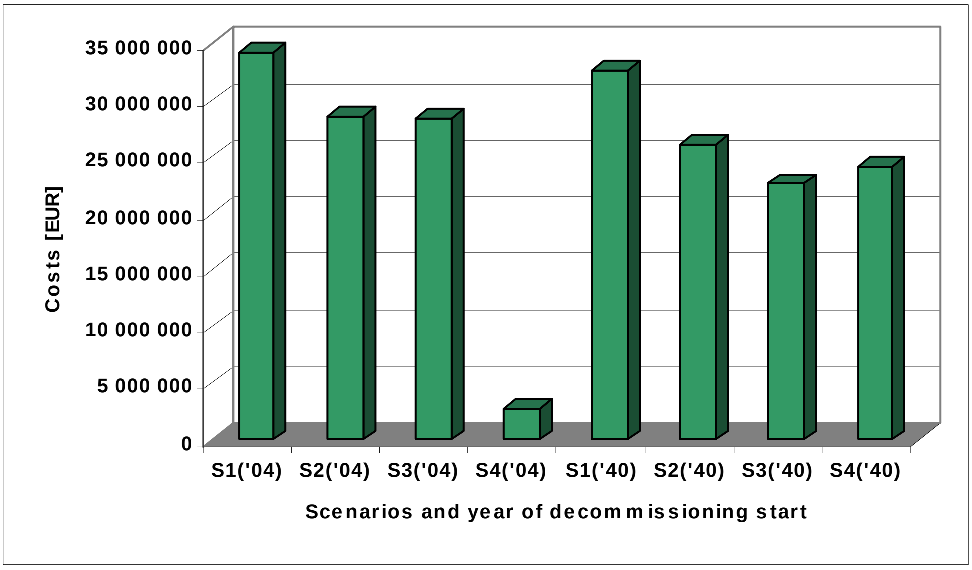


Figure 22: Costs for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for NPP A-1 with 10-times lower contamination level. Applied pre-dismantling decontamination.

Table 12: Sensitivity analysis No. 7 – calculated decommissioning options

Sensitivity analysis No. 7			
Decommissioning option	**Manpower [manhour]**	**CDE [manmicroSv]**	**Costs [EUR]**
N-K2-S1-04-V2	1 081 776	19 417 566	44 703 082
N-K2-S2-04-V2	1 081 726	19 417 428	44 703 349
N-K2-S3-04-V2	1 085 839	19 428 552	44 950 629
N-K2-S4-04-V2	1 081 013	19 414 964	45 001 264
N-K2-S1-40-V2	755 120	1 677 700	23 276 312
N-K2-S2-40-V2	737 004	1 629 030	23 292 795
N-K2-S3-40-V2	525 194	1 141 526	21 018 628
N-K2-S4-40-V2	520 195	1 127 563	21 053 284

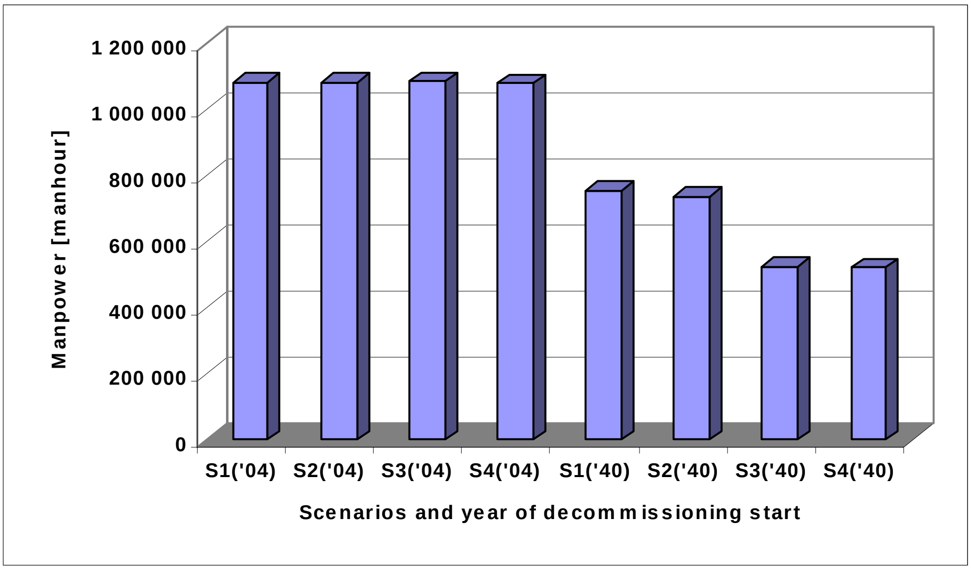


Figure 23: Manpower for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition and the level of contamination of non-accident NPP V-2. No pre-dismantling decontamination applied.

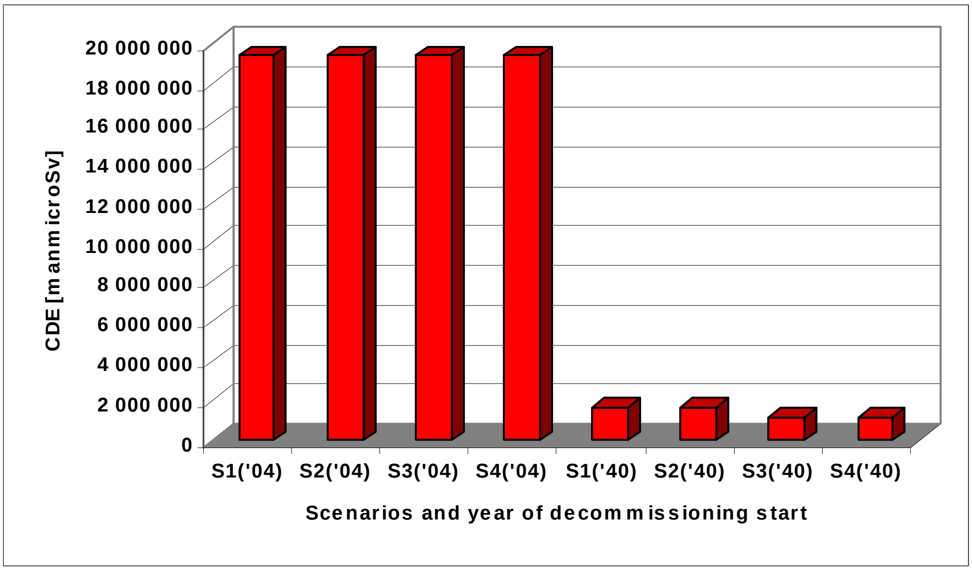


Figure 24: Collective dose equivalent for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition and the level of contamination of non-accident NPP V-2. No pre-dismantling decontamination applied.

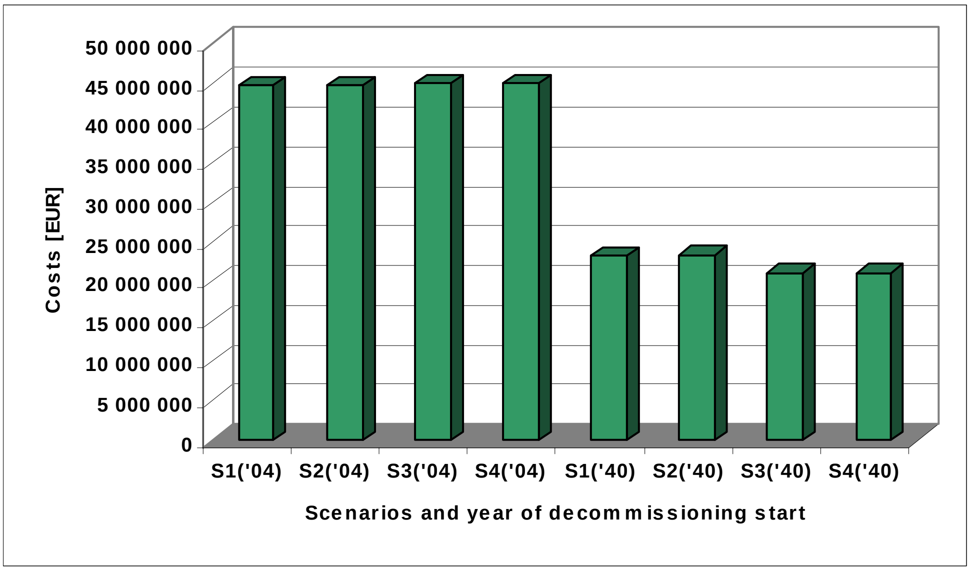


Figure 25: Costs for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition and the level of contamination of non-accident NPP V-2. No pre-dismantling decontamination applied.

Table 13: Sensitivity analysis No. 8 – calculated decommissioning options

Sensitivity analysis No. 8			
Decommissioning option	**Manpower [manhour]**	**CDE [manmicroSv]**	**Costs [EUR]**
P-K2-S1-04-V2	835 867	11 550 902	36 753 164
P-K2-S2-04-V2	833 513	11 544 501	36 761 861
P-K2-S3-04-V2	837 217	11 554 234	37 176 414
P-K2-S4-04-V2	832 364	11 540 566	37 227 465
P-K2-S1-40-V2	759 030	1 585 671	21 397 364
P-K2-S2-40-V2	718 316	1 477 463	21 424 472
P-K2-S3-40-V2	494 691	967 008	19 255 712
P-K2-S4-40-V2	478 328	921 225	19 381 790

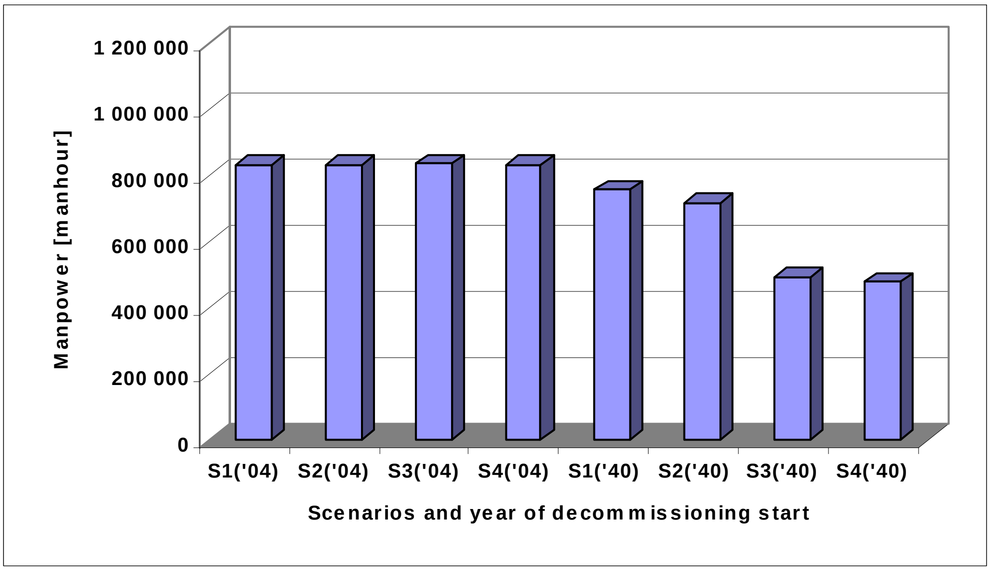


Figure 26: Manpower for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition and the level of contamination of non-accident NPP V-2. Applied pre-dismantling decontamination.

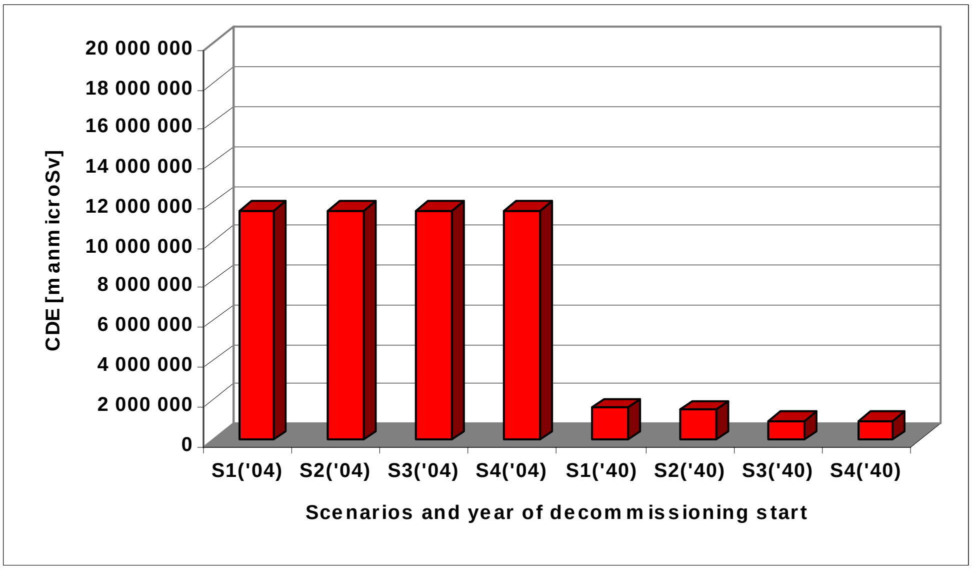


Figure 27: Collective dose equivalent for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition and the level of contamination of non-accident NPP V-2. Applied pre-dismantling decontamination.

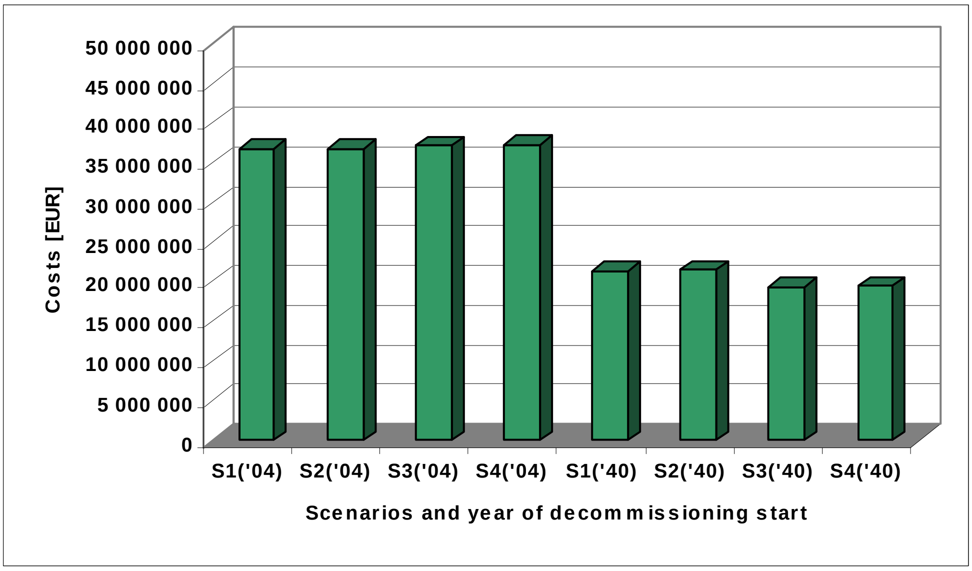


Figure 28: Costs for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition and the level of contamination of non-accident NPP V-2. Applied pre-dismantling decontamination.

Table 14: Sensitivity analysis No. 9 – calculated decommissioning options

Sensitivity analysis No. 9			
Decommissioning option	**Manpower [manhour]**	**CDE [manmicroSv]**	**Costs [EUR]**
P-K3-S1-04-V2	836 516	2 672 630	29 047 771
P-K3-S2-04-V2	820 014	2 628 805	29 053 939
P-K3-S3-04-V2	611 847	2 151 216	27 013 605
P-K3-S4-04-V2	602 513	2 124 931	27 111 785
P-K3-S1-40-V2	592 358	1 120 448	15 795 672
P-K3-S2-40-V2	578 870	1 083 920	15 831 089
P-K3-S3-40-V2	518 014	972 687	15 510 916
P-K3-S4-40-V2	449 750	780 787	16 174 503

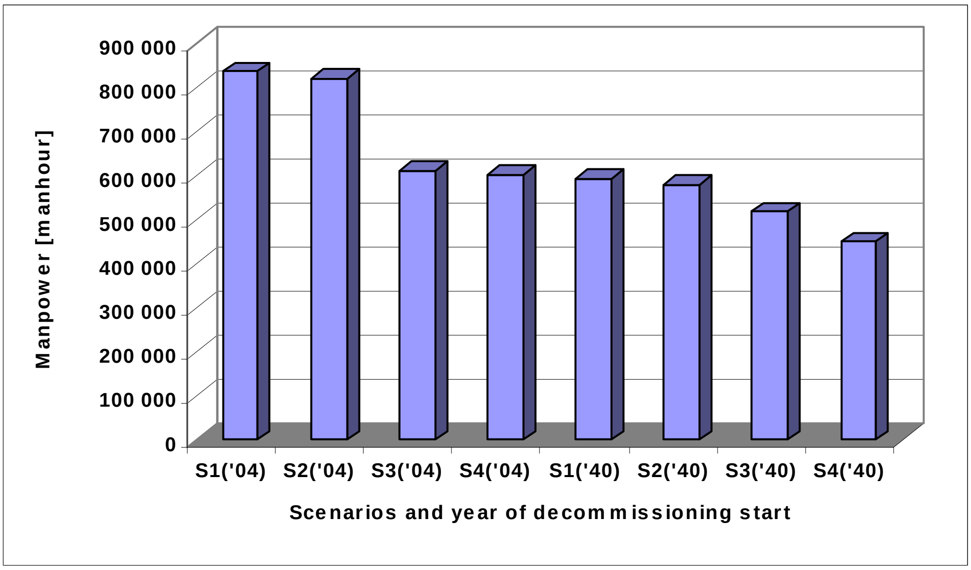


Figure 29: Manpower for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for non-accident NPP V-2 with 10-times lower contamination level. Applied pre-dismantling decontamination.

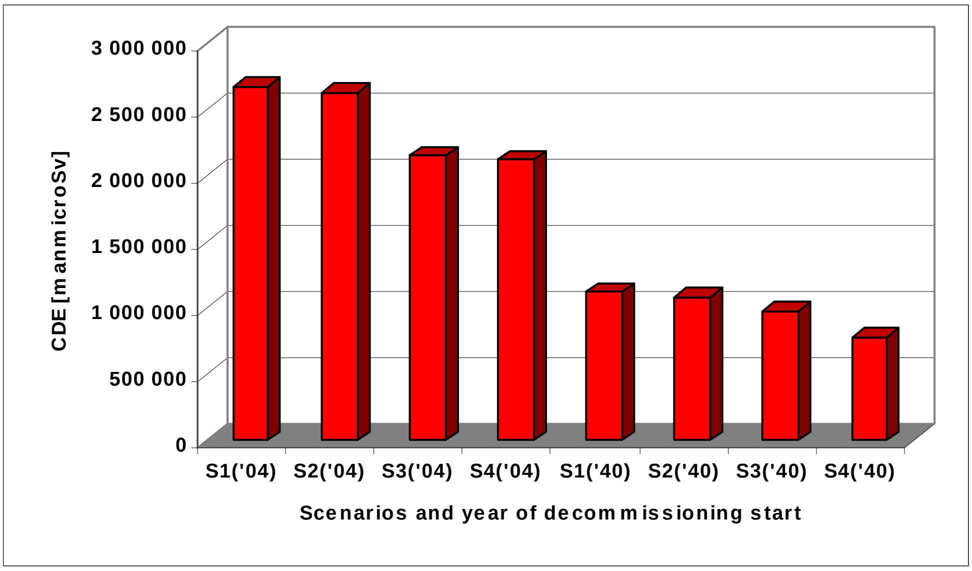


Figure 30: Collective dose equivalent for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for non-accident NPP V-2 with 10-times lower contamination level. Applied pre-dismantling decontamination.

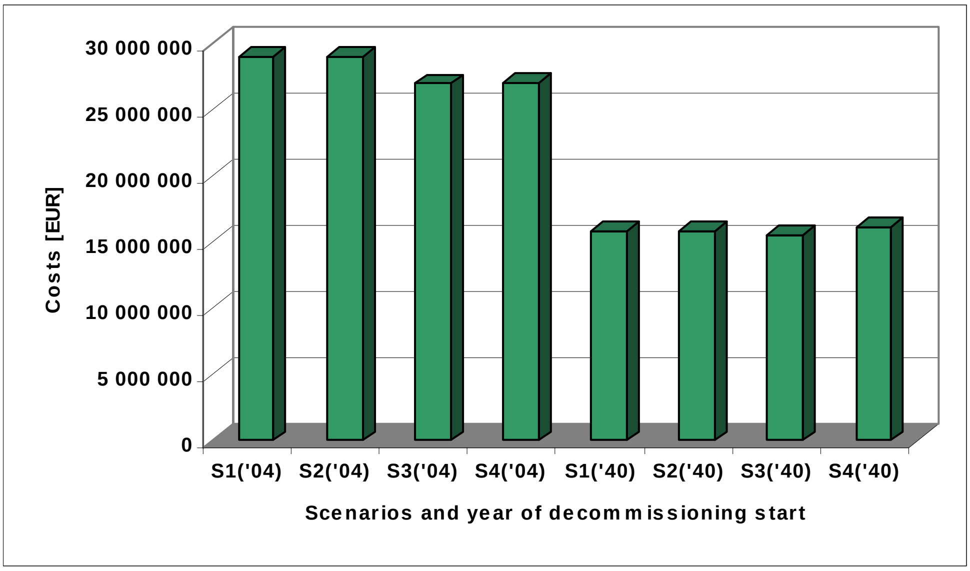


Figure 31: Costs for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for non-accident NPP V-2 with 10-times lower contamination level. Applied pre-dismantling decontamination.

Table 15: Sensitivity analysis No. 10 – calculated decommissioning options

Sensitivity analysis No. 10			
Decommissioning option	**Manpower [manhour]**	**CDE [manmicroSv]**	**Costs [EUR]**
P-K2-S1-04-V2	835 867	11 550 902	36 753 164
P-K2-S1-10-V2	742 025	5 968 446	33 337 757
P-K2-S1-20-V2	833 966	2 895 008	29 217 137
P-K2-S1-30-V2	860 620	2 055 512	27 601 399
P-K2-S1-40-V2	759 030	1 585 671	21 397 364

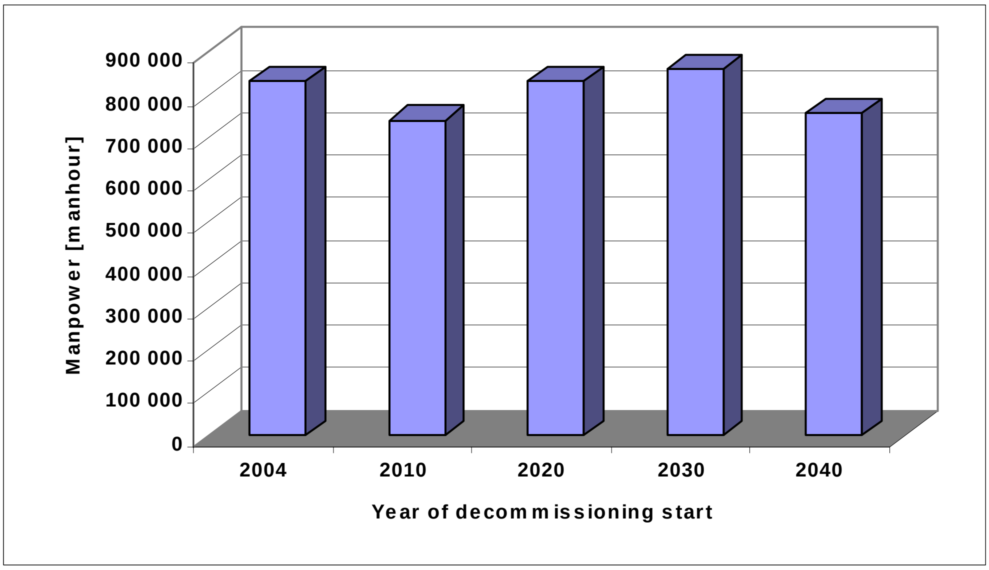


Figure 32: Manpower for different calculated options. These options differ in decommissioning start time (2004, 2010, 2020, 2030 and 2040) for decommissioning scenario S1. Typical radionuclide composition and the level of contamination of non-accident NPP V-2. Applied pre-dismantling decontamination.

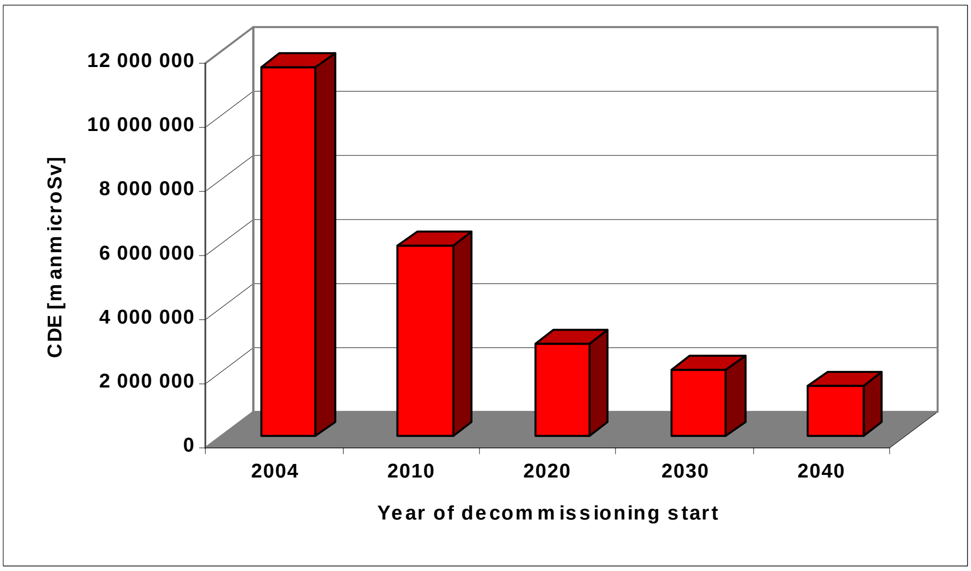


Figure 33: Collective dose equivalent for different calculated options. These options differ in decommissioning start time (2004, 2010, 2020, 2030 and 2040) for decommissioning scenario S1. Typical radionuclide composition and the level of contamination of non-accident NPP V-2. Applied pre-dismantling decontamination.

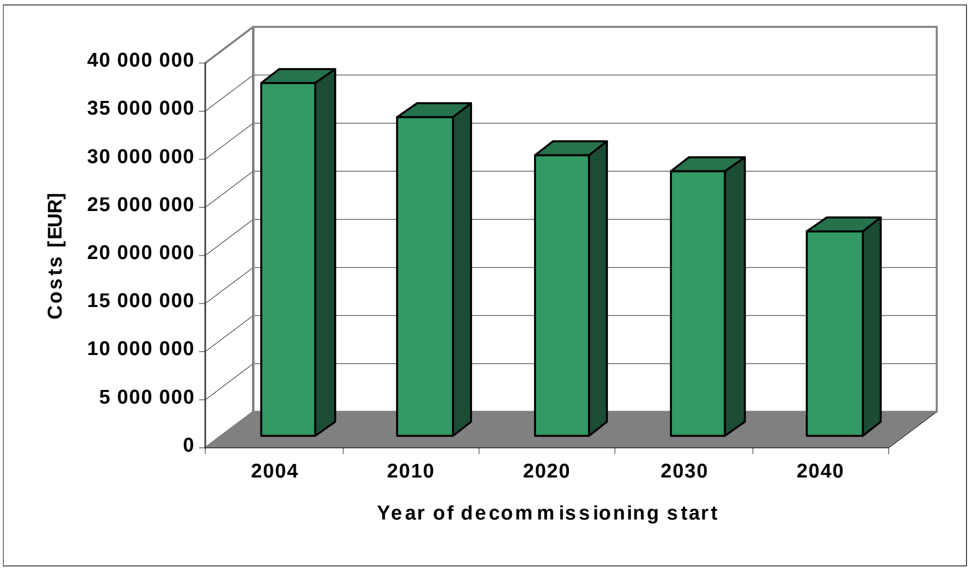


Figure 34: Costs for different calculated options. These options differ in decommissioning start time (2004, 2010, 2020, 2030 and 2040) for decommissioning scenario S1. Typical radionuclide composition and the level of contamination of non-accident NPP V-2. Applied pre-dismantling decontamination.

6.3.2 Calculated distribution of materials from decommissioning

For easier identification of calculated mass distribution of steel arisen from decommissioning and number of containers for disposal, the table below summarizes a set of output figures belonging to each particular sensitivity analysis case [9]. Naturally, used symbols for input parameters remain unchanged and are described in mentioned chapter 6.2.2.1.

Table 16: Sensitivity analysis cases – calculated distribution of materials from decommissioning

Sensitivity analysis No.	Output parameter figures		Input parameters				
	Mass distribution of steel	Number of containers for disposal	Levels of contamination	Scenarios	Pre-dismantling decontamination	Start time of decommissioning	Nuclide vectors
1.	**Figure 35**	**Figure 36**	K1, K2, K3, K4	S1	N, P	2004	A-1
2.	**Figure 37**	**Figure 38**	K2, K3	S1, S2, S3, S4	N	2004	A-1
3.	**Figure 39**	**Figure 40**	K2, K3	S1, S2, S3, S4	P	2004	A-1
4.	**Figure 41**	**Figure 42**	K2	S1, S2, S3, S4	N	2004, 2040	A-1
5.	**Figure 43**	**Figure 44**	K2	S1, S2, S3, S4	P	2004, 2040	A-1
6.	**Figure 45**	**Figure 46**	K3	S1, S2, S3, S4	P	2004, 2040	A-1
7.	**Figure 47**	**Figure 48**	K2	S1, S2, S3, S4	N	2004, 2040	V-2
8.	**Figure 49**	**Figure 50**	K2	S1, S2, S3, S4	P	2004, 2040	V-2
9.	**Figure 51**	**Figure 52**	K3	S1, S2, S3, S4	P	2004, 2040	V-2
10.	**Figure 53**	**Figure 54**	K2	S1	P	2004,2010, 2020, 2030,2040	V-2

Figure 35 shows dependence of mass distribution of steel on the level of technological equipment contamination and on applicability / non-applicability of pre-dismantling decontamination. Input technological equipment contamination decrease causes increase of amount of released steel to the detriment of the disposed steel. Simultaneously increase of amount of released steel is promoted by performing of pre-dismantling decontamination.

Dependence of containers distribution on the level of technological equipment contamination and on applicability / non-applicability of pre-dismantling decontamination is shown on **Figure 36**. Input technological equipment contamination decrease causes decrease of amount of containers destined to geological repository and increase of amount of containers destined to surface repository (see **Figure 36**, mainly the part where pre-dismantling decontamination is not applied). This phenomenon is based on the fact, that the more technological equipment contamination decreases, the more amount of decommissioned technological equipment complies with surface repository limits. Faster increase of amount of containers for surface repository than the decrease of containers for geological repository is given by the fact that surface repository containers include lower amount of metals in the container than geological repository containers. Surface repository containers contain either drums with cemented metal or metal pellets after supercompaction. The limit factor is a specific radioactivity, mass and volume increase of treated metals consequently stored in containers in comparison with the volume of original metal waste. In case of geological repository metals, they are put in the containers directly and the only one limit factor is metal mass given by capacity of the container.

Further contamination decrease causes decrease of amount of geological repository containers. The above mentioned re-grouping of containers from a group destined to geological repository to a group of containers destined to surface repository is less significant or is negligible (due to high level of alpha contamination). Decrease of surface repository containers amount becomes very important (see **Figure 36**, mainly part where pre-dismantling decontamination is applied).

Figure 37, **Figure 38**, **Figure 39** and **Figure 40** show dependence of discussed output decommissioning parameters on applied decommissioning scenarios. In case of non-application of pre-dismantling decommissioning, an applied decommissioning scenario has no important influence on discussed output parameters (see **Figure 37** and **Figure 38**). The only exception is the case of contamination level K3, when nearly all the steel mass and amount of containers is transferred from geological repository to the surface repository.

Strong majority of steel for surface repository and unimportant influence of applied decommissioning scenarios on discussed output parameters is also typical in the case of application of pre-dismantling decontamination and contamination level K2 (see **Figure 39** and **Figure 40**). But in the case of contamination level K3 it is obvious that application of scenario S1 leads to the largest mass of the released steel and the lowest amount of surface repository containers and repository containers generally.

Figure 41 – **Figure 46** show the influence of decommissioning scenarios on the steel mass distribution and number of repository containers when the decommissioning process will start in 2040. In order to emphasize the influence of decommissioning start time delay, output parameters concerning standard decommissioning start time in 2004 (as shown in the **Figure 37 - Figure 40** and discussed above) are also included in **Figure 41 - Figure 46**.

If pre-dismantling decontamination is not applied then for basic contamination level K2, start time delay will lead to the increase of mass of steel released after decontamination and consequent melting in the case of scenario S1 (see **Figure 41**) and also to decrease of number of surface repository containers (see **Figure 42**).

Positive consequence of combination of start time delay and melting for basic contamination level K2 is more obvious in the case the pre-dismantling decontamination is applied (**Figure 43** and **Figure 44**). Increase of released steel mass and decrease of surface repository containers number for the scenario S3 and start time delay is obvious (in comparison with the standard decommissioning start time in 2004). The main reason of this fact is the remarkable occurrence of Cs-137 in the technological equipment internal surface contamination spectrum and its dominant occurrence in the technological equipment external surface contamination spectrum (see **Table 2** in chapter 6.2.1). Only a small amount of Cs-137 remains in the melt, this nuclide is captured by filters and is transferred to slag.

In the case of start time delay, the increase of released steel mass and the decrease of surface repository containers number respectively is stronger for post-dismantling decontamination and consequent melting scenario (scenario S1, **Figure 43** and **Figure 44**).

In the case of contamination level K3 (ten times lower as basic contamination level K2), post-dismantling decontamination application and start time delay, the increase of released steel mass and the decrease of surface repository containers is obvious not only for scenarios S1 and S3 (as in previous case) but also for scenario S2 (**Figure 45** and **Figure 46**). Combination of decreased contamination level (K3), decay of main nuclides Co-60 and Cs-137 (see **Table 2** in chapter 6.2.1) due to deferred dismantling and pre-dismantling decontamination applied on the serious amount of steel leads to the release of the steel into environment. The largest amount of steel is released in the case of scenario S1 and then for scenarios S3 a S2 (**Figure 45**). On the contrary, the smallest number of surface repository containers in the case of deferred dismantling arises from scenario S3, then from scenarios S1 and S2 (**Figure 46**). The reason is liquid radwaste contributes to the increased number of surface repository containers. Liquid radwaste arises from decontamination and it is consequently treated by evaporation, bituminisation of concentrates to drums and cementation of drums to containers.

Output A-1 NPP primary circuit decommissioning parameters discussed until now were based on the fact the isotopic content of technological equipment inner/outer contamination is typical for A-1 NPP. These nuclide vectors represent radiological condition of NPP after the accident. Beside Co-60 occurrence of Cs-137 and alpha nuclides is typical as a consequence of leakage and/or damage of fuel elements cladding.

A-1 NPP primary circuit decommissioning parameters discussed below will be based on the input condition that the isotopic content of technological equipment inner/outer contamination is typical for V-2 NPP. These nuclide vectors (see **Table 3** in chapter 6.2.1) represent radiological condition of NPP without any accident, fuel elements cladding tightness is very good. Co-60 is dominant nuclide of the nuclide vectors, occurrence of Cs-137 and alpha nuclides is negligible.

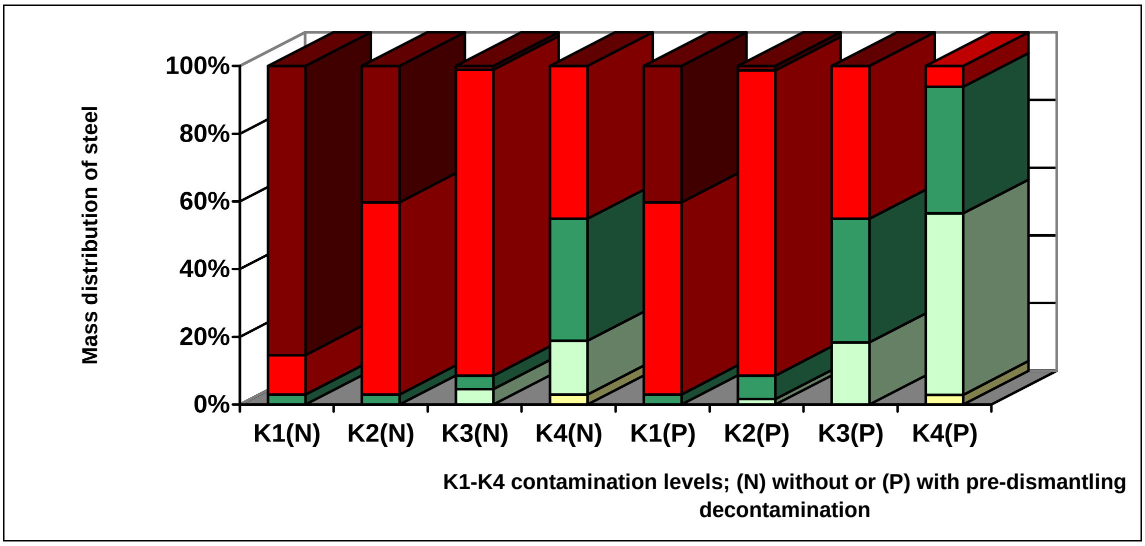
Similar to foregoing cases (shown at **Figure 41 - Figure 46**), **Figure 47 - Figure 52** show the influence of decommissioning scenarios on the steel mass distribution and number of repository containers if the decommissioning process will start in 2004 and 2040, respectively. No steel for geological repository is a general attribute of all the scenarios. Non-alpha contamination level is the reason.

In the case of start time in 2004, basic contamination level K2 and application/non-application of pre-dismantling decontamination type of scenario has no important influence on discussed output parameters (**Figure 47 - Figure 50**). In the case of decommissioning start time in 2004, contamination level K3 (ten times lower than basic contamination level K2) and application of pre-dismantling decontamination it is obvious, that scenario S1 leads to the largest mass of released steel and the lowest number of surface repository containers (**Figure 51** and **Figure 52**).

If the decommissioning start time is 2040, a steel released into environment after dismantling (i.e. without post-dismantling decontamination and melting, respectively) appears. Proportion of that steel is the largest in case of contamination level K3 and application of pre-dismantling decontamination (**Figure 51**). This fact points out the decay as a tool of decrease of radwaste arising from deferred decommissioning (**Figure 53** and **Figure 54**). Sufficiently low radioactivity half-time of contaminants is a necessary precondition.

Proportion of steel released into environment after melting in deferred option (2040) to total steel released is not as large as in the case of A-1 NPP isotopic content contamination because the time of deferral is several times larger then half-time of the NPP V-1 dominant nuclide Co-60. This is the reason of occurrence of the steel released into environment directly after dismantling (mainly if contamination level K3 and application of pre-dismantling decontamination, **Figure 51**) and occurrence of significant proportion of steel released after application of post-dismantling decontamination. Another reason is the phenomenon that significant portion of Co-60 remains in the melt and melting is not an efficient decontamination process in this case.

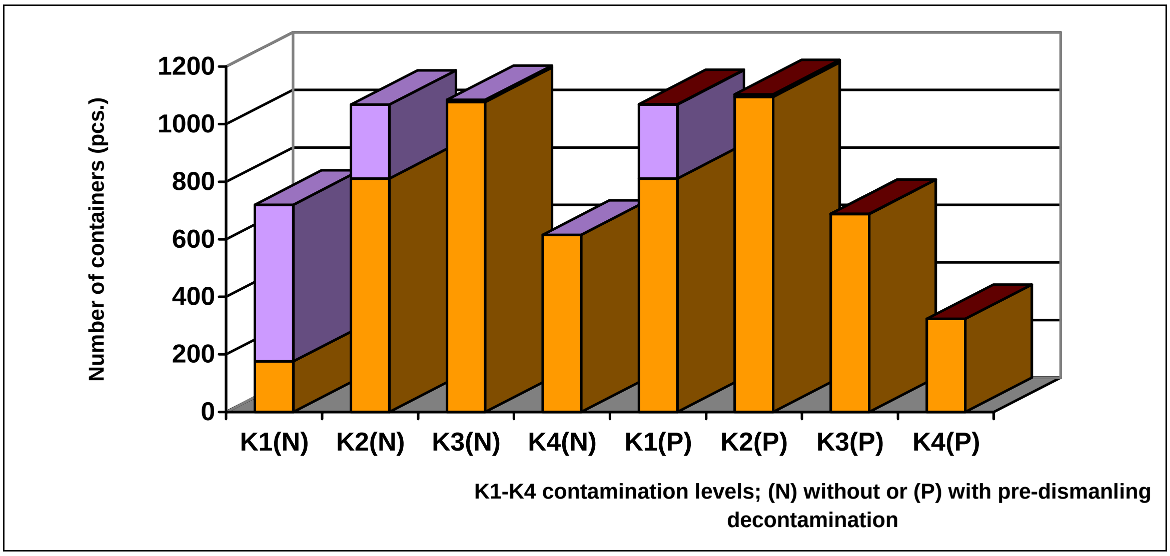
When deferred dismantling cases (2040) and NPP V-2 isotopic content contamination is to be considered (**Figure 47 - Figure 52**), scenario S1 leads to the largest released steel mass and the lowest number of surface repository containers and repository containers generally.



Explanation:

Contamination level	K1		K2		K3		K4	
	Without pre-dismantling decontamination (N)							
Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
Steel destined to deep geological repository	2 561 283	**85,4**	1 207 327	**40,2**	34 799	**1,2**	356	**0,01**
Steel destined to near-surface repository	349 416	**11,6**	1 703 040	**56,8**	2 708 169	**90,3**	1 353 883	**45,09**
Steel released to environment after melting	88 596	**3,0**	88 928	**3,0**	119 932	**4,0**	1 080 370	**36,0**
Steel released to environment after decontamination		**0**	0	**0**	136 395	**4,5**	476 090	**15,9**
Steel released to environment after dismantling	0	**0**	0	**0**	0	**0**	88 596	**3,0**
	With pre-dismantling decontamination (P)							
Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
Steel destined to deep geological repository	1 209 045	**40,31**	38 525	**1,3**	356	**0,01**	0	**0**
Steel destined to near-surface repository	1 701 322	**56,73**	2 704 443	**90,2**	1 353 884	**45,14**	189 767	**3,3**
Steel released to environment after melting	88 298	**2,94**	208 528	**6,9**	1 095 448	**36,52**	1 154 686	**38,5**
Steel released to environment after decontamination	630	**0,02**	47 799	**1,6**	549 607	**18,33**	1 655 732	**55,2**
Steel released to environment after dismantling	0	**0**	0	**0**	0	**0**	89 055	**3,0**

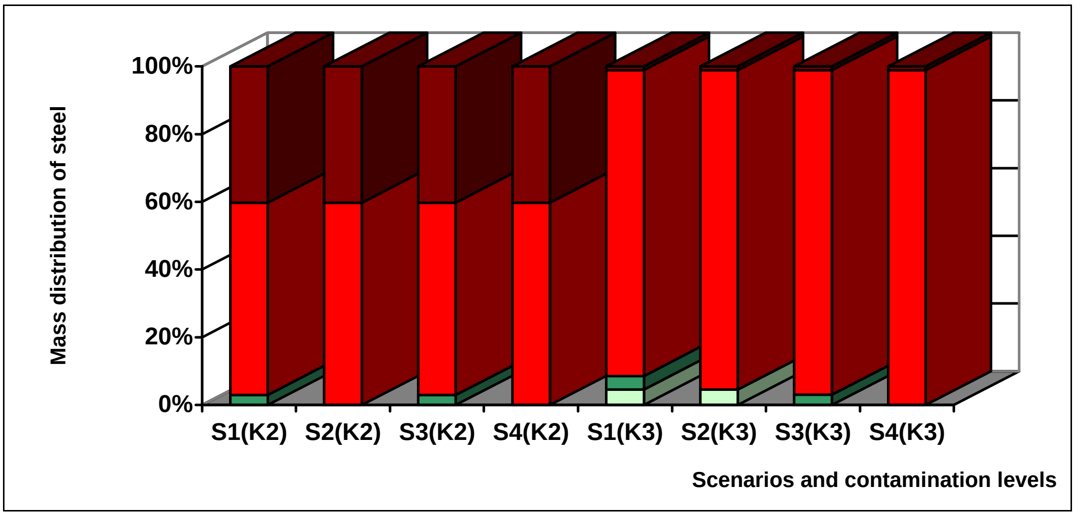
Figure 35: Mass distribution of steel for different calculated options. These options differ in level of contamination of decommissioned technology equipment (with typical radionuclide composition for NPP A-1, decommissioning scenario S1) without (N) or with (P) pre-dismantling decontamination.



Explanation:

	Contamination level	K1	K2	K3	K4
		Without pre-dismantling decontamination (N)			
	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0	0	0	0
	Number of containers destined to deep geological repository with metals (pcs)	544,95	256,88	7,40	0,08
	Number of containers destined to near-surface repository (pcs)	175,34	811,26	1 077,27	615,71
		With pre-dismantling decontamination (P)			
	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0,82	0,75	0,47	0,20
	Number of containers destined to deep geological repository with metals (pcs)	257,26	8,20	0,08	0
	Number of containers destined to near-surface repository (pcs)	811,35	1 095,20	687,97	323,67

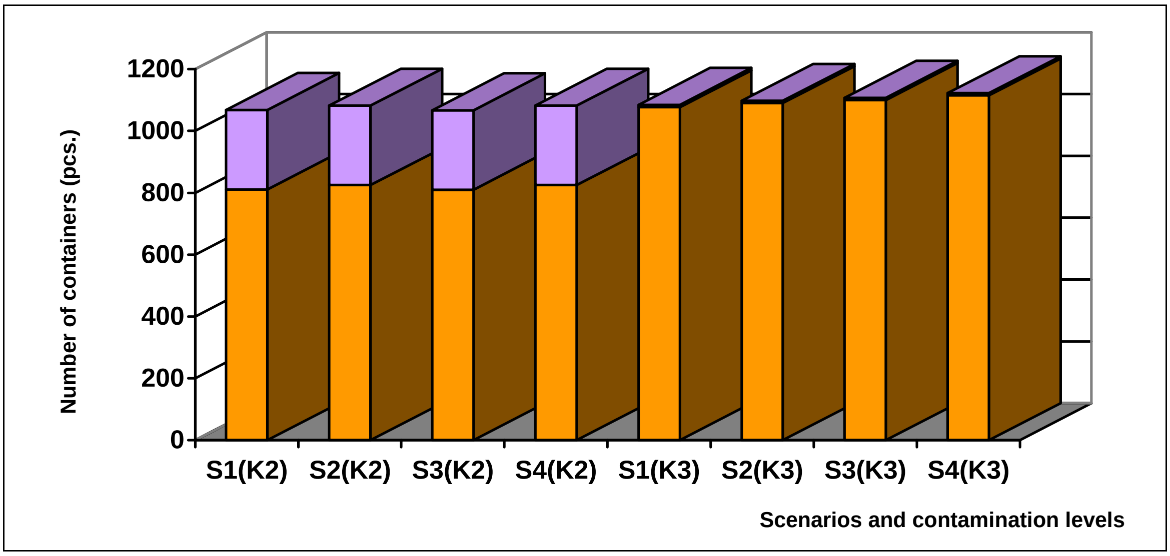
Figure 36: Number of containers destined to repositories for different calculated options. These options differ in level of contamination of decommissioned technology equipment (with typical radionuclide composition for NPP A-1, decommissioning scenario S1) without (N) or with (P) pre-dismantling decontamination.



Explanation:

Scenario	**S1** (decontamination or decontamination and subsequent melting)		**S2** (decontamination)		**S3** (melting)		**S4** (no decontamination, no melting)	
Contamination level	**K2**							
Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
Steel destined to deep geological repository	1 207 327	**40,3**	1 207 327	**40,3**	1 207 327	**40,3**	1 207 327	**40,3**
Steel destined to near-surface repository	1 703 040	**56,7**	1 791 968	**59,7**	1 703 345	**56,7**	1 791 968	**59,7**
Steel released to environment after melting	88 928	**3,0**	0	**0**	88 623	**3,0**	0	**0**
Steel released to environment after decontamination	0	**0**	0	**0**	0	**0**	0	**0**
Steel released to environment after dismantling	0	**0**	0	**0**	0	**0**	0	**0**
Contamination level	**K3**							
Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
Steel destined to deep geological repository	34 799	**1,2**	34 799	**1,2**	34 799	**1,2**	34 799	**1,2**
Steel destined to near-surface repository	2 708 169	**90,3**	2 828 101	**94,3**	2 874 693	**95,8**	2 964 496	**98,8**
Steel released to environment after melting	119 932	**4,0**	0	**0**	89 803	**3,0**	0	**0**
Steel released to environment after decontamination	136 395	**4,5**	136 395	**4,5**	0	**0**	0	**0**
Steel released to environment after dismantling	0	**0**	0	**0**	0	**0**	0	**0**

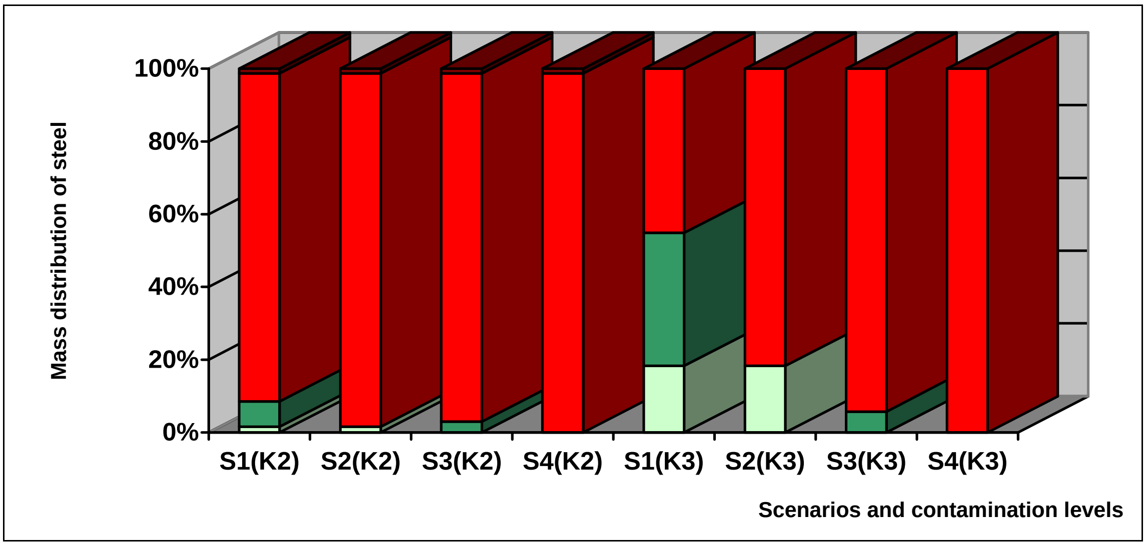
Figure 37: Mass distribution of steel for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and level of contamination of decommissioned technology equipment (either K2 or K3 level with typical radionuclide composition for NPP A-1). No pre-dismantling decontamination applied.



Explanation:

	Scenario	**S1** (decontamination or decontamination and subsequent melting)	**S2** (decontamination)	**S3** (melting)	**S4** (no decontamination, no melting)
	Contamination level	**K2**			
(dark red)	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0	0	0	0
(violet)	Number of containers destined to deep geological repository with metals (pcs)	256,88	256,88	256,88	256,88
(orange)	Number of containers destined to near-surface repository (pcs)	811,26	825,12	810,38	825,12
	Contamination level	**K3**			
(dark red)	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0	0	0	0
(violet)	Number of containers destined to deep geological repository with metals (pcs)	7,40	7,40	7,40	7,40
(orange)	Number of containers destined to near-surface repository (pcs)	1 077,27	1 090,48	1 100,09	1 115,03

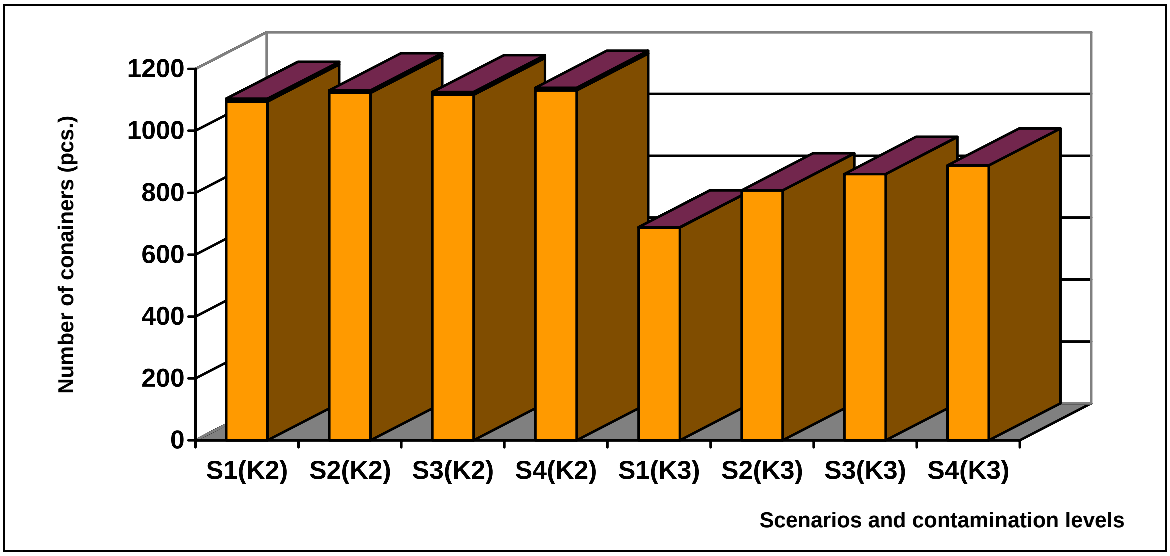
Figure 38: Number of containers destined to repositories for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and level of contamination of decommissioned technology equipment (either K2 or K3 level with typical radionuclide composition for NPP A-1). No pre-dismantling decontamination applied.



Explanation:

	Scenario	**S1** (decontamination or decontamination and subsequent melting)		**S2** (decontamination)		**S3** (melting)		**S4** (no decontamination, no melting)	
	Contamination level	**K2**							
	Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
	Steel destined to deep geological repository	38 525	**1,3**	38 525	**1,3**	38 525	**1,3**	38 525	**1,3**
	Steel destined to near-surface repository	2 704 443	**90,2**	2 912 971	**97,1**	2 870 967	**95,7**	2 960 770	**98,7**
	Steel released to environment after melting	208 528	**6,9**	0	**0**	89 803	**3,0**	0	**0**
	Steel released to environment after decontamination	47 799	**1,6**	47 799	**1,6**	0	**0**	0	**0**
	Steel released to environment after dismantling	0	**0**	0	**0**	0	**0**	0	**0**
	Contamination level	**K3**							
	Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
	Steel destined to deep geological repository	356	**0,01**	356	**0,01**	356	**0,01**	356	**0,01**
	Steel destined to near-surface repository	1 353 884	**45,14**	2 449 332	**81,67**	2 826 402	**94,24**	2 998 939	**99,99**
	Steel released to environment after melting	1 095 448	**36,52**	0	**0**	172 537	**5,75**	0	**0**
	Steel released to environment after decontamination	549 607	**18,33**	549 607	**18,32**	0	**0**	0	**0**
	Steel released to environment after dismantling	0	**0**	0	**0**	0	**0**	0	**0**

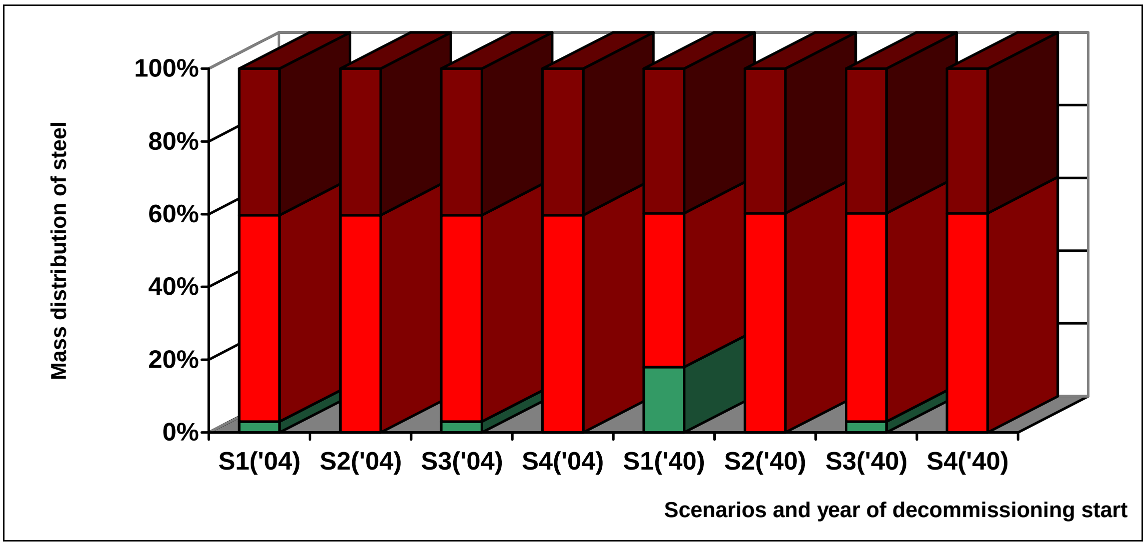
Figure 39: Mass distribution of steel for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and level of contamination of decommissioned technology equipment (either K2 or K3 level with typical radionuclide composition for NPP A-1). Applied pre-dismantling decontamination.



Explanation:

	Scenario	S1 (decontamination or decontamination and subsequent melting)	S2 (decontamination)	S3 (melting)	S4 (no decontamination, no melting)
	Contamination level	**K2**			
	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0,75	0,75	0,75	0,75
	Number of containers destined to deep geological repository with metals (pcs)	8,20	8,20	8,20	8,20
	Number of containers destined to near-surface repository (pcs)	1 095,20	1 122,21	1 116,55	1 130,81
	Contamination level	**K3**			
	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0,47	0,47	0,47	0,47
	Number of containers destined to deep geological repository with metals (pcs)	0,08	0,08	0,08	0,08
	Number of containers destined to near-surface repository (pcs)	687,97	807,50	860,61	888,15

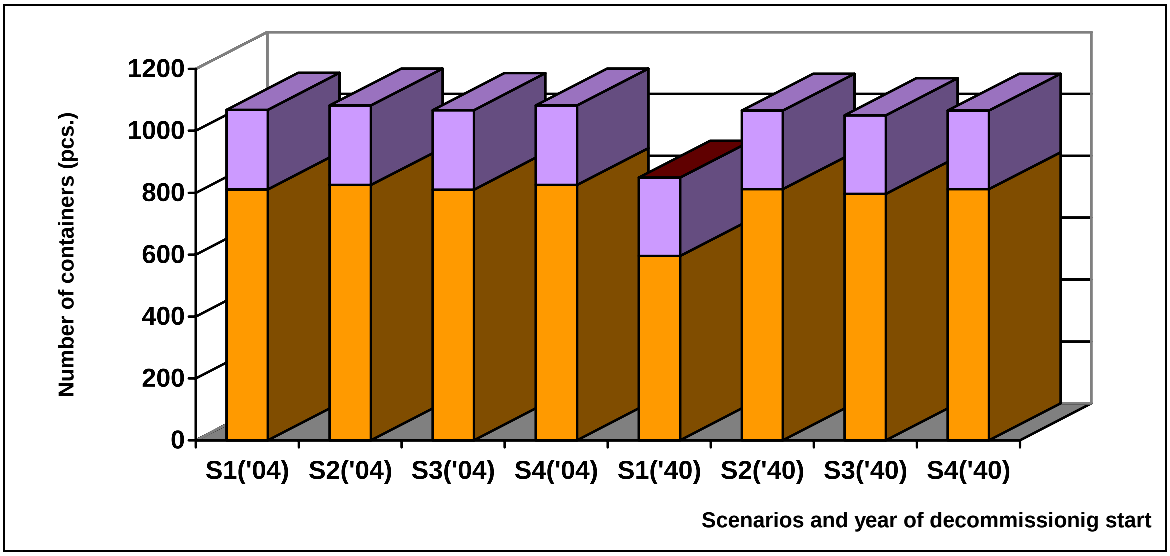
Figure 40: Number of containers destined to repositories for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and level of contamination of decommissioned technology equipment (either K2 or K3 level with typical radionuclide composition for NPP A-1). Applied pre-dismantling decontamination.



Explanation:

	Scenario	S1 (decontamination or decontamination and subsequent melting)		S2 (decontamination)		S3 (melting)		S4 (no decontamination, no melting)	
	Decommissioning start	**Year 2004 (‘04)**							
	Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
	Steel destined to deep geological repository	1 207 327	**40,3**	1 207 327	**40,3**	1 207 327	**40,3**	1 207 327	**40,3**
	Steel destined to near-surface repository	1 703 040	**56,7**	1 791 968	**59,7**	1 703 345	**56,7**	1 791 968	**59,7**
	Steel released to environment after melting	88 928	**3,0**	0	**0**	88 623	**3,0**	0	**0**
	Steel released to environment after decontamination	0	**0**	0	**0**	0	**0**	0	**0**
	Steel released to environment after dismantling	0	**0**	0	**0**	0	**0**	0	**0**
	Decommissioning start	**Year 2040 (‘40)**							
	Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
	Steel destined to deep geological repository	1 193 029	**39,8**	1 193 029	**39,8**	1 193 029	**39,8**	1 193 029	**39,8**
	Steel destined to near-surface repository	1 269 198	**42,3**	1 806 266	**60,2**	1 717 078	**57,2**	1 806 266	**60,2**
	Steel released to environment after melting	537 068	**17,9**	0	**0**	89 188	**3,0**	0	**0**
	Steel released to environment after decontamination	0	**0**	0	**0**	0	**0**	0	**0**
	Steel released to environment after dismantling	0	**0**	0	**0**	0	**0**	0	**0**

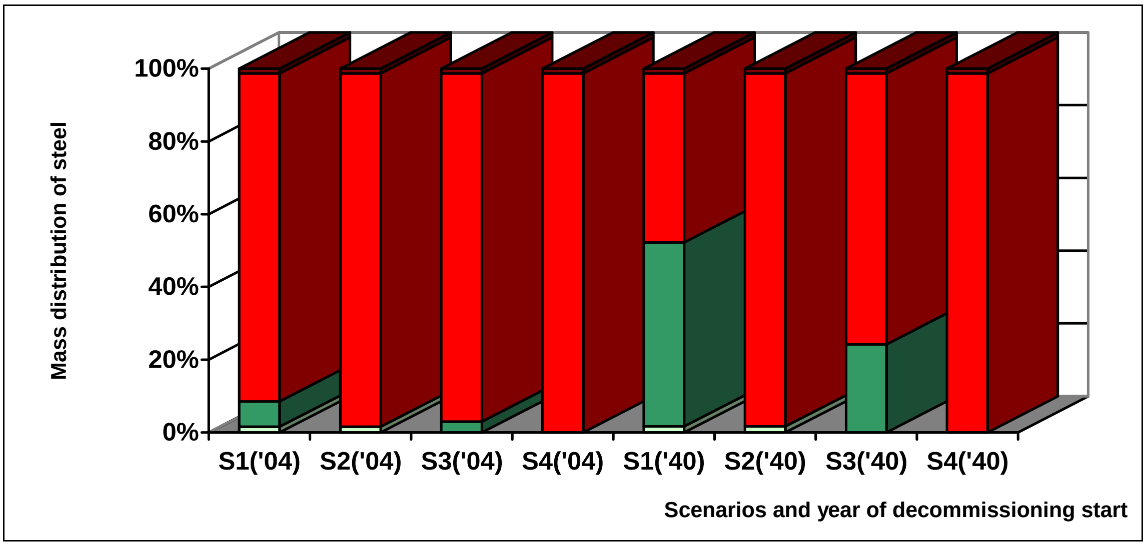
Figure 41: Mass distribution of steel for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for NPP A-1. No pre-dismantling decontamination applied.



Explanation:

	Scenario	S1 (decontamination or decontamination and melting)	S2 (decontamination)	S3 (melting)	S4 (no decontamination, no melting)
	Decommissioning start	**Year 2004 (‘04)**			
	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0	0	0	0
	Number of containers destined to deep geological repository with metals (pcs)	256,88	256,88	256,88	256,88
	Number of containers destined to near-surface repository (pcs)	811,26	825,12	810,38	825,12
	Decommissioning start	**Year 2040 (‘40)**			
	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0,17	0	0	0
	Number of containers destined to deep geological repository with metals (pcs)	253,84	253,84	253,84	253,84
	Number of containers destined to near-surface repository (pcs)	595,05	811,49	796,66	811,49

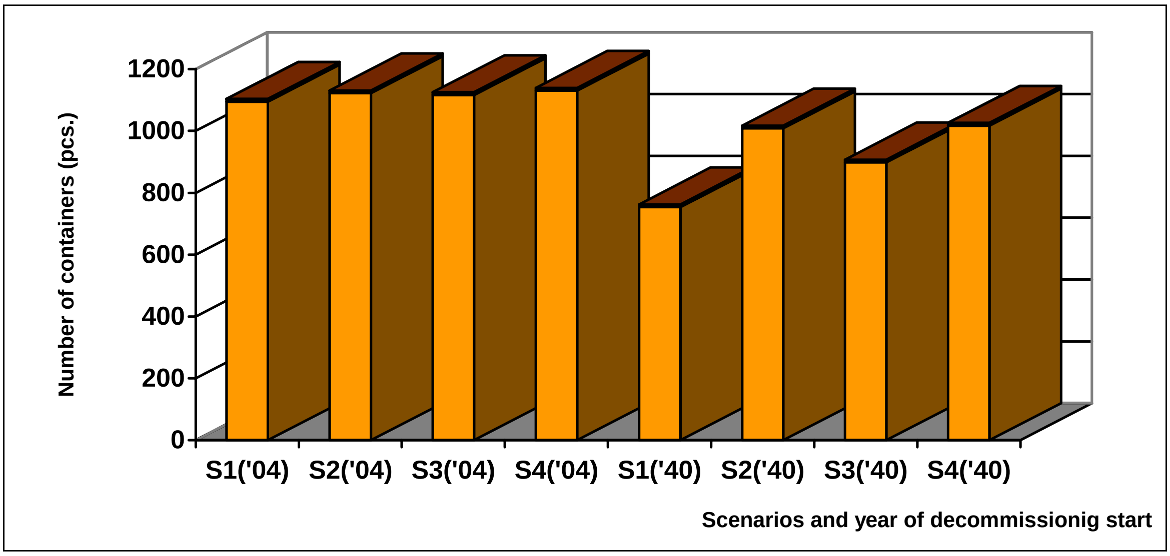
Figure 42: Number of containers destined to repositories for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for NPP A-1. No pre-dismantling decontamination applied.



Explanation:

	Scenario	**S1** (decontamination or decontamination and melting)		**S2** (decontamination)		**S3** (melting)		**S4** (no decontamination, no melting)	
	Decommissioning start	**Year 2004 ('04)**							
	Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
	Steel destined to deep geological repository	38 525	**1,3**	38 525	**1,3**	38 525	**1,3**	38 525	**1,3**
	Steel destined to near-surface repository	2 704 443	**90,2**	2 912 971	**97,1**	2 870 967	**95,7**	2 960 770	**98,7**
	Steel released to environment after melting	208 528	**6,9**	0	**0**	89 803	**3,0**	0	**0**
	Steel released to environment after decontamination	47 799	**1,6**	47 799	**1,6**	0	**0**	0	**0**
	Steel released to environment after dismantling	0	**0**	0	**0**	0	**0**	0	**0**
	Decommissioning start	**Year 2040 ('40)**							
	Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
	Steel destined to deep geological repository	38 525	**1,3**	38 525	**1,3**	38 525	**1,3**	38 525	**1,3**
	Steel destined to near-surface repository	1 393 039	**46,4**	2 910 672	**97,0**	2 235 207	**74,5**	2 960 770	**98,7**
	Steel released to environment after melting	1 517 632	**50,6**	0	**0**	725 563	**24,2**	0	**0**
	Steel released to environment after decontamination	50 099	**1,7**	50 098	**1,7**	0	**0**	0	**0**
	Steel released to environment after dismantling	0	**0**	0	**0**	0	**0**	0	**0**

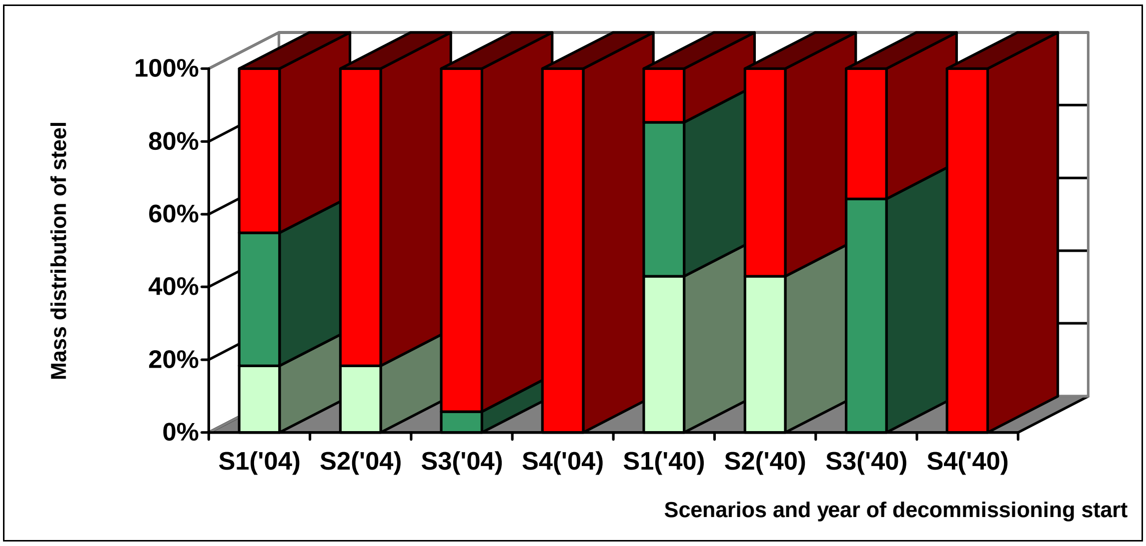
Figure 43: Mass distribution of steel for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for NPP A-1. Applied pre-dismantling decontamination.



Explanation:

	Scenario	S1 (decontamination or decontamination and melting)	S2 (decontamination)	S3 (melting)	S4 (no decontamination, no melting)
	Decommissioning start	**Year 2004 ('04)**			
(dark red)	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0,75	0,75	0,75	0,75
(violet)	Number of containers destined to deep geological repository with metals (pcs)	8,20	8,20	8,20	8,20
(orange)	Number of containers destined to near-surface repository (pcs)	1 095,20	1 122,21	1 116,55	1 130,81
	Decommissioning start	**Year 2040 ('40)**			
(dark red)	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0,75	0,75	0,75	0,75
(violet)	Number of containers destined to deep geological repository with metals (pcs)	8,20	8,20	8,20	8,20
(orange)	Number of containers destined to near-surface repository (pcs)	753,74	1 008,47	898,67	1 017,48

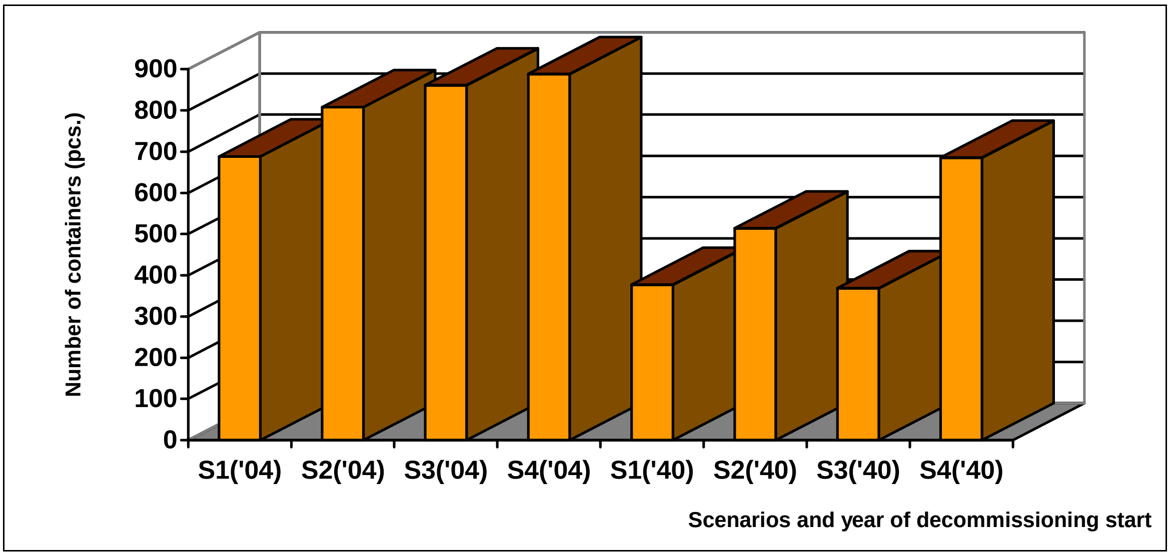
Figure 44: Number of containers destined to repositories for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for NPP A-1. Applied pre-dismantling decontamination.



Explanation:

	Scenario	S1 (decontamination or decontamination and melting)		S2 (decontamination)		S3 (melting)		S4 (no decontamination, no melting)	
	Decommissioning start	**Year 2004 ('04)**							
	Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
	Steel destined to deep geological repository	356	**0,01**	356	**0,01**	356	**0,01**	356	**0,01**
	Steel destined to near-surface repository	1 353 884	**45,14**	2 449 332	**81,67**	2 826 402	**94,24**	2 998 939	**99,99**
	Steel released to environment after melting	1 095 448	**36,52**	0	**0**	172 537	**5,75**	0	**0**
	Steel released to environment after decontamination	549 607	**18,33**	549 607	**18,32**	0	**0**	0	**0**
	Steel released to environment after dismantling	0	**0**	0	**0**	0	**0**	0	**0**
	Decommissioning start	**Year 2040 ('40)**							
	Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
	Steel destined to deep geological repository	356	**0,01**	356	**0,01**	356	**0,01**	356	**0,01**
	Steel destined to near-surface repository	441 420	**14,72**	1 711 456	**57,06**	1 072 606	**35,76**	2 998 915	**99,99**
	Steel released to environment after melting	1 270 036	**42,34**	0	**0**	1 926 309	**64,23**	0	**0**
	Steel released to environment after decontamination	1 287 459	**42,93**	1 287 459	**42,93**	0	**0**	0	**0**
	Steel released to environment after dismantling	24	**8E-4**	24	**8E-4**	24	**8E-4**	24	**8E-4**

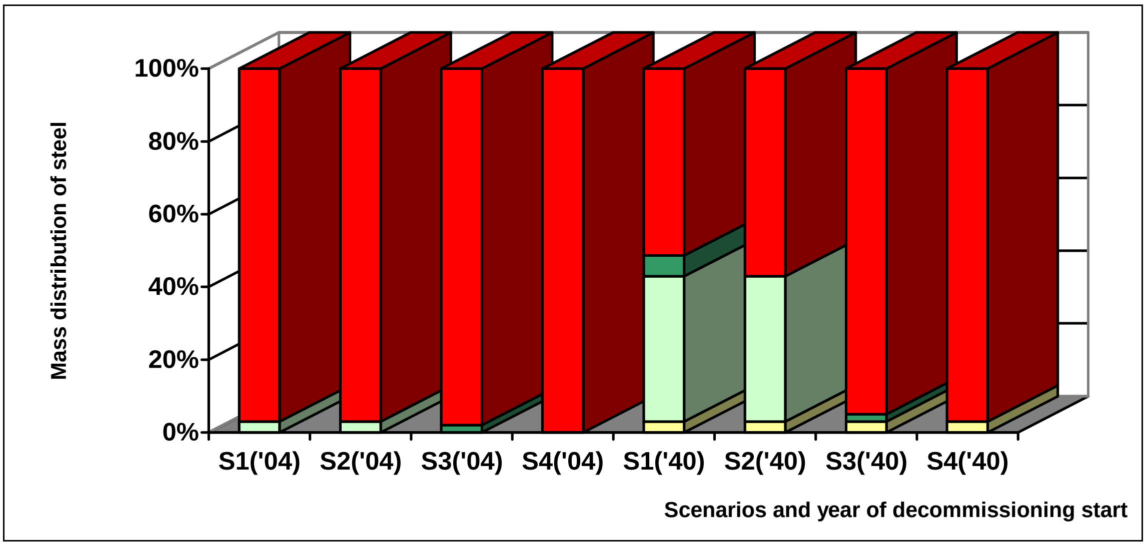
Figure 45: Mass distribution of steel for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for NPP A-1 with 10-times lower contamination level. Applied pre-dismantling decontamination.



Explanation:

	Scenario	S1 (decontamination or decontamination and melting)	S2 (decontamination)	S3 (melting)	S4 (no decontamination, no melting)
	Decommissioning start	**Year 2004 ('04)**			
(dark red)	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0,47	0,47	0,47	0,47
(violet)	Number of containers destined to deep geological repository with metals (pcs)	0,08	0,08	0,08	0,08
(orange)	Number of containers destined to near-surface repository (pcs)	687,97	807,50	860,61	888,15
	Decommissioning start	**Year 2040 ('40)**			
(dark red)	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0,43	0,43	0,43	0,43
(violet)	Number of containers destined to deep geological repository with metals (pcs)	0,08	0,08	0,08	0,08
(orange)	Number of containers destined to near-surface repository (pcs)	376,71	513,46	368,47	685,03

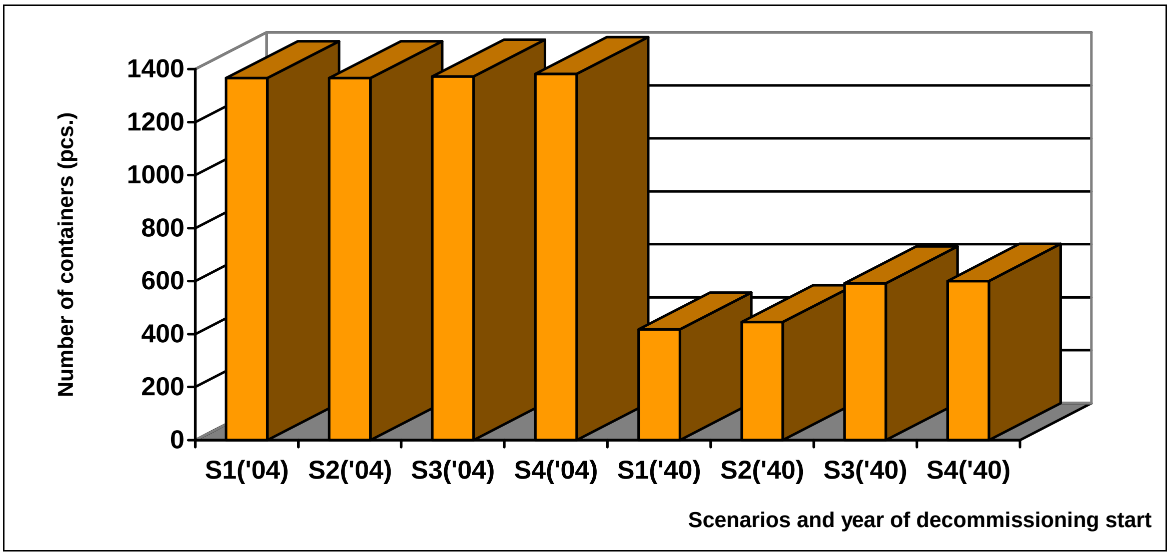
Figure 46: Number of containers destined to repositories for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for NPP A-1 with 10-times lower contamination level. Applied pre-dismantling decontamination.



Explanation:

	Scenario	S1 (decontamination or decontamination and melting)		S2 (decontamination)		S3 (melting)		S4 (no decontamination, no melting)	
	Decommissioning start	**Year 2004 ('04)**							
	Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
	Steel destined to deep geological repository	0	**0**	0	**0**	0	**0**	0	**0**
	Steel destined to near-surface repository	2 910 156	**97,03**	2 910 699	**97,0**	2 939 422	**98,0**	2 999 295	**100,0**
	Steel released to environment after melting	544	**0,02**	0	**0**	59 873	**2,0**	0	**0**
	Steel released to environment after decontamination	88 595	**2,95**	88 596	**3,0**	0	**0**	0	**0**
	Steel released to environment after dismantling	0	**0**	0	**0**	0	**0**	0	**0**
	Decommissioning start	**Year 2040 ('40)**							
	Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
	Steel destined to deep geological repository	0	**0**	0	**0**	0	**0**	0	**0**
	Steel destined to near-surface repository	1 540 064	**51,3**	1 711 862	**57,0**	2 850 078	**95,0**	2 910 675	**97,0**
	Steel released to environment after melting	171 798	**5,7**	0	**0**	60 597	**2,0**	0	**0**
	Steel released to environment after decontamination	1 198 813	**40,0**	1 198 813	**40,0**	0	**0**	0	**0**
	Steel released to environment after dismantling	88 620	**3,0**	88 620	**3,0**	88 620	**3,0**	88 620	**3,0**

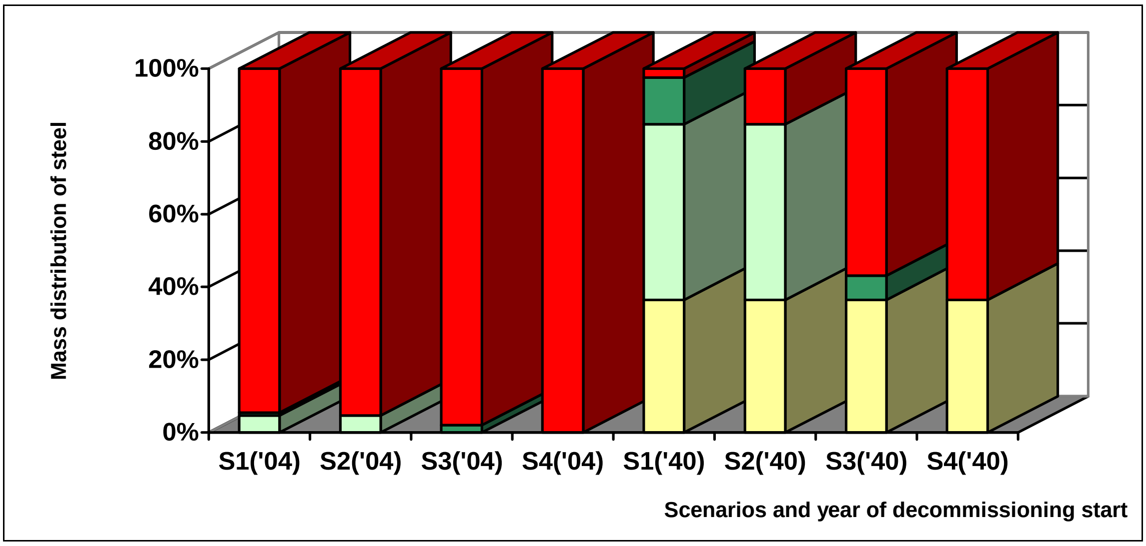
Figure 47: Mass distribution of steel for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition and the level of contamination of non-accident NPP V-2. No pre-dismantling decontamination applied.



Explanation:

	Scenario	S1 (decontamination or decontamination and melting)	S2 (decontamination)	S3 (melting)	S4 (no decontamination, no melting)
	Decommissioning start	**Year 2004 (‘04)**			
	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0	0	0	0
	Number of containers destined to deep geological repository with metals (pcs)	0	0	0	0
	Number of containers destined to near-surface repository (pcs)	1 366,11	1 366,19	1 372,19	1 382,14
	Decommissioning start	**Year 2040 (‘40)**			
	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0	0	0	0
	Number of containers destined to deep geological repository with metals (pcs)	0	0	0	0
	Number of containers destined to near-surface repository (pcs)	418,12	445,46	591,75	601,07

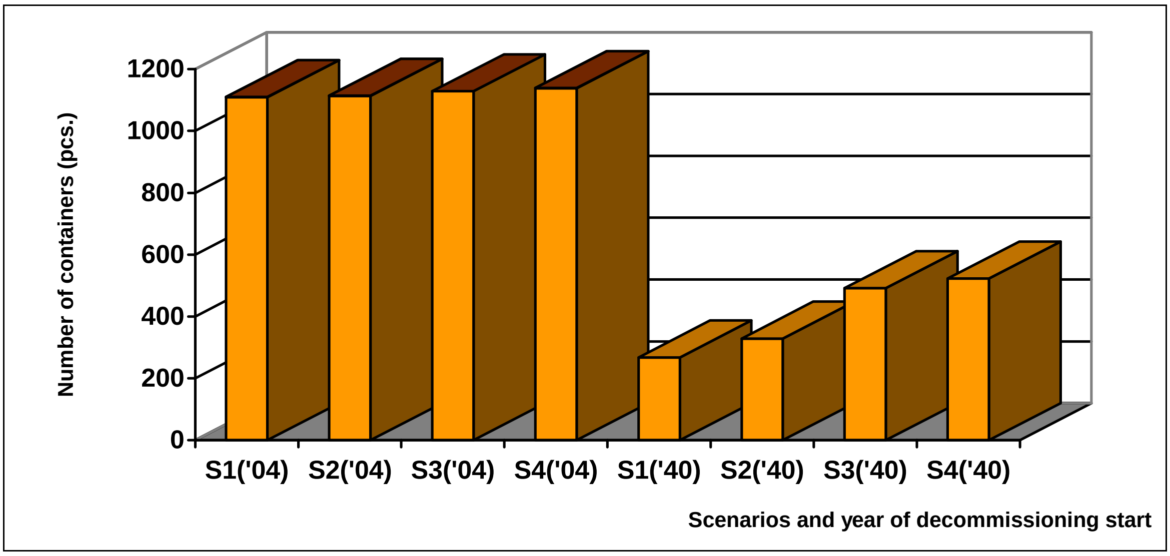
Figure 48: Number of containers destined to repositories for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition and the level of contamination of non-accident NPP V-2. No pre-dismantling decontamination applied.



Explanation:

	Scenario	**S1** (decontamination or decontamination and melting)		**S2** (decontamination)		**S3** (melting)		**S4** (no decontamination, no melting)	
	Decommissioning start	**Year 2004 ('04)**							
	Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
	Steel destined to deep geological repository	0	**0**	0	**0**	0	**0**	0	**0**
	Steel destined to near-surface repository	2 836 256	**94,6**	2 860 601	**95,4**	2 939 069	**98,0**	2 999 295	**100,0**
	Steel released to environment after melting	24 345	**0,8**	0	**0**	60 226	**2,0**	0	**0**
	Steel released to environment after decontamination	138 694	**4,6**	138 694	**4,6**	0	**0**	0	**0**
	Steel released to environment after dismantling	0	**0**	0	**0**	0	**0**	0	**0**
	Decommissioning start	**Year 2040 ('40)**							
	Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
	Steel destined to deep geological repository	0	**0**	0	**0**	0	**0**	0	**0**
	Steel destined to near-surface repository	72 918	**2,4**	458 119	**15,3**	1 706 668	**56,9**	1 906 020	**63,5**
	Steel released to environment after melting	385 201	**12,8**	0	**0**	199 352	**6,6**	0	**0**
	Steel released to environment after decontamination	1 447 901	**48,3**	1 447 901	**48,2**	0	**0**	0	**0**
	Steel released to environment after dismantling	1 093 275	**36,5**	1 093 275	**36,5**	1 093 275	**36,5**	1 093 275	**36,5**

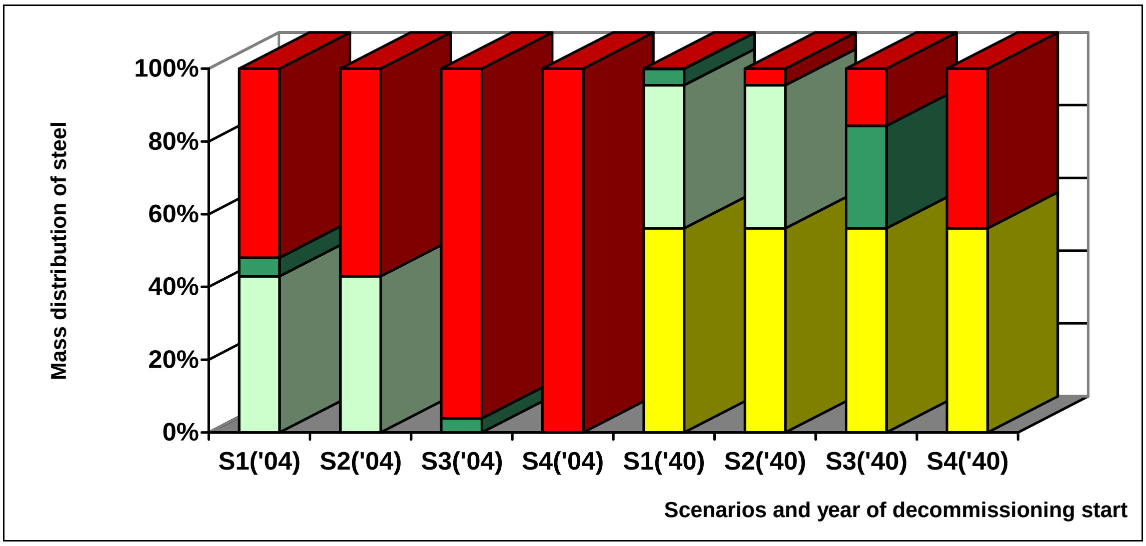
Figure 49: Mass distribution of steel for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition and the level of contamination of non-accident NPP V-2. Applied pre-dismantling decontamination.



Explanation:

	Scenario	S1 (decontamination or decontamination and melting)	S2 (decontamination)	S3 (melting)	S4 (no decontamination, no melting)
	Decommissioning start	**Year 2004 ('04)**			
	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0,27	0,27	0,27	0,27
	Number of containers destined to deep geological repository with metals (pcs)	0	0	0	0
	Number of containers destined to near-surface repository (pcs)	1 109,72	1 113,65	1 128,61	1 138,63
	Decommissioning start	**Year 2040 ('40)**			
	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0	0	0	0
	Number of containers destined to deep geological repository with metals (pcs)	0	0	0	0
	Number of containers destined to near-surface repository (pcs)	267,46	328,73	491,81	523,03

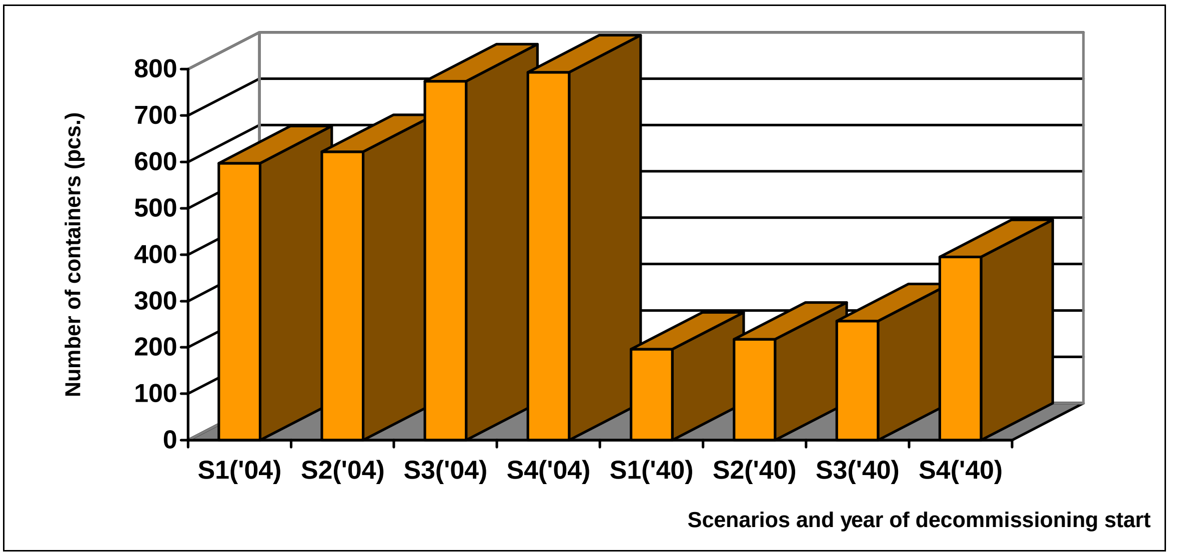
Figure 50: Number of containers destined to repositories for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition and the level of contamination of non-accident NPP V-2. Applied pre-dismantling decontamination.



Explanation:

	Scenario	S1 (decontamination or decontamination and melting)		S2 (decontamination)		S3 (melting)		S4 (no decontamination, no melting)	
	Decommissioning start	**Year 2004 ('04)**							
	Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
	Steel destined to deep geological repository	0	**0**	0	**0**	0	**0**	0	**0**
	Steel destined to near-surface repository	1 557 517	**51,9**	1 712 225	**57,1**	2 883 445	**96,1**	2 999 271	**99,9**
	Steel released to environment after melting	154 708	**5,2**	0	**0**	115 826	**3,9**	0	**0**
	Steel released to environment after decontamination	1 287 046	**42,9**	1 287 046	**42,9**	0	**0**	0	**0**
	Steel released to environment after dismantling	24	**8E-4**	24	**8E-4**	24	**8E-4**	24	**8E-4**
	Decommissioning start	**Year 2040 ('40)**							
	Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
	Steel destined to deep geological repository	0	**0**	0	**0**	0	**0**	0	**0**
	Steel destined to near-surface repository	1 664	**0,1**	136 661	**4,6**	472 739	**15,8**	1 315 465	**43,9**
	Steel released to environment after melting	134 997	**4,5**	0	**0**	842 726	**28,1**	0	**0**
	Steel released to environment after decontamination	1 178 804	**39,3**	1 178 804	**39,3**	0	**0**	0	**0**
	Steel released to environment after dismantling	1 683 830	**56,10**	1 683 830	**56,10**	1 683 830	**56,10**	1 683 830	**56,10**

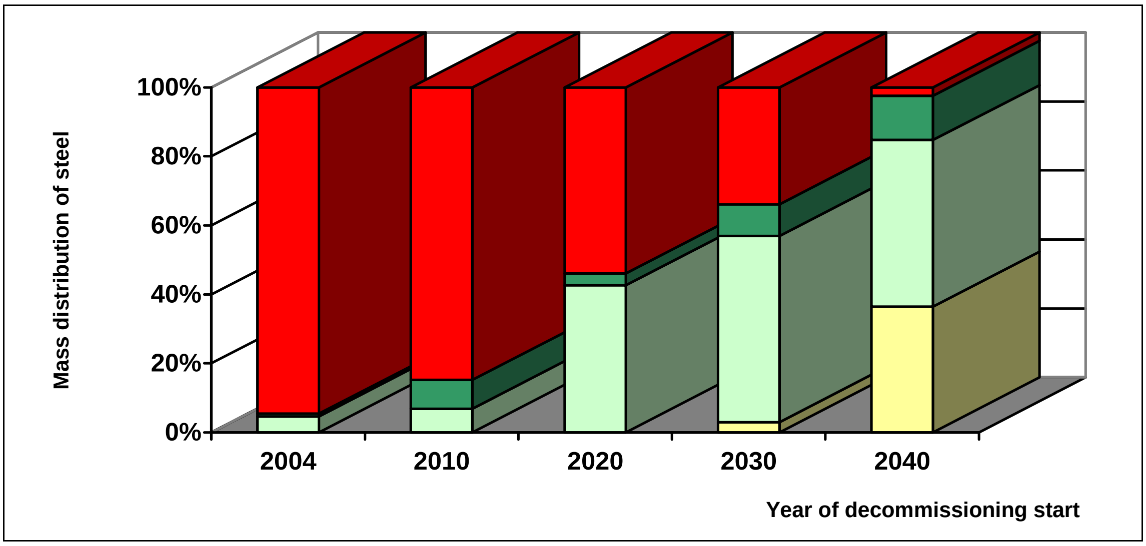
Figure 51: Mass distribution of steel for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for non-accident NPP V-2 with 10-times lower contamination level. Applied pre-dismantling decontamination.



Explanation:

	Scenario	**S1** (decontamination or decontamination and melting)	**S2** (decontamination)	**S3** (melting)	**S4** (no decontamination, no melting)
	Decommissioning start	**Year 2004 (‘04)**			
	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0	0	0	0
	Number of containers destined to deep geological repository with metals (pcs)	0	0	0	0
	Number of containers destined to near-surface repository (pcs)	597,51	622,07	774,31	793,58
	Decommissioning start	**Year 2040 (‘40)**			
	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0	0	0	0
	Number of containers destined to deep geological repository with metals (pcs)	0	0	0	0
	Number of containers destined to near-surface repository (pcs)	195,87	217,57	257,16	395,06

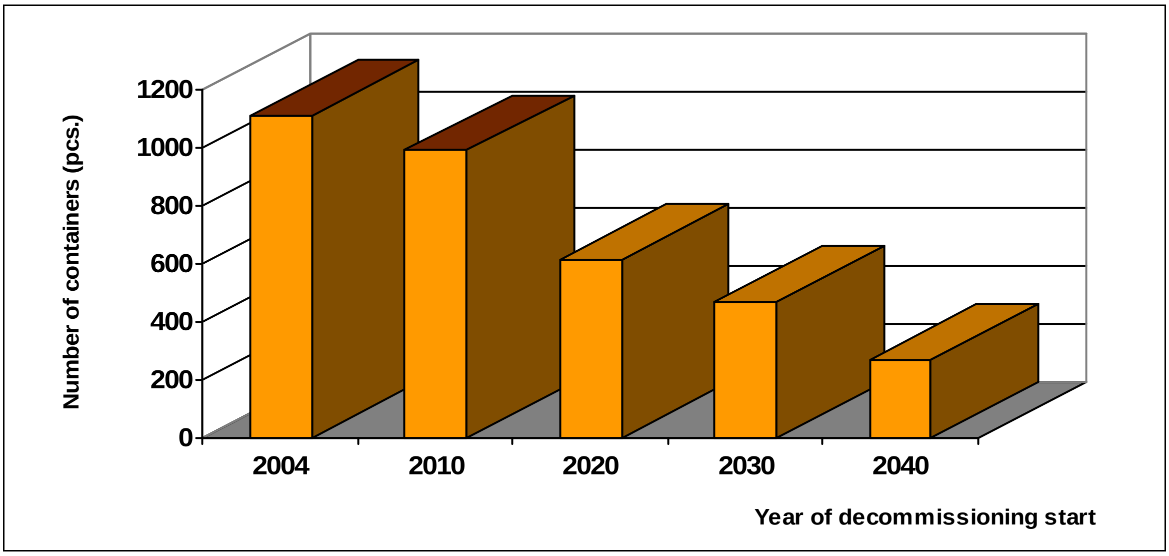
Figure 52: Number of containers destined to repositories for different calculated options. These options differ in decommissioning scenarios (from S1 to S4) and decommissioning start time (either 2004 or 2040). Typical radionuclide composition for non-accident NPP V-2 with 10-times lower contamination level. Applied pre-dismantling decontamination.



Explanation:

	Decommissioning start	2004		2010		2020		2030		2040	
	Mass distribution of steel (kg) and (%)	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**	(kg)	**(%)**
	Steel destined to deep geological repository	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
	Steel destined to near-surface repository	2 836 256	**94,6**	2 542 101	**84,7**	1 616 763	**53,9**	1 014 858	**33,8**	72 918	**2,4**
	Steel released to environment after melting	24 345	**0,8**	251 541	**8,4**	103 233	**3,4**	275 855	**9,2**	385 201	**12,8**
	Steel released to environment after decontamination	138 694	**4,6**	205 653	**6,9**	1 279 275	**42,7**	1 619 654	**54,0**	1 447 901	**48,3**
	Steel released to environment after dismantling	0	**0**	0	**0**	24	**8E-4**	88 928	**3,0**	1 093 275	**36,5**

Figure 53: Mass distribution of steel for different calculated options. These options differ in decommissioning start time (2004, 2010, 2020, 2030 and 2040) for decommissioning scenario S1. Typical radionuclide composition and the level of contamination of non-accident NPP V-2. Applied pre-dismantling decontamination.



Explanation:

	Decommissioning start	2004	2010	2020	2030	2040
	Number of containers destined to deep geological repository with vitrified packages (pcs.)	0,27	0,13	0	0	0
	Number of containers destined to deep geological repository with metals (pcs)	0	0	0	0	0
	Number of containers destined to near-surface repository (pcs)	1 109,72	988,82	612,23	466,76	267,46

Figure 54: Number of containers destined to repositories for different calculated options. These options differ in decommissioning start time (2004, 2010, 2020, 2030 and 2040) for decommissioning scenario S1. Typical radionuclide composition and the level of contamination of non-accident NPP V-2. Applied pre-dismantling decontamination.

7. CONCLUSIONS

Within the frame of the project a set of decommissioning model calculations were performed and except of costs, other decommissioning parameters, such as manpower, exposure and material items were analysed. For presented decommissioning cost calculations, there were applied the real contamination values from A-1 NPP with typical occurrence of high level of alpha radionuclides and fission products as a consequence of operational accident with the leakage of radioactivity from fuel with damaged cladding into primary circuit technologies. In addition, decommissioning cost calculations were performed also with a real isotopic content of contamination of V-2 NPP as a representative example of NPP with an excellent operation with no alpha radionuclides and fission products. Based on this fact, it is possible to compare alpha and non-alpha contamination on calculated decommissioning parameters.

The presented results of decommissioning cost calculation using OMEGA code for A-1 NPP primary circuit technological database documented and analysed in chapter 6.3 can be summarised into the following conclusions:

1. Comparative model calculations with V-2 NPP nuclide vectors with non-alpha contaminants and no fission products show significantly lower decommissioning costs (more than 3-times lower, see Fig. 16 and Fig. 25) together with remarkable decrease of costs with time (Co-60 a dominant representative of V-2 contamination) in comparison with Cs-137 and alpha nuclides of A-1 contamination.

   For calculations with V-2 NPP nuclide vectors, calculated costs for deferred decommissioning in 2040 are 50% lower than calculated costs for immediate decommissioning in 2004 (see Fig. 25). The difference between deferred and immediate decommissioning costs calculated for A-1 NPP nuclide vector is much lower and represents 7% decrease (see Fig. 15).
2. For higher contamination levels (K1 and K2 respectively) when the ratio of remote controlled dismantling is higher than hands-on dismantling, leads to the increase of decommissioning costs and manpower but on the contrary the decrease of collective dose equivalent (CDE). See so called “U-shaped curves” on Fig. 5,6,7.
3. In generally, an application of pre-dismantling decontamination in lower dose ambient leads to the decrease of CDE (41% decrease – see Fig. 9, 12) and to extension of hands-on dismantling instead of remote one. At the same time, it leads to the decrease of costs and manpower needs (around 25% decrease – see Fig. 10,13 and Fig. 8,11). However, there is an exception for pre-dismantling decontamination application in very high dose ambient (especially during preparatory activities for pre-dismantling decontamination) that can lead to significant increase of CDE (14-times increase – see Fig. 6).
4. The more materials released into environment the more need for post-dismantling decontamination or melting respectively might be involved.
5. As Fig. 41 shows 40% of steel mass is destined to deep geological repository (257 containers, expected on the basis of current knowledge 87 500 000 € per container disposal into deep geological repository). This represents 61% from overall calculated decommissioning costs (see Fig.16). Thus, container disposal in deep geological repository increases decommissioning costs. In case of decommissioning options with high ratio of containers destined to deep geological repository, the dominant contribution to total decommissioning costs is represented by the costs for container disposal.

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STATENS KÄRNKRAFTINSPEKTION
Swedish Nuclear Power Inspectorate

POST/POSTAL ADDRESS SE-106 58 Stockholm
BESÖK/OFFICE Klarabergsviadukten 90
TELEFON/TELEPHONE +46 (0)8 698 84 00
TELEFAX +46 (0)8 661 90 86
E-POST/E-MAIL ski@ski.se
WEBBPLATS/WEB SITE www.ski.se