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WASTE DISPOSAL PACKAGE FOR SPENT NUCLEAR FUEL IN THE CZECH REPUBLIC

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Contents

List of abbreviations and units

A.S.I.	Association of Mechanical Engineers of the Czech Republic
ČSN	Czech technical norm
EDU	Dukovany nuclear power plant
ETE	Temelín nuclear power plant
FEM	Finite Element Method
GNS	Gesellschaft für Nuklear-Service
Gy/h	Dose rate unit (D) that expresses the increase in the dose per unit of time (Grey per hour)
hm. %	Weight percentage; expression of composition
DGR	Deep geological repository
IAEA	International Atomic Energy Agency
KTA	Safety standards issued by the German Commission for Nuclear Safety Standards (Kerntechnischer Ausschuss: Nuclear Safety Standards Commission)
MaCoTe	Material Corrosion Test, an international project underway at the Swiss underground laboratory at the Grimsel Test Site
MPa	Unit of pressure (megapascal)
MSK-64	Medvedev-Sponheuer-Karnik scale
mSv	Unit of the equivalent dose of ionising radiation (millisievert)
NNS	New Nuclear Sources
NTD	Normative technical documentation
N/mm^2	Unit of the minimum yield strength (Newton per square millimetre)
PDE	Dose equivalent
WP	Waste package
R_m	Strength limit
$R_{p0.2}$	Yield strength (the stress that causes permanent deformation of 0.2%)
SÚJB	State Office for Nuclear Safety
SÚRAO	Czech Radioactive Waste Repository Authority
Sv/h	The dose equivalent unit (H) that expresses the proportion of the increase in the equivalent dose per unit of time, (Sieverts per hour)
TA ČR	Technological agency of the Czech Republic
WDP	Waste disposal package
SNF	Spent nuclear fuel
VO	Outer casing of the WDP

VP	Inner casing of the WDP
VVER	Pressurised water cooled reactor
WENRA	Western European Nuclear Regulators’ Association
W/m·K	Unit of the coefficient of thermal conductivity (Watts per metre per Kelvin)
σ	Stress (MPa)
σ_{red}	Reduced stress (MPa)
σ_s	Von Mises stress (MPa)

Explanation of terms

Safety function

The safety function refers to the operation of a system, structure, component or other part of a nuclear facility that is significant in terms of ensuring the nuclear safety of the facility.

Deep geological repository (DGR)

A deep geological repository comprises a repository for radioactive waste that is located hundreds of metres below the earth's surface, which is intended for the disposal of high-level radioactive waste and spent nuclear fuel. The deep geological repository is distinguished here from underground repositories, which are defined in section 2 of Decree No. 378/2016 Coll., on the siting of nuclear facilities, as facilities that are located tens of metres below the earth's surface and which are intended primarily for the disposal of low-level and intermediate-level radioactive waste.

Yield stress

The yield stress is the lowest level of stress at which substantial plastic deformation occurs. In cases in which such deformation can be read directly from a diagram, it comprises the so-called significant yield stress.

If the significant yield stress is not evident, it is necessary to determine the yield stress, which is generally defined as the stress at which permanent deformation attains the prescribed values. Experience has shown that, from the computational point of view, the significant yield stress point most often corresponds to the permanent deformation limit of 0.2%, known as the offset yield $R_{p0,2}$.

Waste package (WP)

The waste package is a container that ensures the thermal containment/isolation of the radioactive content of the waste. The requirements relating to the waste package according to its intended use are set out in Decree No. 379/2016 Coll., on the approval of types of certain products used in connection with the peaceful use of nuclear energy and ionising radiation and the transport of radioactive or fissile materials. The type D WDP is primarily intended for the disposal of spent or irradiated nuclear fuel or the radioactive waste resulting from its reprocessing.

Buffer

The buffer comprises the engineered barrier positioned in the immediate vicinity of the waste disposal package that consists of a clay material with the required properties. A specific type of clay, i.e. bentonite provides a good example of a suitable material for the buffer. The buffer is distinguished from the so-called backfill (see below) principally in terms of its technological processing and the method via which it is applied in the DGR. Currently, the use of a buffer in the form of prefabricated compacted bentonite segments with a defined dry density is being considered for the Czech DGR.

Waste disposal package (WDP)

The type D waste disposal package is "intended for the disposal of spent or irradiated nuclear fuel or radioactive waste resulting from its reprocessing" and is not intended for transport purposes according to Decree No. 379/2016 Coll. Previously, it was also known as a *waste storage package*. In this report, the term WDP refers exclusively to the waste disposal package intended for the disposal of spent nuclear fuel.

Spent nuclear fuel (SNF)

Spent nuclear fuel comprises nuclear fuel that has been permanently removed from the core of a nuclear reactor and has been designated as waste by the generator. Before it is declared to be waste, the term “used nuclear fuel” is applied.

Backfill

The backfill comprises the engineered barrier that serves for the filling of the access (loading) corridors for the disposal wells, and consists of a clay material with the required properties. It is assumed that the same material will be used for the backfill as for the buffer, i.e. bentonite. However, the form of the bentonite will differ, i.e. it will not be prefabricated but will consist of the pelletised material that will be applied directly on-site.

Plugs and seals in the DGR

Plugs and seals comprise the engineered barriers that serve for the closure and sealing of the underground spaces of the DGR (the disposal wells and loading corridors). They may consist of simple concrete structures with a purely mechanical function (e.g. the sealing plugs of the disposal wells) or multi-component structures with both mechanical and water isolation functions (e.g. the sealing plugs of the DGR corridors).

List of attachments

Abstrakt

Tato zpráva popisuje referenční řešení ukládacích obalových souborů (UOS) pro vyhořelé jaderné palivo (VJP) na území České republiky (ČR). Oba uvažované materiály, uhlíková ocel (S355J2H+N) pro vnější obal (VO) i austenitická korozivzdorná ocel (EN 1.4404) pro vnitřní pouzdra (VP) jsou dobře známé a technologicky zvládnutelné. Oba materiály plní svou specificky definovanou funkci jak z pohledu mechanické odolnosti, tak z pohledu dlouhodobého korozního napadení. V případě obou materiálů použitých pro konstrukci UOS jsou v praxi úspěšně zvládnuté technologie jejich opracování, svařování atd. Celková životnost UOS dle všech zvažovaných korozních modelů byla navržena a následně vypočtena, nejen pro překonání doby 100 000 let, ale předběžně vypočtena i na dobu 1 000 000 let. V dalších fázích vývoje UOS bude na základě dalších dat z budoucích experimentů, životnost 1 000 000 let dále ověřována. V rámci konstrukčního řešení byly výpočetně ověřeny za pomocí pevnostních výpočtů, teplotechnických výpočtů, výpočtů podkritičnosti, výpočty stínění a výpočty střihu (seismicita) ověřeny mnoha z klíčových parametrů.

Klíčová slova

Hlubinné úložiště, vyhořelé jaderné palivo, ukládací obalový soubor, koroze ukládacího obalového souboru, životnost ukládacího obalového souboru, inženýrské bariéry, konstrukční řešení ukládacího obalového souboru, UOS 440, UOS 1000

Abstract

This report provides a description of the first reference design of the waste disposal package (WDP) to be used for the disposal of spent nuclear fuel (SNF) in the future Czech deep geological repository (DGR). Both of the materials considered for the construction of the WDP, i.e. carbon steel (S355J2H+N) for the outer casing (OC) and austenitic stainless steel (EN 1.4404) for the inner casing (IC) are well known and technologically feasible. Both materials fulfil their defined functions in terms of their mechanical properties and long-term corrosion attack. With concern to the two materials proposed for the construction of the WDPs, the respective processing, welding, etc. techniques have been successfully proven in practice. The total service lifetime of the WDP, calculated via the study of a range of corrosion models, has been verified as exceeding 100,000 years and as likely to reach up to 1 million years. The subsequent phases of the development of the WDP will concern the further verification of their attaining a lifetime of 1 million years based on the data obtained from ongoing and future experimental research. The determination of the reference design included the verification of many of the key parameters via the performance of detailed strength, thermo-technical, subcriticality, shielding and shear calculations (seismicity).

Keywords

Deep geological repository (DGR), spent nuclear fuel (SNF), waste disposal package (WDP), waste disposal package corrosion, waste disposal package lifetime, engineered barriers, waste disposal package design, WDP 440, WDP 1000

1 Introduction

This report provides a detailed description of the reference technical solution, and calculations proving the functionality, of the steel waste disposal package (WDP) intended for the final disposal of spent nuclear fuel (SNF) in the Czech Republic. The report is based on the conclusions drawn in the respective SÚRAO technical report (Forman et al., 2021), from which some parts of this report were adopted.

At the time of the writing of this report (May 2023), the Czech Republic is considering four potential sites - Březový potok, Horka, Hrádek and Janoch (Vondrovic et al., 2020), from which a final and a reserve site will be selected for the construction of the Czech deep geological repository (DGR). Currently, since investigation/exploration work is yet to commence at the four sites, the detailed geological, geochemical, geomechanical, geothermal and hydrogeological conditions at the sites considered for the future DGR, according to which the physico-chemical conditions that will affect the lifetime of the WDP will subsequently be determined, are unknown. Hence, the first part of this report provides a description of the framework marginal conditions determined for the permanent disposal of SNF in the Czech Republic (see chapter 2). These boundary conditions are of crucial importance in terms of the compilation of an initial feasibility study and the subsequent definition of the key phenomena that will influence the resistance of the WDP, and the identification of all the potential significant events that may occur in the DGR in the future, and which may affect the lifetime of the WDP.

The requirements for the WDP, which are discussed in detail in chapter 3, are based on currently valid legislation and fully respect international experience of the preparation of DGR projects. A technical description of the WDP reference design and assumed production technology is provided in chapter 4. This description is then supplemented by calculations (mechanical, thermal, lifetime, shielding and subcriticality) (see chapter 5) that serve to prove the suitability of the WDP design for the conditions anticipated in the future Czech DGR.

2 Boundary conditions for the WDP in the DGR for SNF

The construction of the DGR is planned in a crystalline rock environment at a depth of **approximately 500 m below the earth's surface**. The detailed geological and geochemical conditions of the finally selected repository will be known only after the completion of the surveys of all four sites. The proposed DGR concept envisages the disposal of steel WDPs in compacted bentonite (the buffer). A detailed description of the DGR and its various components is provided in a report by Dohnálková et al., (2022).

The environment around the WDP will be strongly influenced by the buffer, especially its composition and behaviour in the given environment. The most important functions of the buffer will include the retardation of the corrosion rate of the WDP as a result of its limiting contact with water and the corrosion-active substances present in the rock environment (e.g. chlorides, sulphides). The high density (**dry density of around 1600 kg/m^3**) of the buffer will further prevent the activity of microbes and, thus, the microbial corrosion of the WDP (Dohnálková et al., 2022).

The temperature in the DGR will be a key factor that will influence the chemical, physical and biological processes that occur in the vicinity of the WDP. The development of the temperature over time will depend on the residual thermal output of the SNF following its emplacement in the disposal wells, the WDP emplacement approach in the DGR (horizontal/vertical), the distance (spacing) between the disposal wells, the thermal conductivity of the host rock and, importantly, the initial temperature of the host rock. The DGR development project is currently based on a concept that assumes that the maximum permissible temperature on the **surface of the WDP will not exceed 95°C** (Dohnálková et al., 2022). This temperature was determined in order to prevent the potential alteration of the properties of the bentonite at 100°C. Nevertheless, research is currently underway that aims to both verify this hypothesis and explore the potential for disposal under conditions in which the surface temperature of the WDP exceeds 100°C[1], which would allow for the reduction of the spacing between the wells and, thus, the reduction of the overall area of the DGR.

A further parameter that will impact the DGR concerns the mechanical loading be it the action of hydrostatic pressure at the depth of the DGR or the pressure exerted by the bentonite. Moreover, it is likely that shear stress will occur due to the potential displacement of the rock during a tectonic event. The total pressure thus comprises the sum of the swelling pressure of the bentonite, the hydrostatic pressure of the groundwater at the depth of the DGR and the pressure induced by thermal expansion (Hasal et al., 2019). The swelling pressure of Czech bentonite for a dry density of 1600 kg/m^3 does not exceed 10 MPa (Hausmannová et al., 2018), the hydrostatic pressure at a depth of 500 m is around 5 MPa and the pressure induced by thermal expansion is below 0.5 MPa (Hasal et al., 2019). Thus, the currently considered maximum pressure that will act upon the WDP is 15.5 MPa. However, for the purposes of the mechanical calculations, a conservative value for the maximum pressure (the design pressure) that will be exerted on the WDP was selected, i.e. **20 MPa** (Forman et al., 2021).

Since no relevant data is yet available from the candidate DGR sites, no specific values have yet been determined for the potential shear stress. The preliminary assessment process considered a **displacement of 50 mm and a velocity of 1 m/s in the shear plane**, which corresponds to an earthquake with a force of between degrees 7 to 8 on the Medvedev-Sponheuer-Karnik scale (MSK-64) (POSIVA and SKB, 2017).

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[1] See, for example, a study by Lotz et al. (2020), which investigated the corrosion of steel emplaced in MX80 bentonite at a temperature of 120°C.

With respect to the presence of air, **aerobic conditions** will prevail in the vicinity of the WDP following the closure of the repository, the duration of which will be very short relative to the overall lifetime of the DGR and compared to the subsequent prevalence of anaerobic conditions. Nevertheless, from the point of view of the corrosion of the WDP, it is necessary to take this time period into account. The short-term aerobic phase will be followed by the **long-term anaerobic phase**, while it is expected that the complete saturation of the bentonite will occur after approximately 100 years (Landolt, 2009; SKB, 2006).

The gamma radiation dose rate on the surface of the WDP has been preliminarily determined at a level of **0.34 Gy/h**; this value was applied as the input value for the respective computational experiments (Lovecký, 2014).

3 WDP design requirements

A detailed summary of the WDP design requirements is provided in a previous SÚRAO report (Pospíšková et al., 2022), which describes the safety functions of the repository as set out in Czech legislation, primarily the Atomic Act and related decrees (Appendix 1: Legislation) and international expert recommendations (e.g. WENRA, 2014; IAEA, 2011). A summary of the safety functions of the WDP and the corresponding requirements for the WDP is provided in Tab. 1.

The various components of the DGR system, i.e. the natural (host rock) and engineered barriers (the WDP, buffer and backfill) will, together, act to ensure the fulfilment of the various safety requirements. The descriptions of the various barriers are required to specify, *inter alia*, how each barrier will contribute to the fulfilment of the required safety functions. This subsequently allows for the definition of the requirements for the given barrier, which, in turn, paves the way for the determination of the technical design of the respective barrier. The specific requirements set for the WDP with concern to its safety functions are summarised in the table below.

Tab. 1 - WDP requirements related to the safety functions of the DGR (Pospíšková et al., 2022)

	Safety function	WDP requirements
1	To physically prevent the occurrence of critical and supercritical conditions	The technical design of the WDP must exclude the occurrence of critical states (geometry of the emplacement of the SNF assemblies in the WDP and its dimensions). **See chapter 3.2.**
2	To ensure the removal of the heat generated	The material properties of the WDP must prevent the accumulation of generated heat and the consequent negative influences on the disposed of SNF itself and the retardation capabilities of the surrounding barriers. **See chapter 3.5.**
3	To contain the radioactive waste within the WDP	The WDP must be able to withstand the mechanical load exerted in the DGR for a defined period of time (types of materials and their mechanical properties). **See chapter 3.4.** The corrosion resistance of the materials must guarantee the isolation function of the WDP for a defined period of time (types of materials and their chemical properties, thicknesses of the walls). **See chapter 3.1.** The design of the WDP must limit the potential occurrence of corrosion processes (simple design, closure method). **See chapter 4.1.**
4	To retard the migration of radionuclides from the radioactive waste into the environment	The materials used in the construction of the WDP must be compatible with the surrounding environment in order not to reduce the effectiveness of the other barriers.
5	To isolate the waste from the surrounding environment and the events and processes underway on the surface, and to significantly reduce the probability and consequences of unintentional human exposure to the radioactive waste	*The requirements are similar to those of safety function 3 (above).*

6	To limit human and environmental exposure	*This function is dependent on the fulfilment of the requirements related to safety functions 1-5 above.*

The requirements set out in Tab. 1 are described in more detail in the following sections of the report accompanied by the relevant calculational data.

3.1 Lifetime

The main purpose of the DGR and, especially, the WDP concerns the containment of the potentially dangerous radionuclides that are present in the SNF. The key to the fulfilment of the safety requirements is that no WDP is damaged during the high fission product activity period of the SNF; however, the WDP lifetime does not clearly correlate with this period. At the time of the writing of this report, the WDP lifetime is considered to be **1,000,000 years** for the Czech SNF disposal programme. The lifetime of the WDP was evaluated primarily based on the requirement that, during the expected development of the DGR, the exposure for a representative person will not exceed the set dose optimisation limit (0.25 mSv per calendar year; Act No. 263/2016 Coll., par. 82, point (1)).

3.2 Subcriticality

The SÚJB legislative requirement that limits the multiplication coefficient value is as follows (according to Section 13 of Decree No. 329/2017 Coll., on requirements for nuclear facility projects):

"(2) The nuclear installation project design shall, with regard to requirements for compliance with the principles for the safe use of nuclear energy when handling and storing fresh and irradiated nuclear fuel, ensure that

f) the subcriticality of the stored nuclear fuel is maintained by means of the suitable spatial distribution thereof or other physical means and procedures specified using the conservative approach so that the following values are not exceeded

1. ***0.95 of the effective neutron multiplication coefficient** under the assumed conditions of a design basis accident or*
2. ***0.98 of the effective neutron multiplication coefficient** under the conditions of optimal moderation."*

3.3 Shielding

According to Czech legislation, the WDP consists of WP type D, for which no dose rate or dose equivalent limits have yet been set. Notwithstanding, 3 limits have been verified:

1. a limit of 1 Sv/h on the surface of the WDP at the interface of the outer casing and the bentonite buffer (Werme et al., 2002 and Raiko, 2005) in order that the bentonite is not altered due to the radiolysis of water; experimental verification is currently underway in this connection,
2. a limit of 2E-03 Sv/h on the surface of the WDP in the area of the lid; the transport dose equivalent limit according to Decree No. 379/2016 Coll. was chosen due to the handling of the WDP prior to disposal in the DGR,
3. a limit of 1E-04 Sv/h at a distance of 2 m from the WDP in the area of the lid; the transport dose equivalent limit according to Decree No. 379/2016 Coll. was chosen due to the

handling of the WDP prior to disposal in the DGR. In accordance with the conservative approach, the dose equivalent limit of the outer surface of the means of transport is replaced by that of the surface of the WDP.

3.4 Strength – pressure and shear

According to the boundary conditions in the DGR (see chapter 2), the structure of the WDP must be able to withstand external loading, both pressure and shear. A conservative maximum (design) pressure value for the WDP of 20 MPa was selected for the mechanical calculations; this value will have to be reviewed in the future (Forman et al., 2021).

3.5 Temperature

The maximum coating temperature of VVER type fuel elements is 350°C, which is based on the maximum temperature value that does not act to change the properties of the coating material (GNS, 2002). The melting temperature of the materials used for the CASTOR® 440/84M WP for transport and storage is considered to be the maximum temperature of the components of the internal structure of the WDP. The limit temperature at the interface of the outer casing of the WDP and the bentonite buffer has been set at 95°C, see chapter 2.

4 Description of the WDP reference design

According to currently valid legislation (Decree No. 358/2016 Coll.), the **WDP for the disposal of SNF in the Czech Republic is considered to be a pressure device;** hence, the WDP must also currently fulfil the legislative requirements set for pressure devices. As part of the *Research and development of a waste disposal package for the deep disposal of spent nuclear fuel up to the sample realisation stage* project (Forman et al., 2021), boundary criteria were selected for the construction of the WDP based on the boundary conditions (chapter 2) set in accordance with the assumed conditions in the DGR environment and WDP requirements (chapter 3). The various outputs of the project led to the proposal of a design for the WDP for spent nuclear fuel from the two existing Czech nuclear power plants (EDU, ETE) and 3 planned new nuclear sources (NNS), which will ensure the safe disposal of SNF for the whole of the required period. At the beginning of the WDP development process, a total of 13 options were proposed, all of which were assessed in terms of the materials to be used, various layout options and mechanical and corrosion resistance, as well as from the safety, technical and economic viewpoints. The subsequent consideration of the results of the research led to a reduction in the number of options to just 2, one option for each type of spent fuel, i.e. VVER-1000 reactor fuel and VVER-440 reactor fuel. They were later code-named **WDP 440 and WDP 1000**. The reference option comprises a double-walled system consisting of a corrosion-resistant inner casing and a protective outer casing.

In the event that the proposed WDP is deemed unsatisfactory, a backup technical solution is also being considered, which is based on the same double-walled principle and materials, the only difference being in terms of the design of the inner casing. This option also has a carbon steel outer casing and a stainless steel inner casing, with the addition of a stainless steel internal insert so as to secure the relative positions of the fuel assemblies (Pospíšková et al., 2022).

4.1 Structural design

The structure of the WDP consists of an outer casing and an inner container with a framework that serves to ensure the positioning of the container in the WDP.

The WDP has been designed in two versions according to the type of SNF to be disposed of, which differ in terms of the dimensions of the fuel assemblies. The VVER-1000 fuel assembly (ETE) is 4520 mm long and 234 mm in diameter (Westinghouse Nuclear [online], 2022). The VVER-440 (EDU) fuel assembly has a length of 2601.5 mm and a diameter of 144 mm (TVEL [online], 2022). The number of hexagonal fuel assemblies emplaced in the WDP differs for the VVER-440 and VVER-1000 options. The WDP was designed based on the dimensions of the ETE and EDU fuel assemblies, taking into account their residual temperature, which must not lead to the exceeding of the temperature set for the surface of the WDP (see chapter 2).

The two versions of the WDP have the same outer (external) diameters (Forman et al., 2021), which is based on the assumed diameter of the DGR disposal wells aimed at minimising operating costs due to the use of the same handling approach, as well as for the purposes of simplification and the reduction of production costs. It can be assumed that the use of the same outer casings will lead to a hypothetical reduction in the costs of the equipment in the DGR and an increase in the efficiency of production and, thus, a reduction in overall expenses for the supplied semi-finished products since only one semi-finished product will be produced for the outer casing, which will be cut into the appropriate lengths depending on the WDP option. It is likely that if the two options did not have the same diameter, the prices of the supplied semi-finished products would increase significantly.

One of the crucial parameters in the design of the structure of the WDP concerns the thickness of the walls, which is the key factor in terms of proving the feasibility of the proposed structural solution (see chapter 5).

4.2 Materials

The main requirement for the future construction material, from the point of view of the long-term lifetime of the waste disposal packages, concerns the certainty of the predictability of their behaviour. Therefore, it is necessary that from the electrochemical point of view the materials corrode in a state of either activity or stable passivity. In the active state, during which uniform corrosion occurs, potential materials consist of carbon steel and copper. Of the various other materials considered, only titanium maintains a stable passive state from the start of exposure (under aerobic conditions and at high temperatures). However, it cannot be ruled out that hydrogenation (hydrogen sorption) and the formation of hydrides will occur with concern to titanium, which would lead to the embrittlement of the material. Conversely, in the case of stainless steels, a stable passive state can only be expected in anaerobic environments and at lower temperatures (Novák, 2011). As indicated by the to date unpublished results of experiments on stainless steel, the critical temperature (between 40°C and 50°C) acts to reduce the uniformity of corrosion or to restrict corrosion to the formation of pitting. Due to the reduced predictability of the behaviour of stainless steel at elevated temperatures, this material is not suitable for the construction of the outer casing of the WDP (in the initial phase, immediately following the disposal of the WDP in the DGR when the temperature on the surface will exceed the required value and pitting corrosion could occur on the surface of the stainless steel). Carbon steel, on the other hand, corrodes predictably and, therefore, together with copper, appears to be a suitable material for the outer casing of the WDP.

From the point of view of the overall corrosion rate, the behaviour of copper is more favourable than that of carbon steel. However, if one takes into account the localisation of corrosion attack, the properties of carbon steel and copper are comparable (although localisation quickly loses its importance in compacted bentonite). Based on the results of the MaCoTe project (Dobrev et al., 2021), the maximum penetration on a perpendicular section for carbon steel and for copper is of a comparable order. On the other hand, it should be noted that clear differences were evident between the copper used in the MaCoTe experiments and the copper used for WDPs (e.g. in Finland and Sweden). From the point of view of safety, it is considered advisable to base the lifetime of the WDP on two materials rather than one. This factor played a significant role in terms of the selection of a double-walled WDP design. The outer casing material (carbon steel) will actively corrode and allow for an acceptable level of service lifetime predictability at the commencement of disposal. Subsequently, the inner casing material (stainless (corrosion-resistant) steel) will corrode in a stable passive state under anaerobic conditions and at temperatures of below 40°C to 50°C.

The use of carbon steel for the outer casing also has several other practical advantages:

- availability of a wide range of materials and suppliers
- more advanced state of the research of processing technologies
- higher number of archaeological analogues, the only long-term data source concerning corrosion, and the wider availability of sources for destructive analysis
- prices of the materials/processing/production

The inner casing of the WDP will be filled with helium and the outer casing with nitrogen (Forman et al., 2021). These inert gases will help to protect the WDP from potential oxidation and, thus, corrosion. In addition, since helium has a higher thermal conductivity than air, it will dissipate the generated heat more efficiently.

4.2.1 Outer casing – carbon steel

Carbon steel was selected as the material for the outer casing of the WDP; its specific properties will act to protect the inner casing until the conditions in the DGR are favourable for the maximum service lifetime of the inner casing material.

The material to be used for the outer WDP casing has a strictly defined chemical composition with clearly defined limits concerning the content of impurities (see Tab. 2). Furthermore, it must meet set requirements regarding the homogeneity of the microstructure of the material in terms of the spatial distribution of the individual phases (Forman et al., 2021).

The steel considered in the WDP research project (Stage 3+) for the outer casing was **carbon steel S355J2H+N**, the chemical composition of which is shown in Tab. 2. The advantage of this steel concerns its minimal content of carbide-forming elements, which acts to limit the localisation of uniform corrosion attack (pitting corrosion), in contrast to the other materials that were shortlisted in the assessment of steel materials for the outer casing of the WDP.

Tab. 2 - Composition of the carbon steel for the production of the outer casing of the WDP (Forman et al., 2021)

Steel/Ref.	Content of elements [wt. %]												
	C	Mn	Si	P	S	Cr	Ni	V	Mo	Cu	Ti	W	Al
S355J2H+N according to the EN 10219-1 standard (standardised composition)	max. 0.22	max. 1.60	max. 0.55	max. 0.030	max. 0.030	-	-	-	-	-	-	-	-
S355J2H+N (actual composition)	0.16	1.53	0.2	0.011	0.001	0.05	0.05	0.004	0.01	0.04	0.01	-	0.038

According to ČSN EN 10219-1, the code-name of carbon steel S355J2H+N (1.0576) is broken down thus:

S – structural steel for general use

355 – minimum yield stress in N/mm^2 (MPa)

J2 – notch toughness value (grade)

H – hollow section

+N – normalised annealed

The material used for the outer casing must also fulfil the minimum yield stress requirement of 350 MPa.

The thermal conductivity coefficient of this steel is 32.2 W/m·K at 176°C.

4.2.2 Inner casing - stainless steel

Stainless steel was selected as the material for the construction of the inner casing. The advantages of this steel will be maximised once the temperature acting upon the inner casing of the WDP falls below the so-called critical value (40–50°C), i.e. after approximately 10,000 years according to currently available data (Forman et al., 2021). Below the critical temperature, the stainless steel attains a state of so-called electrochemical passivity, in which, following the stage of the predicted corrosion of the outer casing and its subsequent mechanical collapse, it will fulfil the safety functions of the inner casing for the whole of the defined period.

Two types of stainless steel were selected as the most suitable materials in the research and development phase (Forman et al., 2021), and subsequently compared - duplex stainless steel EN 1.4462 and austenitic stainless steel EN 1.4404.

Duplex stainless steel EN 1.4462 was selected due to its higher Cr and Mo content, which contribute to corrosion resistance. Austenitic stainless steel EN 1.4404 was also selected due to its high corrosion resistance.

Although duplex stainless steel EN 1.4462 has a higher content of Cr and Mo, the susceptibility of the two steel materials to pitting corrosion under DGR conditions has been observed to be approximately the same (Stoulil et al., 2019). Due to the susceptibility of duplex stainless steel to hydration, and the associated loss of mechanical resistance, **austenitic stainless steel EN 1.4404** (see Tab. 3) was deemed more suitable due to its resistance to hydration (Forman et al., 2021).

Tab. 3 - The composition of austenitic stainless steel for the production of the inner casing of the WDP according to ČSN technical norms

Steel/Ref.	Content of elements [wt. %]												
	C	**Mn**	**Si**	**P**	**S**	**Cr**	**Ni**	**V**	**Mo**	**Cu**	**Ti**	**W**	**N**
1.4404 according to the EN 10297-2 standard (standardised composition)	0.030	2.00	1.00	0.045	0.015	max 18.5	max 14.5	-	max 2.5	-	-	-	0.11

4.2.3 Stainless steel insert

It is planned that the same type of steel will be used for the insert in the WDP as for the inner casing, i.e. austenitic stainless steel **EN 1.4404** (see Tab. 3).

4.2.4 Wall thicknesses of the inner and outer casings

When determining the thicknesses of the walls of the WDP, the appropriate thickness of the materials used was initially determined with regard to mechanical stability under DGR conditions, to which a so-called corrosion allowance was added. In other words, the thicknesses of the walls of both the inner and outer casings were determined in such a way that even after a certain component becomes corroded, both parts remain stable under the mechanical loading conditions. The thickness of the corrosion layer in the 3D model (Tab. 4) was determined at 15 mm for the carbon steel and 5 mm for the stainless steel (Forman et al., 2021). **The wall thickness of the inner casing is 65 mm for both variants and the wall thickness of the outer casing is 36 mm for the VVER-440 and 40 mm for the VVER-1000**. The difference in the wall thicknesses of the outer casings of the WDP for the two fuel types is due to the differing sizes of the fuel assemblies, particularly the diameter, and, thus, the various mechanical properties and the ideal layout of the assemblies inside the WDP.

The optimisation of the thickness of the structural materials is recommended only once the exact loading effects are known for the lifetime of the WDP and once a detailed description of the materials supported by experimentation is available, including with respect to their lifetimes.

4.2.5 Structural design of the WDP for VVER-440 reactor fuel (Dukovany)

The WDP for SNF from the VVER-440 type reactors will house seven fuel assemblies. It consists of an outer casing, inner casing and internal fittings. The diameter of the WDP has been set at 914 mm and the length at 3790 mm, see Fig. 1 and Fig. 2.

The outer casing is cylindrical with a welded bottom and lid. The thickness of the cylindrical part is 65 mm, the lid 200 mm and the bottom 200 mm. In addition, the lid is equipped with a quick coupler, which is covered by the plug of the outer casing welded to the WDP lid. The quick coupler serves for the adjustment of the gaseous environment in the outer casing. The space inside the outer casing is filled with nitrogen (0.15 MPa).

The inner casing takes the same form as the outer casing, i.e. a cylinder, to which the bottom and lid of the inner casing are welded. The thickness of the cylinder is 36 mm, the lid 130 mm and the bottom 75 mm. The lid, as with the outer casing, is fitted with a quick coupler, which is covered by the plug of the inner casing welded to the lid. The length of the inner casing is 3364 mm, see Fig. 2. The space inside the inner casing is filled with helium (0.1 MPa).

The fitting inside the WDP 440 ensures the fixation of the spent fuel assemblies and their uniform distribution in the required geometry; it has no corrosion or strength function.

A scaled-down drawing of this WDP is shown in Appendix 4: WDP assembly for seven VVER-440 fuel assemblies, and a 3D visualisation is shown in Fig. 2.

The WDP development project included the production of a physical model of the WDP, which is described in a report by Forman and Picek (2021). The model was shorter than the final anticipated design and has a cut-out for visualisation/demonstration purposes (see Fig. 3).

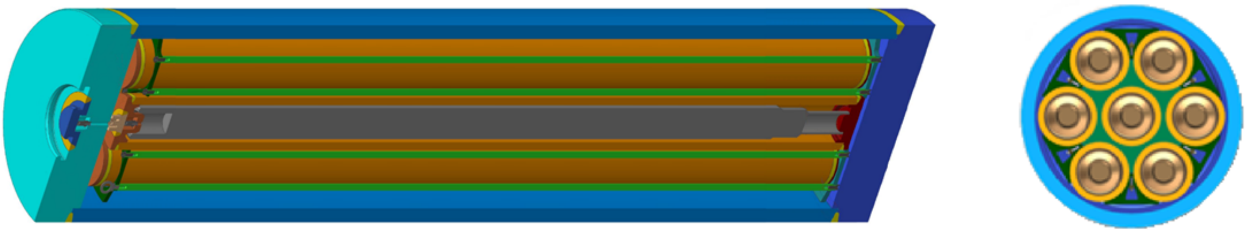

Fig. 1 - Visualisation of the WDP for VVER-440 fuel assemblies (total length – 3790 mm; total diameter – 914 mm)

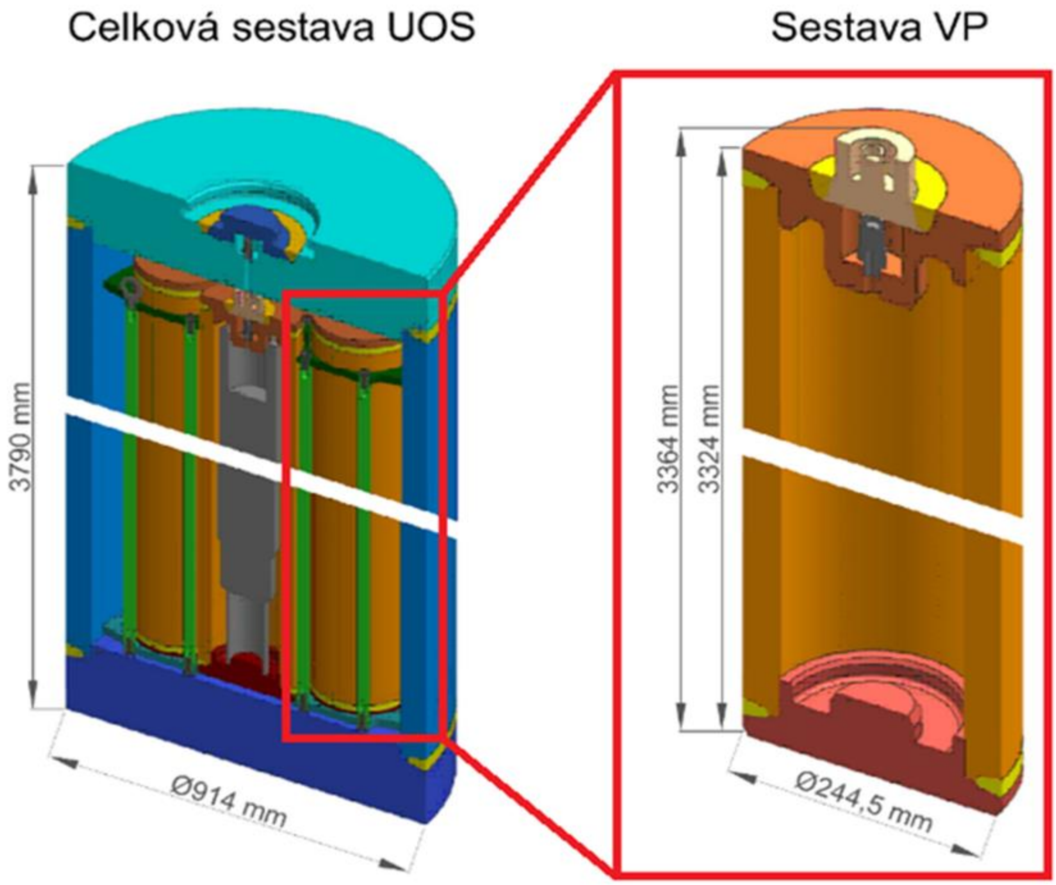

Fig. 2 - Detailed visualisation of the WDP for VVER-440 fuel assemblies

The various parts of the WDP for the VVER-440 fuel assemblies, including their dimensions, alloy types and standards, are listed below (see Appendix 2: WDP 440 list of materials).

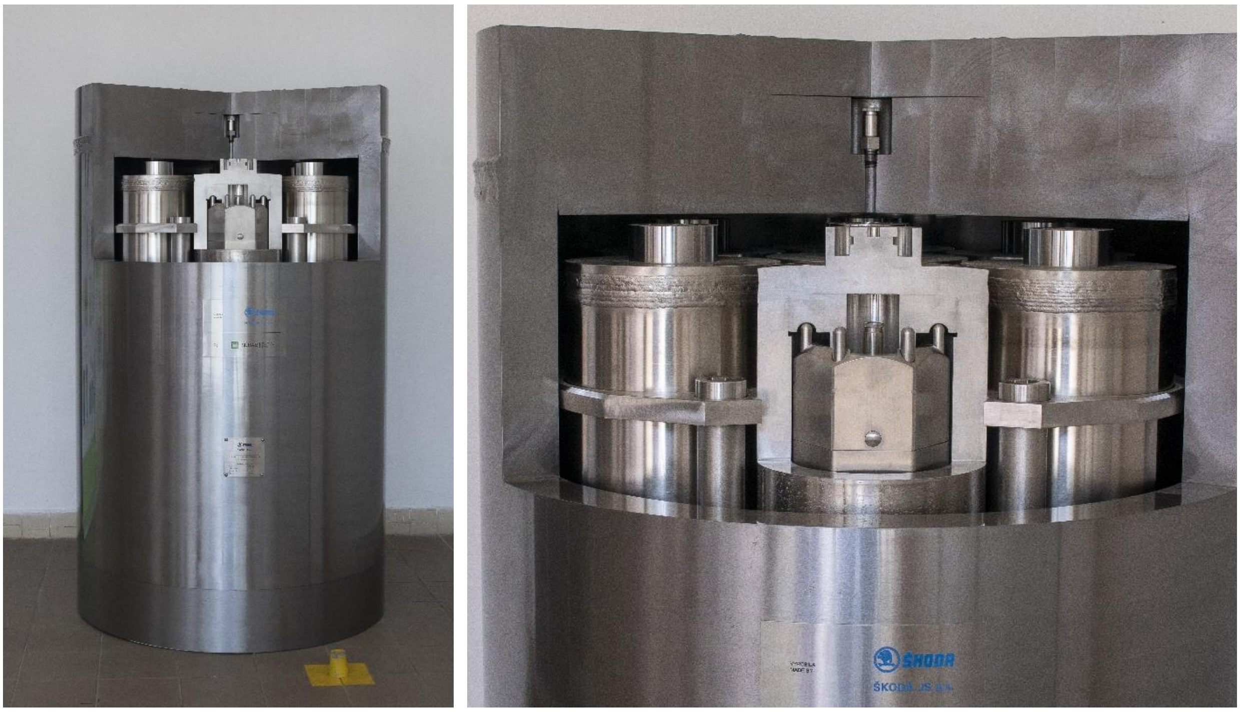

Fig. 3 - Left: Physical model of the WDP for VVER-440 spent fuel, right: detail of the inner space of the WDP with the inner casing and fuel assemblies

4.2.6 Structural design of the WDP for VVER-1000 reactor fuel (Temelín)

The WDP for SNF from the VVER-1000 type reactors will house three fuel assemblies. It consists of an outer casing, inner casing and internal fittings. The diameter of the WDP has been set at 914 mm and the length at 5205 mm (see Fig. 4). The WDP design for VVER-1000 type fuel is shown in Fig. 4. and a scaled-down drawing of this WDP is shown in Appendix 3 of this report: WDP assembly for three VVER-1000 fuel assemblies.

The outer casing is cylindrical with a welded bottom and lid. The thickness of the cylindrical part is 65 mm, the lid 200 mm and the bottom 200 mm. In addition, the lid is equipped with a quick coupler, which is covered by the plug of the outer casing welded to the WDP lid. The space inside the outer casing is filled with nitrogen (0.15 MPa).

The inner casing takes the same form as the outer casing, i.e. a cylinder, to which the bottom and lid of the inner casing are welded. The thickness of the cylinder is 40 mm, the lid 140 mm and the bottom 75 mm. The lid, as with the outer casing, is fitted with a quick coupler, which is covered by the plug of the inner casing welded to the lid. The length of the inner casing is 4779 mm. The space inside the inner casing is filled with helium (0.1 MPa).

The fitting inside the WDP 1000 ensures the fixation of the spent fuel assemblies and their uniform distribution in the required geometry; it has no corrosion or strength function.

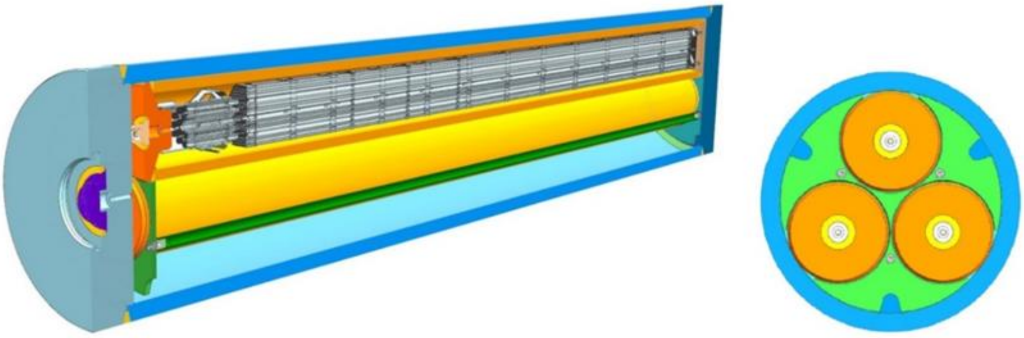

Fig. 4 - Visualisation of the WDP for the VVER-1000 fuel assemblies (total length – 5205 mm; total diameter – 914 mm)

4.3 WDP production technology

The production technology for the WDP 440 and WDP 1000 must be well researched, financially feasible and thoroughly tested and must satisfy the highest attainable safety standards. The current stage of the production technology for the outer and inner casings and the welding of the WDP components resulted from the findings of the *Research and development of a waste disposal package for the deep disposal of spent nuclear fuel* (Forman et al., 2021), which are described in the following chapters.

4.3.1 Production of the outer casing

According to the reference design, the outer casing will be made of carbon steel S355J2H+N. It will consist of the casing, a bottom and a lid that will be welded together via a circumferential weld. The body of the outer casing will, ideally, comprise a seamless annealed tube with an outer diameter of 914 mm, a tube wall thickness of 65 mm (inner diameter 784 mm) and a total length of 12,000 mm (Forman et al., 2021).

From the point of view of the outer casing production technology, for pressure containment purposes (based on the requirements of the EN 10216-3 standard) the current concept envisages the use of a seamless steel tube made of fine-grained steel. It is assumed that the material will be supplied in the normalised annealed state. Alternatively, the supply of a semi-finished product in the form of a welded or forged hollow profile is also being considered.

It is envisaged that the bottom and the lid will be made from the same type of steel as for the body of the outer casing, i.e. standard annealed carbon steel (S355J2[2]); the welding of the outer casing, bottom and lid was verified during the construction of the demonstration model of the WDP.

The material used for the production of the bottom and lid of the outer casing will be based primarily on the requirement for forged steel for pressure containment purposes made of weldable fine-grained steel with an elevated yield strength in the normalised annealed state. A further option comprises hot-rolled sheet metal in the normalised annealed state, or other options that meet all the set material and corrosion requirements.

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[2] In the case of the material for the bottom and the lid, no exact requirement has been set for the use of normalised annealed steel; hence, at this stage of development the material is interchangeable with S355J2H+N.

4.3.2 Production of the inner casing

The inner casing will be made from stainless steel EN 1.4404 and will comprise three main components, i.e. the body, bottom and lid. In the case of the WDP 440, the body of the outer casing consists of a seamless pipe with an outer diameter of 244.5 mm and a wall thickness of 36 mm (inner diameter of 172.5 mm). In the case of the WDP 1000, the body will be same as the outer casing and will differ only in terms of the wall thickness (40 mm) and the outer (355.6 mm) and inner (283.6 mm) diameters. The components will be connected via circumferential welds.

In the case of the body of the inner casing, the specification of the materials will take into account the requirement to meet the set standards for seamless steel tubes used for pressure vessels. The bottom and lid will be based on the requirements concerning stainless steel bars for pressure purposes. In both cases (the body and the lid/bottom), the steel will be subjected to the annealing process.

4.3.3 Welding

A method involving the use of a **non-consumable tungsten electrode (method 141)** will be used for welding purposes. This method was selected in view of its **suitability for automated welding** (Forman et al., 2021), which will be an essential factor in the future from the point of view of welding in the hot chamber. The principle of this welding method comprises the burning of an electric arc between a non-consumable tungsten electrode and the base material. Argon, helium or a mixture of the two are used as the shielding gases. The non-consumable electrode is usually made of pure tungsten.

A technical report by Malina et al., (2017) suggested the potential for the application of a narrow-gap U weld, which was considered at the beginning of the project for the welding of the casing and lid of the WDP; this approach is yet to be verified. Since this technology was still in the development stage at this time, it quickly became apparent that the further development of such technology would be beyond the scope of the R&D project and that it would require a completely separate project focusing solely on the development of narrow-gap U welding. It was subsequently decided to use the commonly-used V welding technique since this technology is already well known, and the consideration of the narrow-gap U welding approach for the WDP has been abandoned. This development will not affect the functionality or safety of the WDP.

4.4 Inspection, marking/registration and handling of the WDP

The inspection of the welds of the WDP will be performed in the hot chamber via the automated analysis of residual stresses in the weld areas and the sealings of the inner and outer casings applying standard methods (e.g. methods using ultrasound or X-ray).

Following the emplacement of the SNF in the WDP and prior to the final disposal of the WDP in the DGR, it will be necessary to handle the WDP so as to ensure that it is correctly positioned in the DGR disposal corridors. In this respect, the option is being considered of equipping the WDP with handling fixtures (handles, anchors, etc.) that will ensure the efficiency and safety of the handling process and minimise the potential for damaging the WDP. The current reference design does not consider such handling fixtures, and further specific research and development will be required if it is decided that such fixtures are needed.

Furthermore, the inclusion of a system is being considered aimed at preventing the occurrence of defects due to handling according to the relevant requirements for the production and processing technology of the WDP. The objective is to avoid potential negative influences on the lifetime of the WDP and systematic uncertainty in terms of the predictability of the lifetime. In order to ensure the maximum level of safety, it will be necessary to eliminate all the potential sources of defects.

A WDP marking system will be introduced for the purposes of the registration of the WDPs as required by legislation, particularly Decree No. 377/2016 Coll., which states that the durability of such marking must be sufficient for the time necessary for the registration and inspection of the status of the WDP prior to the closure of the DGR. The marking of the WDPs must not compromise its safety functions.

5 Calculations for demonstrating the functionality of the proposed WDP reference design

One of the crucial steps prior to the adoption of the proposed WDP concerns the demonstration of its functionality within the defined parameters. The requirements for the WDP must first be computationally verified employing validated computational models. As part of the *Research and development of a waste disposal package for the deep disposal of spent nuclear fuel* project (Forman et al., 2021), key parameters that influence the safety and lifetime of the proposed design solution were firstly identified followed by the computational verification of the fulfilment of the respective requirements by the proposed WDP. The computational and development research conducted to date (Kotnour et al., 2016) shows that the proposed WDP fulfils all the identified parameters and appears to be satisfactory with respect to its required functions.

5.1 Lifetime

A corrosion-transport 3D model with a variable geometry was used to calculate the lifetime of the WDP. Concerning the long-term lifetime calculations, it was necessary to include in the calculation model the precipitation of corrosion products in the pore system of compacted bentonite, which contributes to limiting the diffusion of iron cations. In addition to fitting the experimental data associated with the formation of siderite, the computational model was also able to simulate the formation of alternative corrosion products such as magnetite (which occurs as the main corrosion product in archaeological analogues) and aluminosilicates, which are considered significant in terms of long-term disposal, even though this has not been unequivocally proven experimentally. The results of the computational models are shown in numerical form in Tab. 4 and graphically in Fig. 5. When calculating the lifetime of the WDP, the calculation approach considered the following corrosion allowances: 15 mm for carbon steel and 5 mm for stainless steel.

Tab. 4 - WDP lifetime for various corrosion products considered in the 3D model (Forman et al., 2021)

Corrosion product carbon steel	**Minimum lifetime (years)**		
	Outer casing (corrosion allowance 15 mm)	**Inner casing (corrosion allowance 5 mm)**	**Total**
magnetite	1 026 109	1 315 789	2 341 898
siderite	**3 320 423**	**1 315 789**	**4 636 212**
chamosite	7 098 938	1 315 789	8 414 727

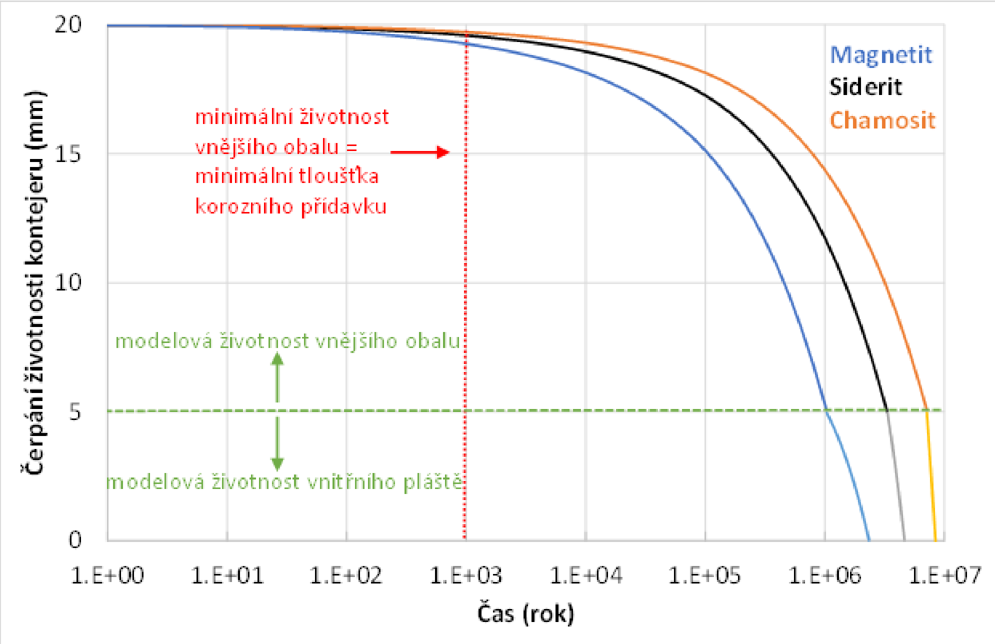

Fig. 5 - Depletion of the lifetime of the WDP for various carbon steel corrosion products (Forman et al., 2021)

5.2 Subcriticality

Requirements relating to subcriticality are set out in the relevant legislation, see chapter 3.2. The calculated neutron multiplication coefficient limiting value is required to be less than 0.95. This value takes into account both a conservative multiplication coefficient value and uncertainty (due, for example, to the calculation model itself, the methodology applied, the cross-section data library employed, fuel enrichment fluctuations, production uncertainty, etc.).

To date, the subcriticality calculation has **only been performed for WDPs for VVER-440 fuel**. The input parameters were selected very conservatively, i.e. fresh fuel with a maximum enrichment of 5.0 wt. % U-235, without a burning absorber and under emergency conditions following the flooding of the WDP with water (Lovecký, 2020a). Clean water inside and outside the WDP, bentonite and granite rock mass are conservatively replaced in the model by so-called moderators. More details can be found in the report by Lovecký (2020a).

The calculations revealed that the multiplication coefficient limit value is 0.71675; **this value satisfies the legislative limit of 0.95 with a significant margin of 0.23.**

As part of future research, it will be necessary to perform the WDP calculations for VVER-1000 fuel.

5.3 Shielding calculations

Requirements concerning the shielding of the WDP are based on safety requirements especially with regard to the workers in the DGR during the operational phase. Three dose equivalent limits have been verified (see chapter 3.3).

Shielding calculations were performed for VVER-440 (Lovecký, 2020a) and VVER-1000 (Gincelová, 2020) reactor fuel. Concerning VVER-1200 reactors (considered in the shielding calculations as the reference for NNS), the fuel is almost identical, so the results also apply to NNS without any significant changes.

The aim was to determine the dose equivalent on the surface of the WDP and in its vicinity at the time of the disposal of the WDP in the DGR. The calculation is especially important due to transport and handling considerations in the DGR.

According to the calculations, it can be concluded that shielding can be achieved with a significant margin for both types of WDP. For reasons of clarity, Tab. 5 shows the percentages from which the given limit is depleted.

Tab. 5 - Calculated dose rate and dose equivalent values at 3 different distances from the fuel, including the defined limits

Dose rate limits and dose equivalent	Dose equivalent of VVER-440 fuel		Dose equivalent of VVER-1000 fuel	
	Sv/h	Depletion limit [%]	Sv/h	Depletion limit [%]
1 Sv/h on the surface of the WDP on the WDP-bentonite interface in order not to alter the bentonite	2.70E-01	27.0	2.30E-01	23.0
2E-03 Sv/h on the WDP surface in the lid area, transport dose equivalent limit according to Decree No. 379/2016 Coll; chosen due to the handling of the WDP prior to disposal in the DGR	1.64E-05	0.8	4.74E-05	2.4
1E-04 Sv/h at a distance of 2 m from the WDP in the lid area, transport dose equivalent limit according to Decree No. 379/2016 Coll; chosen due to the handling of the WDP prior to disposal in the DGR	1.49E-06	1.5	2.14E-06	2.1

5.4 Strength calculations

Strength calculations are particularly important since, together with the corrosion models, they allow for the estimation of the thicknesses of the outer and inner casings. The strength calculation is described in detail in a report by Jeník (2020).

Due to the uncertainty of the external influences to which the WDP will be exposed, it was thought advisable to approach the design of the structure so that the peak stress values for the various parts of the WDP structure were set reasonably below the limit values. As a result, the mean stress values have a sufficient margin compared to the limit value.

The strength evaluation methodology of both the WDP 440 and WDP 1000 options for the inner and outer casings is based on the assumption that the calculation considers the WDP model in the stage at which 15 mm of the surface layer of the outer casing and 5 mm of the inner casing have already been corroded. This means that the WDP is at the end of its design lifetime and the major concern is proving that it will still be able to structurally withstand the external loading anticipated in the DGR. Hence, this is not the initial stage of the DGR lifetime, but the time at which the mechanical properties of the materials have already been fully exhausted and the evaluation of the WDP is approached in the same way as that of the structure of the WDP under emergency operating conditions. From this point of view, the collapse method can be successfully applied with the consideration of the elastic-plastic behaviour of the materials used. This method of assessment meets, for example, the KTA 3201.2 standard, which implies the application of a safety factor of 1.1 with the definition of the limit values of the permitted stress for the materials (see Tab. 6 and Tab. 7). Methodologically, the weld is considered as having the same or better mechanical properties than the base material, as reflected in the experimental measurements of the mechanical properties (Jeník, 2020). Hence, the base material limit is used for the evaluation of the weld. The set limit for the weld and the heat-affected area exceeds the limit for the base material by around 20%.

The various loading conditions that were simulated in the strength calculations are described below accompanied by the results attained.

5.4.1 Uniform pressure of 20 MPa

The first condition that was simulated in the calculations comprised a uniform pressure of 20 MPa (see chapter 3.4) acting on the outer and inner casings. The resulting values are described below for each type of WDP separately:

<u>WDP 440</u>

- the mean stress values for the outer and inner casings are 219 MPa and 100 MPa, respectively
- a peak stress value of **372 MPa** is attained for the **outer casing** at the points of contact of the cylindrical casing and the bottom and the lid, and a value of **194 MPa** for the **inner casing** in the region of the root of the welds on the lid and at the bottom of the casing
- the lid, including the plug, and the bottom exhibit stress values of up to 218 MPa (outer casing).

<u>WDP 1000</u>

- the mean stress values for the outer and inner casings are 242 MPa and 100 MPa, respectively
- a peak stress value of **413 MPa** is attained for the **outer casing** at the points of contact of the cylindrical casing and the bottom and the lid, and a value of **195 MPa** for the **inner casing** in the region of the root of the welds on the lid and at the bottom of the casing
- the lid, including the plug, and the bottom exhibit stress values of up to 250 MPa.

For evaluation purposes, the peak values were compared with the limit values according to KTA (already reduced by the safety margin); this comparison is shown in Tab. 6. All the resulting values were observed to be below the specified limit values.

Tab. 6 - Stress limit values of the materials determined according to KTA 3201.2 and their comparison with the calculated peak values under uniform pressure loading conditions

Material	R_m [MPa]	Limit according to KTA R_m / 1.1 [MPa]	Peak values for WDP 440 [MPa]	Peak values for WDP 1000 [MPa]
Outer casing S355J2H	470	**427**	**372**	**413**
Inner casing 1.4404	490	**445**	**194**	**195**

*R_m – Strength limit

5.4.2 Non-uniform pressure

This chapter focuses on the non-uniform distribution of pressure along the entire length of the WDP. The loading of the WDP via the non-uniform swelling pressure of the bentonite could lead to the local deformation of the WDP.

The calculation focuses on two limit states. The first variant (see variant 1 in Fig. 6) considers the stressing of the WDP by a rotationally symmetric boundary condition under which the loading of the lid and bottom of the outer casing reaches an external pressure value of 20 MPa. This pressure decreases in the axial direction so as to reach zero halfway along the length of the WDP, from which point the load increases linearly to reach a value of 20 MPa at the opposite end of the WDP. The second limiting variant reflects a situation (see variant 2 in Fig. 6) in which loading of 20 MPa occurs halfway along the length of the outer casing of the WDP.

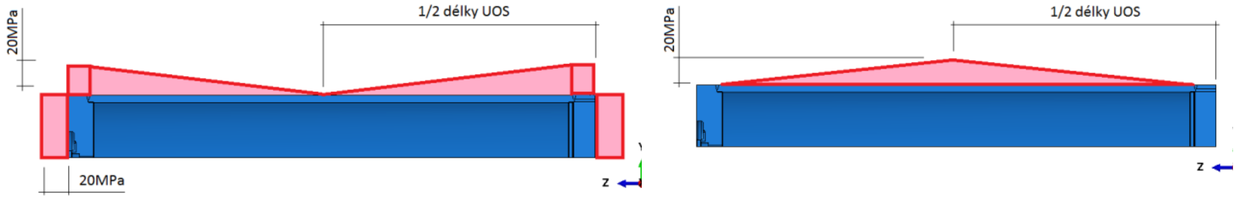

Fig. 6 - Rotationally symmetric boundary conditions for non-uniformly distributed external pressure on the outer casing for the two WDP variants; variant 1 on the left, variant 2 on the right (Forman et al., 2021)

The resulting calculated stress values (peak = maximum), as verified for both of the loading variants, are shown in Tab. 7, together with the limit values. The comparison of the resulting and limit values shows that both types of WDP are sufficiently resistant to non-uniform loading under the pressure conditions considered above.

Tab. 7 - Stress limit values of the material determined according to KTA 3201.2 and their comparison with the calculated peak values under non-uniform pressure loading of 20 MPa

Material	**R_m [MPa]**	**Limit according to KTA R_m / 1.1 [MPa]**	**VAR. 1- peak value for WDP 440 [MPa]**	**VAR. 2- peak value for WDP 440 [MPa]**	**VAR. 1- peak value for WDP 1000 [MPa]**	**VAR. 2- peak value for WDP 1000 [MPa]**
Outer casing S355J2H	470	427	376	180	387	183

*R_m – Strength limit

The strength calculation for the inner casing will form a part of future research.

5.4.3 Shear stress

The requirement for resistance to shear pressure is described in chapter 3.4. Shear stress arises as a result of a seismic event and is defined by the displacement and velocity in the shear plane. The calculation was performed for both the WDP 440 and WDP 1000 options.

The FEM (Finite Element Method) calculation of the mechanical resistance of the WDP to shear pressure (Lopaur, 2020) was conducted considering the displacement of the rock mass by 50 mm, with a shear plane perpendicular to the axis of the WDP at halfway along its length (i.e. the worst possible scenario). The inspection of the integrity of the WDP was performed based on the evaluation of the critical point, which was considered the welded area of the WDP lid, applying groups of stress categories for seismic loading according to the Normative Technical Documentation of the Association of Mechanical Engineers. Our FEM model considered the worst case scenario (M1 bentonite material with the properties described in Forman et al., (2021) and a modelled crack for both the WDP 440 and WDP 1000 variants (Tab. 8)). The calculation was further verified according to KTA 3201.2 (Tab. 9). The yield point was exceeded in the smooth part of the outer casing of the WDP, which, however, was not found to affect the integrity of the WDP. Only partial plastic deformation was predicted, with the preservation of the overall integrity of the WDP.

The calculation served to prove the seismic resistance and preservation of the integrity of the WDP over the considered lifetime. This was a basic calculation that proved the ability of the WDP to withstand design-based force effects. In the future, this calculation should be supplemented by both the more precise calculation of the seismic resistance of the WDP once the final location of the DGR is known, and the calculation of the resistance of the inner casing.

Tab. 8 – Evaluation according to groups of shear stress categories at the point of the welding of the lid of the outer cover of the WDP

Reduced stress			Limit	
Category group	**WDP 440 [MPa]**	**WDP 1000 [MPa]**	**-**	**[MPa]**
$(\sigma_s)_1$	136.3	127.6	1.4 [σ]	253.1
$(\sigma_s)_2$	324.1	307.5	1.8 [σ]	325.4
$(\sigma_s)_2$	215.0	205.6		

Tab. 9 - Shear evaluation according to KTA 3201.2

WDP option	σ_{red} [MPa]	Limit [MPa]
WDP 440	325.4	427
WDP 1000	307.5	427

5.5 Thermo-technical calculations

A report by Šik (2020) contains the results of the temperature analysis of the WDP 440 and WDP 1000 at the time following transportation to the DGR. The purpose of the analysis comprised the temperature verification of the proposed WDP with the aim of confirming that the limit temperature of 95°C mentioned in chapter 3.5 will not be exceeded.

The temperature within the WDP and its surroundings is directly dependent on the residual power of the spent nuclear fuel, which was determined in Lovecký (2015a) and Lovecký (2015b) over a range of 0 - 1 million years (zero represents the emplacement of the WDP in the DGR, i.e. 65 years following removal from the reactor). With respect to the disposal of WDP 440, 655 W is considered the limit value, and for WDP 1000 1,125 W (Pospíšková et al., 2022). The given values thus correspond to those considered in the temperature dimensioning of the DGR according to a report by Kobylka (2019). However, more conservative values were applied for the residual heat in the WDP thermal calculations, i.e. for VVER-440 fuel assemblies 138.140 W (**WDP 440 = 7*138.140 = 966.98 W**) and for VVER-1000 fuel assemblies 450.758 W (**WDP 1000 = 3*450.758 = 1352.274 W**) (Kobylka, 2019).

Concept considered in the calculation:
The WDP is disposed of in a bentonite cylinder; an air gap of 0.01 m was considered between the WDP and the bentonite. This gap was chosen based on an expert estimation. The gap is unavoidable due to reasons of inserting the WDP into the disposal well. This value was selected

for the purposes of performing our own particular calculation; however, it will have to be verified via further research in the future.
The boundary condition of the ambient temperature on the outer surface of the WDP is considered to be 95°C, which is the limit temperature of the bentonite with the heat transfer coefficient through the air gap. This means that no higher temperature can be attained in the bentonite in the calculation. The temperatures were calculated of the various WDP components once the temperature of the bentonite reaches 95°C (see Tab. 10).

Tab. 10 - Calculated maximum temperatures of the WDP components

Component	Maximum temp. [°C] WDP 440	Maximum temp [°C] WDP 1000
Cover of the fuel elements	174.1	193.0
Inner casing	162.4	177.4
Outer casing	108.6	110.4

The thermal calculation proved that the WDP 440 and WDP 1000 meet the conditions for compliance with the limit temperatures of the cover of the fuel elements and the WDP components, provided that only undamaged fuel is emplaced in the DGR, which has been stored for 65 years in an SNF interim storage facility from the time it is removed from the reactor, and it has a residual heat value as listed above. The thermal conductivity of the anticipated air gap (0.01 m) will help to ensure that the temperature of the bentonite does not exceed 95°C.

Conclusion

This report presents the results obtained by SÚRAO as part of the *Research and development of a waste disposal package for the deep disposal of spent nuclear fuel up to the sample realisation stage* project (Forman et al., 2021), which presents a reference design for waste disposal packages (WDP) for spent nuclear fuel (SNF) in the Czech Republic. This unique WDP proposal comprises an outer casing and an inner casing which, together, ensure the required resistance to corrosion and potential mechanical damage. Each part of the WDP contributes to providing maximum resistance and the fulfilment of the safety requirements in all the stages of the disposal process. Both the proposed materials, carbon steel (S355J2H+N) and austenitic stainless steel (EN 1.4404), are well known and readily available. According to the experiments conducted to date, the lifetime of the carbon steel outer casing with a corrosion allowance of 15 mm will be sufficient (with a safe margin) to eliminate any uncertainties surrounding the functioning of the inner casing. The main uncertainties concern the consumption of oxygen in the DGR and the drop in temperature to below 50°C. The total lifetime of the WDP according to all the corrosion models considered was verified not only to exceed a period of 100,000 years but even up to 1,000,000 years. The future stages of the WDP development procedure in the Czech Republic will confirm the expected lifetime of 1,000,000 years based on data provided by ongoing and future research.

The related processing technologies, especially the welding method, have also been extensively researched for both materials used in the construction of the WDP. The main advantage of the reference solution, which considers an inner casing for each fuel assembly, concerns ease of handling in the hot chamber. Of the thirteen candidate design options, one WDP was selected for the VVER 440 fuel assemblies and one for the VVER 1000 assemblies. The WDP 440 will house seven VVER 440 fuel assemblies and the WDP 1000 three VVER 1000 fuel assemblies. The two options have the same outer diameter, which will lead to cost savings on the semi-finished products required in the future. The structures of the WDPs were computationally verified via the consideration of strength, thermo-technical, subcriticality, shielding and shear (seismicity) calculations. These calculations were repeated several times following each change to the design so as to determine the most suitable final design. The thermo-technical calculations are currently being subjected to further research as part of a project funded by the Technological Agency of the Czech Republic named “the optimisation of the spacing in, and preliminary temperature calculations for, the deep geological repository for spent nuclear fuel” (TA CR ORTEV), the aim of which is to develop software that will further contribute to the optimisation of the DGR design, in particular the optimisation of the capacity of the DGR from the point of view of the generation of heat, while ensuring that the maximum level of safety is maintained in the DGR.

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Appendix 1: Legislation

This appendix provides a summary of the currently valid Atomic Act and its various implementing decrees that are relevant to the WDP (see Tab. 11).

In the sense of section 4 paragraph 2, b), 3) of Act No. 263/2016 Coll., the Atomic Act, the WDP serves for the "disposal of fissile substances or radioactive substances" and, according to section 136 b), it comprises a set of "structural components that are necessary to ensure the complete sealing of the radioactive content". According to section 136 m) radioactive content refers to "radioactive substances with all the contaminated or activated solids, liquids and gases inside the WDP". The properties of the WDP are important from the point of view of Decree No. 422/2016 Coll., namely in terms of ensuring safe effective radiation dose limits. Thus, currently valid legislation covers selected requirements that the WDP must meet so as to ensure safety in terms of the development stage and the licensing process, as well as during the filling of the WDPs and the operational phase of the DGR.

Tab. 11 - Implementing Decrees of the Atomic Act relevant to the WDP

Decree no.	*Decree subject*
Decree No. 358/2016 Coll.	*on requirements for quality assurance and technical safety and the assessment and verification of the conformity of selected facilities*
Decree No. 359/2016 Coll.	*on details to ensure the management of radiation emergencies*
Decree No. 377/2016 Coll.	*on requirements for the safe handling of radioactive waste and the decommissioning of nuclear facilities and category III and IV workplaces*
Decree No. 379/2016 Coll.	*on the type approval of certain products in the field of the peaceful use of nuclear energy and ionising radiation and the transport of radioactive and fissile materials*
Decree No. 408/2016 Coll.	*on management system requirements*
Decree No. 422/2016 Coll.	*on radiation protection and the safety of radionuclide sources*
Decree No. 21/2017 Coll.	*on ensuring the nuclear safety of nuclear facilities*
Decree No. 162/2017 Coll.	*on safety assessment requirements under the Atomic Act*
Decree No. 329/2017 Coll.	*on nuclear facility project requirements*

The approval of WPs for the transport, storage and disposal of radioactive and fissile materials is currently governed by *section 137 paragraph 1 of the Atomic Act and section 11 paragraph 1 of Decree No. 379/2016 Coll*. WPs that are "intended for the disposal of spent or irradiated nuclear fuel and radioactive waste resulting from its reprocessing" are, according to *section 11 paragraph 1 e),* classified as type D WPs. Such WPs (known as WDPs) are not intended for transport purposes and the approval organisation is the State Office for Nuclear Safety (SÚJB) in the sense of *section 137 paragraph 1 a) and paragraph 6 of the Atomic Act, as well as section 208 b) of the Atomic Act and section 11 paragraph 1 e) of Decree No. 379/2016 Coll*.

According to management system requirements in the sense of *Decree No. 408/2016 Coll.,* the WDP is a selected safety class 2 device as set out in *Decree No. 358/2016 Coll*. According to *section 2 a),* "pressure equipment is defined as selected equipment under stress from pressure exerted by a process medium with maximum operating pressure in excess of 0.05 MPa, including elements connected to parts exposed to pressure, safety and pressure."

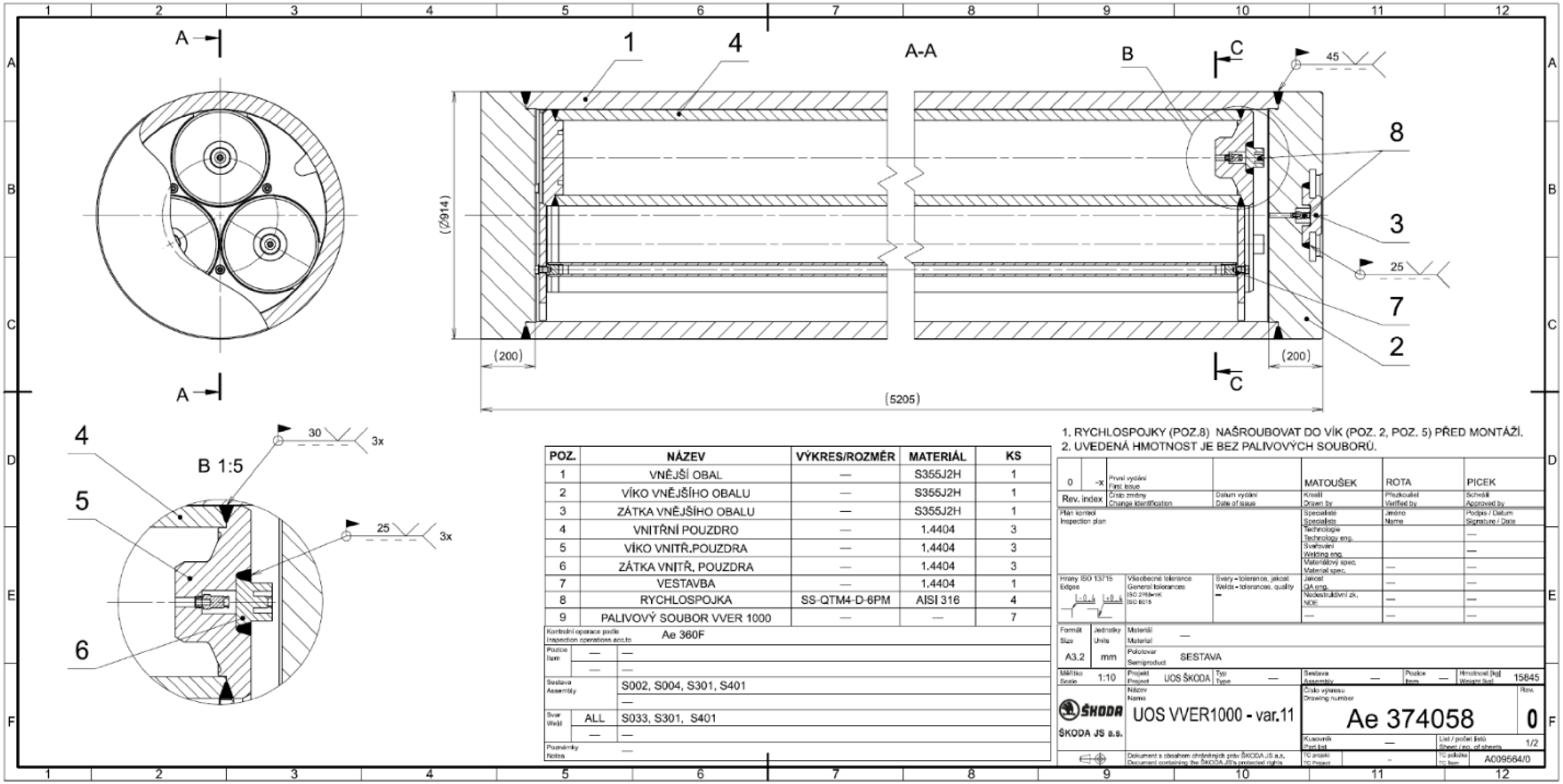
Decree No. 377/2016 Coll. sets out important requirements concerning the WDP, especially in terms of the marking (*section 2*), filling and handling (*section 5*), disposal (*section 8*), documentation (*section 9*) and registration (*section 10*) of the WDP.

Damage to the WDP with nuclear material is, according to *section 6 paragraph 2 f) of Decree No. 21/2017 Coll.* categorised as a significant operational event in the sense of the Atomic Act. The integrity of the WDP is examined in the event of an extraordinary event so as to determine the reason for the event in accordance with *section 6 paragraph 2 a) of Decree No. 359/2016 Coll*. The legislative basis for the requirements for the periodic safety assessment of the future operation of the DGR is set out in *Decree No. 162/2017 Coll*.

Appendix 2: WDP 440 list of materials

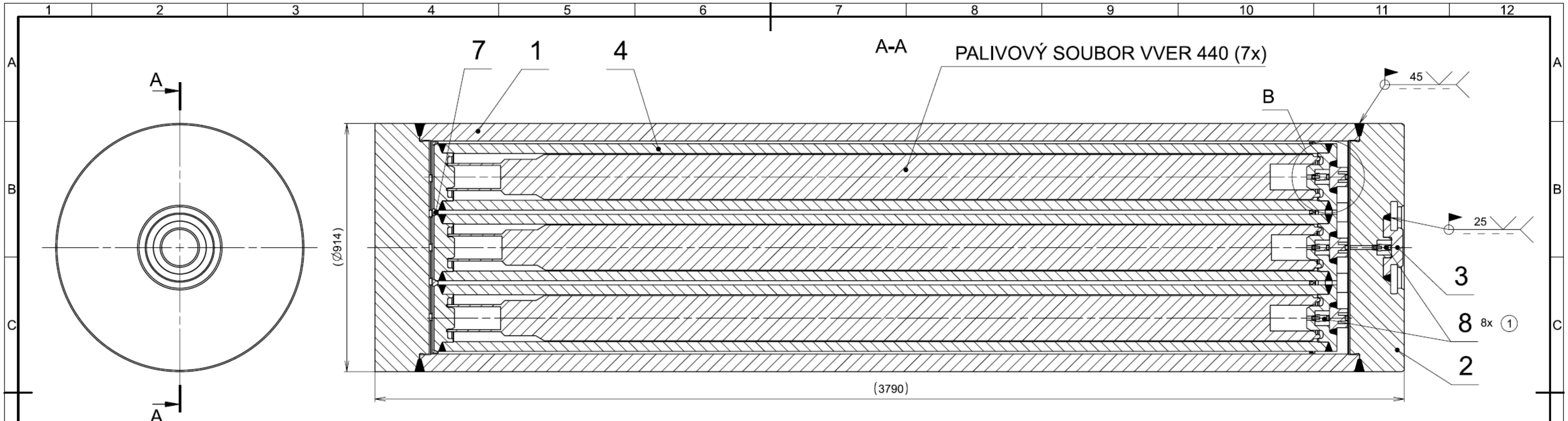
Position	Name	Type	Amount	Dimensions	Material	Dimensions norm	Standard
1	WDP 440	ASSEMBLY	1				
1/1	OUTER CASING	COMPONENT	1				
1/1/1	BOTTOM OF THE OUTER CASING		1	P210 – KR950	S355J2H		EN 10137-1
1/1/2	BODY OF THE OUTER CASING		1	FORGING KR924/774-3490	S355J2H		EN 10222-1
1/2	LID OF THE OUTER CASING		1	P210 – KR950	S355J2H		EN 10137-1
1/3	PLUG OF THE OUTER CASING		1	P70 – KR310	S355J2H		EN 10137-1
1/4	INNER CASING	COMPONENT	7				
1/4/1	BOTTOM OF THE INNER CASING		7	KR250 - 80	1.4404		EN 10272
1/4/2	BODY OF THE INNER CASING		7	TR KR244,5x36 - 3340	1.4404		EN 10297-2
1/5	LID OF THE INNER CASING		7	KR250 - 140	1.4404		EN 10272
1/6	PLUG OF THE INNER CASING		7	KR140 - 75	1.4404		EN 10272
1/7	INSERTS	COMPONENT	1				
1/7/1	BOTTOM PLATE		1	P20 - 788x788	1.4404		EN 10028-7
1/7/2	TOP PLATE		1	P20 - 788x788	1.4404		EN 10028-7
1/7/3	GUIDE ROD		12	KR30 - 3255	1.4404		EN 10272
1/7/4	UNDERLAY		21	17	A2	ISO 7092	
1/7/5	SCREW		21	M16x40	A2	DIN 6912	
1/7/6	SUSPENSION SCREW		3	M16	A2	ISO 3266	
1/8	QUICK COUPLER		8	SS-QTM4-D-6PM			

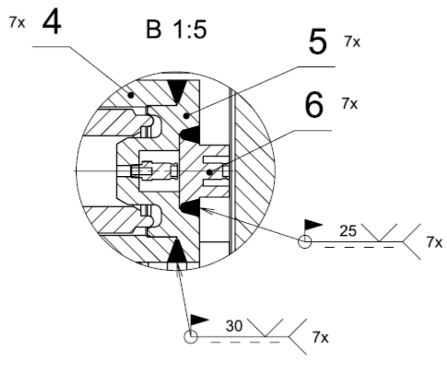
Appendix 3: WDP assembly for three VVER-1000 fuel assemblies



POZ.	NÁZEV	VÝKRES/ROZMĚR	MATERIÁL	KS
1	VNĚJŠÍ OBAL	—	S355J2H	1
2	VÍKO VNĚJŠÍHO OBALU	—	S355J2H	1
3	ZÁTKA VNĚJŠÍHO OBALU	—	S355J2H	1
4	VNITŘNÍ POUZDRO	—	1.4404	3
5	VÍKO VNITŘ.POUZDRA	—	1.4404	3
6	ZÁTKA VNITŘ. POUZDRA	—	1.4404	3
7	VESTAVBA	—	1.4404	1
8	RYCHLOSPOJKA	SS-QTM4-D-6PM	AISI 316	4
9	PALIVOVÝ SOUBOR VVER 1000	—	—	7

Appendix 4: WDP assembly for seven VVER-440 fuel assemblies





POZ.	NÁZEV	VÝKRES/ROZMĚR	MATERIÁL
1	VNĚJŠÍ OBAL	Ae 373508	S355J2H
2	VÍKO VNĚJŠÍHO OBALU	Ae 373506	S355J2H
3	ZÁTKA VNĚJŠÍHO OBALU	Ae 373509	S355J2H
4	VNITŘNÍ POUZDRO	Ae 373514	1.4404
5	VÍKO VNITŘ. POUZDRA	Ae 373517	1.4404
6	ZÁTKA VNITŘ. POUZDRA	Ae 373518	1.4404
7	VESTAVBA	Ae 373504	1.4404
8	RYCHLOSPOJKA	SS-QTM4-D-6PM	-
9	PALIVOVÝ SOUBOR VVER 440	-	-

1. RYCHLOSPOJKY (POZ.8) NAŠROUBOVAT DO VÍK (POZ.2, POZ.5) PŘED MONTÁŽÍ.
2. UVEDENÁ HMOTNOST JE BEZ PALIVOVÝCH SOUBORŮ.

Kontrolní operace podle / Inspection operations acc.to	Ae 360F
Pozice / Item	— —
Sestava / Assembly	S002, S004, S301, S401
Svar / Weld	ALL S033, S301, S401

Rev. index 0 -x První vydání / First issue
Kreslil / Drawn by: MATOUŠEK; Přezkoušel / Verified by: —; Schválil / Approved by: FORMAN

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ŠKODA JS a.s.

Název / Name: UOS VVER440-var.12

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