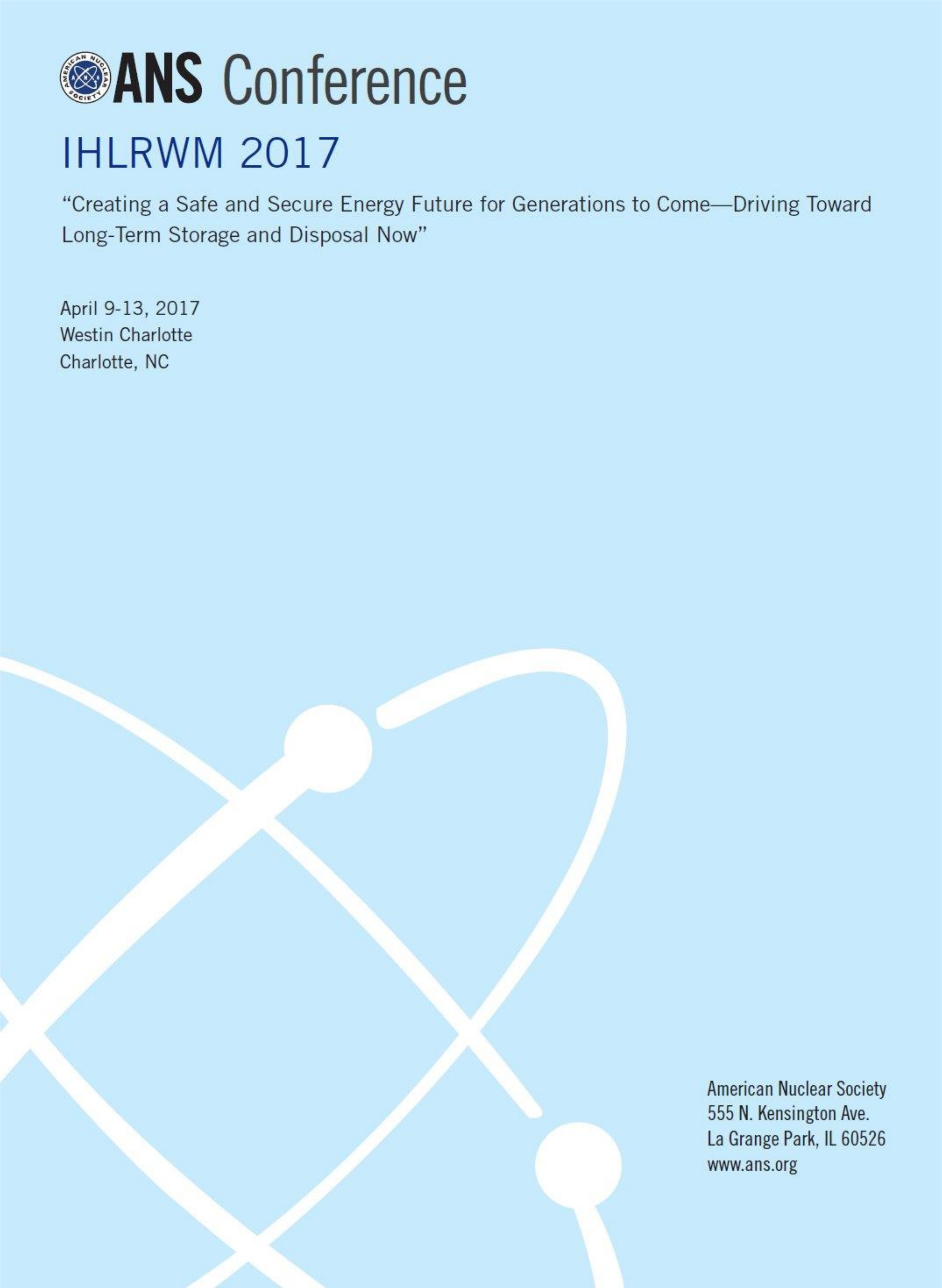

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Logistic simulation of Underground Operation of Future Belgian Geological Repository (Abstract)

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The Belgian radioactive waste management program has focused on the disposal of long-lived radioactive waste in a clay formation. The current repository layout foresees two shafts located in a central service area. One shaft serves the transport of waste packages and the second one is designed for staff and material transport. The two emplacement fields, one for low- and intermediate-level waste (B-waste according to the Belgian nomenclature) and the other for high-level, heat-generating waste (C-waste) are located at two opposite sides of the central area. Two parallel access galleries run through the middle of each emplacement area and connect the disposal galleries that are constructed perpendicular to the access galleries with the central service area of the repository. The disposal galleries are 400 m long, blind or dead-end galleries. The total repository footprint is 4.3 km in length and 0.9 km in width.

During the first construction phase only the central service area and the galleries of the B-waste emplacement field will be excavated. After the end of disposal, backfilling and closure operations in the B-waste part, the C-waste part will be excavated and disposal and backfilling operations will be carried out.

According to the Belgian reference concept, B-waste will be conditioned in concrete monoliths and C-waste in so-called supercontainers (SCs). The waste packages (WPs) will be transported on trolleys of a hybrid rail-wheel configuration using battery driven locomotives. Backfilling of the disposal galleries after WP emplacement is supposed to be carried out in segments of approximately 50 m length. To increase the level of operational safety in the repository, it is planned to strictly separate disposal and backfilling operations.

Considering the framework conditions at the site, it was necessary to develop a specific backfill material, taking into account the particular material requirements resulting from the characteristics of a clay host rock formation and a suitable backfilling technique. The current reference solution is to mix the backfill at the surface and then to pump the mixture through a pipeline distribution system installed inside the access shaft and the galleries.

Based on the boundary conditions derived from the waste transport system, the backfill production and distribution system, the WP production, and certain strategic decisions by the Belgian Waste Management Organization, ONDRAF/NIRAS, a numerical model has been developed to simulate the operational activities during emplacement and backfilling. Results of the simulation demonstrate the influence of certain parameters like working time, dimensions and number of disposal galleries in operation, size of buffer storage for WPs, etc. on the WP emplacement rates. The outcome of the simulation will be used to optimize the emplacement and backfilling concept in a way that the WP emplacement rate does not fall behind the WP production rate, which would prolong the minimum operational period of the repository. At the same time the results will help to prevent significant over capacities in regard to emplacement and backfilling or buffer storage to economically optimize the operation of the repository.

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Logistic simulation of Underground Operation of Future Belgian Geological Disposal Facility

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The Belgian Agency for Radioactive Waste and Enriched Fissile Materials, ONDRAF/NIRAS, proposes to develop a geological disposal facility for the long term management of category B waste and category C waste. Without any preconceived opinion regarding the site location, ONDRAF/NIRAS developed a reference design of a geological disposal facility in a clay formation. The facility consists of two shafts and underground galleries that can be allocated to the shaft and support zones and two wings with connecting access galleries, and branching disposal galleries. The facility for waste disposal package (DWP) production and a buffer/interim storage facility will be erected near to the waste transport shaft at the surface. Long-lived, low- and intermediate level waste (B waste) will be conditioned in concrete monoliths and high-level waste (C waste) in so-called supercontainers (SC).

The DWPs will be transported on trolleys of a hybrid rail-wheel configuration using battery driven locomotives. After the emplacement of a specified number of DWPs a formwork will be installed and voids will be backfilled. It is foreseen to mix the backfill at the surface and to pump the material through a pipeline distribution system.

An insufficient performance of backfill processes and/or emplacement rates that are significantly smaller than the production rate of the DWPs would cause interruptions in DWP production. The total operational phase of the facilities would be extended and associated costs increased. The relation between DWP production rate and emplacement rate is therefore of great importance. To investigate the general feasibility of the planned operation and to identify bottlenecks, areas for optimization etc., DBE TECHNOLOGY GmbH carried out simulations of the future operation. The simulation model considers all relevant boundary conditions, e.g. the disposal facility design, the planned transport and backfill techniques, and strategic decisions of ONDRAF/NIRAS relating to the operation of the facilities. For example, one scenario considered to start the emplacement of the DWPs in the rearmost parts of the emplacement fields, and to carry out the construction of the plugs at the entrance of the disposal galleries, and the backfilling of the access galleries after backfilling of all disposal galleries.

According to the results of the simulations, at the beginning of the disposal operation the production rate will marginally exceed the rate of emplacement due to the longer transport routes. Consequently, the buffer is filled up with monoliths, however, this does not lead to a reduction of DWP production. Before the capacity of the buffer storage is exceeded, the decrease of transport distances and times with disposal operations advancing towards the shaft leads to an increased emplacement rate. The buffer stock is reduced and all new monoliths can be emplaced according to the DWP production rate.

Failures of the emplacement and backfilling technique do not have significant effects for emplacement, because the buffer facility has a sufficient capacity. In addition, a variety of operational measures can be realized to raise the speed of emplacement and backfilling after resumption of the works, e.g. a temporary change from single shift to two shift operation. Consequently, there seems to be little risk that the average emplacement rate will fall back behind the DWP production rates and cause an extension of the total disposal operation period. According to the simulations, the emplacement of the monoliths will last slightly less than 13 years.

The construction of the plugs and a final seal is still at the planning stage and no safe statements can be made to the time period of their implementation. However, a little more than 400 work days (~1.6 calendar years) can be estimated for the backfilling of the access galleries and their connecting galleries of the B waste field, if the works in the access galleries can be carried out simultaneously.

After closure of the B waste field, the second wing of the disposal facility will be constructed and the supercontainers will be emplaced in analogy to the B waste monoliths. Further simulation studies will examine the effects of the major differences between the planned operation of the B waste part of the disposal facility and its C waste part.

I. INTRODUCTION

In Belgium, based on their activity and the half-life of the radionuclides, the conditioned radioactive waste types are subdivided into three categories: A, B and C (TABLE I).

TABLE I. Types of radioactive waste (HL = half-life) according to the Belgium waste classification.

	Low level	Intermediate level	High level
Short-lived: HL < 30 years	A	A	C
Long-lived: HL > 30 years	B	B	C

Conditioned A waste presents a risk for man and the environment on a timescale of hundreds of years. The Belgian government decided in favor of a near surface disposal facility for this waste type, which will be located in the municipality of Dessel where part of the waste is already temporarily stored in the storage buildings of BELGOPROCESS, a subsidiary of ONDRAF/NIRAS. However, the risk that B&C waste present extends hundreds of millennia. For this reason, a geological disposal facility seems to be the only management solution capable of protecting man and the environment. However, no decision is taken up to now in Belgium.

Numerous laboratory investigations and the experiments in the High Activity Disposal Experimental Site (HADES) demonstrate that the disposal of the waste in a poorly indurated clay formation can be a safe and feasible solution. Consequently, ONDRAF/NIRAS proposes poorly indurated clay as a reference host rock formation (working hypothesis) and performs RD&D to develop a disposal facility. Developments have been made regarding the construction and design of the disposal facility and the construction of the technical facilities, for example the hoisting and the waste package transport system.

In addition, to the optimum working conditions, a safe smooth-running disposal operation requires a good coordination of the works, which comprise mainly a stepwise emplacement of the DWPs and a backfilling of remaining voids. Due to this fact, several studies focus on the key aspects of the operation and the closure of the geological disposal facility. The feasibility studies are carried out by DBE TECHNOLOGY GmbH on behalf of ONDRAF/NIRAS.

II. DISPOSAL FACILITY DESIGN

The facility design foresees two shafts and a connecting gallery located in a central service area. One shaft serves the transport of waste packages. The second one is designed for staff and material transport. Two emplacement fields, one for low- and intermediate-level (B) and the other for high-level waste (C) are located at two opposite sides of the central area, which is separated into the shaft zone and seal zones (Fig. 1).

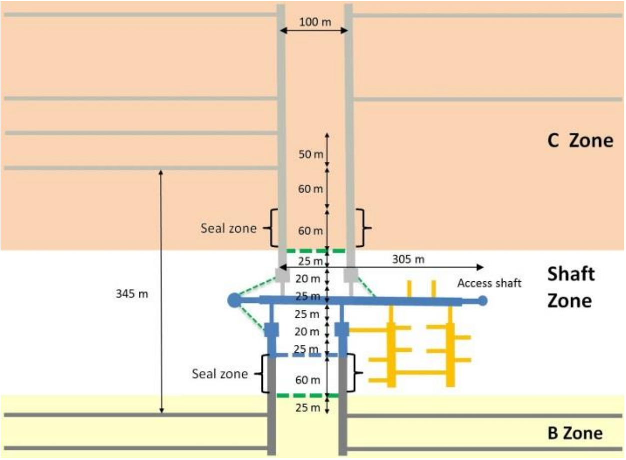

Fig. 1. Reference design of the openings near the shafts (TBM: tunnel boring machine).

Two parallel access galleries run through the middle of each emplacement area and connect the disposal galleries, which are constructed perpendicular to the access galleries. They are 400 m long, blind or dead-end galleries. The use of a tunnel boring machine causes initially a circular cross-section of the galleries. Due to the mechanical properties of the host rock, the galleries will be lined with unreinforced concrete wedge blocks (Fig. 2). For transportation purposes, the galleries will be furnished with concrete floors. The internal diameter of the disposal galleries takes into account the size of the cross-section of the DWPs. The diameter was set at 3.5 m in the B waste field and 3.0 m in the C waste field. The diameter of the access galleries was determined by the space required for turning the waste packages at the entrance of the access and disposal galleries.

Fig. 2. Gallery of the HADES underground research facility (Mol, Belgium) lined with concrete wedge blocks.

The length of the access galleries depends on the number of disposal galleries, the spacing between these galleries, and their distance to the shaft zone. A minimum distance between adjacent disposal galleries is necessary to guarantee the stability of the crossing areas and to avoid interference between processes around adjacent galleries (like the evolution of an excavation damaged zone or the generation of gas). These requirements led to a minimum spacing of 50 m between the galleries for non-heat generating waste disposal. Thermal power of heat-generating waste requires a distance of 120 m between the galleries for high level waste disposal (Fig. 3).

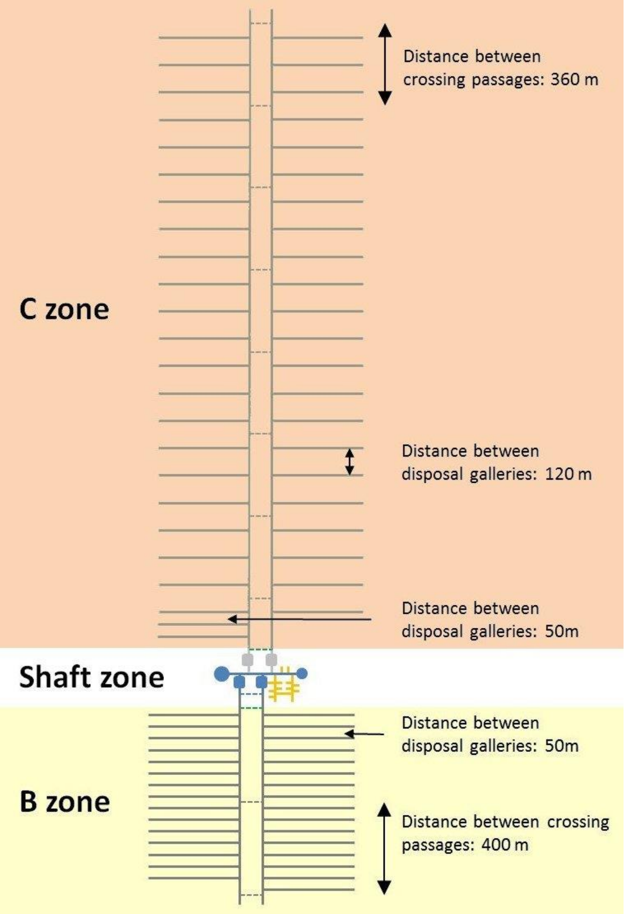

Fig. 3. Geological disposal facility, reference design of the emplacement fields with disposal and access galleries.

III. DESCRIPTION OF WASTE PACKAGES AND BACKFILL MATERIAL

With the objective to provide radiological shielding, to allow safe handling of the waste and to create and maintain favorable geochemical and hydrological conditions after the disposal facility closure, several types of waste packages were developed. With regard to long-term safety, the backfill has to be chemically compatible with the waste packages. The dimensions of the waste packages influence the size of the voids after disposal and, consequently, the backfill placement technique. The following chapters describe the waste packages, the backfill and the selected backfill placement technique in detail.

III.A. Disposal waste packages

In accordance with the categories of radioactive waste basically two different types of disposal waste packages were developed: monoliths and so-called supercontainers (SC).

III.A.1. Monoliths

The primary packages of B waste are immobilized in mortar in concrete caissons made of self-compacting, unreinforced concrete with Portland cement (Ref. 1). The final concrete monoliths are horizontal cylinders with a flat base and have the same outer diameter (2.80 m), base width (2.12 m) and height (2.32 m). Depending on the primary waste type the monolith length varies between 1.9 m –2.9 m. The study considered an average length of 2.76 m and a cross-section area of 5.44 m².

III.A.1. Supercontainers

Long-lived, heat-emitting vitrified waste and spent fuel (category C waste) are placed in supercontainers, which consist of a steel overpack embedded in a concrete buffer, and an outer stainless steel envelope.

The overpack was developed to prevent contact of the waste with the buffer, the engineered barrier system (EBS) and the host formation during the thermal phase. The buffer provides a high pH environment at least during the thermal phase, ensures passivation of the overpack and provides radiological shielding during construction and handling of the SC. The envelope serves as a mould for the casting of the buffer and provides mechanical strength and confinement during transportation and handling.

Depending on the kind of the primary waste four types of SC were designed. Table II shows information about the dimension of SCs with vitrified waste (SC1) and spent fuel (SC2 - SC4). The study does not take into account mixed oxide fuel (SC-5) due to the possibility of reprocessing.

TABLE II. Diameter and length of the SCs (C waste packages).

	SC1	SC2	SC3	SC4
Diameter [mm]	2,144	2,165	2,165	2,165
Length [mm]	4,077	4,193	5,368	6,122

III.B. Backfill

The host rock is the major contributor to long-term safety of the disposal facility. However, voids and decay heat input may induce stresses and the creation of damaged zones close to the galleries along which water and solutes mobility could be enhanced. Water entering openings in contact with waste packages would result in corrosion of the materials. In addition, a collapse of the gallery lining may cause damages and impair the functioning of the engineered barrier systems. Hence, the voids will be backfilled immediately after waste emplacement.

As the space underground is restricted and the need to minimize dust and noise emissions and water consumption, it is preferred to minimize operations in the underground. As backfill materials and implementation procedures are preferred for which broad experience and knowledge already exist, the chosen reference solution is hydraulic backfilling.

Hydraulic backfill placement consists of mixing a suspension that can be transported through pipelines. The method was developed in the 1940s and has evolved over time to be the most widely used backfill method in the mining industry. Compared with discontinuous transport methods (tanks or drums), the main advantages of hydraulic placement systems are the low space requirement, the high reliability, and the transport of the backfill and flushing water in a closed pipeline distribution system. Hydraulic backfilling is independent of other activities in the disposal facility. DBE, the German Company for the Construction and Operation of Repositories carried out a project at the geological repository Morsleben that has large similarities with the future task of backfilling the Belgian disposal facility. This project demonstrated the feasibility of transporting almost one million cubic meters of concrete into the underground openings.

Considering the general objectives, the characteristics of B and C waste packages, the facility design, and the particular properties and sealing function of the host rock, two catalogues of verifiable requirements for the backfill to be used for B and C waste emplacement fields were developed as well as suitable backfilling techniques for the two fields.

III.B.1. Backfill requirements

The first group of requirements relates to feasibility, which in turn relates to the backfill technique and the objective to obtain the highest possible filling ratio. The specification covers a sufficient sedimentation stability. Throughout the flow process and thereafter, no separation may occur between particles of different sizes or densities and between the solids and the liquid phase (no bleeding). Moreover, the time of workability must be sufficiently long.

At the end of the backfill process, there must be a homogenous backfill body, however, during hardening no swelling, significant autogenous shrinkage, or thermal volume expansion should occur. In spite of a satisfying hardening behavior, the strength of the backfill should be low enough to allow potential excavation of waste packages in order to prejudice the potential retrievability of the waste. Preceding experiments demonstrated that backfill with a maximum compressive strength of 10 MPa can be removed by waterjet technology. A current feasibility study examines the feasibility of alternative technologies with the aim to minimize the use of water in the underground structures.

With regard to compatibility of materials with the host formation or the EBS, numerous chemical requirements have been defined. For example, the chloride- and sulfur-containing substances (sulfides) must be minimized due to the risk of initiating corrosion processes. Organic substances and their degradation products have the potential for complex formation increasing the mobility of radionuclides. Furthermore, the production of carbon dioxide can initiate the flow of contaminated waters due to gas pressure build-up. Consequently, the organic content of the backfill is heavily limited, however superplasticizers containing sulfonated naphthalene-formaldehyde condensates (SNF) or polycarboxylate ethers (PCE) can be used.

Differences in the backfill materials result from the specific properties and assumed long-term behaviour of the waste packages. Thus, the backfill of the C waste field must have a significantly higher pH value to limit or prevent corrosion of the SC steel envelopes. Contrary to this, a higher porosity and low gas threshold pressure of the B waste field backfill was intended in order to reduce a pressure build-up due to corrosion processes and the degradation of organic substances. Finally, the thermal stability of the backfill has to be considered.

III.B.2. Backfill composition

On the basis of the material requirements a pool of raw materials were specified. It was decided to use sulfate-resistant (SR) cement of a low-strength class with low heat production (LH). Due to the potential content of sulfides, no slag or slag products are used. In addition, a dosage of fly ashes is not allowed. This also applies to any other substances with organics, except for PCE-containing superplasticizers. The material development resulted in a mixture with Portland limestone cement, silica fume, sand, and tap water. The development and testing of the recipe is described by Ref. 2.

The requirements on the backfill of the C waste field restricted the material selection even further. In order to limit the consumption of hydroxide ions and to stabilize the pH value the use of only Portland and Portland limestone cements was allowed and not the addition of reactive admixtures, such as silica fume or puzzolanic substances in general. With the aim to avoid damaging alkali-silica reactions it was decided not to use SiO_2-containing substances, e.g. quartz power, sand, or aggregate.

DBE TECHNOLOGY GmbH is developing a robust backfill composition. Due to a lower porosity and a higher content of solids, it is already likely that the pressure losses or pressure gradients during the backfilling process of the C waste field will be higher than the pressure gradients during the backfill process of the B waste field. In addition, a shorter workability time of backfill is becoming evident. Despite this fact, the backfill properties with regard to long-term safety have the highest priority in the course of the backfill development. Modifications of the backfill distribution system are one possibility to react to differences in the flow behavior. In order to prove the feasibility of the backfill measures, comprehensive investigations to the design of the hydraulic backfill system are being carried out.

III.B.3. Feasibility studies of the backfill system

The raw materials will be delivered as quality-approved products from external sources. According to the practice in the building sector, a delivery of the solids in silos and of the substances with insufficient pourability with trucks or trailers can be assumed. Due to better accessibility, space savings in the underground openings, the possibility to waive on an interim storage and haulage technique for the solids, and the decrease of water use in the disposal facility it is foreseen to place the batch plant and pump unit at the surface. Another advantage of such a constellation is that the hydraulic head generated by the gravity of the backfill shaft column can be used to support the flow process in the pipeline. This pressure increase (p_g) can be calculated according to Eq. (1), where ρ_B is the backfill density, g the gravitational acceleration, and h the height of the backfill column or the length of shaft section.

$$p_g = (\rho_B \cdot g \cdot h) = \rho_B \cdot 9.81\ m/s^2 \cdot h \qquad (1)$$

During the flow process, the sum of the pump pressure and the pressure caused by gravity must exceed the pressure losses due to friction. These pressure losses increases with the flow rate and decreases with the pipeline diameter. For the backfill of the B waste field, a pipeline with an inner diameter of 0.1 m, and the desired flow rate of 25 m³/h, a pressure loss value of 4.0 kPa/m or 4.0 bar per 100 m pipeline length was estimated based on laboratory pump tests. Fig. 4 shows an example of a pressure profile, which considers a length of the pipeline surface section of 200 m and an access shaft depth of 200 m (backfill density 1,420 kg/m³, 28.0 bar). The remaining pressure at the pipeline opening (5.0 bar) considers in particular pressure losses due to bends and valves.

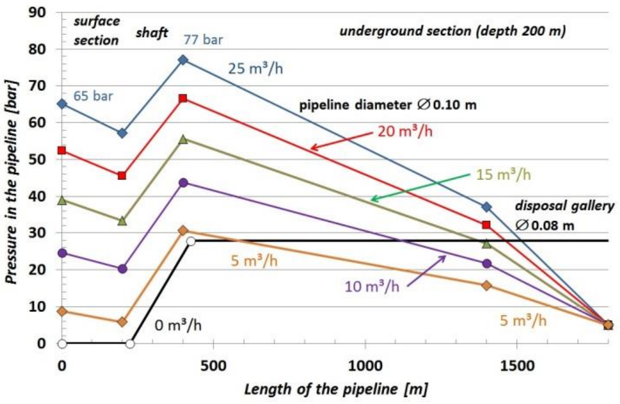

Fig. 4. Pressure profile along a pipeline as a function of the flow rate – facility depth 200 m (B waste field).

According to Fig. 5 a pump pressure of 65 bar is required to guarantee the flow rate of 25 m³/h. This pressure lies in the range of standard backfill pumps. In addition, the workability time of the backfill has to be long enough to allow the flow through the pipeline and the filling of the underground openings. Table III summarizes flow times. Considering a workability time of 5.5 hours, a maximum volume of a backfill segment in the disposal galleries was calculated.

TABLE III. B waste emplacement field – Flow time in the pipeline (T_{FP}) and the backfill segment (ΔT_{BS}= workability time minus TF) considering a backfill workability time of 5.5 hours, a flow rate of 25 m³/h, and a pipeline diameter of 0.1 m. V_B: Backfill volume during ΔT_{BS}.

Pipeline length	T_{FP}	ΔT_{BS}	V_B
1,820 m	34 mins.	296 mins., 4.9 h	123 m³
2,170 m	41 mins.	289 mins., 4.8 h	120 m³

Currently, it is proposed to pump the backfill into the lower section of the galleries. In this case, the backfill volume of the segments shall not significantly exceed 125 m³ according to the values of TABLE III. A volume of 125.4 m³ corresponds to a segment length of 34.4 m with 12 monoliths. The total length of 10 backfill segments with 12 monoliths and of one segment with 10 monoliths is 372.9 m. In this case, the length of the plug at the gallery entrance is 27.1 m. These findings are conclusive and demonstrate the fundamental feasibility of the planned backfill operation foreseeing surface production of the backfill and hydraulic transport of the material via a piping system to the underground working site.

Regarding the C waste emplacement field the maximum pipeline length is considerably longer and consequently, the maximum flow time and the required pump pressure increase as well. A higher pressure gradient is assumed due to the lower water content of the backfill (5.6 bar per 100 m). Fig. 5 shows flow times and pump pressure demands along the underground section of 3.450-m-long pipelines.

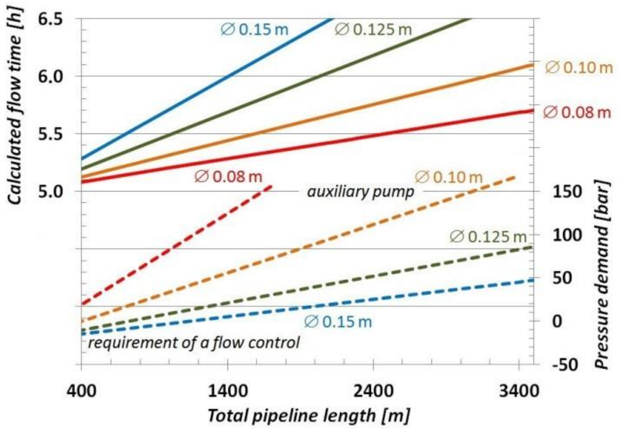

Fig. 5. Calculated flow time of the backfill and pressure demand vs. total pipeline length in the B waste emplacement field. Backfill time of a segment 5 hours (125 m³/h).

If pipelines with a diameter of 0.08 m or 0.1 m are used, pressure demands can occur that are problematic with regard to the use of a single backfill pump. However, when using pipelines with a diameter of 0.125 m or 0.15 m, the flow time can be too long. A smaller pipeline diameter can be used when installing an auxiliary pump in an access gallery. However, this measure results in an even longer time period to pump the backfill to the job site. Considering the maximum workability time, calculations result in theoretical backfill segment volumes of significantly less than 100 m³ that would be disadvantageously with regard to the facility operation, particularly, as the SCs have a greater length and only a low number of SCs can be emplaced in each backfill segment.

A feasible solution would be to install a pneumatic conveying system and to use a mobile mixing and pumping plant at least for the backfilling of the disposal and connecting galleries and the part of the access galleries that are located far from the shafts. Many systems to transport solids, e.g. powders as cement, through a pipeline network over long distances from above ground to underground working faces have been designed. In automatic operation, modern systems are capable of working without involvement of any operation-personnel. The system and the operation could be simplified by hauling a pre-mixture of the solids. In Germany, comparable pneumatic conveying systems are operated at the Konrad mine and the Asse mine.

IV. LOGISTICS OF FACILITY OPERATION

During the first construction phase, the shaft zone and the galleries of the B waste field will be excavated. At the end of the stepwise performance of disposal, backfilling and closure operations, the C waste part will be excavated and disposal and backfilling operations will be carried out. To increase the level of operational safety in the facility, it is planned to strictly separate disposal and backfilling operations.

IV.A. Waste package transport

The main operational activity within the facility is the transfer of disposal waste packages from the surface to the underground, their transport from the shaft landing station towards the designated emplacement location, and the emplacement of the waste packages. The waste packages (DWPs) will be transported on trolleys (carts) of a hybrid rail-wheel configuration using battery driven locomotives. Grooves in the floor with rails will guide the locomotive and the transport trolley through the access gallery. The rails can be removed during closure operations. At the crossings with the disposal gallery removable turning tables will be installed. The wheel configuration allows the emplacement of the waste packages and avoids the use of rails inside the disposal galleries. The waste packages, monoliths or SCs, will be emplaced horizontally one after the other (with small gaps between them) in the disposal galleries. The study considered a distance of 0.1 m.

All systems for transport are based on state-of-the-art equipment or components that have been built and tested at full scale during R&D work carried out by DBE in connection with German repository projects. In total, the studies considered an amount of 3,343 monoliths and a safety margin of 20 % leading to a total number of 4,012 monoliths to be considered for planning purposes. With regard to the SCs a safety margin of 10 % in total was considered for planning purposes on top of the expected number of SCs leading to a total number of 3,341 SCs.

IV.B. Backfilling

Due to the limited workability time of the backfill, the galleries have been subdivided into emplacement or backfill segments. The approach of segmentation considered the length of the waste packages, a distance between the waste packages of 0.1 m, and a desired backfill volume of approximately 125 m³. In addition, calculations of the backfill volume require information about the free cross-section of the galleries (TABLE IV).

TABLE IV. Number (#), length (L), and free cross-section (FCS) of the access galleries (AG), crossing passages (CP), and disposal galleries (DG).

	B waste field			C waste field		
	AG	CP	DG	AG	CP	DG
#	2	3	31	2	8	46
L [m]	800	100	400	2810	100	400
FCS [m²]	28.9	8.88	8.88	30.8	5.94	5.94

IV.B.1. B waste emplacement field

Considering an emplacement of 12 monoliths a backfill segment has a length of 34.4 m and a volume of 125.4 m³. Due to the plug construction at the gallery entrance the number of monoliths in the last segment was reduced (10 DWPs, 28.7 m length, 104.6 m³). In this way each gallery has 11 segments at maximum and 130 monoliths can be emplaced in one gallery over a length of 372.9 m. The backfill volume amounts to 1,358.5 m³. Accordingly, 3,900 monoliths can be emplaced in 30 galleries. Only 112 DWPs are left for disposal in the last disposal gallery so that the left empty space is larger than in the other galleries.

Every backfill measure requires preparatory works as well as the construction and removal of a formwork. To estimate the effort needed for this kind of work, the number of segments was calculated. In total, it is necessary to backfill 341 segments of the disposal galleries. Thereafter, the plugs at the entrances of the disposal galleries will be constructed. According to the length of the backfilled part (372.9 m), each plug can have a length of 27.1 m. It is assumed that the liner and the gallery floor will not be removed. According to the volume of a single plug (241 m³) multiplied with the number of disposal galleries (31), in total, the construction material of the plugs will have a volume of 7,471 m³. As there is no clearly defined concept how to plug the disposal galleries, this assumption is very uncertain and just serves to estimate reasonable values in regard to the amount of material needed for this purpose.

Backfilling of the access galleries and crossing passages is supposed to be carried out in segments of approximately 50 m length. The total gallery length of 1,900 m require the backfilling of 38 segments (2·16 + 6). TABLE V shows an overview of the backfill volumes. In total 42,414 m³ of backfill is needed to backfill the disposal galleries.

TABLE V. Backfill volumes in the B waste emplacement field.

	AG	CG	DG
Total length [m]	1,600	300	11,625
Free cross-section [m²]	28.94	8.88	8.88
Backfill volume [m³]	46,304	2,664	42,414

IV.B.1. C waste emplacement field

The length of the SCs ranges from approximately 4.1 m to more than 6.1 m. Differing from the approach of the monoliths this fact must be considered, when planning the works in the C waste field. In the first step the length and volume of the backfill segments were calculated in dependence of the number of SCs. The number of DWPs per gallery was increased until either the maximum length or the maximum backfill volume is reached. TABLE VI shows the length of the segments. Table VII summarizes segment volumes.

TABLE VI. Length of the backfill segments depending on the number of supercontainers (SC1–SC4).

SC	SC1	SC2	SC3	SC4
4				25.0 m
7				43.7 m
8			43.8 m	49.9 m
10		43.0 m	54.8 m	
11	46.1 m	47.3 m		
12	50.2 m			

TABLE VII. Volume of the backfill segments depending on the number of supercontainers (SC1–SC4).

SC	SC1	SC2	SC3	SC4
4				58.2 m³
7				101.3 m³
8			102.1 m³	115.7 m³
10		101.0 m³	127.5 m³	
11	111.4 m³	111.1 m³		
12	121.4 m³			

The second step considered the usable length of the galleries (375 m). In the ideal case, 89 (SC1), 87 (SC2), 68 (SC3), and 60 (SC4) supercontainers could be emplaced into a gallery. However, 84 SC1 has to be emplaced into an eleventh gallery. In addition, the study expects that a low amount of SC4 (11) will be emplaced with SC3 (38). It is important to note that the emplacement of different SC types into one gallery is extremely unlikely. For example, the safety margin of 10 % is very large. Consequently, a lower number of SC can be expected. The results of the evaluation show TABLE VIII.

TABLE VIII. Total number of supercontainers (SC1–SC4) including the safety margin, number of supercontainers in the backfill segments (BS), and total number of backfill segments and disposal galleries (DG).

	SC1	SC2	SC3	SC4
Amount SC	974	435	1,273	660
Number BS	87	40	132	88
Number DG	11	5	19	11

In total 347 backfill segments were calculated for the 46 galleries containing 3,342 SCs. The total number of segments is 350. Table IX illustrates the calculation of the gallery volumes along their used length. Overall, the free volume amounts to 101,961 m³. Subtracting the volume of the SCs (61,112 m³) a backfill volume of 40,849 m³ can be calculated. The values in parentheses are valid for the disposal galleries with SC3 and SC4.

TABLE IX. Used length, number, total length and total free volume of the disposal galleries (DG) in the C waste field.

	SC1	SC2	SC3 (SC3+4)	SC4
length used [m]	372.6	374.2	372.5 (375.0)	374.1
Number DG	11	5	18 (1)	11
Total length [m]	4,098.6	1,871.5	6,705.0 (375.0)	4,115.1
Total free volume [m³]	24,346	11,117	39,828 (2,228)	24,444

For the construction of the plugs in the B and C waste field the same requirements apply and the same assumptions are made. Their total volume is about 7,335 m³ considering the free cross-section of 5.94 m³ and the number of disposal galleries (46). Due to the length of the access galleries (2,700 m) and their free cross-section of 30.76 m², the total backfill volume amounts to 166,719 m³. It is planned to disassemble the rails and the turntables in the access galleries, so that an estimated backfill volume of approximately 170,000 m³ results. Table X summarizes the values and takes into account the crossing passages. In total, it is necessary to produce 212,320 m³ backfill or about 215,600 m³ after removal of the rails and turntables. Realizing an average flow rate of 25 m³, the pump unit requires a total time of 8,493 hours (8,624 hours) to fill the openings.

TABLE X. Backfill volumes of the access galleries (AG), crossing passages (CP), and the disposal galleries (DG) in the C waste field.

	AG	CP	DG
Total length [m]	5,420	800	17,250
Free cross section [m²]	30.76	5.94	5.94
Backfill volume [m³]	166,719 (170,000)	4,752	40,849

Backfilling of the crossing passages will be carried out in sections of 50 m. The formwork will be placed in the middle of the galleries and 16 segments result. In the access galleries the formwork shall not be fixed at the plugs. In the vicinity of the seal zone it is planned to arrange four segments with a length of 50 m and a volume of 1,538 m³, when neglecting the removal of the rails and turntables. In the rear section of the galleries two formworks will be positioned between the disposal galleries. Their distance is 40 m and their volume 1,230 m³ due to the free cross-section of 30.76 m². However, the last segment will have a length of 30 m and a volume of 923 m³. In total, 134 segments will have to be backfilled in the two access galleries of the C waste emplacement field.

V. SIMULATIONS

The simulation of the emplacement and backfill process require the assignment of time periods to the individual work steps. After that the work sequence must be specified with regard to the framework conditions of facility operation and strategic decisions of ONDRAF/NIRAS such as the separation in time between emplacement and backfilling activities. These boundary conditions were implemented into a software tool that was used to carry out the simulation for the B waste reference case and the calculation of variants.

V.A. Boundary conditions

Considering the transport, loading and unloading procedures 18 tasks can be identified (TABLE XI). Fixed time periods and transport speeds were specified, due to the size of the disposal facility.

TABLE XI. Information about the temporal extent of the disposal waste package (DWP) transport and disposal. The average hoisting velocity is 1 m/s.

1	Waste package production	2 DWP/day
2	Waste Package Buffer Zone	28 days
3	Transport to shaft hall	30 minutes
4	Shaft hoisting of locomotive	20 minutes
5	Empty cage upwards	10 minutes
6	Shaft hoisting of cart with DWP	20 minutes
7	Transport inside connecting gallery	5 km/h
8	Turning process at AG entry	12 minutes
9	Transport inside AG	5 km/h
10	Turning process at DG	12 minutes
11	Transport inside DG	5 km/h
12	Emplacement process	10 minutes
13	Transport back inside DG	5 km/h
14	Turning process at DG entry	12 minutes
15	Transport inside AG	5 km/h
16	Turning process at AG	12 minutes
17	Transport inside connecting gallery	5 km/h
18	Shaft hoisting of empty cart	20 minutes
	If more than one DWP per shift go back to step 6	
	Empty cage downwards	10 minutes

The time needed for transporting the waste packages down through the shaft, along the galleries towards the emplacement location, and the back transport of the empty cart to the surface varies between approximately 129 min for the most distant emplacement location of the B waste field and 95 minutes for the nearest emplacement location. The temporal differences of the waste package transport and the return transport of the cart required a more detailed evaluation of the potential disposal strategies (Fig. 7).

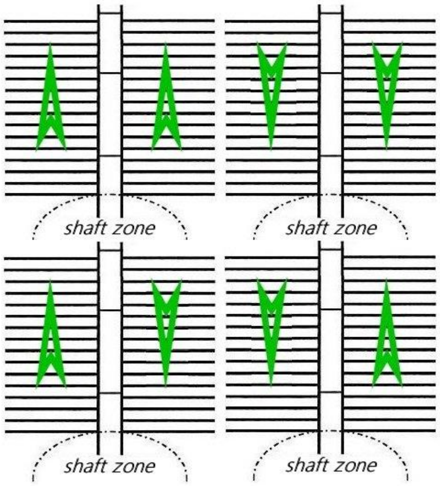

Fig. 7. Approaches of waste disposal and backfilling.

Clockwise and counterclockwise disposal and backfilling operations are unfavorable for the operation of the pump unit, because it is necessary to use a throttle line at the beginning and the end of the backfill measure. This throttle line helps to avoid breaks of the material column in the shaft section of the pipeline. In the case of a disposal and backfilling from the front towards the distant disposal galleries, backfilling of the access gallery is not possible until the works at the last disposal gallery has been completed.

With regard to the backfill measures the works can be divided to four work phases. The first phase comprises preparatory works, for example the removal of equipment (air ducts, cables, lighting installations). The formwork is installed and the contact surfaces to the liner are sealed by means of insulating tapes and silicone. The second phase comprises works in connection with the backfilling or pumping process such as tests of the backfill equipment.

Time estimates require information about the time span of the pump process and the time periods necessary for starting up the system and the shut-down phase. The work time of the pump unit correlates with the volume of the backfill section. Pump times of 5 hours and overall work times of 7 hours are considered for the galleries that have a volume of less than 130 m³. The work must not be interrupted. Consequently, the backfilling of the low volume segments will be carried out in one working day and require at least a two-shift operation. Information about the backfilling of the connecting and access galleries is shown in Table XII. It is assumed that the access and connecting galleries will be backfilled in layers and in several backfill stages with the use of backfill and vent pipelines at the gallery roofs. DGR indicates the remaining volume (the last backfill segment) in the disposal galleries with 112 DWPs.

TABLE XII. Volume, pump and work time of the backfill segments in the access (AG), crossing passages (CP), and disposal galleries (DG).

	AG	CP	DG	DG_R
Volume [m³]	1,447	444	<130	458
Pump time [h]	57.9	17.8	<5.2	18.3
Pump time [h/d]	4.8	4.5	5.0	4.6
Work time [h/d]	7.0	7.0	7.0	7.0
Work days	12	4	1	4

Immediately after the backfilling process has been completed, it is necessary to clean the equipment and to dispose residual substances (phase 3).

The formwork should not be removed until the backfill has hardened so that it can safely carry its own weight and any other loads it is subjected to. The supporting period (period between placing of backfill and removal of forms) differ according to the type of construction material and the design, e.g. the height of formwork. This time span is not a working phase in the strict sense, however, it can be used for a variety of works. It is called the hardening period (phase 4). It was assumed that this period begins after backfilling the last material charge and it was estimated that this period will last 7 days and 3 days in the case of the plugs (TABLE XIII). After this, the formworks will be removed. TABLE XIV gives an overview of the time periods of all backfill steps.

TABLE XIII. Temporal extent of the works for gallery backfilling.

1	Preparation Works	7 hours, 1 work day
2	Backfilling (Pump process)	See TABLE XI
3	Cleaning & Removal of Equipment	7 hours, 1 work day
4	Hardening (stripping time)	7, 5, 3 days
5	Removal of formwork and preparation of the pipeline	7 hours, 1 work day

TABLE XIV. Volume (V), number (#) of segments and work days (WD) of the backfill segments (S) in the access galleries (AG), crossing passages (CP), and disposal galleries (DG).

	AG	CP	DG	DG_R
V [m³]	1,447	444	<130	458
#	32	6	340	1
WD/S	22	14	11	14
Σ WD	704	84	3,740	14

General boundary conditions are a number of 250 working days per calendar year, 5 working days per week, and a single-shift operation of the facility as far as possible. One shift comprises 7 effective working hours. The capacity of the buffer facility is 60 waste packages and the emplacement starts with an initial stock of 20 waste packages. The loading of the locomotive batteries will be carried out at the surface. This condition results in additional shaft transports of the locomotives. Another general assumption is that nuclear and non-nuclear activities will not be carried out simultaneously. This results in some more specific assumptions for the emplacement and backfilling process:

- The underground works for the backfilling of the segments do not start until the transport cart arrives on the surface.
- Backfilling activities in different disposal galleries cannot be implemented simultaneously.
- DWP transport and disposal in another gallery can take place in parallel to the hardening of the backfill in the galleries.

V.B. Simulation software

The framework and boundary conditions were implemented into the dynamic process simulation software tool Witness. This software is a discrete and continuous event simulation tool. It uses a brick construction logic. The user builds the model from predefined bricks or elements, connects them, adds the logic and starts the simulation run. This way, the operational activities, such as the flow of waste packages, staff, etc. between the elements and the progress of the emplacement and backfill measure as a whole can be investigated. The initial stock of waste packages was implemented to the model for technical reasons in such a way that on the first day 22 DWPs instead of 2 DWP are produced.

Witness allows the probabilistic implementation of perturbations, failures etc. For the reference scenario it was assumed that events related to the occurrence such failures would be equally distributed in time and that the respective downtime would be constant. This approach was selected to receive smooth simulation results, which allow clear interpretation of the general coordination between the main operational tasks that are not blurred by superimposed stochastic events.

V.C. Simulation results

Fig. 8 shows the number of monoliths that are stored in the buffer storage facility and the sub-quantity of monoliths that are already matured and ready for emplacement.

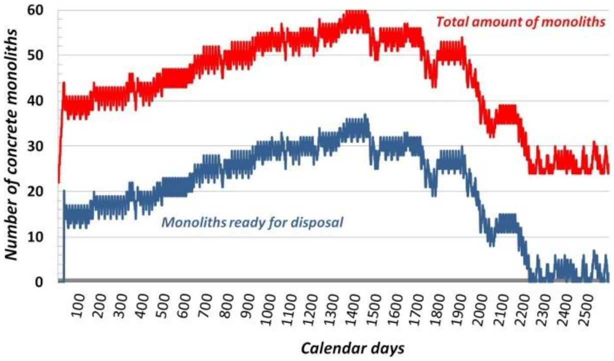

Fig. 8. Chronological development of the total number of monoliths and the number of monoliths ready for disposal.

Initially, the lines increase towards values of nearly 35 (blue) and 60 (red). The slope is about 20 monoliths per 1500 days. It indicates that during the first 4 years, the production rate is higher than the emplacement rate by approximately 5 monoliths per year. After this first phase, the lines show a decline with a slope of approximately 30 monoliths during a period of 2 years. The reason for this decrease of the buffer stock is the reduced average emplacement time, due to the decrease of the transportation route lengths. During the third phase, between 24 and 31 monoliths will be stored in the buffer. This phase extends to the end of the disposal activities, however, Fig. 8 is limited to the first 2,600 days of the operating period. The difference between the blue and the red curve corresponds to 24 monoliths, irrespective of the buffer stock. This target value reflects the average number of monoliths that are produced during the 28 days of the maturing time period.

Fig. 8 illustrates a sufficiently high emplacement rate and buffer storage capacity. In this case, a reduction of the waste package production is not necessary and the last monolith can be produced on day 4,657 of the emplacement operation. The results of the simulations confirm the simple calculation and demonstrate sufficient efficiency of the emplacement and backfill works despite the fact that failures and the performance of maintenance measures were taken into account. Fig. 9 shows the number of DWPs emplaced on each day of the disposal operation period.

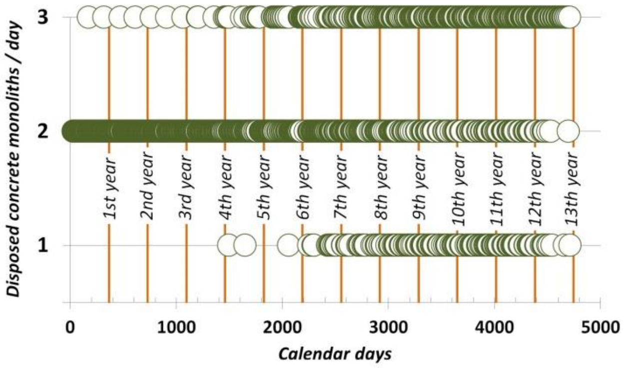

Fig. 9. Daily emplacement rate of concrete monoliths in dependence of the calendar days.

Most of the time, the emplacement rate is two monoliths per working day and equals the production rate. Failures of the hoisting system and waiting times due to an insufficient hardening of the concrete monoliths reduce the emplacement rate. These two reasons are responsible for the days when only one monolith can be emplaced. The days when no monoliths are emplaced, are mainly due to weekends, public holidays, and periods of backfilling activities. With increasing duration of the facility operation, there is also the option to emplace three monoliths per day. This is caused by the shortened travel distances. The higher emplacement rate allows to compensate the effects of the failures and maintenance works.

VI. CONCLUSIONS

According to the Belgian reference concept B waste monoliths will be produced every working day, stored in a buffer facility, and disposed of in a nearby geological disposal facility. The disposal facility operation mainly includes monolith emplacement and backfilling operations. Due to the fact that the processes and works will take place in succession and simultaneously, a dynamic process simulation software tool was used to investigate the coordination of waste package production and disposal.

The simulations show that the conditions assumed or estimated for the buffer storage capacity and the workflows lead to a nearly optimal relation between waste package production and emplacement rate. Due to the efficient use of the buffer storage and the disposal facility operation, the minimum total disposal operation period, which is defined by the monolith production rate is not extended.

In case of a higher number of failures, an elevated demand for maintenance works or an increase of the monolith production rate, numerous possibilities exist to increase the emplacement rate. For example, a study of the boundary conditions and the simulation of variants show that a temporary or continuous two-shift operation will be sufficient to match the monolith production rate. In addition, an underground battery loading of the locomotives or an increase of the shaft hoisting cage speed would be easily realizable and would have a significant positive effect on the emplacement speed. Consequently, a compelling reason for a modification of the emplacement or backfill strategy could not be identified.

With regard to C waste the number of backfill segments increases only marginally and it is assumed that the stripping time of the formwork slightly shortens. However, a more important difference is the larger extension of the emplacement field due to the greater distance between the disposal galleries and the larger number of galleries. The field extension lengthens the driving time of loaded and unloaded carts and may also have substantial influences on the backfill technique. The result would be a significant lower emplacement rate at the beginning of the disposal operation. Assuming an improvement of the emplacement rate during this time span, for example by virtue of a two-shift facility operation, the works in the C waste field would need less time because of the lower number of waste packages. Further simulations will quantify the relationships and will supply information about the total operating time of the disposal facility.

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