Impact of Dutch Nuclear Fuel Cycle Scenarios on Radionuclide Inventory Intended for Disposal - 15201

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ABSTRACT

One of the main subjects of Dutch five-year research program into geological disposal of radioactive waste, OPERA[1], is the post-closure radiological safety assessment. Reliable estimates of the radionuclide inventory and matrix composition are an important input for the safety assessment. The amounts and categories of waste foreseen to be disposed in 2130 the Netherlands have been compiled by the Dutch waste management organisation COVRA. Additionally, NRG has made a characterisation of the waste (radionuclides and matrix). This reference inventory is based on the Dutch base nuclear energy scenario of operating the Dutch single reactor, the Borssele NPP, until its presently scheduled shut-down in 2033.

However, changes in the presently adopted nuclear fuel cycle strategy in the Netherlands may impact both the quantities of generated radioactive waste and its composition, and therefore the source term of the radiological safety assessment. To get a grip on this uncertainty a set of alternative future fuel cycle scenarios in the Netherlands, which are in compliance with scenarios formulated in the Dutch vision documents, has been considered and evaluated. The scenarios have been analysed with the computer code DANESS, "*Dynamic Analysis of Nuclear Energy System Strategies*". The result of the DANESS analyses concerns the amount and type of the radioactive waste to be finally disposed in a deep geological repository. This also includes the inventories of the individual radionuclides that are relevant for the post-closure safety assessment to be performed in a subsequent stage of the OPERA program.

INTRODUCTION

The Dutch national policy states that all radioactive waste will be stored above ground in dedicated facilities, allowing its retrieval whenever required, for a period of at least 100 years. After this period of long-term surface storage, geological disposal is proposed. An important decision to be taken after the period of interim storage is whether to continue with above ground storage or to start construction of a repository. During interim storage, research is to be conducted into the development of a repository, either in a national or a multinational context.

Changes in the presently adopted nuclear fuel cycle strategy in the Netherlands may impact both the quantities of generated radioactive waste as its composition. The present study addresses the outcomes of analyses of a set of alternative future fuel cycle scenarios in the Netherlands that are in compliance with scenarios formulated in the Dutch 'Energierapport 2008' [1]. For the production of nuclear energy, several technological and logistic options have been assessed, i.e. reprocessing of spent fuel, the utilisation of MOX-fuels in current reactors, the deployment of gas-cooled high temperature reactors (HTRs) or other 3rd or 4th generation technologies, including fast breeder reactors.

The aim of the present analyses was to provide estimates of the types, amounts, and speciation of radioactive waste expected to be disposed in a radioactive waste repository by the year 2130 under the assumption of a variety of nuclear fuel cycle scenarios in the Netherlands. The estimated inventories serve as input for the post-closure safety assessment, which will be performed in the forthcoming year as part of the OPERA project.

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[1] *OPERA* is the Dutch acronym for research program into geological disposal of radioactive waste

ALTERNATIVE FUEL CYCLES

The NRG project *OPCHAR* ("OPERA Waste Characteristics") has characterised the waste foreseen to be disposed of in 2130 in the Netherlands, both in terms of the radionuclide inventory as well as of the matrix composition of all waste forms and fractions [2], [3]. That inventory is based on the Dutch base nuclear energy scenario '1a' in the 'Energierapport 2008' [1] which assumes no deployment of new nuclear power plants and operation of the present Borssele reactor until its foreseen closure in 2033. Additionally, several alternative future nuclear energy scenarios have been assessed in terms of waste impact. The alternative scenarios partly deviate from the present Dutch strategy of reprocessing of spent fuel and will result in other types of high-level wastes with deviating radionuclide spectra that need be disposed of. The following nuclear fuel cycle scenarios have been assessed:

TABLE I Fuel cycle scenarios considered in present study

Scenario Nr	Scenario Name (this paper)	Scenario denotation in 'Energierapport 2008'
No New Nuclear Power Plants		
Scenario 1	Continuation of current practice	1a: No new nuclear power in the Netherlands
Scenario 2	Application of MOX fuel	1a: No new nuclear power in the Netherlands
Scenario 3	No further reprocessing of spent fuel	1a: No new nuclear power in the Netherlands
New Nuclear Power Plants		
Scenario 4	MOX-fuelled Generation III Light Water Reactors	3: New nuclear reactors after 2020
Scenario 5	High Temperature gas-cooled Reactors (HTRs)	1b: No new nuclear reactors, unless inherently safe
Scenario 6	Fast reactors	3: New nuclear reactors after 2020

The following sections describe these nuclear fuel cycle scenarios in more detail.

Scenario 1 - Continuation of current practice

Scenario 1, the base scenario, assumes that no new nuclear power plants will be introduced in the Netherlands and that the present Borssele reactor, an LWR "Gen II reactor", will be operated until its presently scheduled shut-down in 2033. The present practice of spent fuel reprocessing will be continued, and the vitrified HLW will be stored on surface until it is finally disposed of in a deep geological disposal facility by 2130. The process scheme is depicted in Fig. 1.

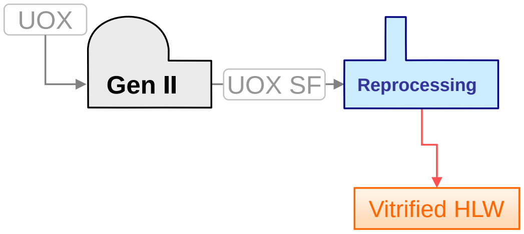

Fig. 1. Process scheme of Scenario 1 – Continuation of current practice

Scenario 2 - Application of MOX fuel in Borssele NPP

Scenario 2 assumes changing the fuel cycle options for the existing Borssele NPP, which is licenced for MOX fuel use as well. This scenario assumes that 40% of the nuclear fuel of the Borssele NPP will consist of MOX [4] and so-called "c-ERU[2]" UOX fuel [5]. It is further assumed that both the spent c-ERU-UOX and MOX fuel will be reprocessed once. The simplified process scheme is depicted in Fig. 2.

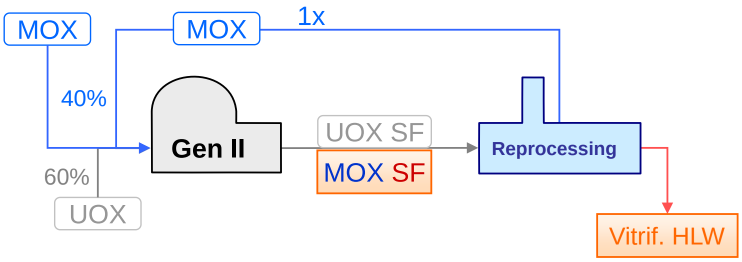

Fig. 2. Process scheme of Scenario 2 – Application of MOX fuel

Scenario 3 – No further reprocessing of spent fuel

This scenario assumes that spent fuel of the Borssele NPP, the Gen II reactor, will no longer be reprocessed after the year 2013 but, after conditioning, will eventually be disposed directly instead.

Scenario 4 - Deployment of MOX-fuelled LWR Gen III

To account for a postulated increasing nuclear electricity demand, this scenario assumes that from 2020 on the Gen II Borssele NPP will be supplemented by LWR Gen-III type reactors, which will partially (i.e. by 40%) use MOX fuel. As in Scenario 2, it is assumed that both spent UOX and MOX fuel will be reprocessed. The simplified process scheme is depicted in Fig. 3.

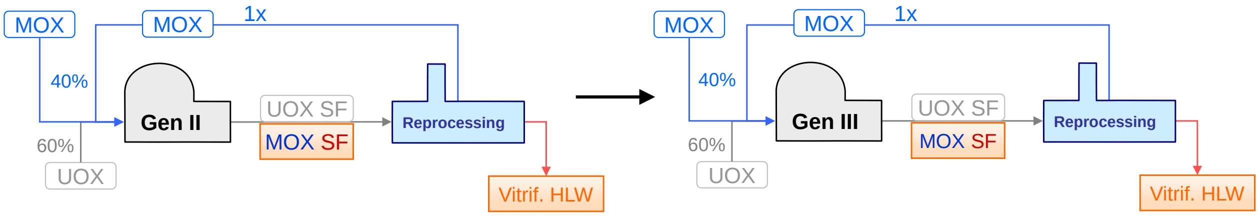

Fig. 3. Process scheme of Scenario 4 – Deployment of MOX-fueled LWR Gen III

Scenario 5 - Deployment of HTRs

To account for a postulated increasing nuclear electricity demand, this scenario assumes that from 2020 on the Gen II Borssele NPP will be supplemented by High-Temperature gas-cooled Reactors (HTRs). The HTR UOX spent fuel pebbles will not be reprocessed but instead stored on surface prior to their disposal starting in 2130. The simplified process scheme is depicted in Fig. 4.

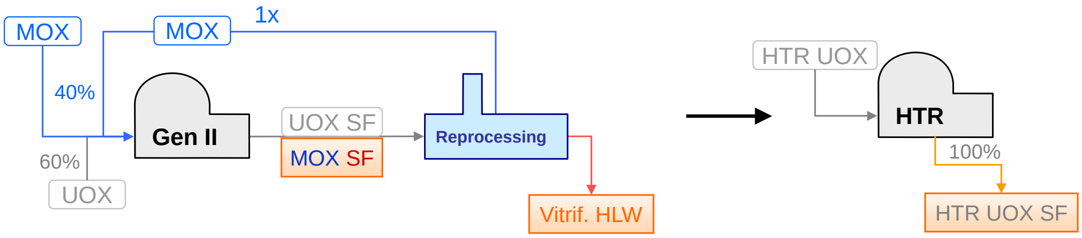

Fig. 4. Process scheme of Scenario 5 – Large-scale deployment of HTRs

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[2] c-ERU UOX: "compensated enriched recycled uranium", 4,6% enriched in U-235.

Scenario 6 - Deployment of fast reactors

In this scenario it is assumed that the increasing nuclear electricity demand is covered by LWR Gen III reactors from 2020 on, as at that time Gen IV type reactors will not yet be available on a commercial basis. The deployment of fast reactors, starting around 2040, and assuming full reprocessing of the spent fuel, will result into different types of HLW since actinides will be removed from the waste in order to be applied in the manufacturing of FR-MOX fuel. This scenario is depicted in Fig. 5.

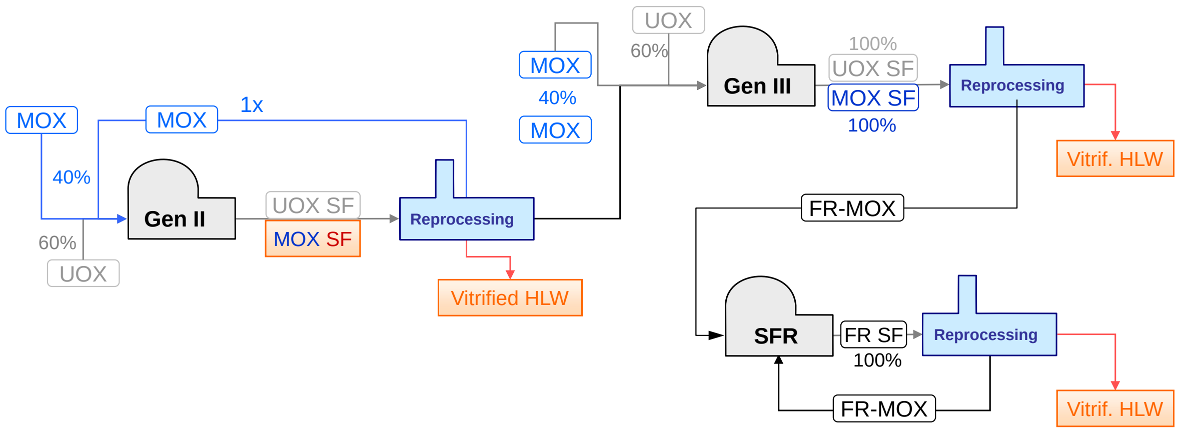

Fig. 5. Process scheme of Scenario 6 – Deployment of fast reactors

COMPUTER TOOL – DANESS

For the assessment of the nuclear fuel cycle strategies, the DANESS code ("Dynamic Analysis of Nuclear Energy System Strategies") [6] Version 5.1 has been applied. DANESS is an integrated dynamic nuclear process model for the analysis of today's and future nuclear energy systems and simulation of the flows of fissile material, fresh fuel, spent fuel, high level waste, all intermediate stocks and fuel cycle facilities' throughput. Starting from today's nuclear reactor park and fuel cycle situation, DANESS analyzes nuclear energy system scenarios over time and allows the simulation of changing nuclear reactor parks and fuel cycle options. New reactors and fuel cycle facilities are introduced based on the energy demand and the economic and technological ability to build new reactors.

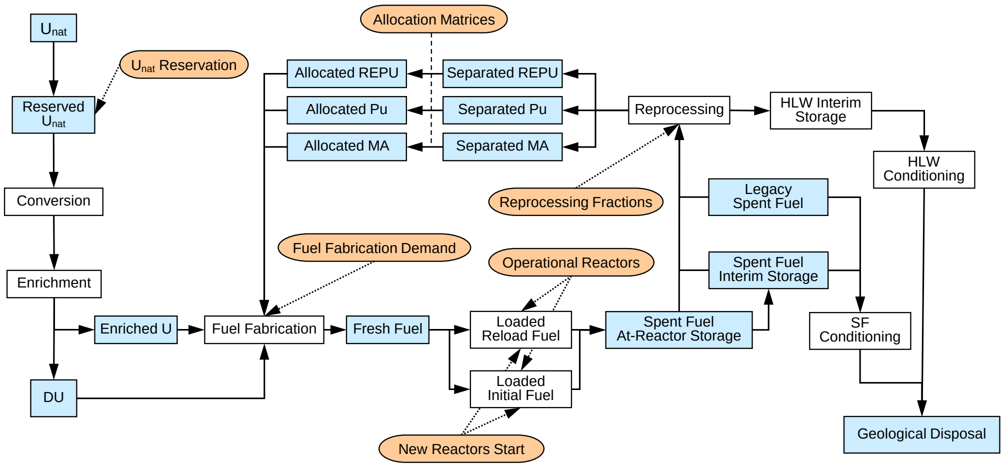

Fig. 6. Fuel cycle model of DANESS

Fuel cycle costs are calculated for each nuclear fuel batch for each type of reactor over time and are combined with capital cost models to arrive at a cost of energy for the modeled nuclear energy system. A utility sector and government-policy model are implemented to simulate the decision-making process for new generating assets and new fuel cycle options. For the calculation of the amount of nuclear waste, DANESS uses the fuel cycle model as shown in Fig. 6. For each reactor, a fuel type and back-end route (direct storage or/reprocessing) is set.

ASSUMPTIONS AND TECHNOLOGY CHARACTERISTICS

The various analysed scenarios are based on a given nuclear energy demand, the characteristics of the existing nuclear reactor (Borssele NPP) and its foreseen phase-out, the characteristics of Gen-III and Gen-IV reactors, the assumption of various fuel cycles, and unlimited fuel cycle facility capacity. This last assumption is justified considering the relatively small nuclear program in the Netherlands compared to other European countries. The following additional assumptions have been made.

- The time horizon of the analyses is 2130, which at present is the foreseen start of the final disposal of the radioactive waste in the Netherlands;
- For the assumed electricity demand growth scenarios 4, 5, and 6, the current Gen II reactor, i.e. the Borssele NPP, may be replaced by Gen III Light Water Reactor(s) (LWRs), which are presently available. The High Temperature gas-cooled Reactors (HTRs) are assumed to be available around 2020, whereas the Fast Reactors (Sodium Fast Reactor, SFR) will be commercially available after 2040. The FRs operate as breeder to ensure minimal uranium use, and minimise waste.

The characteristics of the nuclear power plants are summarized in TABLE II; they have been collected as part of several fuel cycle studies performed previously.

TABLE II NPP-type characteristics used in scenario analysis

	Borssele NPP	***LWR Gen III***	***HTR 180 UOX***	***SFR Gen IV***
Unit Power [MWe]	482	900	180	900
Thermal Efficiency [%]	35	33	45	40
Average Capacity Factor [%]	93	90	90	90
Technical Lifetime [yrs]	20	60	40	60
Reference	[7]	[8]; [9]	[10]	[8]; [9]

Based on considerations presented in several policy reports [1, 11, 12] the nuclear electricity demand for the growth scenarios 4, 5, and 6 has been implemented as follows:

- From 2015 on, the nuclear energy demand increases from the present 450 MWe to 5000 MWe,
- From 2040 on, the nuclear energy demand remains constant throughout the simulated time frame.

This assumed growth scenario implies that new reactors, esp. LWR Gen III and HTRs would hypothetically be ready for operation around 2020. The nuclear energy demand curve in terms of TWh(e)/yr is depicted in Fig. 7.

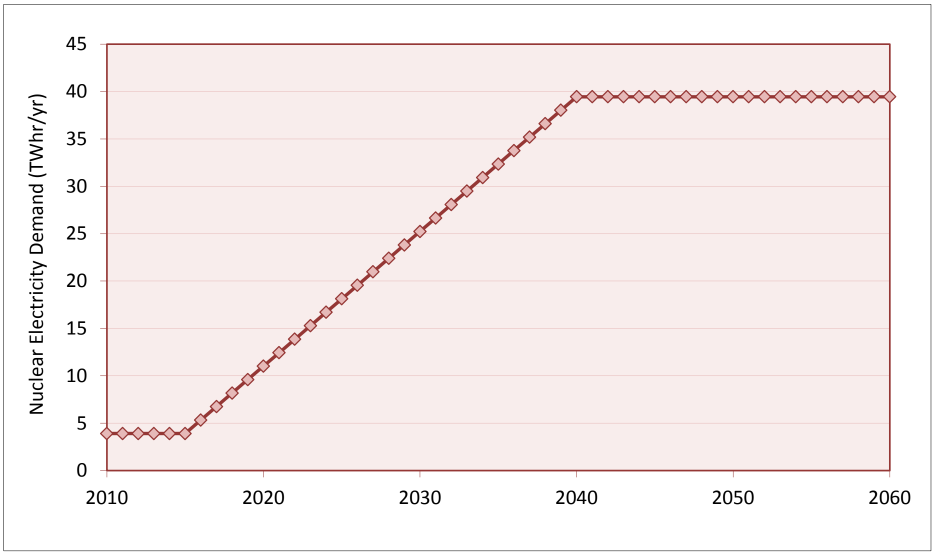

Fig. 7 Assumed nuclear electricity demand in the Netherlands for the adopted growth scenarios 4, 5, and 6

Fuel characteristics

Characteristics of the nuclear fuels have been collected from several fuel cycle studies performed previously:

- Generic LWR Gen II UOX fuel, representative for the presently operating Borssele NPP fuel [13, 14];
- Generic LWR Gen II UOX/MOX fuel [4, 8];
- LWR Gen-III fuel UOX, MOX fuel [8];
- Standard HTR fuel pebbles, each containing about 10’000 coated UO_2 fuel kernels [10];
- SFR fuel, to be applied in a sodium-cooled fast reactor (FR-MOX) [8].

For the standard set of radionuclides presently being tracked in DANESS the isotopic composition of the spent fuels and HLWs have been obtained from a variety of sources:

- Vitrified HLW (CSD-V canisters), resulting from the reprocessing of the LWR Gen II (Borssele) [2];
- Vitrified HLW residues (CSD-C canisters), resulting from the reprocessing of spent fuels:) [2];
- Reprocessed LWR Gen-III UOX fuel [15];
- Reprocessed LWR MOX fuel [15];
- Standard HTR fuel pebbles [10];
- Reprocessed SFR fuel (FR-MOX) [15];

The total inventory at 2130 is calculated taking into account the chain decay of the radionuclides.

Waste Forms

Different types of radioactive waste have be managed and disposed of in geological repositories in each of the scenarios: collos loaded with UOX/MOX spent fuel assemblies (SFA) and Universal Canisters loaded with vitrified HLW (CSD-V) and remains of the compacted hulls and ends (CSD-C) from the different reprocessing operations. The technology parameters have been taken from the RED-IMPACT project [16].

For the final disposal in a geological repository it has been assumed that the HTR spent fuel pebbles are disposed in CASTOR casks (*cask for storage and transport of radioactive material*). A single CASTOR cask can hold about 2030 HTR spent fuel pebbles [17].

Depleted uranium (DU) originates from the uranium enrichment facility of URENCO [18]. It has been assumed that the DU will be immobilized in concrete and eventually disposed of in KONRAD type II containers (volume 4,6 m^3).

RESULTS OF THE SIMULATIONS – NO NEW NUCLEAR POWER PLANTS

Scenario 1 – Continuation of current practice

In this base-case scenario it is assumed that the presently operating LWR Gen II Borssele NPP will be shut down as foreseen in 2033. The waste characteristics are shown in Table III. The total estimated number of containers is composed of (1) the stocks presently stored in a surface storage facility, (2) containers resulting from the continuing operation of the Borssele NPP up to 2033, and (3) containers, resulting from the reprocessing of spent fuel presently stored in the spent fuel pool or at other locations. From the start of the simulation in 2000 until termination of the reactor operation, approximately 477 KONRAD II with depleted uranium (DU) containers will be produced. As mentioned earlier, DU is also foreseen to be disposed in a geological repository.

Table III Waste characteristics per 2130 – Scenario 1 – Continuation of current practice

	Gen II UOX
Nr of CSD-V canisters	625
Nr of CSD-C canisters	1250
Nr of KONRAD II containers (DU)	477
Nr of CSD-V canisters per TWh(e)	3.08
Nr of CSD-C canisters per TWh(e)	6.16
Nr of KONRAD II containers per TWh(e) (DU)	6.35

Scenario 2 – Application of MOX fuel

As in scenario 1, in this scenario it is assumed that the Borssele NPP will be shut down in 2033, and no new NPPs will be deployed. Additionally it is assumed that from 2013 on the Borssele NPP will be fuelled with a mixture of MOX (40%) and c-ERU-UOX fuel (60%). The stocks of vitrified waste containers (see Table IV and Fig. 8) consist of containers presently stored on surface, containers resulting from the future reprocessing of the c-ERU UOX fuel, and containers resulting from the future reprocessing of the MOX fuel. Note that the amount of generated DU is less than for Scenario 1 due to the application of recycled MOX fuel.

Table IV Waste characteristics per 2130 – Scenario 2 – Application of MOX fuel

	Gen II UOX	c-ERU UOX	MOX
Nr of CSD-V canisters	285	205	133
Nr of CSD-C canisters	570	410	266
Nr of CSD-V canisters per TWh(e)	-	2.88	
Nr of CSD-C canisters per TWh(e)	-	5.76	
Nr of KONRAD II containers (DU)	295		
Nr of KONRAD II containers per TWh(e) (DU)	4.28		

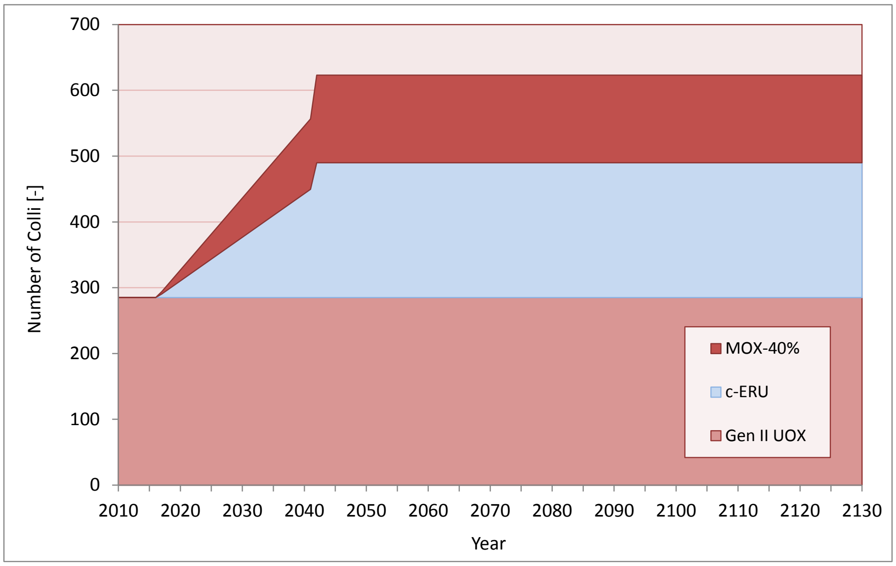

Fig. 8. Number of HLW containers (CSD-V) – Scenario 2 – Application of MOX fuel

Scenario 3 – No further reprocessing of spent fuel

Table V shows the total amount of spent fuel (UOX and MOX) and HLW CSD-V containers. The 285 HLW CSD-V containers result from the already reprocessed Gen II UOX spent fuel, and from the Gen II UOX spent fuel assumed to be present in the “reprocessing pipeline”. Note that the amount of MOX spent fuel spent fuel containers is significantly larger than that of the c-ERU UOX. Due to the significant higher heat output from spent MOX fuel, a single spent fuel container can hold only one spent fuel MOX assembly, compared to four spent fuel c-ERU UOX assemblies.

Table V Waste characteristics per 2130 – Scenario 3 – No reprocessing of spent fuel

	Gen II UOX-33 HLW	c-ERU UOX Spent Fuel	MOX Spent Fuel
Nr of CSD-V canisters	285	-	-
Nr of CSD-C canisters	570	-	-
Nr of SF canisters	-	86	232
Nr of SF canisters per TWh(e)	-	0.73	1.97
Nr of KONRAD II containers (DU)	295		
Nr of KONRAD II containers per TWh(e) (DU)	4.28		

RESULTS OF SIMULATIONS – NEW NUCLEAR POWER PLANTS

The scenarios 4, 5, and 6 refer to an increasing nuclear electricity demand (cf. Fig. 7).

Scenario 4 – Deployment of MOX-fuelled LWR Gen III

The deployment of LWR Gen III reactors (see Fig. 9) starts in 2020, and reaches its maximum after about 2040. A total number of six 900 MWe reactors supply somewhat more than the anticipated 5000 MWe of electricity. Upon reaching their anticipated lifetime, the Gen III reactors are replaced by other reactors of the same type.

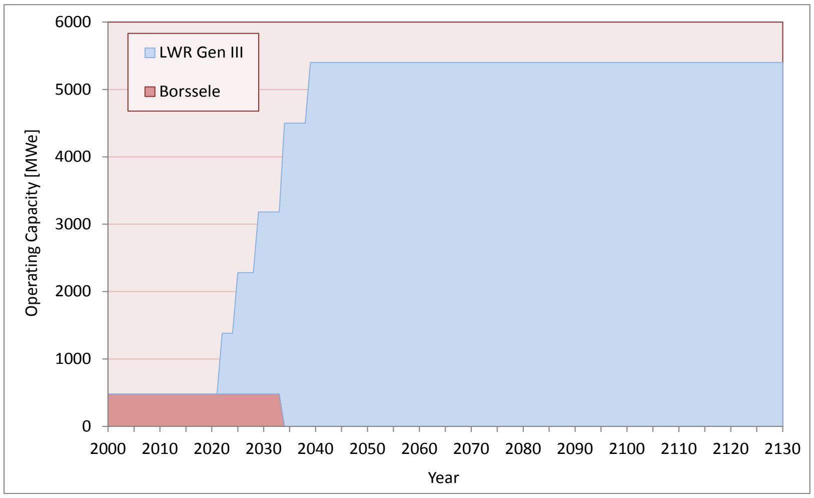

Fig. 9. Operating reactor capacity – Scenario 4 – Deployment of Gen LWR III

Fig. 10 and Table VI show the total amount of HLW CSD-V containers, resulting from the reprocessing of the different reactor fuel types. In 2130 a total amount of about 15’000 CSD-V (and in addition 30’000 CSD-C containers) would be produced under the presently adopted assumptions. These amounts will continue to increase as long as nuclear power plants continue their operations. The total amount of approximately 164’000 t_{HM} of DU, produced for the manufacturing of the nuclear fuel, requires 17’465 KONRAD II containers by the year 2130.

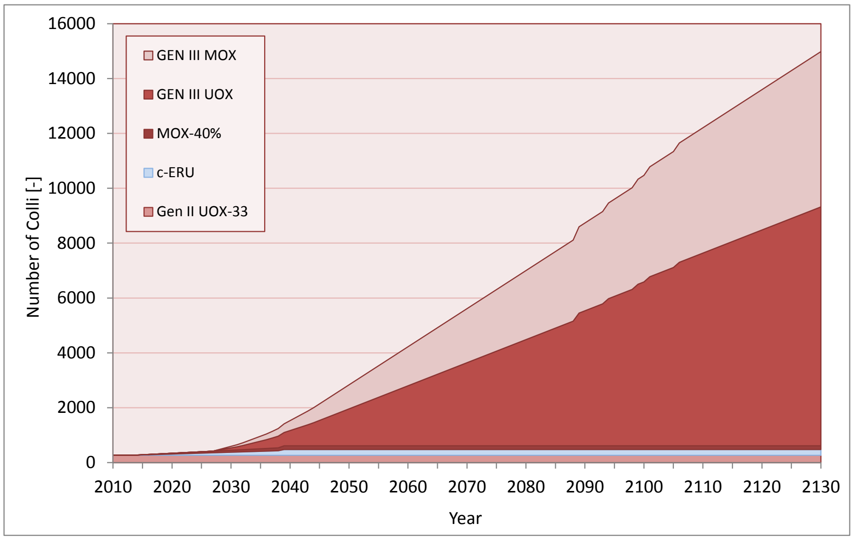

Fig. 10. Number of HLW containers (CSD-V) – Scenario 4 – Deployment of LWR Gen III

Table VI Waste container characteristics per 2130 – Scenario 4 – Deployment of LWR Gen III

	Gen II UOX	c-ERU	MOX	Gen III UOX	Gen III MOX
Nr of CSD-V canisters	285	210	136	8710	5660
Nr of CSD-C canisters	570	420	273	17420	11320
Nr of CSD-V canisters per TWh(e)	-	2.88		2.74	
Nr of CSD-C canisters per TWh(e)	-	5.76		5.48	

	Gen II UOX	c-ERU	MOX	Gen III UOX	Gen III MOX
Nr of KONRAD II containers (DU)	17’465				
Nr of KONRAD II containers per TWh(e) (DU)	3.72				

Scenario 5 – Deployment of HTRs

The deployment of HTR reactors starts in 2020, and reaches its maximum at about 2040 (see Fig. 11). A total number of 28 HTRs (180 MWe) supply the anticipated 5000 MWe of electricity. Upon reaching their anticipated lifetime, the HTRs are replaced by other reactors of the same type.

Due to the large volume ratio of the graphite pebbles and the embedded coated UO_2 fuel kernels, the number of CASTOR containers is substantial (see Table VII). By the year 2130 approximately 576 million HTR spent fuel pebbles would be held in storage, having a total net volume of over 65’000 m^3. The amount of depleted uranium per TWh(e) is substantially larger than for the previous scenarios due to the higher initial enrichment of the HTR-UOX fuel (9%) compared to to fresh Gen II/III UOX fuel (4-4.5%).

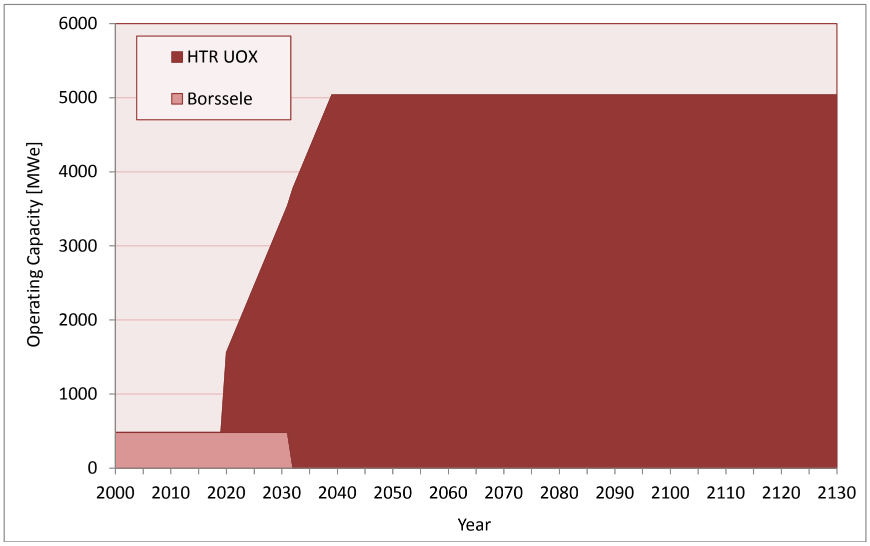

Fig. 11. Operating reactor capacity – Scenario 5 – Deployment of HTRs

Table VII Waste characteristics per 2130 – Scenario 5 – Deployment of HTRs

	Gen II UOX-33	c-ERU UOX	MOX	HTR UOX
Nr of CSD-V canisters	285	198	129	-
Nr of CSD-C canisters	570	396	258	-
Nr of CASTOR containers (HTR Spent Fuel Pebbles)		-		284’000
Nr of CSD-V canisters per TWh(e)		2.88		-
Nr of CSD-C canisters per TWh(e)		5.76		-
Nr of CASTOR containers per TWh(e) (HTR Spent Fuel Pebbles)				55.5
Nr of KONRAD II containers (DU)	28’785			
Nr of KONRAD II containers per TWh(e) (DU)	7.03			

Scenario 6 - Deployment of fast reactors

Fig. 12 shows that from 2020 on LWR Gen III reactors are capable to fill the nuclear electricity demand, whereas the first Gen IV reactor starts its operation around 2040. Note the temporary drop in electricity production from about 2085 to 2095, which is likely due to a numerical issue in the decision logic of DANESS. As the Gen III reach their end of life, they are gradually replaced by Gen IV reactors. That transition would be completed around 2100.

Fig. 13 and Table VIII show the amount of CSD-V containers originating from the reprocessing of spent fuel. The Gen-IV reactors generate about half the amount of HLW canisters per TWh(e) compared to the LWR Gen III reactors. The amount of DepU per TWh(e) is significantly less than for the other scenarios due to the assumed full reprocessing of the FR Gen IV fuel.

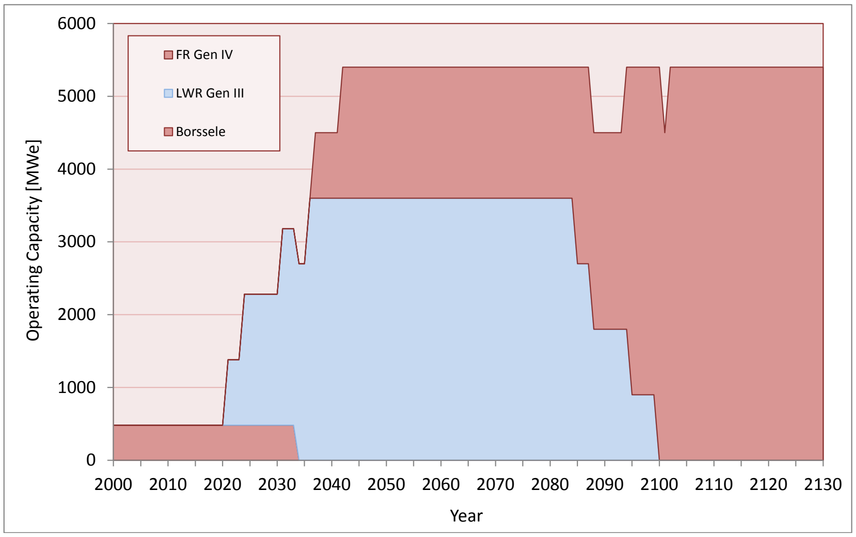

Fig. 12. Operating reactor capacity – Scenario 6 – Deployment of Fast Reactors

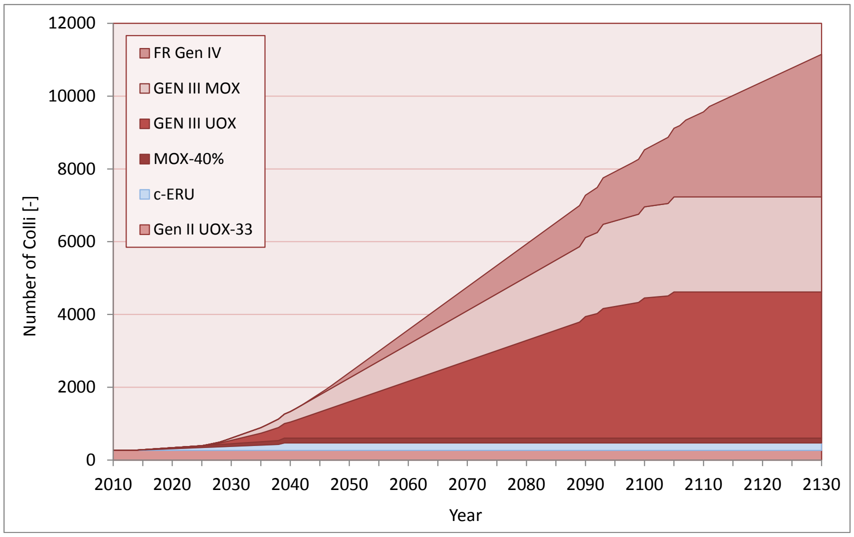

Fig. 13. Number of HLW containers (CSD-V) – Scenario 6 – Deployment of Fast Reactors

Table VIII Waste container characteristics per 2130 – Scenario 6 – Deployment of Fast Reactors

	Gen II UOX-33	c-ERU UOX	MOX	Gen III UOX	Gen III MOX	Gen IV
Nr of CSD-V canisters	285	205	133	4015	2610	3920
Nr of CSD-C canisters	570	410	263	8030	5220	7840
Nr of CSD-V canisters per TWh(e)		2.88		2.92		1.59
Nr of CSD-C canisters per TWh(e)		5.76		5.48		3.18
Nr of KONRAD II containers (DU)	5530					
Nr of KONRAD II containers per TWh(e) (DU)	1.71					

SUMMARY OF WASTE CHARACTERISTICS

Characteristics of the waste forms (containers, canisters) are provided in TABLE IX. The following observations apply:

- In the case of the reprocessing of spent fuels, the number of vitrified HLW containers per TWh(e), both CSD-V and CSD-C, is approximately similar for all scenarios.
- The HTR fuel cycle generates by far the largest amount of waste containers, both in total and per generated TWh(e). One reason is that the HTR spent fuel pebbles take up a relatively large volume per fissile mass compared to the other (UOX, MOX) fuels. Additionally, the HTR fresh fuel is 9% enriched in U-235, implying that about twice the amount of natural uranium is required to manufacture fresh HTR fuel compared to fresh Gen II/III UOX fuel (approx. 4.0-4.5% enriched). This also generates more DU per TWh(e) compared to the other fuel cycles.
- The Fast Reactors fuel cycle generates considerable less DU per TWh(e) than the other fuel cycles. DU is only generated as a result of the necessary deployment of UOX-fuelled reactors in the next decades, thereafter the FR spent fuel is assumed to be fully recycled.

TABLE IX Waste characteristics per 2130 for the considered scenarios

Characteristic	***Scenario 1 Continuation***	***Scenario 2 MOX Fuel***	***Scenario 3 No Reprocessing***	***Scenario 4 LWR Gen III***	***Scenario 5 HTRs***	***Scenario 6 Fast Reactors***
# CSD-V canisters	625	623	285	15’000	612	11’170
# CSD-C canisters	1250	1246	570	30’000	1224	23’240
# CSD-V canisters per TWh(e)	3.08	2.88	N/A	2.75	2.88	2.51
# CSD-C canisters per TWh(e)	6.16	5.76	N/A	5.50	5.76	5.02
# Spent fuel canisters	-	-	318	-	284’000	-
# Spent fuel canisters per TWh(e)	-	-	2.70	-	55.5	-
# KONRAD II containers (DU)	477	295	295	17’465	28’785	5530
# KONRAD II containers per TWh(e) (DU)	6.35	4.28	4.28	3.72	7.03	1.71

RADIONUCLIDE INVENTORIES

Based on information about the radionuclide inventories of the different types of waste, and the results of the DANESS simulation, the inventories of in total 46 radionuclides by the year 2130 have been calculated. These inventories will serve as a “source term” for the post-closure safety assessment that will be performed at a later stage.

An overview of the summed radionuclide inventories and radiotoxicity values generated by the different scenarios by the year 2130 is given in Fig. 14 for the fission products and in Fig. 15 for the actinides (only for radionuclides with half lives < 10 years and total estimated radiotoxicities > 10^3 Sv). The blue bars represent the “no new nuclear” scenarios, whereas the orange bars represent the growth scenarios. For the radionuclide inventories the following observations apply:

- For scenarios assuming direct disposal of spent fuel, (Scenario 3 *No reprocessing*; Scenario 5 *HTRs*) obviously considerable more plutonium and uranium, and about 10-20 times more curium must be finally disposed than for the “reprocessing” scenarios. During the reprocessing step these compounds are removed from the nuclear waste and stored at locations outside the Netherlands.
- The fission products that contribute most to the total radionuclide inventory and radiotoxicity in all scenarios at the foreseen time of emplacement in a disposal facility (the year 2130) are Ni-63, Sr-90, Tc-99, Cs-137, an Sm-151 (and Kr-85 for Scenario 3 *HTRs*). In a post-closure safety assessment these nuclides would contribute most to the radiological consequences of *short-term* scenarios.
- Considering a post-closure safety assessment the long-lived isotopes Ni-59, Se-79, Zr-93, Nb-94, Tc-99, Sn-129, I-129, and Cs-135 would contribute most to the long-term radiological effects.
- The actinides that contribute most to the total radionuclide inventory and radiotoxicity in all scenarios at the foreseen time of emplacement in a disposal facility (the year 2130) are isotopes of Pu, Am, and Cm.
- Considering a post-closure safety assessment the long-lived actinides Pu-239, Pu-240 (mid-term), Am-241, and Cm-245 (mid-term) would contribute most to the ultimate radiological effects in the biosphere.

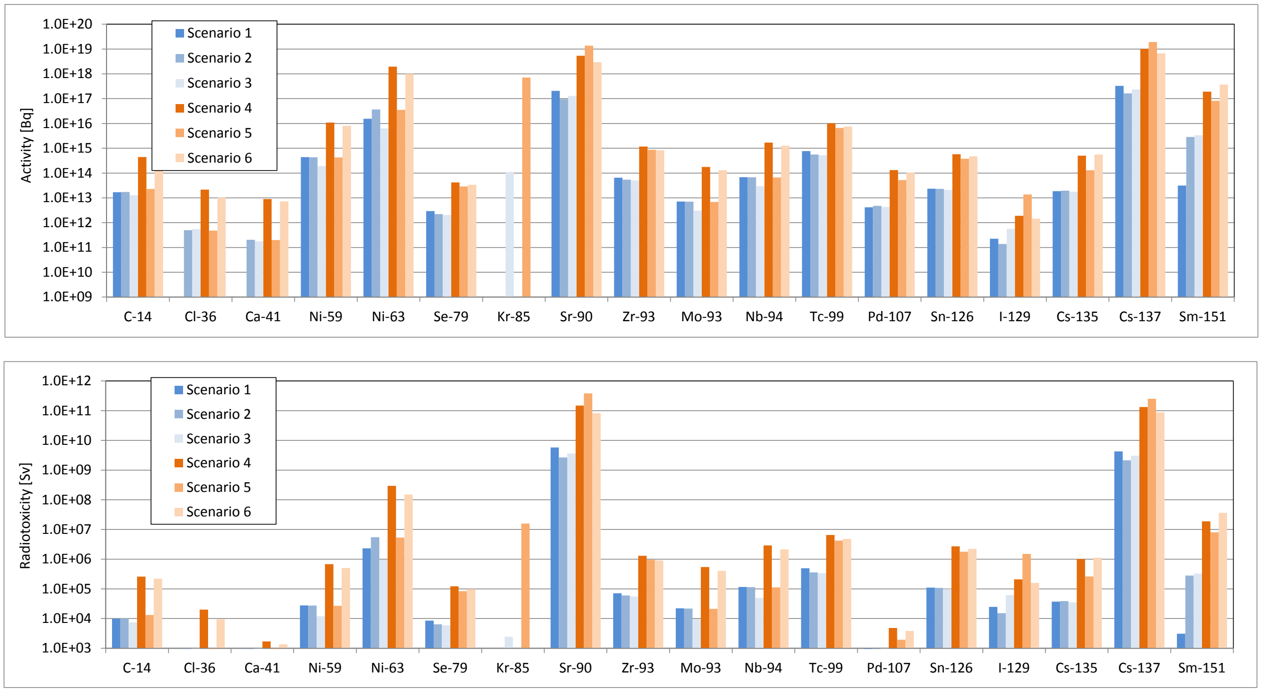

Fig. 14 Total estimated fission product inventory (top) and radiotoxicity (bottom) for the year 2130 – blue: no new nuclear scenarios; orange: nuclear growth scenarios

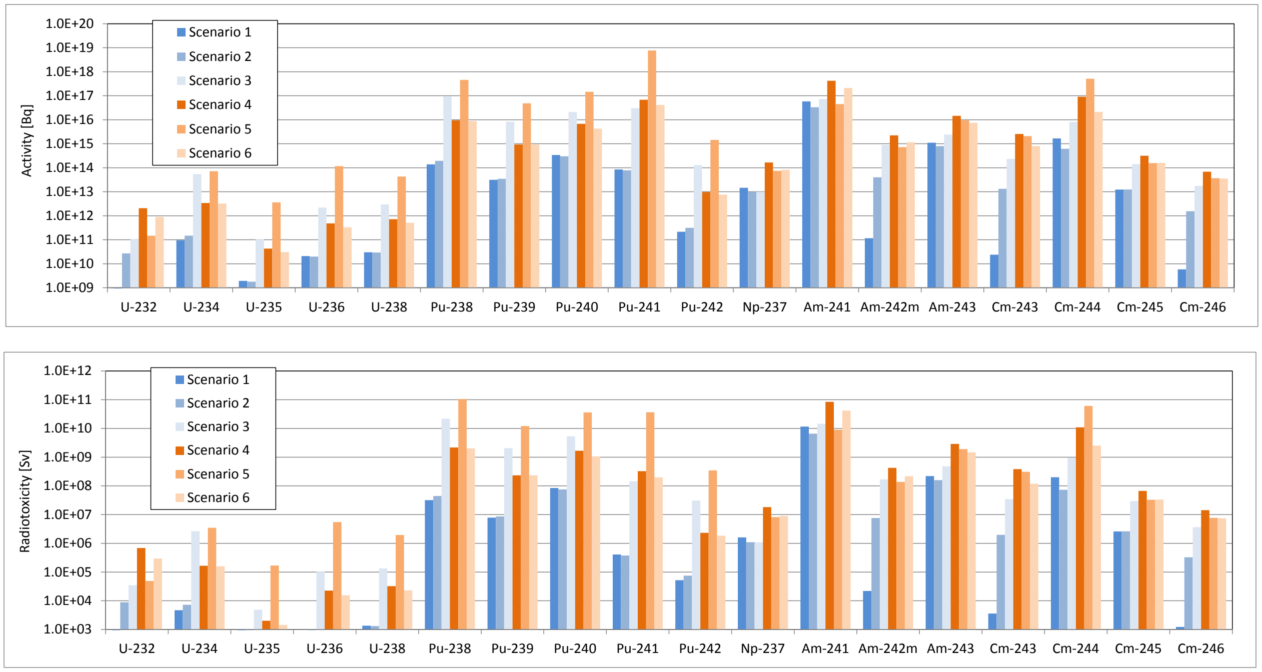

Fig. 15 Total estimated actinides inventory (top) and radiotoxicity (bottom) for the year 2130 – blue: no new nuclear scenarios; orange: nuclear growth scenarios

CONCLUSIONS

Based on considerations outlined in several Dutch policy reports, a number of future nuclear fuel cycle scenarios has been identified and modelled using the DANESS computer tool. The fuel cycle scenarios comprise several aspects such as continuation of the current practice, the use of MOX fuel, the direct disposal of spent fuels, the deployment of new generations of power reactors, and a significant increase of nuclear electricity demand compared to the present state in the Netherlands.

For each of the six assessed cases the types and amounts of radioactive waste have been calculated. In addition, the respective radionuclide inventories have been estimated by the time geological disposal of Dutch radioactive waste would become effective, i.e. by the year 2130. The estimated inventories serve as input for the post-closure safety assessment, which will be performed in the forthcoming year as part of the OPERA project.

The HTR fuel cycle generates by far the largest amount of waste containers, both in total and per generated TWh(e), due to the fact that the HTR spent fuel pebbles take up a relatively large volume per fissile mass compared to the other (UOX, MOX, FR-MOX) fuels. The Fast Reactors fuel cycle generates considerable less depleted uranium per TWh(e) than the other fuel cycles since FR spent fuel is assumed to be fully recycled.

In relation to the post-closure safety assessment the long-lived isotopes Ni-59, Se-79, Zr-93, Nb-94, Tc-99, Sn-129, I-129, and Cs-135, and long-lived actinides Pu-239, Pu-240, Am-241, and Cm-245 may contribute most to the ultimate radiological effects in the biosphere. The radiological contribution of the shorter lived nuclides (half lives less than 30 years) to the long-term safety is insignificant due to the extended surface storage period adopted in the Netherlands.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the Dutch research programme on geological disposal OPERA, under the contract NRG111&112.

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