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GOSSER II – Final report

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SÄTEILYTURVAKESKUS
STRÅLSÄKERHETSCENTRALEN
RADIATION AND NUCLEAR SAFETY AUTHORITY

Contents

Abstract

Projects GOSSER I and GOSSER II lasted altogether 8 years, from 2015 to 2023. The first project developed a national safeguards concept for the spent nuclear fuel disposal in Olkiluoto and conducted necessary research and development for the purpose. The second project concentrated on developing the concept further.

Safeguards methodologies of the two selected non-destructive assay (NDA) tools, PGET (Passive Gamma Emission Tomography) and PNAR (Passive Neutron Albedo Reactivity), were tested extensively and developed to the level where safeguards implementation will be straightforward. Further development and testing needs exist, which require adequate resourcing, but the risk for negative technical surprises is now limited.

During GOSSER II phase STUK also developed the first version of LOST&FOUND database (L&F), which will be STUK's key tool for the analysis and documentation of NDA verification data. The continuity of knowledge of nuclear material information can also be followed through the database. The database is meant to store all relevant information to further generations for drawing their individual conclusions if the disposal had been performed as declared. Testing the database with real data remains to be done.

During operation of the disposal facility, STUK's continuous presence at the disposal site will be the main way to confirm that there are no undeclared activities related to the disposed nuclear fuel. In addition, GOSSER II performed a few research studies related to geological environment. The objective of the studies was to examine how the society can remain confident that the disposal volume has not been intruded. The research was conducted on microseismic and other geophysical methods applied in the monitoring of the repository environment. These methods monitor the stability of the host rock as long as monitoring is continued. In addition, a literature study was made on the scenario, where the disposed spent fuel is dissolved in Nitric acid in its canister underground and the dissolved fuel is pumped up in liquid form. The study revealed, that scenario can be considered very difficult to implement and highly implausible.

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Tiivistelmä

Projektit GOSSER I ja GOSSER II kestivät yhteensä 8 vuotta, vuodesta 2015 vuoteen 2023. Ensimmäinen projekti kehitti kansallisen ydinmateriaalivalvontakonseptin käytetyn ydinpolttoaineen loppusijoitukselle Olkiluodossa ja teki tarvittavaa tutkimus- ja kehitystyötä tätä tarkoitusta varten. Toisessa projektissa keskityttiin kehittämään konseptia edelleen.

Kahden valitun ainetta rikkomattoman todentamistyökalun, PGET (Passive Gamma Emission Tomography) ja PNAR (Passive Neutron Albedo Reactivity), kyvykkyyksiä testattiin laajasti ja kehitettiin tasolle, jossa valvontatoimenpiteiden toteuttaminen on suoraviivaista. Lisäkehitys- ja testaustarpeita on olemassa, ja ne vaativat asianmukaista resursointia, mutta riski kielteisistä teknisistä yllätyksistä on nyt rajallinen.

GOSSER II -vaiheen aikana STUK kehitti myös ensimmäisen version LOST&FOUND-tietokannasta (L&F), joka on STUKin keskeinen työkalu NDA-varmennusaineiston analysointiin ja dokumentointiin. Ydinmateriaalitietojen jatkuvuutta voidaan seurata myös tietokannan avulla. Tietokantaan on tarkoitus tallentaa kaikki asiaankuuluvat tiedot, jotta tulevat sukupolvet voivat tehdä omat päätelmänsä siitä, onko loppusijoitus tehty ilmoitetulla tavalla. Tietokannan testaaminen oikeilla tiedoilla on vielä tekemättä.

Loppusijoituslaitoksen toiminnan aikana STUKin jatkuva läsnäolo loppusijoituspaikalla on pääasiallinen tapa varmistaa, ettei loppusijoitettuun ydinpolttoaineeseen liity ilmoittamattomia toimintoja. Lisäksi GOSSER II suoritti muutaman tutkimuksen kallioperään liittyen. Tutkimusten tavoitteena oli selvittää, kuinka yhteiskunta voi pysyä luottavaisena siihen, ettei loppusijoitusalueeseen ole tunkeuduttu. Tutkimuksessa tarkasteltiin mikroseismisiä ja muita geofysikaalisia menetelmiä, jotka on otettu käyttöön loppusijoituksen ympäristön seurannassa. Näitä menetelmiä käytetään kallioperän vakauden valvomiseen niin kauan kuin valvonta jatkuu. Lisäksi tehtiin kirjallisuustutkimus tilanteesta, jossa loppusijoitettu käytetty polttoaine liuotetaan typpihappoon kanisterissaan maan alla ja liuotettu polttoaine pumpataan ylös nestemäisessä muodossa. Tutkimus tuli johtopäätökseen, että skenaario on erittäin vaikeaa toteuttaa ja sen tähden sitä voidaan pitää erittäin epätodennäköisenä.

Sammanfattning

Projekten GOSSER I och GOSSER II pågick sammanlagt under 8 år, från 2015 till 2023. Det första projektet utvecklade ett nationellt kärnmaterialövervakningkoncept för slutförvaring av använt kärnbränsle i Olkiluoto och genomförde nödvändig forskning och utveckling för detta ändamål. Det andra projektet koncentrerade sig på att vidareutveckla konceptet.

Dugligheten av de två utvalda icke-destruktiva verifieringsverktygen, PGET (Passive Gamma Emission Tomography) och PNAR (Passive Neutron Albedo Reactivity), testades omfattande och utvecklades till en nivå där genomförandet av övervakningsåtgärder blir enklare. Det finns behov av ytterligare utveckling och testning, vilket kräver adekvat resursallokering, men risken för negativa tekniska överraskningar är nu begränsad.

Under GOSSER II-fasen utvecklade STUK också den första versionen av LOST&FOUND-databasen (L&F), som är ett centralt verktyg för analys och dokumentation av NDA-verifieringsdata. Kontinuiteten i informationen om kärnmaterial kan också spåras genom databasen. Syftet med databasen är att lagra all relevant information så att framtida generationer kan dra egna slutsatser angående om slutförvaringen har genomförts enligt avgedd deklaration. Testning av databasen med riktiga data återstår att utföra.

Under driften av slutförvaringsanläggningen är STUKs kontinuerliga närvaro på platsen det huvudsakliga sättet att säkerställa att det inte förekommer oanmälda aktiviteter i samband med det slutförvarade kärnbränslet. Dessutom utförde GOSSER II några undersökningar relaterade till berggrunden. Syftet med studierna var att undersöka hur samhället kan vara övertygat om att det inte har inträffat några intrång på slutförvaringsområdet. I undersökningen granskades mikroseismiska och andra geofysikaliska metoder som används för övervakningen av slutförvaringsmiljön. Dessa metoder används för att övervaka stabiliteten i berggrunden så länge övervakningen pågår. Dessutom utfördes en litteraturstudie om scenariot där det använda kärnbränslet som slutförvarats löses upp i salpetersyra i sin behållare under marken och det upplösta bränslet pumpas upp i flytande form. Studien kom fram till att scenariot är mycket svårt att genomföra och därför anses det synnerligen osannolikt.

1 Introduction

GOSSER project was a 4-year project in 2015–2018. The objective of GOSSER was to develop a national safeguards concept for the disposal project in Olkiluoto, run by Posiva ltd. (Honkamaa, et. al, 2019). Project GOSSER II lasted the calendar years 2019-2023. The project was a continuation of the GOSSER-project. In GOSSER II project, further R&D was conducted to develop the concept towards a more practical approach.

GOSSER II results are presented in this report. The objective of GOSSER II project was to ensure the national readiness for the start of the disposal of spent nuclear fuel. The main goals of GOSSER II were achieved. Safeguards tools and approaches were developed to a level where safeguards implementation will be straightforward. The methods were intensively tested during GOSSER II. Further development and testing needs exist, which require adequate resourcing, but the risk for negative technical surprises is now limited.

The contribution of the Helsinki Institute of Physics (HIP) was of utmost importance for the success of GOSSER I-II projects. HIP recruited a professor and researchers to develop NDA methods through FiDiPRO programme (Finnish Distinguished Professor). HIP has developed knowledge, expertise, networks and tools for both GOSSER-project phases.

2 Project objectives and results

Project GOSSER II plan consisted of 10 separate tasks. The outcomes and results of each task are listed in the following table.

Task # and name	Description and objectives as in the original plan (2019)	Results obtained
TASK 1 PNAR development, optimization study and documentation	(January 2019 – December 2019) This task begins with the GOSSER PNAR test, which is planned to be organized in April 2019 in the Teollisuuden Voima Oy's (TVO) spent fuel storage. Although the PNAR prototype is carefully designed in GOSSER, it is expected that during the tests in 2019 development ideas will pop up. In Task 1 the lessons learned will be taken in account and optimization studies will be conducted. In addition, the PNAR method for the Finnish disposal project will be documented in a MSc thesis. The work also includes the	Results: A PNAR MSc thesis and one scientific paper were published. These describe the method scientifically. PNAR is very robust technology, and the analysis criteria are simplistic, which is a benefit. The determination of acceptance criteria based on the PNAR ratio is a single figure, which can be recorded with high statistical accuracy and is ready to be used. More sophisticated PNAR analysis combined with Origen module was

Task # and name	**Description and objectives as in the original plan (2019)**	**Results obtained**
	development of analysis software and inspection criteria. The report from this study will be used while planning the details of the next steps of the project. This task is jointly implemented at STUK and at HIP. In particular, HIP provides necessary support in detection technology and simulations.	developed by Oak Ridge National Laboratory, ORNL. This analysis can be used to verify the history of the fuel. The ORIGEN module was tested for the first time in the field in Olkiluoto in August 2022. Operational implementation requires still some development to be done together with the EC. IAEA’s interest towards PNAR has remained limited.
TASK 2: Improvement and optimization of a national PGET analysis toolbox	(Early 2019 – early 2021) A few PGET imaging software packages are being developed in the scientific community. So far, none of them is openly published in literature. This is a problem since the imaging results are very sensitive to the choice of image reconstruction algorithm and its parameters. The conclusiveness of PGET results depends on the software and how it is used. It has already been shown that PGET is sensitive at the level of individual fuel pins, but sometimes the presence or absence of a specific pin may be disputed. The anticipated encapsulation process is such that there is no extra time to have long discussions; the conclusions are needed quickly, within a couple of days. Therefore, none of the currently existing PGET software packages is mature enough for Posiva’ s encapsulation process. Moreover, Finland shall develop its domestic capability to	In-depth research has been conducted in this area jointly by STUK and HIP. Multiple papers have been published. Research cooperation exists with internationals partners in USA, Italy, Sweden, the European Commission and the IAEA. The first in-air measurements of mockup fuel with the PGET instrument at Atominstitut Vienna were conducted in June 2022. Irradiated Co-60 rods were used. Measurements with real spent fuel are required for conclusive results. Discussion of further campaigns is undergoing. ZWILAG, Switzerland hosted the first PGET in-air measurements in

Task # and name	Description and objectives as in the original plan (2019)	Results obtained
	interpret PGET data independently. Task 2 provides information for Task 3 of the project. The work includes the collection of more data from measurement campaigns using the existing PGET prototype and through simulations. The task is conducted mainly at HIP. Eventually, STUK needs to have the capabilities to use and maintain the toolbox, so STUK's involvement is necessary.	September 2023. The tests were successful. Detailed research to optimize the measurement arrangement has been conducted. In 2022-23 the IAEA made a series of tests for unattended PGET measurement. Further development ideas are proposed, but currently the available hardware does not support them, at least easily. Documentation of the software package and hands on training is required.
TASK 3: Development of commonly accepted inspection criteria of PGET data	The accomplishment of this task requires that there is enough real measurement data available for evaluation of the capability of PGET method. STUK performs verification campaigns annually in Finnish NPPs. A part of the measurements is done with PGET and PNAR. (Early 2021 – late 2021) All inspectorates shall draw their independent conclusions on PGET data using their own methodologies. However, it would be an unwanted situation if the conclusions of the inspectorates differ. TASK 2 and cooperation with other inspectorates should lead to the project phase where commonly accepted criteria for PGET data evaluation are developed and agreed upon. STUK, EC, and the	PGET campaigns in Olkiluoto were conducted in 2019, 2021, 2022 and 2023. In Loviisa, campaigns were performed in 2020, 2021 and 2023. Covid-19 seriously affected the international cooperation in 2020-2021. The IAEA has developed its analysis package. STUK/HIP analysis is independent from that and is more complicated since it constructs both activity and attenuation patterns simultaneously. IAEA has developed its own software for analysis, but it could be developed further. Discussions of the acceptance criteria shall be

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	IAEA should have an agreement based on the criteria to decide whether a measurement result is conclusive and pursuant to the operator's declaration or not. These criteria shall be based on scientific studies. The use of multiple imaging software in the development phase is a benefit from the scientific point of view, but on the other hand it complicates the "standardization" of commonly accepted verification criteria. This task is conducted jointly at HIP and at STUK. The task needs deep scientific understanding of the properties of the method and of the fuel to be measured and practical experience on the implementation of safeguards. Multiple workshops and meetings with the IAEA and EC are expected. The work can be partly conducted under the umbrella of the Support programme mechanism.	followed. The work continues.
TASK 4: Specification and commercialization of the NDA verification system	(Early 2020 – Mid 2022) This task follows Task 1. The PNAR instrument needs to be integrated with PGET. This task also involves discussions with mechanical designers and PGET vendors. The system needs to be fitted in the TVO's spent fuel storage and possibly in the encapsulation plant. Commercialization of PNAR is part of the task. This task is mainly implemented at STUK. HIP provides crucial support in detection technology. Helsinki University also has a mechanical workshop, and its	PGET+PNAR integrated verifier exists. It is designed with transportability in mind, but it is suitable for continuous use. The electronics and the firmware of the PGET could be improved and possible evolutionary steps need to be discussed. Automatization of the PNAR cadmium sleeve movement is designed and the components procured. Building and documenting the system remains to be done. Deployment shall be

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	services may be needed for the purpose. Provedos and TVO Nuclear Services (TVONS) may offer engineering services.	done together with TVO in 2024.
TASK 5: Arrangements for maintenance	(Mid 2021 – Late 2022) In this task the arrangements of system maintenance will be planned. This task is mainly implemented at STUK. HIP may provide necessary support in detection technology.	Recovery arrangements have been discussed but not yet formalized. A preventive maintenance program needs to be developed, also including the software. PGET is a commercially available instrument and comes with maintenance instructions and program. PNAR is designed and built by Provedos Ltd. Drawings and assembling instructions exist. They form a basis for maintenance instructions. Manufacturing of an essential PNAR reserve part (one detector pod) is ongoing.
TASK 6: Development and testing of the automatic data collection, processing, analysis and storage pipeline	(Late 2021 – late 2022) This development will rely on lessons learned from the earlier campaigns. The goal is to develop a system which can be operated remotely, with data being shared with all inspectorates and the analysis performed automatically. This task will include the necessary hardware and software development and testing in the field. The existing infrastructure set by the IAEA and EC will be utilized.	IAEA has tested unattended collection of data from the PGET. PNAR will use the same VPN infrastructure installed at the TVO's spent fuel storage. Also the so-called operator's declaration format and practices shall be agreed on. This problem shall be resolved in development of subsidiary arrangements with the IAEA. Role of GOSSER II has been in

Task # and name	Description and objectives as in the original plan (2019)	Results obtained
	This task is conducted jointly at STUK with international stakeholders. The work can be conducted under the umbrella of the IAEA safeguards support programme. Academic interest in this part is likely to be lower, so HIP contribution is smaller.	provision of testing opportunities. From the national point of view, STUK, EC and the IAEA still need to agree upon how the data is provided to STUK and how STUK will analyze data and store them in the database (TASK 8).
TASK 7: JOY R&D projects	JOY projects are planned yearly. For 2019 the main subject to be investigated is usability of micro seismic data. This subject is urgent, since boring of the canister shaft is ongoing providing a good chance to collect relevant data. This will be the last large-scale drilling planned in the repository. The methods to analyze the excavation damaged zone have been develop for their safety purpose. This R&D generates also safeguards-relevant understanding with will be analyzed. In addition to the methods to verify the integrity of the host rock, also called the geological containment, the possibility of in in-situ recovery of the disposed of materials in the copper canisters was one of the JOY topics to be investigated	The seismic data from borings were analyzed by Finnish experts, but after that, continuous seismic recordings were collected for the IAEA during 2022 when the first deposition tunnels were excavated and finalized. The analysis of the seismic method to safeguard the repository is still ongoing at the IAEA, and the results of the new method may need further analysis by the Finnish experts. The geophysical methods to analyze the safety relevance of the excavation zone were widely analyzed for their safeguards applicability by Heikkinen (2021). From these methods, in particular muon tomography has raised interests within the international safeguards community, and thus a IAEA Support programme task was established in 2023.

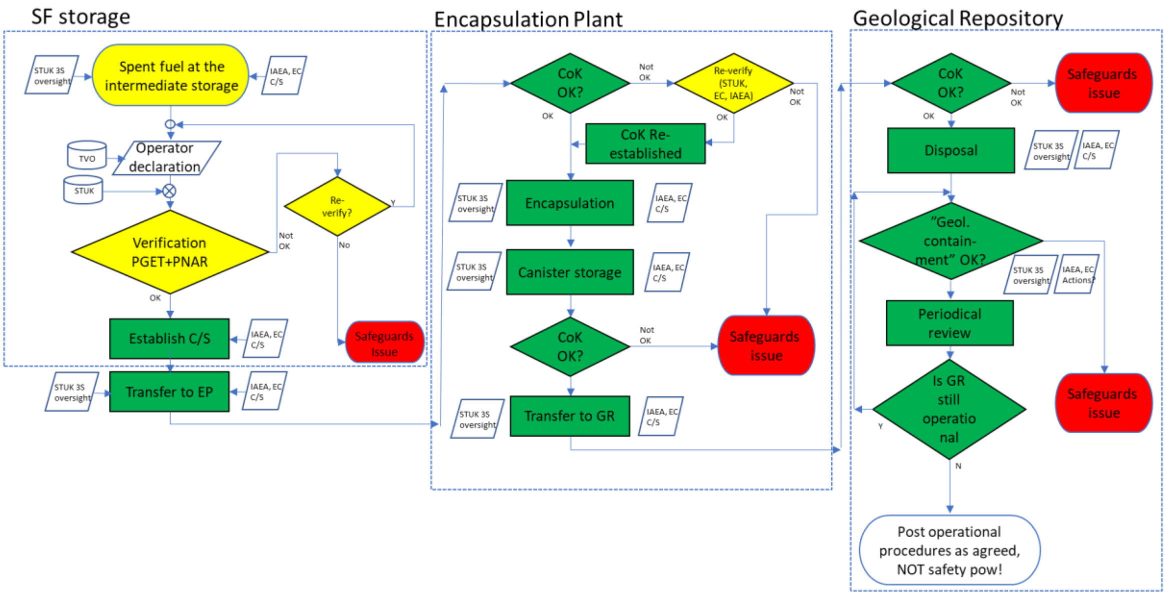
Task # and name	**Description and objectives as in the original plan (2019)**	**Results obtained**
		GOSSER II included a literature study on the scenario where spent fuel is dissolved in Nitric acid in its disposal canister. The study showed that there are multiple major problems from the diverter's point of view (Koivula, 2022). The scenario is not plausible. Intensive R&D effort would be required, which, as such, would be subject to declaration under Additional Protocol and under scrutiny of the IAEA.
TASK 8: Database development	Development of a measurement database is not urgent, but requires attention, as measurement data becomes available. Also, the following of Posiva's fuel database development is important to ensure that the operator provides verifiable fuel data that will be archived. The database can also contain data collected from other instruments than verification systems. Long term archiving of disposal related data is another internal development project in STUK and GOSSER II will not duplicate these efforts. The work is started in mid-2019 and continues throughout the project.	The database, called LOST&FOUND (L&F) was specified in STUK in summer 2022 and developed in 2023. Long term archiving of the data shall be done nationally, and most likely will be based on the data structures of the L&F database. STUK is ready to discuss if EC or the IAEA want to possess the data.
TASK 9 Preparation for practical implementation	(2022 – mid 2022). This subtask is concentrating how safeguards and other regulatory oversight activities are performed in operational phase. How we check the documentation, how measurements are performed, how and what to inspect and so on. This subtask will make use of the technical development work	The so-called 3S integration and cooperation within STUK have been discussed at the Nuclear Waste Regulation and Safeguards department at STUK. The safety-safeguards interaction for the host rock analysis has already been identified

Task # and name	Description and objectives as in the original plan (2019)	Results obtained
	in other subtasks. Cooperation and coordination with safety, security and safeguards and between different sections in STUK are discussed.	(e.g., Okko & Heikkinen 2021), but the generic 3S work continues.
TASK 10: Wrapping up documentation and reporting	(Mid 2022 – end 2022). The final report of the whole project, summarizing the final verification concept, is concluded in late 2022 and published in the STUK report series.	This report.

3 Summary of the foreseen verification concept

Details of the safeguards approach and concept will be officially agreed upon in Subsidiary Arrangements (SA) and Particular Safeguards Provisions (PSP) documents and are therefore outside the GOSSER-project. The SA are discussed with Posiva, STUK, EC and the IAEA as a part of safeguards planning and implementation. However, the role of GOSSER and GOSSER II projects has been paramount for the concept development. Without the R&D work done in GOSSER projects, there would not have been a scientific and tested basis for the discussion and agreement. It should be noted that the NDA verification campaigns were organized under coordination of the Finnish Support Programme to the IAEA safeguards, since it provided a direct link to the IAEA's PGET developers.

At the time of writing, negotiations of SA/PSP documents are underway, but the following schema has been discussed, which could form a basis for the safeguards arrangements. It is important that the probability to end up in the red boxes (dead-ends) is minimized as much as practically possible and the way out from those boxes is agreed upon.



Flowchart of the proposed verification concept 1

4 Further R&D work remaining

GOSSER and GOSSER II have been internal projects of STUK but involved multiple stakeholders. As the start of fuel disposal approaches, a decision was made in 2022 to discontinue the separate R&D project and address R&D needs under the regular oversight project. It can be concluded that following work remains to be done:

1. Further development of the selected NDA methods (PNAR and PGET) is still required.

2. The inspection criteria for PGET&PNAR data have been developed. For PGET, further testing is needed to achieve better reliance on the results. The work shall be concentrated on BWR fuel.

3. The PGET method can be developed further. The IAEA has no current intention to upgrade the instrument. However, recent advancements in detector and electronics design may facilitate the use of the method also for quantitative purposes. However, this is beyond STUK's main goals, but research should be supported and promoted. HIP and partners are planning to continue this more fundamental research, including advanced mathematical image reconstruction techniques, Monte Carlo simulations, artificial intelligence techniques and large position-sensitive CZT detectors.

4. Database implementation for NDA data (Database called LOST&FOUND) is underway. The implementation and processes shall be finalized. Data should be obtained from TVO for testing.

5. Discussion on operator’s declarations has been underway between Posiva, STUK, EC and the IAEA. The outcome of this work is important for the database and data flow implementation. The format shall be agreed upon.

6. The PNAR Cadmium sleeve movement automatization is designed. Final documentation is still needs to be developed. The automatization shall be implemented and tested in 2024.

7. The PNAR-PGET NDA verification system has been specified. The deployment of the system for continuous use requires changes at the TVO’s spent fuel storage. These changes are subject to rigorous acceptance procedures. Final documentation for the implementation by TVO remains to be done in 2024.

8. A recovery plan for NDA systems in case of failures is discussed with stakeholders. A final version of the plan shall be approved, and necessary investments made.

9. Using geophysical e.g. microseismic data for safeguards conclusion is a new challenge. During the project period, it has been proposed by the IAEA that the geophysical methods can be used for the confirmation in the intactness of the host rock instead of the traditional conclusions. STUK has gathered experience on host rock and groundwater monitoring during the past years, and these methods can be considered to be useful in detection of undeclared activities. STUK will review the monitoring results also from safeguards point of view, this process needs be established. IAEA’s ability to utilize national findings is limited, but STUK will also report its observations to the international inspectorates.

10. Finally, new geoscientific technologies entering in the international and scientific discussions for their suitability and applicability in safeguarding geological repositories should be followed. The methods challenging the safety principles cannot be utilized in Olkiluoto repository. Current understanding is that to be effective, several techniques need sensors in the vicinity of the fuel canisters, or specific observation tunnels beneath disposal tunnels for the transillumination principle. A recent example is myon tomography. The method cannot be used after closure of the repository because of no additional sensors shall not be left in the underground.

5 Conclusions

The GOSSER project in 2015-2018 and its extension GOSSER II in 2019-2022 and 2023 resulted in the development of a national safeguards concept for disposal of spent nuclear fuel. The work has been done in cooperation with the international safeguards inspectorates and other stakeholders. The project provides a firm and scientifically proven basis for safeguards implementation and remaining R&D work.

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