THE PLACE OF CIGÉO IN THE FRENCH MANAGEMENT OF SPENT FUEL

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Abstract

ANDRA is preparing an application for the creation of a geological disposal facility in East of France, Meuse Haute-Marne area: Cigéo Project. The project will be implemented in the vicinity of ANDRA's Meuse Haute Marne Underground research laboratory which has been operated since 2000. The project aims at disposing of vitrified HLW produced by the reprocessing of spent fuel, as well as a range of ILW, including metallic parts of the fuel assemblies separated during reprocessing and various operational wastes. Cigéo design capacity covers existing HLW and ILW in France as well as wastes which will be produced in the next decades by the operation and decommissioning of all existing French nuclear facilities. ILW will be disposed of from early stages of the operational phase while HLW will be accommodated after a few decade storage phase for thermal decrease. A total 100 year operational period is envisaged. By law Cigéo project is designed consistently with reversibility requirements. This includes a number of means to make it possible to modify decisions along the process, such as progressivity and flexibility in the implementation of disposal cells. Within this framework the very first period of the project will be a pilot industrial phase. A particular emphasis is being given to the « adaptability » of the project, which is considered as part of its reversibility and is expected to be assessed within the application. Provisions are made so that next generations can adapt the operational process to accommodate potential changes in the French spent fuel and waste management policy and strategy. This includes the potential direct disposal of spent fuel.

1. INTRODUCTION

The state company ANDRA is responsible for the long term management of radioactive waste in France. ANDRA operates industrial disposal facilities on the surface for low level waste (LLW) and very low level waste (VLLW) most of them being generated by the operation of NPPs and the nuclear fuel cycle. Waste with significant amounts of long-lived radionuclides cannot be accepted in surface repositories for safety reasons. Therefore ANDRA is developing the French geological disposal project in order to accommodate long lived-intermediate level (ILW) as well as high level waste (HLW).

The program started in 1991 with the first French Act on radioactive waste management. This Act provided for three research routes to be performed in parallel: long term storage, partitioning-transmutation and geological disposal. The research on the geological disposal route included field investigations. After a siting phase on a voluntarism basis, the Meuse Haute-Marne Underground research laboratory (URL) was licensed in 1999. Construction and operation of this research facility started in 2000 to evaluate the containment capacity of the selected Callovo-Oxfordian clay layer and the ability to construct underground facilities at the considered depth. The feasibility of geological disposal was assessed in 2005 thanks to iterations between field data acquisition, conceptual design and safety assessment which made it possible to deliver a first full safety case in 2005. After national and international reviews, the French Parliament selected geological disposal as the reference route to manage waste that cannot be disposed of on the surface or at shallow depth for safety reasons. A new siting phase started in 2007 within a 250km^2 area around the URL where data gained underground might be transposed. Technical criteria as well as societal criteria on the basis of local concertation were used to define in 2009 the location of the future facilities of the new "Cigéo" project, where detailed geophysical survey was undertaken. In parallel new programs were developed in the URL to support the design of the project and its safety case (Fig. 1). They included the study of interactions between materials and processes as well as scale effects. Demonstration tests have been progressively implemented underground and above ground to develop construction, operation and sealing methods. New iterations made it possible to complete a full range of detailed design requirements in 2010 and to start the industrial design on this basis. In 2016 ANDRA provided the Regulator (Autorité de sûreté nucléaire - ASN) with safety options to be reviewed [1]; [2]. Outcomes are currently being taken into account in the detailed design [3]. A national public debate on the project also took place in 2013 resulting in several evolutions. In particular an industrial pilot phase will be integrated into the

facility start-up phase, which has been confirmed by a new Law in 2016. The 2013 public debate also results in a higher involvement of civil society in the project. The detailed design is being completed during the year 2019 and the application for the creation of the facility is under preparation.

This paper presents the wastes to be disposed of in Cigéo in accordance with the French strategy for the management of spent fuel, the main features of the project to accommodate these wastes, a view of the construction and operational phases which are planned to last over 100 years with a focus on the reversibility and the status of the project (Fig. 2).

FIG. 1. Photographs of the Meuse Haute-Marne Underground research laboratory (Aerial view - left, an experimental drift - right).

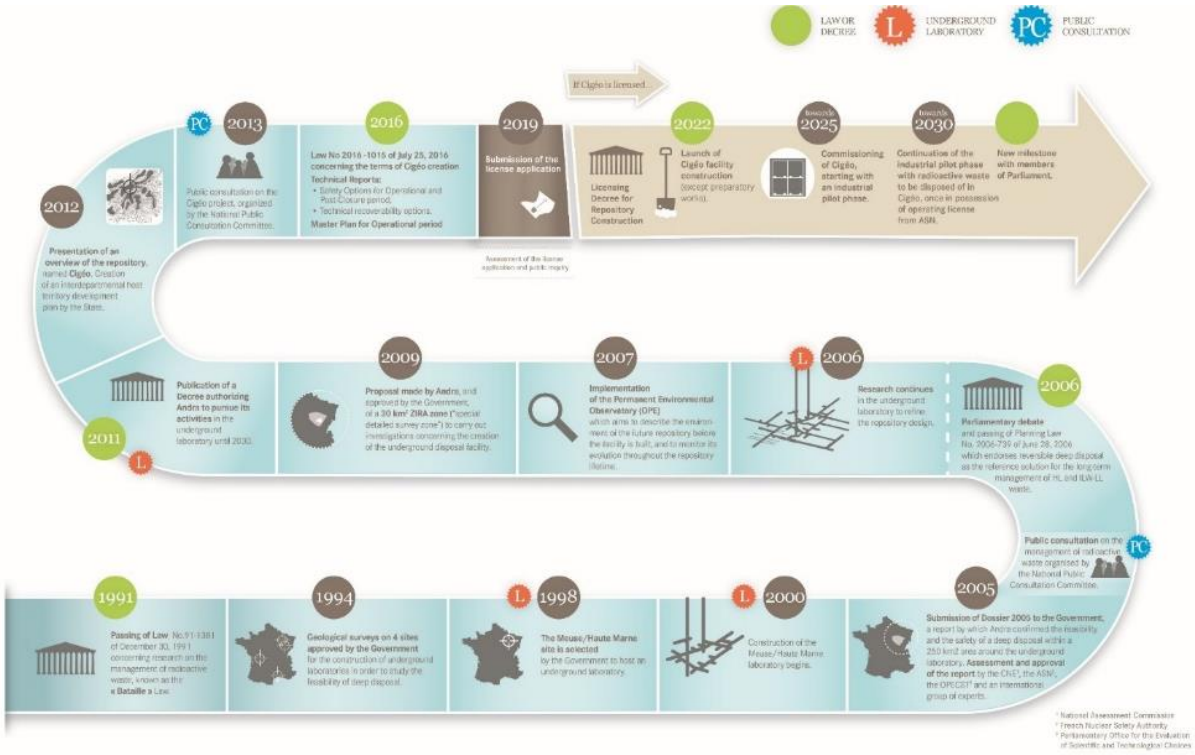

FIG. 2. Cigéo roadmap since the 1991 Act, behind and in front of us.

2. ILW AND HLW GENERATED BY THE FRENCH PROGRAM

EDF nuclear fleet in France includes 58 NPPs in operation with an installed capacity of 63 GWe and one under construction. Figure 3 presents the French strategy for the fuel cycle [4]. All Uranium oxide spent fuels are being reprocessed at Orano's La Hague Plant, which represents more than 1,075 tons of heavy metal each year. The plutonium from UOx fuel reprocessing is totally recycled into MOx fuels. These MOx fuels can be used in part of the reactor fleet, they correspond to 125 tons every year. The uranium from spent UOx fuels is also intended to be recycled on the basis of dedicated fuels "URe". Unloaded spent MOx and URe fuels are or

will be stored. Delayed reprocessing is envisaged for these two types of fuels in view of the potential recycling of their valuable material in future fleets.

Cigéo reference design capacity covers existing HLW and ILW in France as well as waste which will be produced in the next decades by the operation and decommissioning of all existing French nuclear facilities. This includes the reprocessing of all MOx and URe spent fuel. On the other hand waste that would be generated by future fleets are not taken into account in order not to anticipate future policy choices.

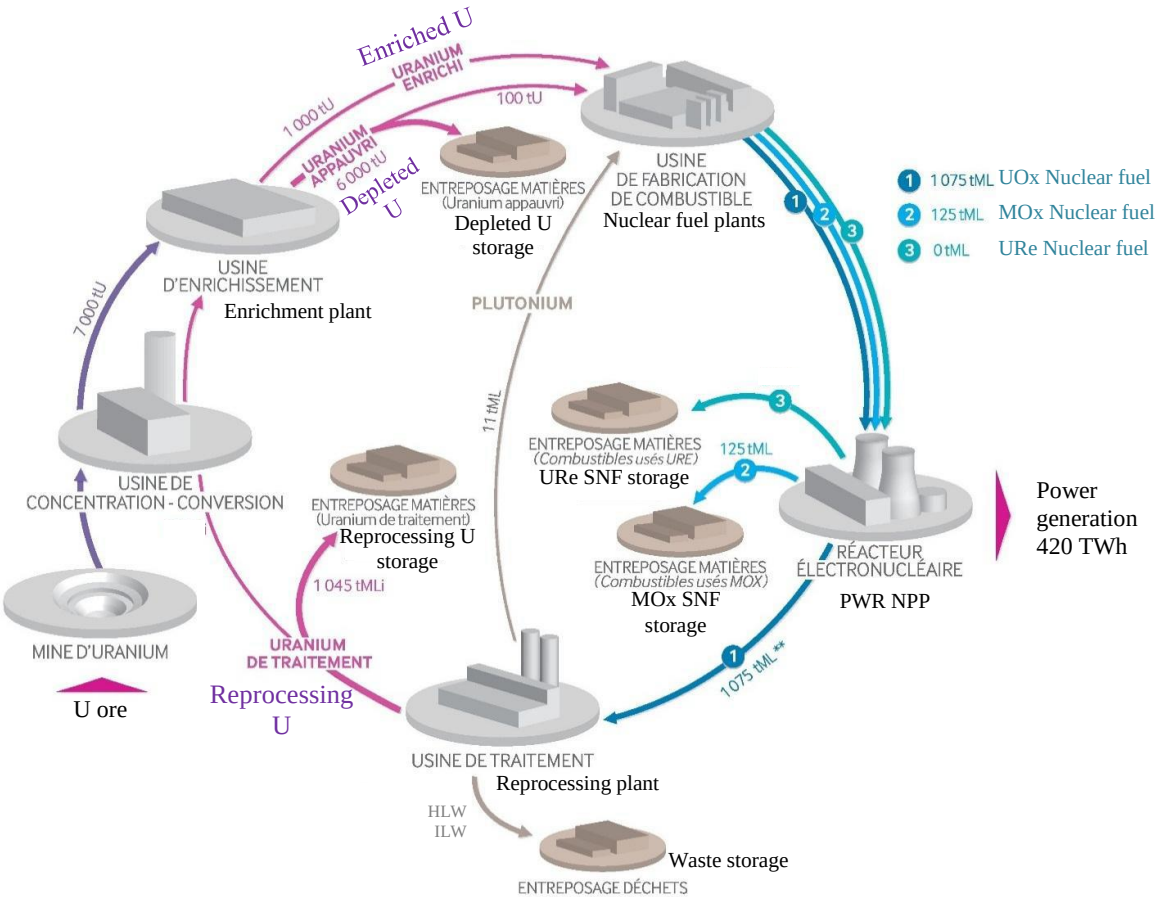

FIG. 3. Current French strategy for the management of nuclear fuel [4].

HLW are fission products and minor actinides formed by nuclear reaction within the fuel. They were separated from uranium and plutonium during reprocessing. They are calcined and incorporated into a glass matrix. The glass thus produced is cast in temperature in a standard stainless steel container.

Along with HLW generated by the current reprocessing of uranium oxide fuels, special attention should be paid to:

— On one hand older HLW with a moderate thermal output;
— On the other hand HLW from the reprocessing of MOx spent fuels (mixed with UOx fuels) with a larger amount of americium which provides a higher thermal output.

Except for some moderately thermal HLW a storage period of several decades is required prior to disposal in order to benefit from sufficient thermal decrease. Storage facilities are periodically extended in La Hague to make it possible to manage HLW packages until their disposal, which is planned to start in 2080. Then delivery of all vitrified HLW generated by the current fleet would extend over 60 years. Some moderately thermal HLW will be disposed of in an early stage to contribute to the industrial pilot phase of Cigéo.

Before the used fuel pellets can be processed, it is essential to separate the fuel itself from the metal structures around it. These metal structures are ILW: they are compacted online in the reprocessing plant and conditioned in a standard stainless steel container.

Other ILW from reprocessing include solid maintenance waste and solidified liquid effluents.

Along with reprocessing waste, Cigéo will also accommodate operational and decommissioning ILW directly produced by NPPs. They include control rod clusters and various metal parts from the vicinity of the reactor core. Cigéo reference inventory also includes significant amounts of waste issued by the French first NPP generation as well as research and development performed to support the nuclear program.

ILW is now stored on the sites of the waste producers, awaiting for the availability of geological disposal.

Total amount of HLW to be disposed of in Cigéo is 10,000 m^3 of which 30% is already produced and stored. Total amount of ILW is around 75,000 m^3 of which 60% is already produced and stored [5]. These volume figures correspond to the "primary packaging", ie the form in which the waste is currently conditioned and stored (Fig. 4). Over-packing would be done before disposing a number of these waste packages.

FIG. 4. Reprocessing waste primary packages: vitrified HLW; compacted metallic structures; cemented maintenance ILW; bituminized effluents.

3. MAIN FEATURES OF CIGÉO

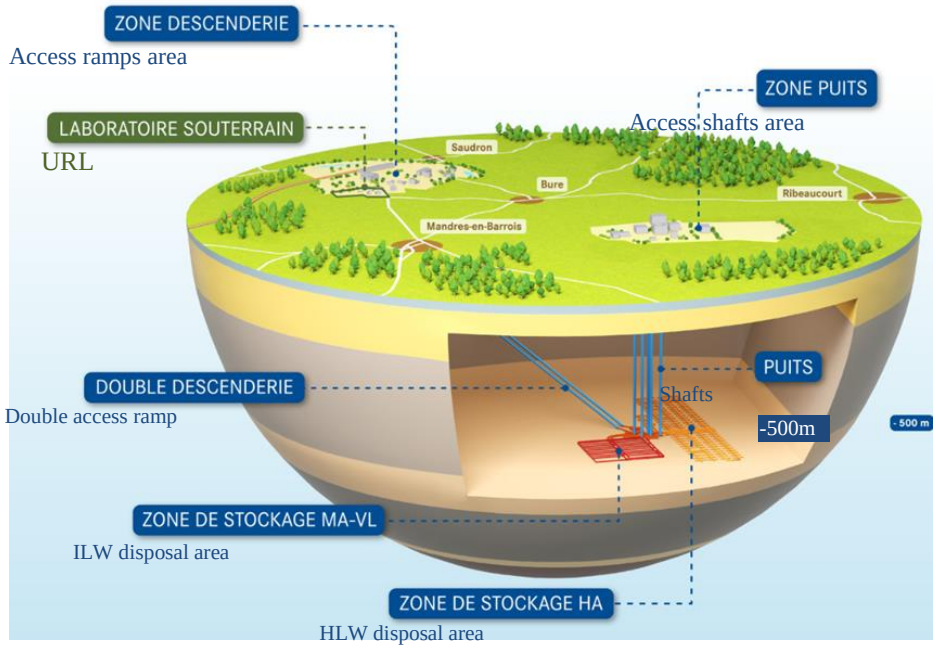

FIG. 5. Overview of Cigéo Project.

Isolation of disposed waste will be provided over very long periods of time by depth as well as the geodynamic stability of the selected site.

Cigéo is designed to provide a high level of containment consistent with the radiological content of ILW and HLW. Cigéo's post closure safety will be mainly based on the host clay layer, in particular its low permeability at various scales, low hydraulic gradients, the thickness of the clay layer (130-150m), its geological continuity and geodynamic stability and its high sorption capacity. Investigations of the Callovo-Oxfordian clay layer carried out for 25 years provide a high degree of confidence in its containment performance. In particular in situ characterization and demonstration are being carried out since 2000 within the Meuse Haute-Marne URL.

The disposal vaults will be implemented horizontally in the middle part of the host clay layer. More than 50 meters of clay above and below disposal vaults will greatly retard and mitigate the migration of the radionuclides which would be released by waste packages. Safety assessment shows that the retardation of the most mobile radionuclides such as iodine 129 and chlorine 36 is more than 100,000 years. Diffusion induced dispersion considerably decreases the molar concentration or released radionuclides and therefore its impact on Man and the environment in the very long term.

The major role of the host clay layer in the containment makes it possible to adapt requirements on the engineered barriers, which are secondary in the long term compared to the geological barrier. However waste forms and packages also contribute to safety as well design features such as the general layout of underground facilities.

Provision is made in the design of the repository to limit disturbances induced in the host clay rock. The main disturbances with regard to the facility design are of mechanical origin for all the waste, and thermo-hydro-mechanics in particular for the HLW. Local desaturation and oxidation of pyrites is also to be taken into account.

Underground disposal facilities for HLW and ILW are separate in order to avoid interactions between these two categories of waste (Fig. 5). The disposal areas are connected to a central logistic zone where accesses to the surface are grouped to enhance long term safety.

Surface facilities are divided into two zones consistently with the territorial integration of the project. One zone is dedicated to the reception, control and preparation of waste packages prior to underground transfer. This zone will be connected to the national rail network by means of a specific track to be built. This will promote the shipment of waste packages from storage sites by rail as well as the transport of building materials to limit their impact on the environment. Underground transfer will be performed in a ramp by means of a cable car system: this system aims at optimizing the safety during transfer. In particular this system makes it possible to significantly reduce fire hazard.

The other surface facilities are located above the underground logistics area. They are dedicated to underground service such as the extraction of excavated clay and ventilation. They are linked to the underground by vertical shafts.

Prior to underground transfer, HLW will be placed in carbon steel overpacks which will provide for watertightness for several hundreds of years. The overpacks will prevent glass leaching during transient phases after closure in particular as long as temperature in the repository is high. The overpack is being designed on the basis of the best available technology, in particular to reduce stress corrosion and radiolysis corrosion. In the HLW disposal area, HLW disposal packages will be pushed in horizontal micro-tunnels located at the median of the host clay layer (Fig. 6). The horizontal design optimizes heat dissipation and cost. The spacing of micro-tunnels and the potential spacing of waste packages inside each micro-tunnel are defined to comply with thermal criteria with regard to long term safety. The main one aims at limiting the large scale THM coupled effects to avoid any damage in the host clay layer. The diameter of the microtunnels corresponds to the diameter of waste packages plus a handling clearance and the thickness of the steel liner which provides for rock support during the operational period. The length of the disposal tunnels is in the order of 150 metres. It can be optimized with regard to technological limits and cost

In the ILW disposal area, repository cells will consist in horizontal tunnels with a length of 400 m (Fig. 7). Waste packages are stacked in the tunnels by a remote controlled handling crane. ILW primary packages can be grouped into robust disposal containers prior to their transfer to the underground facility: disposal containers are parallelepiped and made of concrete. Provided they meet with acceptance criteria, primary waste packages may also be directly emplaced in the disposal cells which provides for a higher compactness. Thick concrete rings provides rock support during operation. ILW repository cells are ventilated as long as they are kept open in

order to dissipate hydrogen generated by radiolysis. Various types of ILW are emplaced in separate dedicated cells to avoid unwanted chemical interactions such as complexing agents. Provisions are also made to avoid criticality hazard for the waste which contain some fissile material. The cross section of the tunnels can be optimized with regard to geo-mechanics and cost.

Cigéo design also includes a sealing system to enhance long term safety. Bentonite based seals will be constructed in the access ramps and shafts for final closure at the end of the operational period. These seals are the most important seals for long term safety. However seals and backfills for horizontal drifts are also been developed to be emplaced in the underground facilities. The closure process will be progressive and performed step by step. The design does not require the immediate sealing of parts of the repository after filling with waste, which allows flexibility in decision making with regard to the benefits and disadvantages.

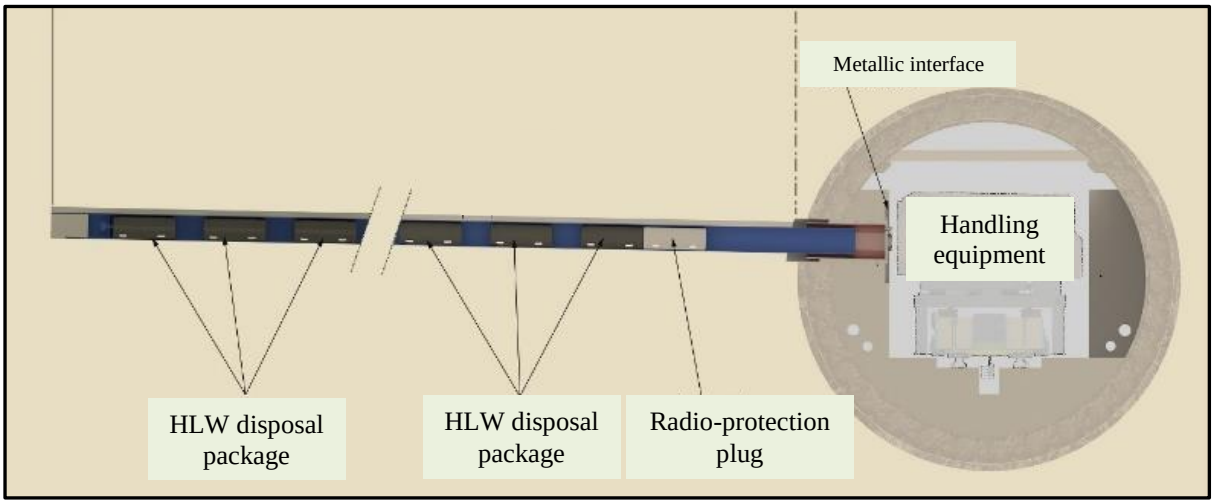

FIG. 6. Disposal cell for HLW.

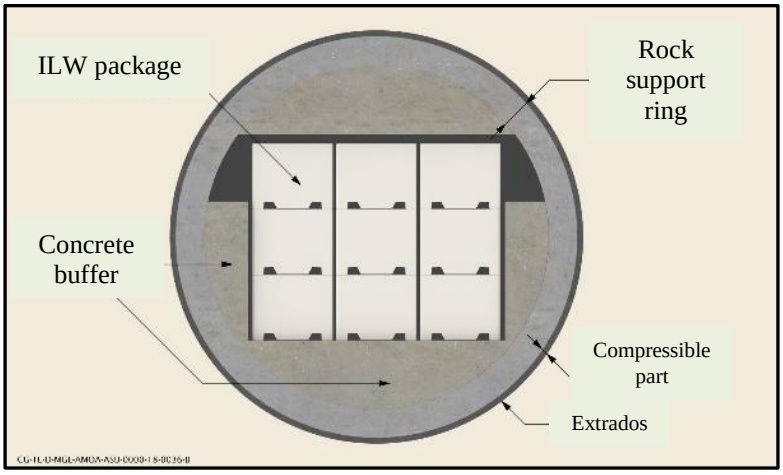

FIG. 7. Typical cross section of a disposal cell for ILW.

4. OPERATION AND REVERSIBILITY

Waste package emplacement in disposal cells will be performed online with its shipment from storage sites. Cigéo project does not include storage facilities except an industrial buffer as required by operational considerations. Disposal cells will be constructed progressively along with waste emplacement. During the operational phase of Cigéo, parts under construction and parts under nuclear operation will be as separate as possible to reduce co-activity induced hazards.

Waste delivery is intended to last over 100 years. Therefore the disposal process will involve at least four next generations up to the final closure. Over such a duration one can easily imagine that these future generations may want to reconsider some of the choices we are making today. This observation allows to better understand the reversibility as required by the French law. The last act in this field was voted by the French Parliament in 2006 [6]. This law specifies the modalities for the creation of a geological disposal facility with respect to this reversibility. It defines the reversibility as "*the capacity, for successive generations, either to continue the construction and then the operation of successive tranches of a repository, or to re-evaluate the choices previously defined or to change the management solutions. Reversibility is implemented by the progressive construction, the adaptability of the design and the operating flexibility of a deep geological repository of radioactive waste to integrate technological progress and adapt to possible evolutions of the inventory of consecutive waste, in particular to a change in energy policy. It includes the possibility of recovering waste packages already emplaced in a manner and for a period consistent with the strategy of operation and closure of the disposal facility*."

The reversibility includes a set of complementary provisions that constitute as many tools at the disposal of the future decision-makers.

4.1. Incremental development and progressivity of construction

Along with the delivery of waste and related construction of new disposal cells, the development of the underground facility will be very progressive during the operational period (Fig. 8). In the very beginning the size of the facility will be limited and it will increase step by step in a modular approach. This makes it possible at each stage to adapt the design of the next modules in particular to benefit from technical or scientific progress. The very first disposal cells will be used as part of the pilot industrial phase as implemented by the 2006 act: *"The operation begins with a pilot industrial phase to reinforce the reversibility and safety demonstration of the installation, in particular through an in-situ test program. All waste packages must remain easily retrievable during this phase. The pilot industrial phase includes waste package retrieval tests."* [6].

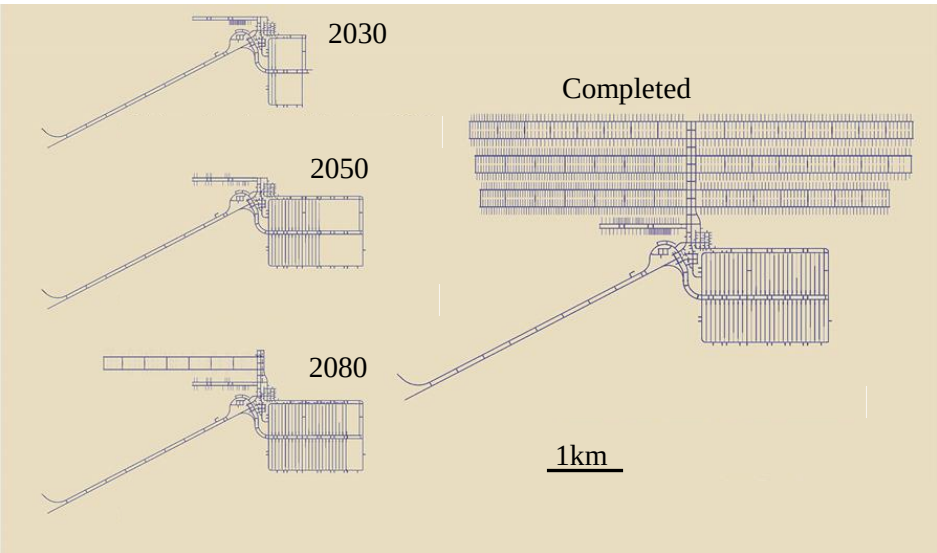

FIG. 8. Illustration of the progressivity of the development of the underground facilities (on the basis of the configuration studied in 2016 for the first version of the operational master plan [8]).

4.2. Flexibility in the operation

The progressivity of the construction along with waste delivery provides flexibility regarding the delivery time-schedule. The design of Cigéo also decouples to some extent the emplacement of the waste and the closure steps, which provides flexibility of the closure time-schedule.

4.3. Adaptability with regard to potential changes in spent fuel and waste management policy and strategy

A key issue is the capability of Cigéo project to provide for a high level of adaptability of the installations to allow for future evolutions in the technology as well as in the waste inventory. The application will include a set of adaptability studies. These studies especially aim at assessing the ability to adapt the facilities in the future to accommodate new types and/or new quantities of waste especially in case of changes in the French spent fuel and waste management policy and strategy. Relating assumptions are described in the "*reserve inventory*" which provides input data for the adaptability studies [7]. This includes in particular legacy low level waste in the case of difficulties encountered in the ongoing development of a specific disposal solution at shallow depth: graphite waste, low level bituminized waste. With regard to the French management of spent fuel, the most important issue is the potential once through disposal of some spent fuel in lieu of their reprocessing for the recycling of valuable material. The reserve inventory includes MOx and URe spent fuel currently stored or to be produced in the next decades. Provision is also made to investigate the potential accommodation of future unprocessed UOx spent fuel.

The reference design of disposal cells for spent fuel is similar to reprocessing HLW: spent fuel would be packed in steel thick canisters (one PWR type fuel per package). Disposal packages would be emplaced in horizontal micro-tunnels. For UOx fuels an alternate option based on larger packages has also been considered (4 PWR type fuels par container); it requires more complex disposal cells due to a larger diameter. For spent fuel, special attention should be paid to the length of disposal packages which impact the sizing of the handling equipment and access drifts. Particular attention is also to be paid to criticality (especially in the case of multiple fuel canisters). The higher volume of spent fuel compared to vitrified HLW results in higher amount of steel in the repository and therefore higher corrosion induced gas build up. Another issue relates to the higher thermal generation of spent fuel compared to reprocessing HLW due to its content in plutonium. The sizing of the disposal zone is to be adapted resulting in an increase in rock excavated volumes and the underground footprint of the repository.

4.4. Retrievability

Provisions are made in the design of the operational equipment, the waste disposal packages and the disposal cells to enhance waste package retrievability, in particular as long as the disposal vaults are not closed. Full scale demonstration tests were already performed on the surface by replicating the conditions of underground structures including large potential defaults. As provided by the 2016 Act, retrieval is to be provided during the pilot industrial phase.

4.5. Continuous improvement of knowledge

A continuous improvement of knowledge is to be organized along with the development of the project to support future decision making. A monitoring programme is incorporated in Cigéo design. Other research and development programs should also continue.

4.6. Transparency, participation of Society in decision making

Reversibility also implies the involvement of Society in the preparation of decisions at each stage of the disposal process. Periodic appointments with stakeholders would be organized to review the process. To do so a supporting document to be updated by ANDRA is the "Operational master plan" describing the status of the facility and the best view of the next phases of its development such as: new disposal facilities, vaults or cells to be constructed; new types of waste to be received and emplaced; closure steps. The plan clarifies in particular the next decisions to be taken. ANDRA already published a preliminary version of this plan to support ongoing concertation with stakeholders [8].

The process will continuously be controlled by the French Government under the supervision of the French Parliament. In particular the 2016 Act provides that a new law will be necessary to pass from the pilot industrial phase to the next phases of the operation.

5. PROJECT STATUS

At the current stage ANDRA has carried out large concertation with stakeholders and the public on various important topics to promote the co-design of the project where consistent. Along with the above mentioned operational master plan, concertation also addresses the insertion of the project in the Meuse Haute-Marne territory. Related topics include: water supply and effluent management; power supply; surface transportation of materials and waste, connection to existing road and rail networks, link to be created between the two surface facility zones; insertion in the local landscape, design and operation of excavated rock piles, architecture of surface buildings; etc. Dialogue with stakeholders and the public has been particularly developed in the fields of the environmental impact of Cigéo project and the health.

A national public debate is being currently organized in France on the management strategy of radioactive wastes and materials. This debate has been launched by the French Government and is being carried out under the auspices of the independent National commission for the public debate. Topics regarding Cigéo may include the management of spent fuel, the pilot industrial phase and the respective values of extended storage and geologic disposal.

As above mentioned, ANDRA is completing in 2019 the detailed design of Cigéo project. This takes into account the outcomes of the concertation with stakeholders as well as the 2018 outcomes of the review of Cigéo's safety option by the Regulator [3]. Among various technical topics under development, a particular issue addresses legacy bituminized waste which is intended to be disposed of in Cigéo. The reviewers have estimated that current Cigéo's design options do not make it possible to fully assess the safety with regard to fire hazard associated to this waste. Two routes are under investigation: a potential processing to make this waste more inert; a specific reinforcement of the design of disposal cells dedicated to this particular type of waste.

ANDRA is currently preparing regulatory files for administrative and technical instructions, public inquiries and authorisations. This includes public interest and application for the creation of Cigéo facilities.

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