Making nuclear waste governable

Deep underground disposal and the challenge of reversibility

Edited by Luis Aparicio

Springer

ANDRA
La maîtrise des déchets radioactifs

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Contents

Foreword **5**
François-Michel Gonnot and Marie-Claude Dupuis

Introduction **7**
Luis Aparicio

Nuclear waste: The meaning of decision-making **9**
Yannick Barthe

Irreversible geological disposal,
or the "clear-cut decision" model 11

Reversible geological disposal,
or the "stepwise decision" model 16

"Enduring" surface storage,
or the "iterative decision" model 22

Mere "technical" choices? 25

The French approach to reversibility in radioactive waste management **29**
National Radioactive Waste Management Agency (Andra)

The project to create a reversible deep disposal facility,
a socio-technical programme 29

The gradual inclusion of the demand for reversibility in the
geological disposal concept 32

Andra's design for the reversible deep repository 42

The place of innovation and research
in designing reversible deep geological disposal 52

The argumentative trajectory of reversibility in radioactive waste management **71**
Pierrick Cézanne-Bert and Francis Chateauraynaud

Introduction 71

Author-Actors in the controversy 75

The definitions (and motivations) given to the concept of reversibility 79

Development of the notion of reversibility in the corpus 84

An irreversible path? 89

Conclusion 95

Foreword

France has set the concept of reversibility at the core of its high-level radioactive waste management policy.

The French approach on reversibility stands out in that it grants future generations the possibility of going back on certain decisions made during the deep disposal process. It thus goes beyond mere waste package retrievability.

The concept of reversibility appeared in French law with the Waste Act dated December 30th, 1991, which mentions the possibility for disposal of being reversible or not.

Following fifteen years of research, particularly in its Meuse/Haute-Marne underground laboratory, Andra has demonstrated in the Dossier 2005 the feasibility of a disposal concept in which reversibility is possible for a period of at least one hundred years. As a result of the public debate on radioactive waste held in late 2005, the reversibility rationale has become a major stake in the very acceptance of deep disposal.

The Planning Act dated June 28th, 2006 establishes this rationale as a governance principle. Ever since, it has been a topic of thought, both for Andra scientists and engineers and for human and social sciences researchers. The effective conditions of disposal reversibility will have to be passed into law, before the geological repository licence is granted.

From an international perspective, Andra has played a leading role so that all the countries involved in deep disposal could share a common understanding for reversibility. A retrievability scale has been developed to this purpose that highlights the gradual aspect of the disposal process and which will help determine the associated decision-making models when moving from one level of retrievability to the next one. Dialogue is crucial in defining a project that will be robust, both in social terms and in scientific and technical terms.

Through this work, Andra invites readers to take part in the elaboration of a shared definition, one that will act as the foundation for the future French law on the reversibility conditions of deep disposal.

François-Michel GONNOT
Chairman of the Board, Andra

Marie-Claude DUPUIS
Chief Executive Officer, Andra

Introduction

This book is the result of a collaboration that began over two years ago between researchers from the social sciences and Andra engineers and natural scientists. Contributions to the various chapters have been discussed and enhanced, especially during the workshop and the interdisciplinary conference both held by Andra in 2008 and 2009 respectively. The French approach to reversibility will also once again be developed and open to debate during the international conference organised under the aegis of the OECD's Nuclear Energy Agency in Reims from December 14th to 17th, 2010.

Devoted to the application of the reversibility principle to radioactive waste management, this work is divided into three chapters. The discussion throughout the chapters deals mainly with the issue of how to implement the "definitive securing" of the waste, as stated by the French Planning Act dated June 28 2006, while providing a flexible management programme that keeps options open over time to make radioactive waste governable. The originality of this work is, precisely, to focus on the specific operational provisions being considered today to allow present and future generations to ensuring the protection of persons and the environment sustainably.

The first chapter was written by Yannick Barthe, researcher at the CNRS and member of the Centre for the Sociology of Innovation at the Mines ParisTech School. He examines the political qualities of technology, analysing the action modes related to the various management solutions being suggested. According to the author, different decision-making models – as well as specific approaches to safety – are inscribed within technical devices. In this regard, the introduction of the reversibility principle appears to be a radical innovation, both in technical and in political terms.

The second chapter reports on Andra's current positioning with respect to the project of a reversible deep disposal facility. It presents a recursive definition for reversibility, which relates scientific and technical development to the decision-making process. The envisioned repository is thought of on the basis of current knowledge, so as to ultimately be sealed in. How it precisely progresses in time will depend on intermediate decisions, which will be made according to regularly-performed assessments and the state of knowledge of the time, within the framework of a stepwise management and a modular repository design.

The third and last chapter, written by Pierrick Cézanne-Bert and Francis Chateauraynaud from the Pragmatic and Reflexive Sociology Group (GSPR) at the School for Advanced Studies in Social Sciences (EHESS), is based on the results of a study commissioned by Andra about the argumentation repertories raised by the concept of reversibility in France. The work especially looks at how this issue has been put forward since the late 80s as a condition for social acceptance of the deep disposal solution, particularly in the mediatic arena.

A shared, collective credit is addressed to the many people who made this book possible. Special thanks are owed to the authors Yannick Barthe, Pierrick Cézanne-Bert and Francis Chateauraynaud, and the representatives of the various teams in Andra who took part with me in the writing Bruno Cahen, Jean-Noël Dumont, Jean-Michel Hoorelbeke, Thibaud Labalette, Patrick Landais, Louis Londe, Stefan Mayer, Rodolphe Raffard and Sylvie Voinis.

Luis APARICIO
Andra Scientific Division

Nuclear waste: The meaning of decision-making[1]

by Yannick Barthe

In a memorable article published in the early 80s, technology philosopher Langdon Winner wrote there was nothing more provocative than the idea that technical devices possess political qualities (Winner, 1986). Thirty years later, things have changed in a big way: everyone now agrees that "no technology is neutral". This view has even become a cliché among works concerning scientific expertise, collective risk management, planning conflicts, and in a more general way what one could call the relationship between science and politics. However, beyond that kind of basic assertion, those works only usually give limited importance to technical devices per se. For instance, researchers in political science who deal with this kind of issue only very rarely spend much time on it; they would rather explore more familiar terrain and focus on the strategies deployed by various special interest groups, on the power of experts or on that which triggers mobilisation. More often than not, their objective is to show that *behind* every technical project there are dominant actors. We know very little about the political properties of projects per se, meaning the constraints they bring about and the resources they provide in terms of political action and, ultimately, the governing mode they are suited to. In a word, despite extensive literature these days about the problems

1 This chapter is a slightly modified version of a previous publication: Yannick Barthe, "Les qualités politiques des technologies. Irréversibilité et réversibilité dans la gestion des déchets nucléaires", *Tracés*, n° 16, 2009, p. 119-137.
I wish to thank Jacques de Maillard for his comments about the initial text, as well as Luis Aparicio for his comments about this version.

and conflicts that go hand in hand with technological development, we are sorely lacking in works on the *political sociology of technology.*

This is the kind of sociology I would like to contribute to in this article, positioning myself in the extension of the now-classical studies in anthropology of technics (Akrich, 1987, 1989; Latour, 1992, 1993). The approach will consist in shining the spotlight on technical projects per se, making every effort to render explicit the kind of politics and of decision-making model they imply. The idea is to study the technological concepts, seeking to clarify the problems which they are supposed to solve, the roles they cause the various actors to perform, the scenarios and assumptions they subsume and the way in which those assumptions are challenged during the controversy.

As a means of bringing this exercise to a successful conclusion, nuclear waste management in France appears to be a textbook case (Barthe, 2006). Indeed, the controversy about the fate of those cumbersome leftovers brings forward various technological options with highly different political properties, in that they suggest means of addressing uncertainty that are in every way in contradiction with one another, and they imply highly contrasted decision-making timelines. Throughout this controversy, one issue in particular focuses the debate: Should we favour an *irreversible* solution regarding this waste, or should we rather tend towards *reversible* solutions? In the following pages, I shall return to both those approaches in greater detail, by examining three technological concepts which have, at one time, been at the heart of the discussions and about which the issue of irreversibility and reversibility came up. I shall show that every one of those technical devices can be related to a particular conception of the political decision. Yet the passage from one device to another is far more than mere technological reorientation: it implies a deeply significant transformation in the action modes favoured in uncertain situations, of the kind which can moreover be seen in a host of other fields (Barthe, Callon and Lascoumes, 2009).

Prior to actually going to the heart of the matter, I think it is useful to specify the limitations of this approach right away, so as to anticipate any criticism it could legitimately raise. In this article, I shall deal very little with the "actors" who are generally found when analysing technological controversies. Accordingly, there will be virtually nothing about the identity of experts on the issue, nor about the kinds of initiatives conducted by protest groups, nor about the political procedures put in place to deal with the conflicts caused by nuclear waste disposal. All of those aspects should be taken into account to show the whole dynamics of the controversy. But such is not my purpose. To better highlight and stress the importance of the political stakes that exist within technical projects per se, it might be, to the contrary, more appropriate a method to deliberately put aside those aspects, and thereby to rectify simultaneously the asymmetry found in a great number of works on the topic.

Irreversible geological disposal, or the "clear-cut decision" model

At the inception of all the public controversy that has surrounded the issue of nuclear waste management in France for close to twenty years, there lies a precise technological concept, namely that of *irreversible geological disposal,* also sometimes referred to as *burying*. Unlike what it may seem, this is in no way an easiness solution, nor is it a last resort. Quite the contrary, it is a solution that has been thought out at length over several decades of research, and which is meant to bring an answer to the main problem with nuclear waste, that of its "lifespan".

Some radioactive waste, such as that coming from medical applications, is considered as being "short-lived", meaning that the duration of its radioactive decay is estimated at a few hundred years, by which time it should normally present no further hazards. But other kinds of waste, such as radioelements coming from irradiated fuel reprocessing, have a period that can sometimes exceed several hundred thousand years. The toxicity of this waste is such that should those radioactive materials come into contact with Man during those very long periods, it would have detrimental radiological consequences. The whole issue has been to find out how to protect ourselves from this waste and dispose of it securely for thousands of years.

An awesome question, actually, and this for at least two reasons. On the one hand, technological confinement possibilities offer limited reliability over the very long term; their lifespan is anyway much shorter than that of nuclear waste. One can condition, vitrify, embed and package it as much as one wants to delay dispersion, it will be to no avail: sooner or later, erosion will do its work and radionuclides will inexorably be released. On the other hand, during all this time, these hazardous repositories will require constant institutional monitoring, which not only represents a substantial burden for future generations, but also implies that they will be in a position to preserve the memory of the disposal sites and monitor them over such lengthy time frames.

To scientists who are working on the tricky issue of nuclear waste disposal, that assumption is tenuous, and their oft-repeated view is that it would simply be crazy to gamble on the "stability of social institutions" over such lengthy timescales.

So to guarantee nuclear waste confinement over thousands of years, something more robust and lasting than available conditioning materials had to be found, something that would also be more "stable" than "society", or at least less unpredictable then the behaviour of future generations. This is where the idea of using the confinement potential of certain geological formations of known stability came in, as well as the idea of keeping the waste inside a "geological safe" located at a depth of 500 metres, and whose main benefit would be its resistance to the passing of time. The geological structure would thus become a trap, isolating the waste from the environment once the packages had been destroyed by erosion. That was the birth of the geological disposal concept.

While the concept did not fully do away with the uncertainty caused by the staggering timeframe attached to nuclear waste, it did have the benefit of considerably simplifying the problem's features. Indeed, thanks to deep disposal, it was now possible to *dissociate* the issue of long-term safety of the stocks of nuclear waste from the hazards of history, from all that could happen "above ground", and ultimately to be unaffected by it. All of the uncertainty relating to the historical changes in institutions and to the behaviour of future generations could be transferred to another form of uncertainty and be considered as far less impervious to forecasting: the uncertainty with respect to geological formation behaviour. This transformation, or "condensation" of uncertainty (Shackley and Wynne, 1996), allowed us to go from an *undetermined* situation, where the future was entirely open and unpredictable, to one of *risk*, where uncertainty about the future could to the contrary be understood and controlled through calculations, forecasting models and scientific extrapolation.

At this point, it may be fitting to insist on the difference between both those situations, and especially what is implied by going from one to the other. The concept of risk has been so tarnished of late that we too often lose sight of that which distinguishes it from the concept of radical uncertainty or of being undetermined. Let us not forget that in a condition of radical uncertainty, we ignore the list of "possible worlds" at D+1, as well as, all the more, the probabilities of occurrence relating to each such worlds. For its part, a situation of risk assumes that the list of possible worlds at D+1 is known, and that probabilities of occurrence may be assigned to each of those possible worlds. Thus going from uncertainty to risk implies two kinds of operations: on the one hand, defining and finalising the list of possible worlds, and on the other, calculating their probability of occurrence. Whenever the issue of risk is raised, we often tend to only focus on the second kind of operation, that of probability calculations, even though the first kind of operation has far more heavy consequences: it is in fact a particularly powerful *framing* since it leads one to *close* the list of possible worlds to the benefit of world conditions that are known and "pertinent" from the perspective of probability calculations, and this to the detriment of possible worlds as yet unknown and undefined, for they have not been imagined or are unimaginable, as well as of possible worlds that may be imaginable but are resistant to calculations.

And that is precisely the kind of operation involved in favouring the geological disposal concept, for it replaces an infinite number of possible worlds with two perfectly identified situations, both of which can be forecast: either those geological formations are stable over the long term, or they aren't. By choosing an adequate geological formation, it is possible to make highly probable the occurrence for the first condition, so as to render the risk negligible.

Using geology did not have as a sole consequence the move from an undetermined situation to one of risk. It also led to set the identity of the "problem owners", to quote the notorious term coined by Gusfield (1981). Since responsibility for isolating nuclear waste was "*delegated*" to geological structures, their "spokesmen" became the only ones entitled to make statements on the issue. *Trusting* this geological safe implied trusting those in a position to speak on its behalf and to forecast its behaviour, meaning above all the geologists.

However, the plan to totally confine nuclear waste was to be confronted to new "anti-programs" (Latour, 1992), which it would be necessary to take into account. Among those, the possibility that future generations might unexpectedly run into waste disposed of deep underground, for instance during some subsoil exploitation, a scenario which challenged the radical dissociation between the "above ground" and the "underground". How, in such a case, could we warn them of the danger? At this point, many specialists began therefore to tackle this inter-generations communication issue, attempting to imagine universal alert messages, markers likely to be understood by future generations speaking a different language to ours (Nolin, 1993; Lomberg and Hora, 1997). But the problem with this kind of discussion is that it led once again to speculation on those future generations' abilities, while the aim of geological disposal was precisely to sidestep all that. This is why other methods allowing the inclusion of this anti-program were favoured: first, choosing geological formations whose benefit in the future appears nonexistent – granite or clay, for instance, rather than saline formations; then, preventing by all means possible any kind of access into the geological site, to seal it definitively, in an *irreversible* manner, so as to prevent future generations from having access into it, and this for their own safety. Protecting human beings from waste meant in fact protecting waste from human beings, by forestalling any violation of its sanctuary through accidental intrusion. In addition, this irreversible disposal solution had the advantage of meeting another anti-program, not an accidental intrusion in this case, but one with malicious intent, meaning an intrusion aiming at retrieving deep-stored radioactive material to use it as a weapon. In this respect, the benefit of sealing the site irreversibly was not only that we could harmlessly *allow ourselves to forget* about the waste, but more than that, that we would *foster this amnesia:* the faster any memory of the site was lost, the smaller the risk of its being used for military or terrorist purposes. During a parliamentary debate on the issue in 1991, the argument was clearly summarised by the then Minister for Industry, Dominique Strauss-Kahn:

> "If five hundred, one thousand or two thousand years from now, we want to avoid having some terrorist of the time retrieving that waste for criminal purposes, it is no aberration to think that if it is to be buried, it should be irreversibly buried, meaning in such a way that no one would remember exactly where the sites are."
>
> *Journal officiel des Débats*, Sénat, November 6th, 1991, p. 3 555

Far from being a harebrained idea, irreversible geological disposal thus provides an answer to precise problems. It appears as the result of a lengthy work in technical problematisation, meaning the transformation of problems of various kinds into challenges likely to find a solution through technology. By providing at last, following several decades of discussions and scientific research, a solution to the problem that was seen as "reasonable", irreversible geological disposal could meet ethical aspects with respect to equality between generations: as was mentioned by a committee of experts at a meeting on the issue in 1995, held by the Organisation for Economic Cooperation and Development's Nuclear Energy Agency,

> "from an ethical standpoint, including long-term safety considerations, our responsibilities to future generations are better discharged by a strategy of final disposal [i.e. irreversible geological disposal] than by reliance on stores which require

> surveillance, bequeath long-term responsibilities of care, and may in due course be neglected by future societies whose structural stability should not be presumed"
>
> *Nuclear Energy Agency* - OECD, 1995, p. 8

While this solution could be provided with moral qualities, it also had definite political qualities with respect to a traditional view of public decision-making in uncertain situations. On the one hand, using geology made a *rational* decision possible, meaning one based on risk calculations to help bypass and reduce the uncertainty, a decision rendered legitimate by scientific expertise. On the other hand, the irreversible nature of the disposal was in keeping with the idea according to which public action allows to "solve" problems[2], and this, in this particular case, in a definitive manner. This made it possible to confront nuclear waste's lengthy timeframe with the short timeframe of a decision that could resolve the issue here and now, *once and for all*. In short, geological disposal made possible a "clear-cut decision" (Callon, Lascoumes and Barthe, 2009), one that was unquestionable and irrevocable, and consequently one it would not be necessary to review at a later time.

Appearing as a robust solution, irreversible geological disposal reflected, and also permitted, a highly specific way of managing uncertain situations resulting from the externalities of scientific and technological development. Yet the fact is that this solution owed its sturdiness and consistency to the sole grouping of several imperative conditions. On the one hand, as stated earlier, it required acceptance of a delegation process and needed to show it trusted the ability of scientists to forecast the behaviour of geological formations over the long term. On the other hand, it demanded that the selection of possible world states permitting such forecasts be beyond discussion. In other words, one had to not only bet on geological formation stability, but beyond that, on the stability of all entities making up this possible and desired world: in this case, future generations incapable of monitoring or proposing new treatment methods, and in any event reluctant to the idea of having to manage this cumbersome heritage. It would take no more than one of those conditions to be missing, and the weakness of this technological scheme would immediately become apparent. Mere doubts being expressed about geological formation behaviour, or that of future generations, would suffice to put

2 For a critical appraisal of this view on public action, refer to Muller and Surel, 1998.

into question that fine consistency of irreversible geological disposal, and of the decision-making process it contains.

That is precisely what happened when the irreversible geological disposal project moved on to the implementation phase.

Reversible geological disposal, or the "stepwise decision" model

I have no intention here of making a detailed description of the conflicts which, starting in the mid-eighties, surrounded the implementation of irreversible geological disposal projects. Within the framework of this exercise in the political sociology of technology, I shall merely analyse the kinds of criticisms that were faced by this concept, and the displacements they produced, including in particular the invention of a new technological device, namely that of *reversible geological disposal*.

Criticism of irreversible geological disposal developed in two ways. The first concerns the risk assessment of this mode of management. In 1987, during the initial public information meetings held at preselected sites for a disposal facility, one of the main spokesmen for the National Radioactive Waste Management Agency (Andra) introduced the project thusly: "Man is incapable of guaranteeing absolute safety. Given that the ground has been stable for several hundred thousand years, scientists are entitled to extrapolate and say that the ground will not move for the next hundred thousand years"[3]. It is precisely this right to extrapolate which was first questioned by opponents to geological disposal. They went on to censure the scientists' pretentiousness in forecasting geological formation behaviour over thousands of years and in making confident pronouncements on the topic. Wasn't it a little presumptuous to assert that the risk may be deemed negligible when there are such considerable timeframes at stake? Through this objection, it was therefore the possibility of calculating risk, of assigning probabilities to various scenarios which was being questioned. This objection was to extend into experts' quarrels about how robust the predictive models and the parameters to be considered

3 Quoted by J.-P. Pagès, B. Bermann and J.-N. Ponzevera, About political and social problems raised by high-level radioactive waste disposal: local controversy between 1987 and 1990, Note by SEGP-LSEES, CEA, January 1991.

really were. Besides, it led geological disposal supporters to improve their methods, to make their analyses more sophisticated, in the hope of demonstrating how appropriate the device was and of reviving the trust.

But a second kind of criticism of geological disposal, in a way more subversive, was about to be expressed. The prime target was no longer the possibility of calculating risk, but the very usefulness of such calculations. The issue raised was that the "framing" required for this *mise en risque* operation usually spelt out the exclusion of certain possible world states, resistant to probability calculations. This was how the issue of a possible interest that future generations could have in keeping the option of retrieving nuclear waste at any time came on the table. Why indeed not make the assumption that those future generations should one day have more extensive knowledge, and effective technological means superior to ours, and thus be in a position, for instance, to *destroy* this waste, or even to exploit its industrial potential? Should we not, in that case, leave them the option to do so? Such an assumption was tantamount to reintroducing a philosophy of history into the debate, that of progress, which the irreversible geological disposal had decidedly brushed aside. Very long-term uncertainty, heretofore seen exclusively from the perspective of a threat, suddenly became synonymous of hope. It was this philosophy of history that had led some of the locals involved to say that "changes in technology will make us regret having definitively buried the waste. Burying waste is unscientific"[4].

From this debate, the justification of irreversible geological disposal backfired by putting all scientists and engineers defending the project in an untenable position: they were forced to claim full confidence in science, while at the same time justifying the irreversibility principle as a result of being unsure as to possible advances in research.

At the same time as it was helping turn the project's scientific legitimacy against the very same project, this assumption of progress in knowledge and techniques was also ruining its moral foundation. For a serious exploration of this scenario would inevitably lead to reopen the debate on the moral responsibility of present generations towards future generations. Irreversible nuclear waste geological disposal was indeed a way not to leave this legacy to our descendants,

4 See "Dossier réalisé par les habitants des Deux-Sèvres destiné à Monsieur le Premier ministre", October 30th, 1989, p. 12-14, quoted in "Les déchets nucléaires : un problème mondial", a file made by J.-P. Schapira, *Problèmes politiques et sociaux*, n° 649.

but it simultaneously was depriving them of this valuable asset called freedom of choice, which it was vital to preserve if future generations were, should it be required, to retrieve the disposed waste to give it a new destination. In a word, a *reversible* solution had to be favoured.

This was a hard blow for irreversible geological disposal and all of its supporters, meaning for most of the experts on the issue. Especially since things would not get easier over time. In December 1991, following the initial conflicts over the project, an act was passed which postponed the final decision to the benefit of a fifteen-year research programme devoted to studying other options, including reversible disposal. However, within this research programme, irreversible burying was still the dominant solution. But during the 90s, prospection campaigns to find new sites suitable to geological disposal began once again being confronted to claims in favour of reversibility. This demand was then transferred to the national arena by elected officials in the areas concerned, who demanded a review of the act in order to prohibit irreversibility, soon followed by some ministers. They ended up winning the day: in December 1998, the Government released a communiqué announcing that nuclear waste management policy would from now on clearly be considered with a reversibility rationale, while reminding in passing that "the condition of acceptance for decisions is related to their reversibility", and that it is "crucial that future generations not be bound by decisions that have already been made and that they be in a position to change their strategy according to any technological and sociological changes that may have occurred in the meantime"[5].

Would this redefinition of nuclear waste management policy mean abandoning geological disposal? One might have thought so at first, given that this device had entirely been designed to allow for a definitive confinement of the waste, prohibiting by definition any possibility of later retrieval.

Yet, and surprisingly so, the geological disposal concept was going to resist, to soften the blow, but not without having to redefine its parameters so as to take into account this new constraint: it was no longer a question of irreversible burying, but one of *reversible geological disposal*.

5 Report on the conclusions of the inter-ministerial meeting of December 9th, 1998, regarding nuclear issues (fuel-cycle backend and nuclear transparency)

Engineers and scientists at the National Radioactive Waste Management Agency would modify the disposal project's technical design so as to make a later retrieval of the waste possible. They would do their utmost in order to guarantee reversibility and thus comply with the government's injunction. To say that this new direction was being followed gladly would be highly exaggerated: they were loyal to a safety concept inherited from the previous idea and based on irreversibility, and they sometimes saw reversibility as a constraint that not only complicated things, but that did not really make sense in terms of safety. In fact, reversibility was often referred to as a "social constraint", one which they had to accept, even if unhappily so, in order to get the projects accepted. So the reversible geological disposal concept would be considered to be a useful compromise, in that it mostly helps improve social acceptance for the device.

But to those supporting this device, it is obvious that the compromise can only be temporary. Once again, the reversibility principle is fundamentally contrary to the long-term geological disposal concept: by taking this principle to its logical conclusion, one loses all of the benefits attached to this solution, especially the right to forget which it provides, and the dispensation it grants with respect to post-closure monitoring. Thus reversibility in geological disposal is necessarily *limited in time*, and it is therefore the initial concept, that of final and irreversible disposal, which will ultimately have the last word. And this, let me say it again, on sheer principle. Yet not just that: it does indeed appear that deterioration caused by evolution of the geological environment and of the packages stored there, as well as other problems like hydrogen emissions or the presence of water, will *a priori* make applying the principle of long-term reversibility difficult, not to say impossible. Any would-be retrieval of the waste will be more and more complex to undertake, even less and less possible, as time goes by. Unless new discoveries during the next two or three centuries allow us to dispense from such a device, reversible geological disposal will little by little, through successive steps, turn into irreversible geological disposal.

One might ask, in that case, what does this new geological disposal concept really change? Such a question is legitimate, since the preceding comments give a strange feeling of going back to square one. While the change is admittedly no breakthrough, it is significant. To begin, let us note that this period of reversibility, restricted as it is, does nevertheless provide an interlude of a few centuries. This period of time can be used constructively to monitor *on site* the behaviour of geological formations and waste packages, verify the accuracy of forecasting models and to intervene in the event problems were to appear. Besides, during all of that time, and as long as research on the issue continues, it is not unreasonable to think that new scientific discoveries will come about. They could be exploited to determine alternative solutions and to consider other possible world states. In other words, although irreversible geological disposal still obscures most of the horizon, it does not totally block the view. But the benefit of this device mostly stems from the approach's gradual nature. The final closure of deep disposal facilities, should they be sealed off, will happen through successive steps, and the outline of the final device will only appear very gradually. Thus the political quality of this technological device is to allow for a "stage-by-stage decision". Yet at every step it is possible to put an end to the process, or even to go back to the previous step, and in any event, to re-discuss the benefit of going to the next step. As social psychologists or certain organisation sociologists would say, this is a kind of "escalation of commitment", but one that is organised and controlled, which will gradually reduce the range of possibilities. The short timeframe of the "clear-cut decision" is confronted here with the lengthy timeframe of a decision-making process that is better adapted to the timelines involved in nuclear waste issues. Of course, it will not be possible to say the problem has been solved "once and for all", but only that "the solution is underway". This lengthy timeframe is supposed to help *play down the importance of* the decision and build its acceptability one step at a time. The difference with the previous model, and it is a fundamental one, stems from the fact that this acceptability rests upon the assessment of the device and its progress, to be repeated at every step. The condition for things to proceed smoothly is that every micro decision punctuating this stepwise process will be discussed. Thus, while the clear-cut decision model clearly relates to a concept of "delegative" democracy, this stepwise decision model marks a major move towards a "dialogic" democracy (Callon, Lascoumes and Barthe, 2009).

Yet things are not that simple, for this new technological concept is vulnerable. Being a hybrid device, meeting the reversibility requirement over the short term but still favouring irreversibility over the long term, it derives its strength from its capacity to combine both those radically opposite principles. But we have to be aware of how all this rests in large part upon some form of intellectual *bricolage* very much open to criticism. For instance, it is sometimes felt that some of the entities making up the "world" of this device are assigned interests and wishes that are programmed to suddenly undergo a metamorphosis with time: indeed, in the event that the process should lead to a final closure of the facility, future generations are as a result supposed to be wanting to retain their freedom of choice, and thus the possibility of retrieving the waste – which justifies reversibility – then, after some time has passed (for instance, after three hundred years), they are to the contrary supposed to be tired of bearing the burden of monitoring the facility, and wanting to entrust that chore to the geological formations, and to be ready to that end to abandon their freedom of choice. We have to admit that the rationale in such reasoning is somewhat wanting. But there is more: reversible geological disposal, meaning the possibility of going back on what was done and retrieving the waste, is not only limited in time but is also *regressive*: the longer the time, the less possible this retrieval will be, to ultimately become virtually impossible. Yet it is permissible for us to think that it is precisely with time that this reversibility will become especially interesting: if adequate research efforts are carried out, the chances of having alternative methods to process the waste are indeed likely to increase over the years. Consequently, the paradox here is that the more innovative methods become available and of interest, the less we shall be able to use them. Lastly, the stepwise decision model which matches this technological concept also has some failings. Waiting for the decision's importance to be played down thanks to this gradual approach is tantamount to assuming a little too fast that all of the steps are equal, meaning that all of the micro decisions to be made throughout the process will carry the same weight, contain the same level of commitment and imply the same level of closure. But one does not have to be fond of cycling to know that not all stages are equal, and one can easily imagine that some of those micro decisions will have a far more dramatic impact than others, will imply more commitment, and will as a result be more likely to polarise opposition. This is particularly true of the ultimate step, that of the final closure of the deep disposal facility, which will be terminating a process which could up to that point claim, to the contrary, to be open. In fact, one may well wonder whether the stepwise decision is not merely a way of postponing a final decision which will inevitably be a "clear-cut decision", with all of the political drawbacks it has, and whether this is not a case of running back in order to give a better jump forwards. Besides, this is what opponents of geological disposal seem to have understood very clearly, waving as they do the red flag of that ultimate step in the process in order to deflate the hoped-for playing-down benefit of this gradual approach towards a decision.

"Enduring" surface storage, or the "iterative decision" model

Even though it remains unseen and unsaid, there is in fact a point on which both even the fiercest opponents to geological disposal and its staunchest supporters agree: the concept of reversibility, as we have seen, does not fit well with that of burying. The way in which they differ centres on the manner in which to address this fundamental disagreement and to draw the consequences from it. For geological disposal supporters, still the solution "of reference" as a new act voted in 2006 reminded us, the contradiction is manageable as long as the reversibility is transitional, limited in time. The marriage may viably be considered as long as it is a paper marriage. To geological disposal opponents, it is precisely because it is of paper that the marriage should be denounced, and the acknowledgment of this antinomy between reversibility and geological disposal should on the contrary lead to immediate divorce. To one side, the case for reversibility comes second to the safety that the disposal's irreversibility must ultimately provide. To the other, the hierarchy is reversed: one must begin with the compulsory need for reversibility, and only then think about which technological devices respect it best.

In the debates surrounding this issue about the fate of nuclear waste, opponents to geological disposal will thus be doing their utmost to "radicalise" the demand for reversibility to such an extent as to make it untenable for geological disposal. Confronting political authorities and nuclear operators with their own speeches, which these days praise the flexibility of the approach and concept of reversibility – without however making too much of its limited aspect – opponents will ask the following questions: If you're really behind the reversibility rationale, why are favouring a valid solution over a limited period? And if the idea really is to have the possibility of retrieving the waste, why on earth make it so complicated by emplacing it 500 metres underground? Wouldn't it be more suitable to have it at hand, and rather than bury it, *store it above ground*?

To tell the truth, this surface storage is nothing new since it has long been implemented by the nuclear industry. Indeed, "long-lived" waste is stored on the surface for the time being. This is merely *temporary* storage. At this time, the most heavily radioactive waste, for instance, gets the benefit of pools referred to as "cooling pools", as well as daily dips intended to lower their thermal charge and thus make it possible to perform their handling and their final disposal. After enjoying the benefits of this cure for several decades, their fate is well mapped out: they will be transferred into the depths of geological layers, there to remain for eternity. So this storage is in effect a waiting device, prior to geological disposal, and it is in no way a "real" solution that could be an alternative. Yet that is precisely what opponents to geological disposal are calling for, meaning that this surface storage device should change status and become a bona fide total solution allowing to rule out any future burying. Surface storage as a temporary solution? No matter, all that is needed then is to *make the temporary last*, to accept it, to not assign it any limits in time, and to consider using, as per the current vocabulary, *"enduring" surface storage*.

This proposal for enduring storage, which was clearly articulated following the debates held on the issue in 2006 by the National Public Debates Commission, clashes so strongly with the postulates underlying nuclear waste management that those in charge of that policy have the hardest time taking it seriously. They immediately bring up two problems that appear to be insurmountable. First of all, "making the temporary last" at a surface storage facility is not something you can simply command: confinement properties of those kinds of facilities are limited over the long term. Given available techniques, the reliability of this kind of disposal for high-level waste cannot be guaranteed for a period exceeding one hundred years. While it is admittedly possible to seek to extend that period, leaks are bound to appear sooner or later. Second, to consider this device as an enduring solution once again causes a problem that we have repeatedly encountered in the preceding pages: it would in effect be tantamount to basing the safety of facilities on the monitoring abilities of future generations and betting on that notorious "social stability". The bet is far too risky, as history shows us, to be considered seriously. In short, surface storage can in no way represent a true solution.

At first sight, the argument seems convincing, but a closer look reveals a flaw. For far from reinforcing one another, both arguments cancel each other out. Indeed, if one accepts that surface storage can only have a limited "lifespan", specifically about a century, it becomes superfluous to make projections beyond that time period since one hundred years later, the issue of the fate of nuclear waste will necessarily have to be faced again. In other words, there is no need whatsoever to bet on social stability over thousands of years because the issue does not exist: there is a bet, to be sure, but now it only concerns the next one hundred years. At the end of that period, it will be up to future generations to decide whether or not to extend this bet for the following one hundred years, meaning whether or not to build a brand new, reliable surface facility, and so on and so forth. Consequently, far from being a weakness, the limited lifespan and the necessarily temporary nature of surface storage are precisely that which gives it its strength: indeed, the device offers the considerable benefit of avoiding the need of very long-term forecasts, of permitting some degree of myopia in that regard, and of banishing all predictions about the behaviour of geological structures as well as that of future generations. Suffice it to wager on the fact that the waste repository will be properly monitored and that the memory of the site will be retained throughout the facility's lifespan, meaning one century. One can always express doubts about this postulate, but in that case one would also have to consider refusing to site most hazardous facilities above ground, starting with nuclear power plants.

In any event, the enduring surface storage concept is clearly based on and permits new terms for decision-making and a new political stance in the face of uncertainty. While irreversible geological disposal and clear-cut decision-making resulted in shutting off the future and definitively taking the issue away from history, and while reversible geological disposal and stepwise decision-making led to initiating an interlude that was eventually meant to end, enduring storage for its part leaves the future open. The decision-making model sketched out by this technological model is neither that of a single decision, solving things once and for all, nor that of a succession of micro decisions meant to gradually bring up a final solution; it is rather like an *open-ended process*, one that has nothing linear about it but that becomes cyclical, repetitious, and with no previously-determined end: at regular intervals, a decision will have to be made, which should have a range of possibilities at least as wide as that which was available to the previous decision. To say that this decision-making process, which I shall call iterative, has no previously-determined end does not however mean to say that it should go on eternally: it is highly likely that at some given time, a century from now, or three, or fifteen, a decision will be made that will put an end to this cyclical motion. But such an assumption, and this is the significant point, remains open.

As is the case with both of the other concepts, the enduring surface storage concept and the iterative decision model which it introduces also have their limitations and generate their own constraints. Since this device is mainly justified by the fact it leaves future generations their freedom of choice, including that of suspending the iteration, such a choice needs to be possible, meaning that alternatives to storage should be explored. Which is equivalent to asserting there is a requirement to pursue long-term research on the issue, particularly regarding innovative processes that would allow the final "destruction" of the waste. This represents not only substantial financial sacrifices, which one might wonder whether they are worth it, but also requires maintenance of the competences in these fields. In short: to renounce a would-be "phasing-out" of nuclear energy. In addition, and still in keeping with the transferring of freedom of choice, it is not clear why one should deprive future generations of the option of choosing, if needed, geological disposal, whether reversible or irreversible. In that perspective, and quite logically, it becomes necessary to also pursue research on those options. This would not per se be a problem or a contradiction if one omitted to mention that the main supporters of enduring surface storage, and antinuclear groups in particular, also call for the abandonment of this kind of energy as well as that of research relating to deep disposal. That is the reason why, in the event that this device were to be examined seriously, it is not unlikely that we should witness another "backfiring" debate, where the storage option could win new supporters among those in charge of this policy, even though they have until now been very hostile, and it could inversely be under attack by those who were initially its spokesmen.

Mere "technical" choices?

Whatever happens with this controversy, and whatever decisions are made about the fate of nuclear waste, we could agree in concluding this analysis that it would be simplistic to call those decisions mere "technical" choices. Those decisions will be political, and this in two ways. First, as a standard analysis of decision-making processes would show, and as the preceding pages have suggested here and there, because they will be the result of power struggling, of conflicts of interest and of negotiations between the various actors taking part in the discussions on the issue. But they will be political also, and this is what I wanted to highlight here, by favouring a political sociology of technology approach, because it will involve devices enshrining a definition of what it means to make decisions. To choose this or that solution among those available is, indeed, inseparably choosing a mode of technical treatment of nuclear waste and sketching the outline of a decision-making style when confronted with the uncertainty relating to the long term. Both those levels are so intertwined that it would be useless to attempt to separate them in the analysis, and the assertion that "technology is not neutral" should in fact lead to a meticulous examination of that intertwining, rather than being put forward as a postulate to justify that one should focus on everything except, precisely, on the technical devices themselves.

What is at stake in this contrasting way of perceiving the relationship between what is technical and what is political obviously goes beyond mere theory. This touches on a possible contribution from social sciences to the debates about what technical choices are made, and to criticism in these fields. To accept, as is still often the case, to limit this contribution to a discussion on the expertise and decision-making modes, without taking into account the "technical aspects" in the issues that give rise to controversy, will often result in being stuck talking to a wall. For what is the use of wondering about decision-making procedures when they have already, for the most part, been set by the very characteristics of the technical devices? In such situations, one should therefore first of all focus on explaining those characteristics if one wants to help make the choices arguable. Far from fostering efforts to unveil hidden interests, the contribution of social sciences stems mostly from their ability to *clarify* the technical devices, by showing the assumptions they enclose and by articulating the criticism they elicit.

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The French approach to reversibility in radioactive waste management

by the National Radioactive Waste Management Agency (Andra)

The project to create a reversible deep disposal facility, a socio-technical programme

The legal framing of the reversible disposal concept[1]

The inclusion of the issue of reversibility in radioactive waste management goes back a very long way. It was already the subject of debate as experts from the 50s to the 70s were asked to compare sea immersion and land disposal (Barthe, 2006). The irreversible nature of immersion may have contributed to a gradual preference for disposal: confining waste in a place that is accessible to Man does preserve a certain reversibility. But nowadays, reversibility is fundamentally a social and political requirement. In France, it happens to be significantly related to the project to create a disposal facility for high and intermediate level long-lived waste (referred to as HLW and IL-LLW)[2] and is part of a specific process of juridical formalisation.

Socio-political demand for reversibility gradually materialised within the framework of the research and study programme set up by Act n° 91-1381 dated December 30th, 1991, which considered "the study of possibilities for reversible or irreversible disposal within deep

1 It should be noticed that "disposal" translates here the French term "stockage", which refers both to the process of disposal and to the disposal facility or repository.

2 See chapter 3 in this same work.

geological formations" for HLW and IL-LLW waste[3]. The mission was assigned to the National Radioactive Waste Management Agency (Andra) which, through the same act, became an independent public institution, and was asked to submit the results of its research 15 years later. Accordingly, in 2005, Andra demonstrated the feasibility of deep reversible disposal in a clay formation, mainly on the basis of experiments performed at the Underground Research Laboratory in Meuse/Haute-Marne.

The integration of reversibility in the technical concept of a deep repository was formalised further with the enforcement of Planning Act n° 2006-739 of 28 June 2006[4]. It prescribes that studies and investigations be continued on the reversible disposal of radioactive waste in a deep geological formation, with a view, after holding a public debate, for the relevant licence application to being reviewed by 2015. But before the accruing licence would be issued, a new law would be required to set forth the relevant reversibility conditions. Andra is therefore responsible for conducting studies and investigations not only to select a suitable site and to design a reversible disposal facility, but also, after a public debate, to file a repository licence application before a new law would prescribe the exact reversibility conditions of the facility[5].

This legal framing of reversibility defines a new innovation regime for Andra, in which the proposed solutions are built gradually according to the commitment from the parties involved. In order for a decision to be made, the Agency must find socio-technical compromises, which means solutions that are robust both in technical and social terms, and so become a major actor in configuring the possible choices. Indeed, at the crossroads of political decision-making and scientific and technical design, the definition of reversibility can only be established on the basis of a dialogue between actors from both those fields. This collective construction effort, which to date is merely at an intermediary stage, should act as a support for a drafting of a future law that will determine the conditions for reversibility in deep disposal.

3 Act n° 91-1381 dated December 30th, 1991 on radioactive waste management research.

4 Planning Act n° 2006-739 dated June 28th, 2006, regarding the sustainable management of radioactive waste and materials.

5 The Act dated June 28th, 2006 specifies that disposal reversibility must be ensured, as a precautionary measure, for a minimum duration no shorter than 100 years.

Determining conditions of reversibility through recurrence

The issue of the reversibility of a radioactive waste deep disposal facility is far from simple. The definition used by Andra at this stage – following mediation efforts between the aforementioned technical, political and social aspects – deals with the possibility of a stepwise and evolving management of the disposal process, leaving future generations a certain freedom to decide upon its progress. While reversibility is closely linked to the ability to retrieve stored packages, Andra's approach mostly concerns the ability to act on the disposal process itself. After decisions are made to create the facility and to commission it, the approach consists in providing the possibility of making several choices in management during the intermediary operational stages: either to proceed with disposal according to the predetermined scheme, or to procure the means for reassessment, or to bring about changes in the disposal process or else to reverse it, up to stored packages retrieval.

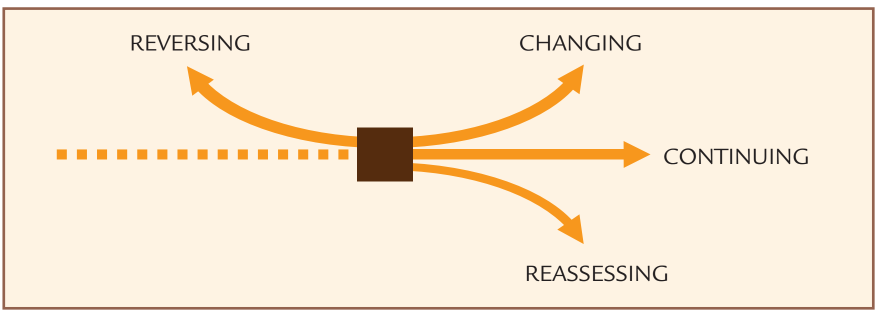

Figure 1 – The possible choices in management at each stage in the disposal process

The periods when a stage is passed will thus represent an appointment for the disposal managers and all stakeholders to meet in order to assess all available options at every stage, thus profiling a reversibility "through recurrence" on the basis of decisions that will have already been made.

The ability to intervene in the disposal process provides flexibility over time for passing a stage, and facilitates technical reorientation. It also gives subsequent generations the possibility of implementing intermediary sealing stages, while still verifying that the possibility of retrieving stored packages remains afterward. Lastly, it makes it possible to change the repository design concept as its implementation proceeds, according to advances in research, to experience feedback and to technical progress. In addition, the observation and monitoring of the repository will provide information about the facility's operations and how it matches forecasts, so as to be in a position to periodically re-examine the terms of reversibility.

The requirement for passive safety as the founding principle of geological disposal

The fundamental objective of radioactive waste disposal in deep geological formations is, as is indicated in the Nuclear Safety Authority's Safety Guide (ASN, 2008), to protect people and the environment from risks relating to the dissemination of radioactive substances and chemical toxics. The definitive securing of radioactive waste also aims at preventing or reducing the burden to be borne by future generations, in compliance with article 2 of Act n° 2006-739 dated June 28th, 2006. The disposal repository is therefore designed in such a way as to ultimately be sealed off and to guarantee the protection of people and of the environment through passive means.

This "passivity" of the repository in its post-closure phase represents the fundamental difference between disposal and storage. The favourable properties in the geological formation ensuring such passivity must be preserved. Full compliance with safety requirements of the repository is a prerequisite to defining the conditions of reversibility: the reversibility conditions must not compromise the operational or post-closure safety.

The gradual inclusion of the demand for reversibility in the geological disposal concept

A collective appropriation process

Generally speaking, on the strength of their conviction that geological disposal is safe, engineers and scientists in the field tend not to promote reversibility; to the contrary, they often see it as move towards unnecessary complexity, as expressing doubt with respect to geological disposal, or even as being antonymic to the concept. Andra's appropriation of the reversibility principle follows the realisation that it is not the direct result of a technical or scientific need, but of social demand and of a political choice, which engineers and scientists are duty-bound to accept. It is up to them, on the one hand, to seek and provide reasonable technical solutions to meet that demand, and on the other to express the technical and scientific limitations of reversibility, relating for instance to the durability of materials or to compliance with other requirements to be satisfied, particularly in terms of safety.

As mentioned previously, Act n° 91-1381 dated December 30th, 1991 introduces the idea of reversibility in parallel to that of irreversibility ("the study of reversible or irreversible disposal within deep geological formations"). Although the act generally prohibits any irreversible underground waste disposal (holders of an administrative authorisation must remove the stored waste when the authorisation period runs out, unless a new act prescribes otherwise), it is unclear when it comes to radioactive waste: is the idea to study two different views on disposal, or to consider on a sequential basis that disposal should initially be reversible, then to become irreversible once sealed off?

During the search for a site to establish the Underground Laboratory, starting in 1992, local stakeholders were consulted by MP Christian Bataille – Rapporteur for the 1991 act and mediator – and they expressed interest in the study on reversible disposal. During the 1997 public enquiries leading up to the licensing of the Laboratory, Andra also records that same interest. From that point on, reversibility gradually became a major issue.

At the end of 1998, when Andra was authorised to implement the Meuse/Haute-Marne Laboratory, a new light was shed on the notion of reversibility. At the Government's request, the National Assessment Commission (CNE) filed a report on reversibility in June 1998, following a series of hearings on the issue with various actors, including Andra. To the CNE, disposal reversibility includes "all of the technical and administrative measures allowing one to retrieve, if one so desires, matter considered as waste, in a safe way, and with a clear benefit to society". From a technical standpoint, the CNE thinks that the issue of reversibility cannot be separated from considerations regarding storage, and it suggests envisaging three main situations:

i. long-term surface or subsurface storage, the most simple, which is perfectly reversible, but which is necessarily bound to end with retrieval;

ii. geological storage that is convertible into so-called "reversible" geological disposal, with various decreasing levels of reversibility;

iii. so-called "irreversible" geological disposal, in which package retrieval, while possible even following the final sealing-off of the facility, would be extremely arduous.

In addition, Andra holds an international workshop on reversibility in November 1998, where it presents its new technical approach on reversibility, which goes beyond the sole idea of waste package retrieval:

- a stepwise repository management, with decisions to be taken at every phase;
- a gradually decreasing reversibility level throughout the phasing sequence (the levels are designated as "initial reversibility", "transient reversibility" and "possible reversibility";
- initial design options chosen so as to favour flexibility through stepwise management and the potential retrieval of packages (modularity, preservation of handling clearance of disposed packages, etc.);
- an identified objective for studies to be conducted: to assess how much time every reversibility level may be provided, especially the "initial reversibility" phase.

Lastly, in December 1998, the government decides to set the studies about disposal according to a "reversibility rationale". An ambiguity then disappears: the geological disposal concept to be studied by Andra will integrate reversibility, at least during its initial period.

Andra details its approach in the progress report it submitted in 2001. Without presenting any technical and scientific developments at that stage, Andra introduces the principle of an analytical reversibility method (based on the model of a safety analysis) and the interest of an "observation programme", associated with the reversible management of the repository.

In March 2001, the Underground Laboratory's Local Information and Oversight Committee (CLIS) holds a symposium on reversibility and its limitations.

At the international scale, a working group which was created under the aegis of the OECD Nuclear Energy Agency (NEA) and in which Andra participates, establishes a distinction between retrievability and reversibility[6], with reversibility corresponding to the "possibility of reversing one or a series of steps in repository planning or development at any stage of the programme". This does involve the reversibility of decisions in the programmes of definitive waste disposal. Hence, it has a broader scope that the strict retrievability, which is defined as "the possibility of reversing the waste emplacement operation itself"[7].

The experts of NEA's working group insist strongly on the fact that the safety and the security of a repository in service and over the long term must not be compromised by design or management measures designed to facilitate waste retrievability.

Andra's approach is part of those international considerations, which it has contributed to develop, and so it defines reversibility as the possibility for progressive and evolving steering of the disposal process, thus providing future generations with a freedom of decision with respect to the process.

On that basis, Andra develops in its Dossier 2005 its own notion of reversibility from a scientific and technical standpoint, with:

- innovative technical solutions, whose development involved reversibility as a creativity factor (Andra, 2005b);
- a detailed "analysis" of the reversibility provided by those technical solutions, consisting in assessing at each step of the disposal process:
    i. the ability to intervene on the pursuit of the process,
    ii. the ability to retrieve packages,
    iii. the ability to bring changes in the design, and settling on a possible duration for reversibility of 200 to 300 years (Andra, 2005c),

6 The group associated the distinction between "retrievability" and "reversibility" to a stepwise disposal approach in accordance with a cautious and flexible process, which would correspond to "good practices".

7 The NEA (2001) uses the definition for disposal that was chosen by the International Atomic Energy Agency (IAEA): "final disposal" means "the placing of radioactive waste inside a repository with no intention of retrieving it". Even though the intent is not expressed, it is possible to retrieve waste packages from a final geological disposal facility.

- the design of a repository monitoring programme, the analysis of the possible reversibility motivations having reinforced Andra's conviction that it forms an essential component of reversibility; Andra introduced notably the principle of "reference" structures integrating a detailed instrumentation (Andra, 2005d).

The Dossier 2005 submitted by Andra led to several scientific assessments. The review conducted by a group of international experts under the aegis of the NEA, at the request of the French government, concluded that the report provided a viable approach to reversibility without any compromise relating to operational or long-term safety. While recognising that package retrievability was also required in other countries and could be fulfilled through other concepts than Andra's, the group of international experts noted that Andra's concepts were more oriented towards reversibility than the others, over relatively long timescales. However, the group also noticed inconveniences, which were not considered to be redhibitory, regarding the reference of a 200-300-year period. The CNE indicated, among other things, the need to enhance the credibility of the reversibility notion. On the other hand, ASN does not considered that the readily retrieval of waste packages was guaranteed over two to three centuries, as advocated by Andra; it also indicated that if a given reversibility phase were to be selected, Andra will be required to confirm the possibility of retrieving waste packages during that phase, while meeting the safety and radiation-protection objectives. Nevertheless, the assessors did not cast any doubt on the principle of Andra's proposals. And neither were those proposals questioned during the government's follow-up to the public debate on waste management organised by the National Commission on Public Debate (Commission nationale du débat public – CNDP)[8].

On that basis, Planning Act n° 2006-739 dated June 28th, 2006 sets forth disposal as the reference option for long-term waste management and imposed that the deep geological repository be designed in full

8 Following the public debate, the Government insisted on a gradual and controlled implementation of disposal. Regarding reversibility, the CNDP report (CNDP, 2006) states that "studies conducted by Andra on reversibility help to provide the concept with a genuine technical explanation taken into account in the disposal process. This would allow for waste retrieval for a period of at least one century without the need for substantial operations. (…) However, it remains that this issue should be further investigated by Andra. Questions and reactions heard on this topic within the context of the public debate have shown that dialogue about this topic should continue, in order to share all of the possibilities offered by reversibility and to make the concept more concrete and understandable to the general public".

compliance with the reversibility principle. Given the aforementioned constraints, engineers and scientists are expected to offer precise and robust proposals, both in technical and in social terms, in order to help legislators rule on the conditions of reversibility.

To that end, in parallel to conducting scientific and technical work, Andra seeks to develop a dialogue between all stakeholders, within the framework of an approach based on information and consultation[9], through advanced discussions on an international level, and by including human and social sciences in its scientific programme. The latter especially materialised in both the scientific meetings that were to prepare this work: a workshop in October 2008 (Andra, 2009b) and a multidisciplinary conference in June 2009 (Andra, 2009c). Further discussions also helped establish Andra's approach to reversibility during the period following Act 2006.

Andra has presented its approach on reversibility to the Parliamentary Assessment Office for Scientific and Technological Choices, to the CNE and to the Nuclear Safety Authority. The approach has also been presented during a meeting held in October 2009 by the High Council for Transparency and Information on Nuclear Security, with the presence of representatives of the CNE and the ANCLI (National Association of Local Information Committees on Nuclear Activities).

Locally, Andra has initiated discussions with the Local Information and Oversight Committee (CLIS) for the Meuse/Haute-Marne Laboratory, and in particular with their thematic commission devoted to reversibility[10]. Andra was also involved in a session devoted to the topic during the *Forum on Stakeholder Confidence* (FSC), held in Bar-le-Duc in April 2009.

9 The approach proposed by Andra in terms of information and consultation was delivered in 2008 to the National Public Debate Commission, to the High Committee for Transparency and Information on Nuclear Security, to the National Assessment Commission, to the Nuclear Safety Authority, to the Local Information and Oversight Committee for the Bure Laboratory, to the Prefects and County Councils of Haute-Marne and Meuse. The approach was also reviewed during discussions with the Parliamentary Assessment Office for Scientific and Technological Choices, the Economic, Social and Environmental Council, as well as Members of Parliament and local elected officials of Haute-Marne and Meuse.

10 Several CLIS members also took part in the multidisciplinary conference held by Andra in Nancy in 2009. The CLIS also focused on the issue of "practical reversibility from the viewpoint of territorial players" within the context of work performed by the French group in the European "COWAM in Practice" project (2007-2009).

In addition, several discussions about reversibility have taken place on an international level, especially with the "Reversibility and Retrievability" working group set up by the OECD's Nuclear Energy Agency under Andra's initiative. Within this context, an international conference has been programmed in Reims from December 15th to 17th, 2010.

Planning Act n° 2006-739 dated June 28th, 2006 also sets down storage, for which Andra has been mandated to conduct the studies and the coordination with disposal, as being complementary to disposal[11]. Accordingly, Andra is investigating innovative technical storage options to help contribute to disposal reversibility. Yet storage cannot, over the long term, be a substitute for disposal. In terms of safety, the originality of the disposal concept is its ability to ultimately ensure the protection of people and of the environment in a fully passive manner, without any human intervention.

Ensuring compliance with the safety requirements of the repository

Normative and regulatory frameworks

The regulatory background governing French nuclear facilities calls for periodic re-examination of each facility's safety, to be conducted by operators and the Nuclear Safety Authority, typically every 10 years following commissioning. Thus there is no definitive given for operators in terms of safety.

Those re-examinations are performed within the framework of ongoing safety and design improvements, which relies on taking into account operational and monitoring feedback, and on an analysis of scientific and technological advances. New assessments are also performed whenever a substantial modification in the facility is being considered. For instance, this would include an important change in design of the repository, or a sealing-off stage of part of it. Every re-examination could lead to reassessing the

11 For instance, high-level waste must be stored for at least 60 years prior to disposal, in order to manage its thermal release, which is very high initially but which decreases in time. The availability of storage facilities thus provides flexibility in decision-making. In addition, having storage capacity will allow acceptance of waste packages in the event they were to be removed from disposal.

flexibility available over time in view of a decision to seal off the repository.

In any event, Act n° 2006-739 dated June 28th, 2006 calls for reversibility for at least a one-hundred-year period. During that time, protecting operators, the public and the environment will mobilise active systems needing to be monitored and maintained. This implies the possibility of transferring knowledge between successive generations about the design, the operation, the maintenance and the behaviour of the facility. Keeping systems active (such as ventilation) may however prove difficult over time as some structures may age. This will eventually mean restrictions on the length of the period during which sealing may be postponed, particularly that of the disposal cells. Such restrictions will be determined during safety re-examinations.

Reversibility also implies the possibility of deciding to remove the packages. The risks appertaining to package removal operations must be assessed and reduced. The same safety approach applies as for package emplacement operations: therefore, designing reversible disposal also involves studying risk prevention in package removal operations, working out monitoring actions relating to retrieval, and the limitation of impacts from package removal incidents, as well as possibilities of intervention. This leads to setting up protection measures for workers and for the public during retrieval, with similar objectives to those of disposal. The state of the packages and the structures at the time of retrieval will also have to be taken into account.

As indicated previously, the repository is designed so it can be sealed off and remain safe after sealing. Safety operations required after sealing rest upon entirely passive provisions: the repository requires no maintenance or human intervention to play its protective role over the long term. Technical options and actions relating to reversibility should therefore not alter those long-term safety operations.

Hence, reversibility is governed by safety requirements, as follows:

- with regard to operational safety, every review shall include a reassessment of the available flexibility over time, as well as closure modalities;
- progressing ahead through the successive steps of the disposal process and the evolution of the structures will modify the package-retrieval modalities over time;
- long-term safety requirements limit the designer's freedom when seeking reversible technical solutions.

The safety approach

Deep geological disposal safety rests above all on choosing a site with a thick layer of clay of very poor permeability, stable over time, geologically simple and well-known. It also relies on a detailed knowledge of the packages[12], together with their inventory, location and characteristics, while noting in particular, the very-long-term containment capability of nuclear vitrified embedding matrix. Lastly, safety rests upon the very design of the disposal facility, the underground excavations, the means used in handling the packages and the organisational procedures of disposal.

The design and organisation of the repository include several defence levels with regard to risks in order to ensure that, if any level were not fully operative, the following levels would trigger an alert and allow for corrective actions. The first defence level consists in technical solutions to manage uncertainties and to prevent incident risks; the second involves the implementation of repository-monitoring activities, whereas the third level deals with the specification of suitable means to mitigate the effects of potential incidents; lastly, the possibility of intervention is also implied with a view to correcting an incidental situation, if need be.

At the first defence level, Andra identifies as systematically as possible the uncertainties about the behaviour of the repository and of its environment over both the short and long terms. In order to reduce the impact of those uncertainties, favourable design measures are integrated in the architecture of the repository, including notably conservative margins in the specifications.

Risks involving defects and incidents are analysed methodically. Similarly to the management of uncertainties, the objective is to minimise risks in design options by implementing processes designed to reduce occurrences, by using well-known and reliable technologies and by adding margins and redundancies as required.

At the second defence level, the safety approach includes the enforcement of monitoring actions. Waste packages will be monitored and controlled before disposal, which implies not only the waste itself, but also the containers and the matrices in which they will be conditioned. The monitoring system calls upon multiple control

12 The decision to transfer a package from a surface storage facility to an underground disposal cell involves a prerequisite review of the waste-package acceptance application in order to authorise its take-over by the disposal facility.

modes, the same way as for waste packages being received at Andra's disposal facilities in the Aube district. Measurement and analytical means will be enforced in order to verify the normal operation of disposal installations.

In spite of the precautions being taken, however, it is necessary to envisage as early as the design stage the potential occurrence of failures and incidents. The approach consists at that point in identifying the suitable technical or organisational means to limit effects on workers, the population and the environment in case of accident (third defence level).

If, following an incident, the repository were to be in a situation, which is unacceptable in the short term or would be unacceptable over the long term, the possibility to intervene should be envisaged (fourth defence level). An intervention consists in implementing technical and organisational means to correct the situation and restore the safe operation of the repository. In the case of non-conforming or damaged packages, the intervention might extend, for instance, to retrieving and removing them from the repository, if necessary. Hence, Andra has planned to test demonstrators of handling equipment under altered conditions. The best solution will be selected in relation to the risks and the expected advantages with regard to every foreseeable option.

Disposal design and organisation feature several levels of defence against risks, so that if one level were not to be fully operational, the next levels could alert and compensate. The first level of defence consists of technical solutions to mitigate uncertainties and prevent the risk of incidents, the second level is the setting up of disposal monitoring procedures, and the third level determines means to reduce the impact of would-be incidents; lastly, it is possible to intervene to correct unexpected difficulties should it be necessary.

So the safety approach matches the demand for reversibility in several ways:

- a cautious approach to manage risks and uncertainties;
- the monitoring of the facilities;
- the possibility of intervening, which can stretch to retrieval if needed;
- regular re-examinations to decide whether to continue the process, to conduct new operations, to improve disposal management or to design future systems (for instance, disposal cells, or monitoring means).

Andra's design for the reversible deep repository

In 2009, Andra proposed reversibility options that orient the study and research phase in view of the public debate and in preparation for the repository-licence application[13]. Those options constitute also the base for exchanges with assessors and stakeholders.

As indicated previously, Andra's approach to reversibility aims at allowing the possibility to intervene on the disposal process itself. Decisions will be made at the various stages in the operation, with intent to continue the disposal process, to maintain it as is or to revert to a previous stage. Figure 2 illustrates those choices.

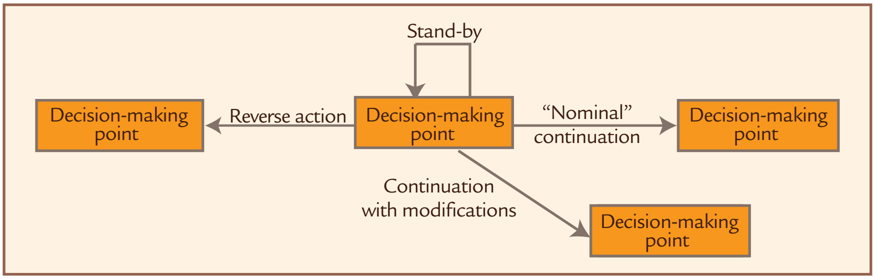

Figure 2 – The choices available at every decision-making stage

Andra has defined three major functionalities: the ability to perform retrievals, the ability to act on the disposal process, and the ability to bring changes in repository design. Those functionalities are included in concrete technical provisions intended to facilitate a would-be retrieval of packages, and within a decision-making process linked to the gradual development of the disposal facility and to its sealing-off in stages.

Technical provisions to facilitate package retrieval

The capability to retrieve waste packages that are already disposed of is the functionality corresponding to the most concrete form of reversibility. As mentioned above, it may be designated by the term

13 In compliance with Decree n° 2008-357 dated April 16th, 2008, setting the obligations with respect to the National Radioactive Waste and Matter Management Plan.

"retrievability". It relies notably not only on the durability of packages and disposal structures, but also on the specifications of adapted operating processes.

Waste packages are placed inside disposal packages, which are assigned safety functions and operational functions. Given their durability, disposal packages will facilitate any would-be retrieval operations over one century.

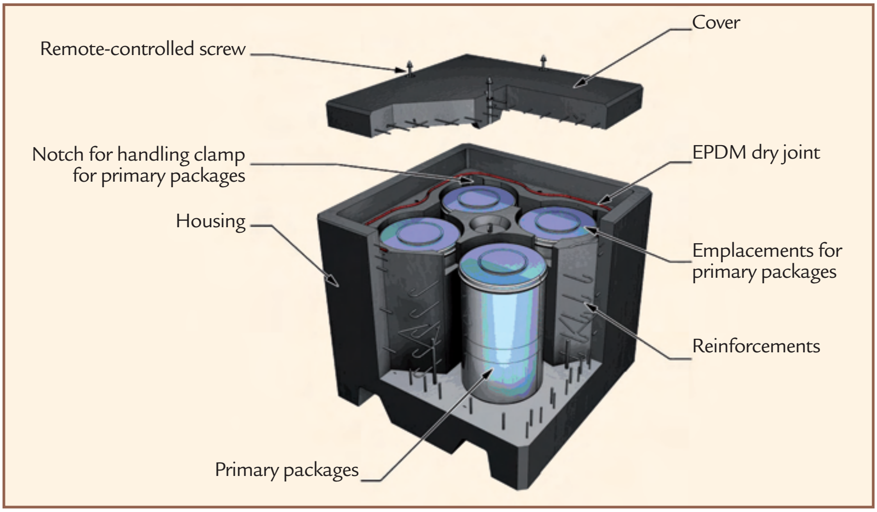

Figure 3 – Disposal package designed for intermediate-level long-lived waste (IL-LLW)

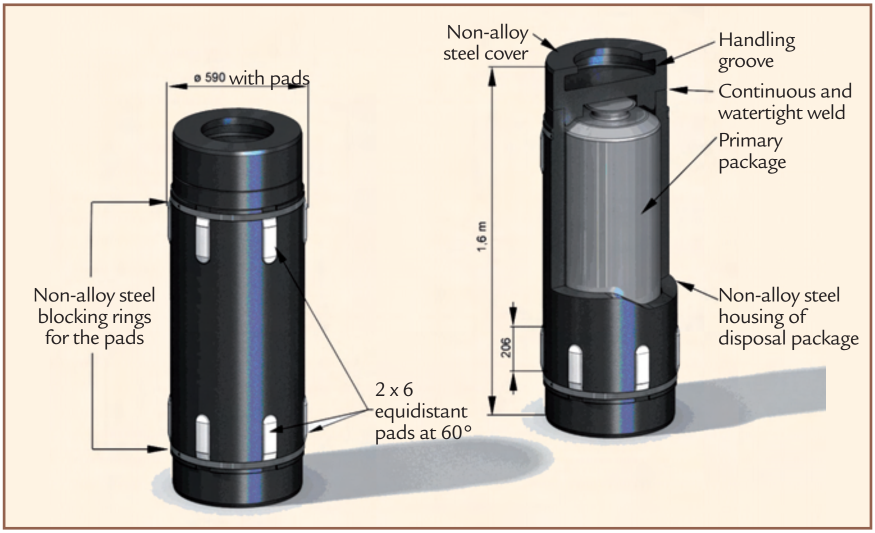

Figure 4 – Disposal package designed for high-level waste (HLW)

Once made up in this way, the disposal packages are placed inside dedicated disposal cells, as shown in Figure 5 (intermediate-level long-lived waste) and Figure 6 (high-level waste). Disposal packages will be taken down into the underground facilities and transferred into the cells using a reusable "cask" to protect staff from radiation. Each package will be removed from the cask at the cell entrance and transferred to its disposal location. Package retrieval may be performed by inverting the process.

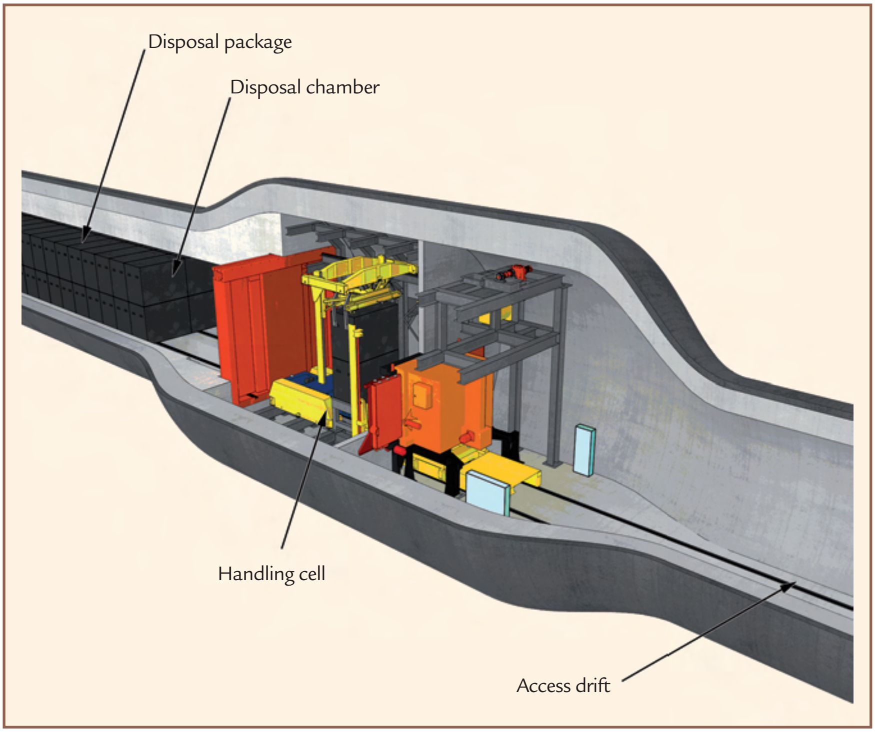

Figure 5 – Disposal cell for IL-LLW packages

The durability of packages and structures is closely associated with the constituting materials, the fabrication processes and the environmental conditions of the repository. Hence, the thickness specifications integrate the phenomenological evolution of the repository.

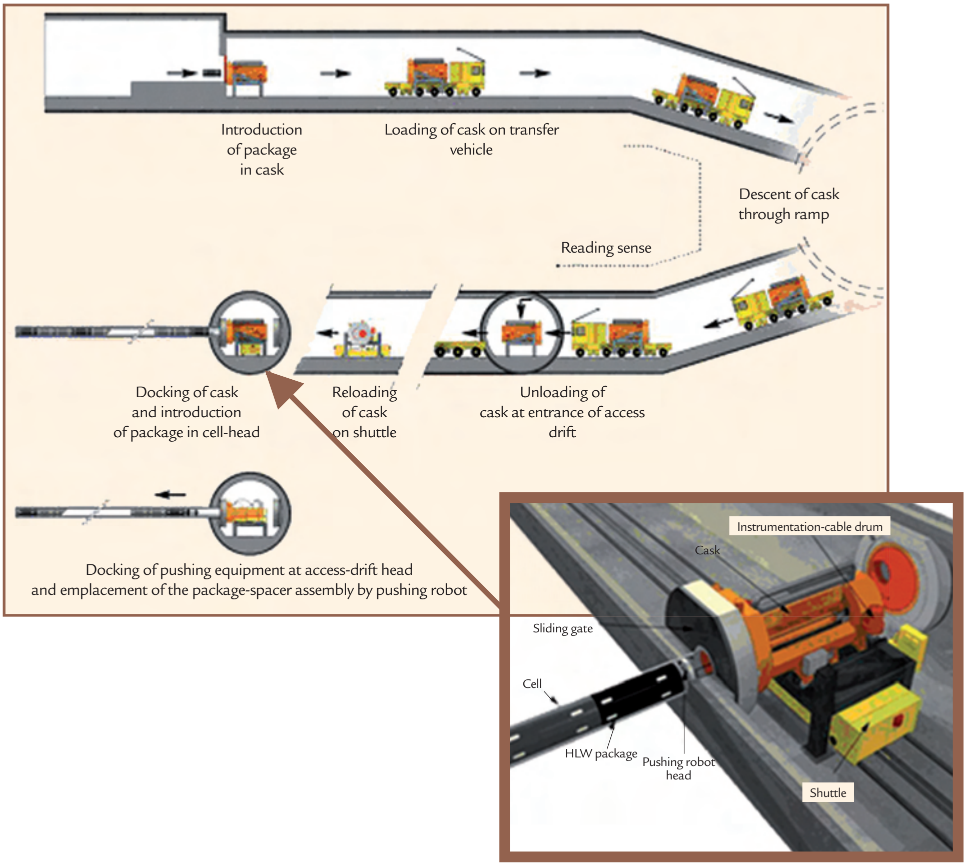

Figure 6 – Disposal cell for HLW packages, and the transfer process

The design provisions adopted to facilitate any would-be retrieval operations are the following:

- determining compatible handling interfaces;
- keeping sufficient clearances, while minimising residual empty space;
- controlling environmental conditions inside the cell so as to preserve physical package integrity and the clearances.

Tests are being performed at the Underground Research Laboratory in Meuse/Haute-Marne to assess the behaviour of materials over time within a Callovo-Oxfordian argillite environment. Underground technological tests are also underway to assess implementation procedures in the coating of structures. Surface technological tests allow the assessment of package retrieval possibilities (see Figure 16, page 59).

A certain storage capacity is required to manage packages that could be removed from disposal, but reversibility does not demand that the storage capacity match the total volume of waste placed under disposal[14]. It is also worth noting that some highly exothermal waste requires cooling-off storage prior to disposal.

Stepwise implementation of the repository

The figure below (Figure 7) shows the various parts of disposal at the end of the one-century operational phase:

i. surface facilities, required in receiving transport packaging, in preparing disposal packages and for the works;
ii. links between surface facilities and underground facilities, to manage the flow relating to construction and nuclear operations (operators, equipment, shielded casks to transfer disposal packages, building materials, muck removal, ventilation, networks);
iii. underground facilities, broken down into zones adapted to each waste category (intermediate-level long-lived waste/high-level waste). The use of a sloping ramp helps dissociate some surface facilities from the underground facilities (for instance, those relating to package reception). The shafts are particularly adapted to functionalities relating to ventilation and the transfer of materials.

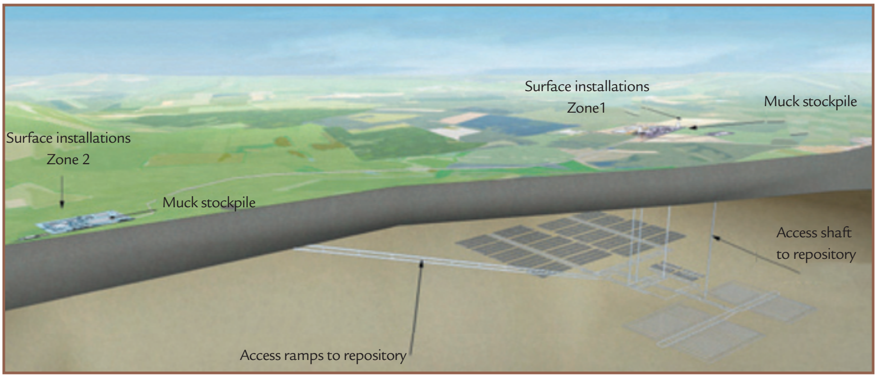

Figure 7 – Overall disposal architecture

14 It is indeed inconceivable to retrieve packages at a faster pace than they are being put into disposal. So from a technical perspective, a few years would be sufficient to create new facilities, possibly in successive batches, which would be able to manage packages that would be removed from disposal. The storage facilities could be established at the disposal site or remain at the production sites (La Hague, Marcoule or Cadarache in particular).

The repository's modular architecture makes it possible to consider development in successive batches – each one corresponding to about ten years of operation – and for spreading decisions about the construction of new modules, as shown in Figure 8, for instance[15].

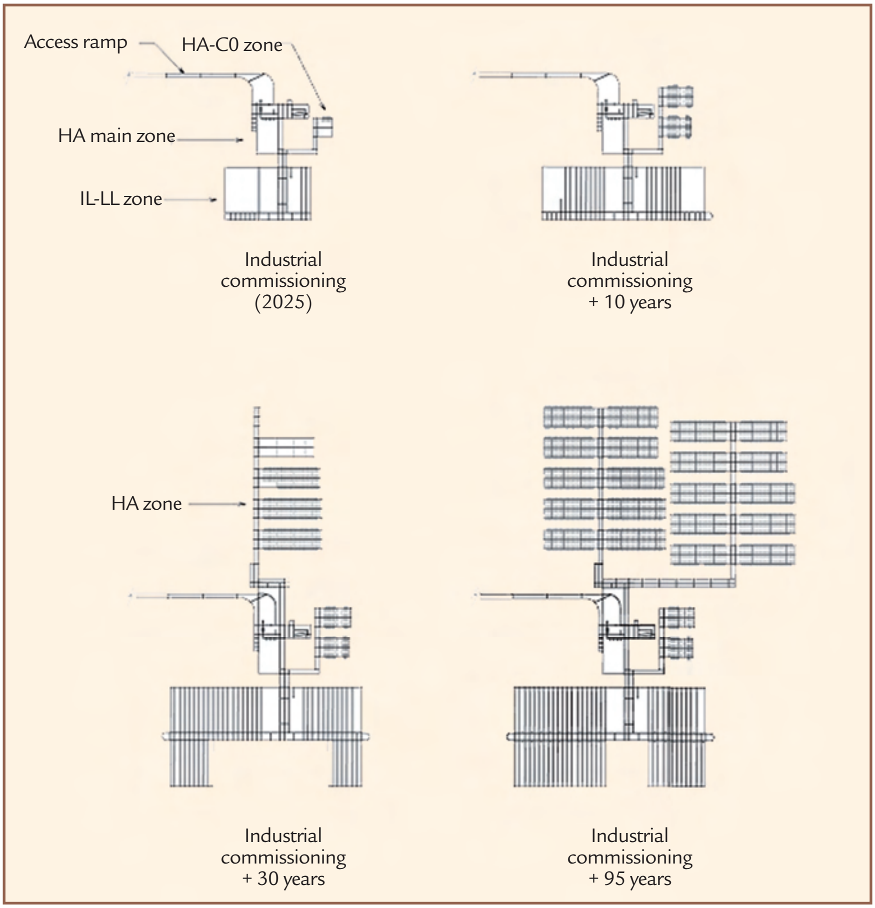

Figure 8 – An example of gradual development of the repository

The repository is designed so as to allow conducting package disposal operations and new module construction concurrently, following the commissioning of the first cells. Dedicated underground linking

15 The illustration assumes the earliest possible disposal of highly exothermal HLW waste, and uses basic scenario data from the 2009 sizing inventory model.

galleries would help separate works-related flow from that relating to nuclear activities. Figure 9 shows this.

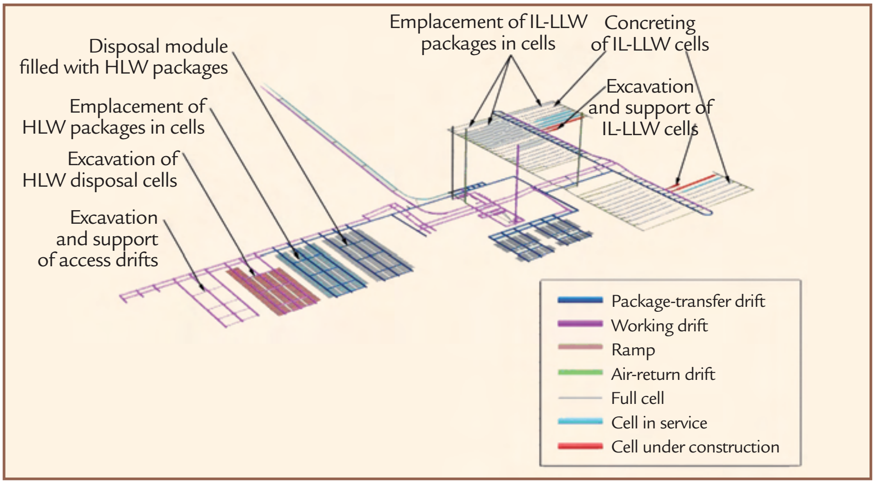

Figure 9 – Concurrent construction and disposal operations

The progressive development of the repository provides experience feedback throughout the process. It provides the possibility of bringing changes to the design of new structures, as explained earlier. A regular reassessment of the terms and duration of reversibility may be considered, on the basis of the observation and monitoring of the structures, in the same way as any nuclear facility operator must conduct regular reassessments of the safety of his facility[16].

16 Article 29 of Act n° 2006-686 dated June 13th, 2006, on nuclear transparency and security, specifies: "Operators of standard nuclear facilities shall periodically conduct a re-examination of the safety of their facility, taking international best practice into account. This re-examination should allow an assessment of the facility's condition with respect to applicable regulations, and an update of the assessment of any risks or drawbacks existing at the facility to the detriment of those interests mentioned in paragraph I of article 28, taking into particular account the facility's condition, any experience acquired in the course of operations, any changes in knowledge, and the regulations applicable to similar facilities. (…) Safety re-examinations shall be conducted every ten years. However, the authorisation decree may stipulate a different periodicity should it be justified by the characteristics of the facility".

Sealing off the disposal structures stage-by-stage

The repository is designed so it can be sealed off, and so lighten the burden of waste management for future generations. Accordingly, in completing the application for authorisation, the facility's safety will have to be understood in the light of the various stages of management, including that of final sealing off.

In order to provide flexibility in running the disposal process, Andra has proposed that the sealing-off may be implemented gradually. The more it is decided to pass on to the following sealing stage by deploying seals or by closing down galleries, the more the level of retrievability is gradually lowered[17]. Intermediary steps could thus be identified, for instance with regard to the sealing of a module for a family of waste or a disposal zone. Once the structures linking surface and underground facilities are sealed, this will mark the beginning of the site's institutional control phase, and the obligation to maintain the memory of the repository. Yet, in accordance with article L542-10-1 of the Environmental Code, only an official Act may authorise final sealing off of the disposal facility.

Concerning the HLW cell, the following intermediate states have been identified:

- filled cell: packages are emplaced in the cell. A metal closing plug with a radiation-protection shield is installed. The operating sliding gate, constituting the opening and closing device of the cell, is dismounted and replaced by a panel to which pipes for sampling and controlling the entrapped air in the cell are connected;
- sealed cell: the cell is sealed by a swelling-clay plug buttressed with a concrete plug. Monitoring may continue through parallel boreholes to the cell for temperature-monitoring purposes. Sensors may also be maintained inside certain "reference" cells;
- backfilled module: all equipment is removed from the access drifts inside the module and those drifts are backfilled;
- sealed zone: all equipment is removed from the access drifts inside the zone and those drifts are backfilled. Seals are installed between modules. Other sub-zones may remain in operation.

17 The long-term limitation of water flow within the disposal structures and of mechanical warping in the argillite contributes to long-term disposal safety, which must be provided in a totally passive manner. Sealing it off would make any would-be package retrieval more complex, ultimately requiring the implementation of mining and nuclear technology.

Concerning the IL-LLW cell, the following states have been identified:

- filled cell: packages are emplaced in the cell and radiation protection is ensured by concrete blocks. Ventilation is maintained;
- sealed cell: the airlock is backfilled with concrete, which in turn will serve to buttress the seal. Ventilation is interrupted. The sealing assembly may include provisions for a potential ventilation restart and the feed-through of observation/monitoring cables;
- backfilled module: a seal is set in place;
- closed zone: all equipment is removed from the access drifts inside the zone and are backfilled. Other zones may be operated.

The observation and monitoring of the disposal structures will help verify their behaviour and provide enhanced knowledge for the decision-making process. The observation/monitoring system should be adapted as the development of the repository proceeds and along the various sealing stages. Certain control cells may be equipped with more specific instruments.

In order to facilitate dialogue with the stakeholders, Andra has proposed the development of a Retrievability Scale at international level, within the framework of the NEA-coordinated "Reversibility and Retrievability" project. This scale designates various levels of retrievability, which also correspond to the gradual addition of passive safety elements. It is possible to set forth decision-making milestones matching the passing of levels in the scale.

Stage and location of waste	*Passive safety*	*Active control*
1. Waste package in storage	Conditioning	Active management of storage facilities
2. Waste package in disposal cell	Engineered disposal cell	Active cells management
3. Waste package in sealed disposal cell	Sealing of cells	Maintenance of access ways
4. Waste package in sealed disposal zone	Sealing of cells acces	Detailed records and Institutional control
5. Waste package in closed repository	Sealing of surface-underground access	Maintaining records and Institutional control
6. Distant future evolution	Radioactivity decreasing	Memory

Figure 10 – Project for a chart of retrievability levels

This scale may be used to indicate the choices available at the various decision-making stages, as shown in the following figure.

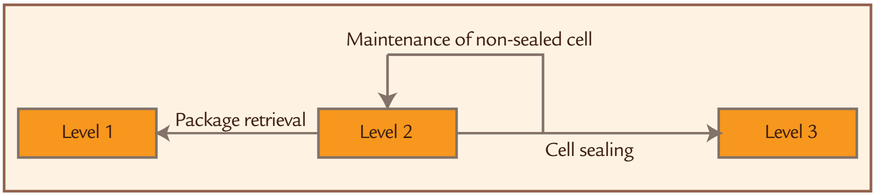

Figure 11 – Available options for non-sealed cell (level 2)

The range of possibilities open to each decision-making stage results mainly from the initial design, the decisions made earlier in the process and the data obtained from observation/monitoring. The following diagram shows a possible sequence through time of the various management decisions concerning a group of packages, from level 1 (surface storage) to level 3 (sealed cell).

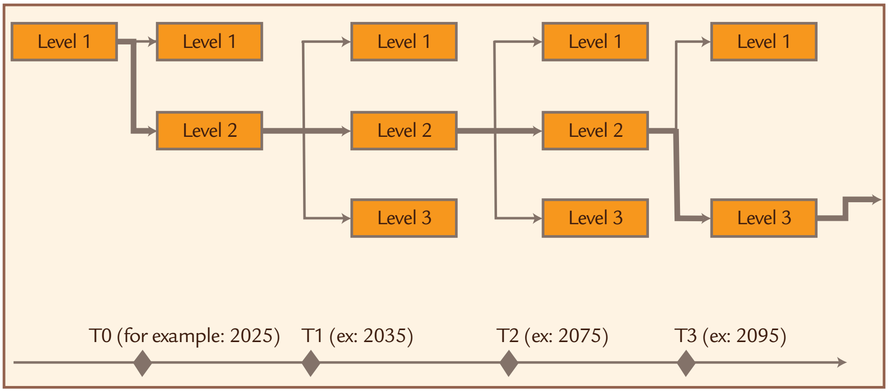

Figure 12 – An example of a possible sequence of decisions concerning a group of packages

The place of innovation and research in designing reversible deep geological disposal

Showing and demonstrating reversibility

A reversible deep disposal facility is a most uncommon kind of facility, and this for many reasons. The timescales involved, which imply evaluating long-term safety on a scale of a million years, lend it a unique character. The material technical solutions included at the very design stage are assessed prior to construction. Few other kinds of facilities have been studied in such depth, and few can boast the incomparable wealth of scientific and engineering knowledge underlying the description of expected progress.

Scientific knowledge, digital simulations of experiments performed on site and technical test models are marshalled to show and demonstrate that reversible management is realistic and achievable. A range of uncertainty is taken into account in the design, which is likely to gradually progress through knowledge acquired during construction and then throughout operations. Accordingly, it appears necessary to monitor the condition of the structures, and more broadly the progression in the processes affecting the repository during the reversible operational phase. This will be conducted on the basis of appropriate observation/monitoring strategies, in order to verify and confirm the modelling and to add useful precisions for the progressive management being implemented. Experiments and tests performed on site (or under comparable situations) will also be needed to support engineering evolutions. Lastly, the design and analysis of the lifecycle of the facilities should include a socioeconomic assessment, especially with a view to balance converging constraints (reversibility, safety, operational optimisation, funding) and to take technical advances into account for future structures.

The scientific and technical demonstration of reversibility

Studies and researches implemented in relation to reversibility include in particular the description and phenomenological analysis of the repository's evolution, the studies and tests on package retrieval processes, and the development of means of observation/monitoring for the disposal facility.

The constraints imposed by the geological environment

Geological settings are characterised by properties (mostly mechanical) that partly determine reversibility, whatever kind of infrastructure is involved. If we consider the three major types of rock studied worldwide to host radioactive waste repositories (granite, clay and salt), we realise that their respective behaviour gives rise to a highly different positioning with respect to the concept of reversibility. Their progression after structures have been dug out shows a wide range in convergence kinetics[18]. Granite, mostly studied in Scandinavian countries, is a hard rock whose motion will be very limited. Quite the opposite (see Figure 13), saliferous formations, favoured in the United States for instance and under study in Germany, show high convergence rates. Argillaceous rock, particularly studied in Belgium, Switzerland and France, shows intermediary behaviour, mostly depending on its mineralogical composition (the carbonate or quartz content, for instance).

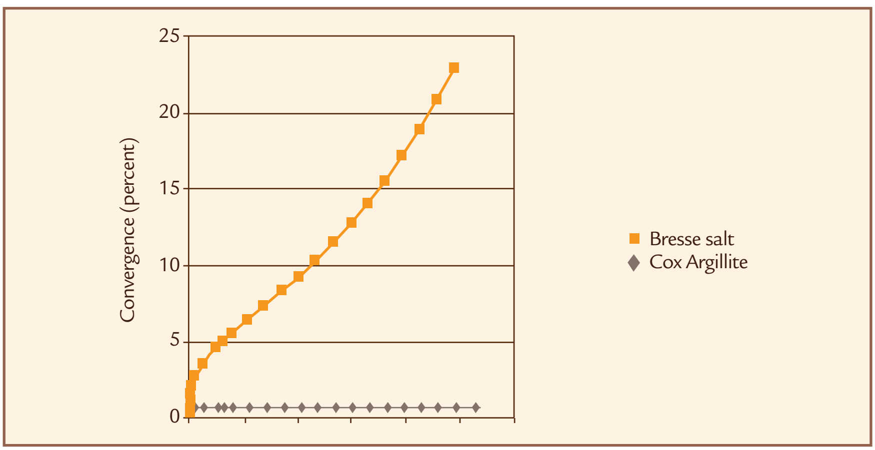

Figure 13 – Convergence rate for saline and argillaceous rock

Accordingly, the choice of a site for disposal, and especially the nature of the hosting rock – for its properties in confining radioactivity – will very significantly determine the reversibility features. In Andra's case, the site in Meuse/Haute-Marne was above all selected on the basis of characteristics such as the layer geometry, its homogeneousness, its

18 The convergence phenomenon refers to a decrease in void volume by time unit, which tends to gradually shrink in underground infrastructures in the absence of lining or supporting structures.

poor permeability and the propensity of the clay materials it contains to retain radionuclides. It was only afterwards that it became possible to adapt the design of the infrastructures, their geometry and their sizing to the environment's characteristics while taking the requirement for reversibility into account.

Assessing the behaviour of the repository

In order to assess the conditions required to conduct operations relating to reversibility, it is necessary to describe the progress of the disposal system during the initial centuries, including the operational phase and an initial post-sealing period (about 100 years).

To that end, Andra has set up an approach called the Phenomenological Analysis of Repository Situations (APSS). This original approach consists in analysing all phenomenological processes of thermal, hydraulic, mechanical, chemical and radiological origin that will over time affect repository components (cells, galleries, wells, etc.) and the geological environment. In order to understand a complex system involving a variety of often paired phenomena, the analysis is based on the segmentation of the disposal facility's lifecycle in situations assigned to the various disposal zones. This segmentation, made possible by the repository's modular design, also takes the various stages in its management into account.

Initially, the APSS was mainly focused on the post-sealing phase (Andra, 2005a), before turning more towards the operational period in disposal (Andra, 2009a), so as to deal with the various conceivable reversibility time periods, using sliding chronograms. This approach helps to obtain a sequential chart showing, for a variety of operational or choice configurations concerning reversibility, the modifications affecting the various repository components and indicating which processes come into play.

The phenomenological analysis of disposal situations in *Dossier 2005 Argile* had already described the processes pertaining to the operational phase and had highlighted the importance of transitional processes and strong phenomenological couplings during the period. By focusing the analysis on the operational phase and adding the scientific and technical advances achieved since 2005, the APSS-Operations (Andra, 2009a) confirms the major phenomenological findings relating to the one-hundred-year operational and reversibility period. Thus, the APSS-Operations provides characteristic timeframes to assess possible areas of flexibility in the disposal process management. It contributes in the identification of parameters to be used within the context of disposal observation/monitoring and also describes the likely physical and chemical condition of components located inside the sealed-off areas in the disposal facility, should it be decided to regain access to it.

That period of a few hundreds of years is undoubtedly the hardest one to describe. Many transient processes and strong un-balances between the repository and its environment occur. Beside the geomechanical aspects relating to the nature of the host rock mentioned above, some hydraulic, thermal and chemical processes already affect the repository as early as its opening or as early as packages are emplaced. Their consequences on reversibility vary greatly. In the case of hydraulic processes, for instance, the ventilation of drifts and IL-LLW cells induces a desaturation of the structures and of the surrounding rock. Consequently, it delays the return of water and, in turn, the chemical-alteration processes of the cement structures, as well as the potential dissolution of radionuclides. As a first approximation, it is possible to consider that the preservation of a readily access to IL-LLW packages (and therefore of reversibility) constitutes a chemical-stability factor for that type of cells.

Things are different with HLW cells (vitrified waste). Indeed, those are mainly associated to metal materials (steel). If we keep those cells open (or at least easily accessible), the oxygen there will be partly renewed and will contribute to faster steel alteration. Handling would be curtailed over time and the chances of retrieving packages from an unscathed lining would be reduced. This phenomenon is shown in Figure 14, where one can see that oxic corrosion occurs 30 times faster than anoxic corrosion.

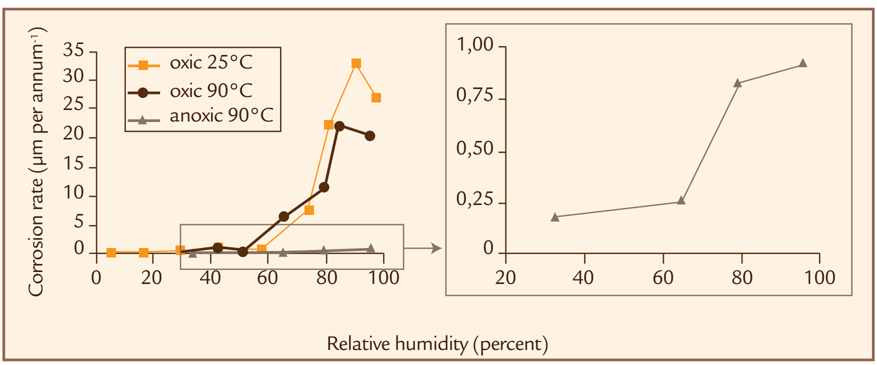

Figure 14 – The impact of the presence of oxygen on steel corrosion speed: the role of relative humidity and temperature

Other examples can be mentioned. The voids left between various components to facilitate package placement or retrieval operations are significant elements with respect to reversibility. They are also a source of relatively complex scientific problems. Mechanical constraints pertaining to the nature of contacts between materials and chemical reaction specifications are likely to happen within an environment made discontinuous because of voids. The filling of those voids (caused by the weight of the soil) will cause interfaces between materials that are fairly unpredictable. This inevitably introduces uncertainties when modelling the complex processes occurring at those interfaces.

Another phenomenon concerns hydrogen produced in the course of disposal. There are two processes contributing to hydrogen production:

- the anoxic corrosion of metallurgical materials, especially in HLW cells;
- the radiolysis of organic components found in certain IL-LLW waste packages.

While the first process is mainly expected once the structures have been sealed off, the second begins as soon as the packages concerned are placed under disposal. Given the materials used and hygrometric conditions inside the IL-LLW cells, the hydrogen produced could migrate outside the packages fairly quickly. The ventilation being considered for IL-LLW cells will facilitate hydrogen dilution in the air and its evacuation in such a way as to ensure at all times a concentration below a volume of the order of 10^{-3}%.

This will not be the case in the event of an accidental halt in the ventilation or once the IL-LLW cell has been sealed. Any reactivity during operations or any return within the context of reversibility would then require knowing the composition of the gaseous mix inside the cell, in order to prevent any risk of explosion when put in contact with oxygen in the air[19].

There are currently no sensitive, lasting sensors with which to measure the breakdown in hydrogen content inside an IL-LLW cell (see below). So at this stage in the studies, there is an obligation to perform digital simulations to describe physical-chemical conditions and the distribution of hydrogen content. The following figure shows an example of a simulation (Figure 15).

19 In the event of an accidental halt in ventilation lasting a few days, primary package specifications limiting hydrogen production to 10 litres per annum will nevertheless avoid explosive conditions for the period required to restore ventilation.

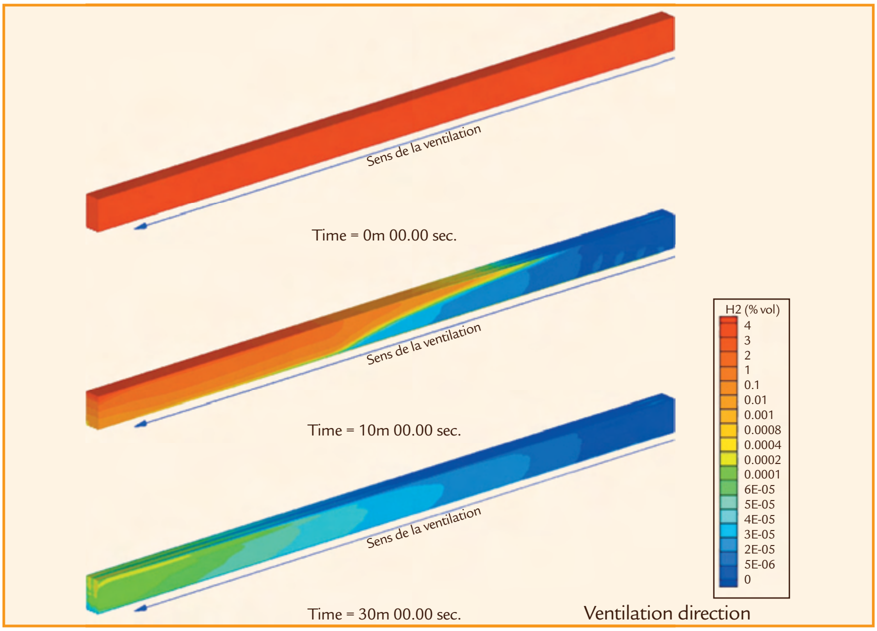

Figure 15 – Variations in hydrogen concentration inside the longitudinal clearances of an IL-LLW cell during ventilation return following a stoppage of several months (simulation).

It is therefore apparent that preparing for reversible disposal management sometimes requires additional means to mere experimentation or observation in order to possess the elements necessary for implementing reversibility in specific contexts.

Technical studies, scientific experiments and technological tests

Technical studies relating to reversibility mostly concern:

- the design of underground structures and disposal containers so as to ensure their durability;
- the handling processes to place the packages, and to retrieve them if needed;
- storage capacity requirements to manage any packages that could be removed from disposal;
- package control procedures prior to disposal;
- observation/monitoring means (see infra).

Those technical studies are conducted in close relation to safety studies during operations and following the sealing-off of the repository.

In-situ experiments, integrated from an engineering standpoint, which are representative of the constraints mentioned above and include a sufficient timescale, are contemplated with a view to reproducing the constraints imposed by the behaviour of the repository and especially the mechanical, thermal, hydraulic and chemical processes, which – as it should be noted – are particularly complex during the first hundreds of years. A special mention should be made about full-scale thermal tests on the designs to be launched in 2012 for HLW cells. Otherwise, the behaviours at the interfaces between argillites and materials, for instance, are the subject of studies in surface laboratories to be confirmed in situ and for which tests were set in place in 2009 in the Underground Laboratory. An experiment also deals with the study of the impact of ventilation-induced desaturation over a drift section.

Technological tests are also conducted at the MHM-URL with a view to controlling construction processes of underground structures and to following the behaviour of those structures. In that regard, the experience feedback from tunnels monitoring shows the profits to be drawn from observations over time.

Another approach consists in implementing different types of experiments for testing the repository components that may affect the management of reversibility. Such tests may include, for instance, alteration tests for different materials (steel, concrete and glass), or ventilation effects on the mechanical properties of the rock and of its ground-support. Those experiments must contribute in providing sufficient elements to demonstrate – this time on the basis of experimental results, physical models and digital simulations – what are the potentialities and limits of reversibility.

At this stage in the project, there is substantial scientific understanding of the main processes likely to affect disposal during a reversible operation[20]. Various scenarios have been studied, leading to homogeneous and physically consistent results. Even though the

20 This understanding is mostly the result of work performed by Groupings of Laboratories (GL) set up by Andra, which help combine the efforts of a number of international research teams such as the British Geological Survey, the CEA, EDF, the Institute of Fluid Mechanics in Toulouse, the Laboratoire Environnement Géomécanique et Ouvrages, the Institute of Geology and Geochemistry of Petroleum and Coal at Aachen University, the Laboratoire des Matériaux et des Structures du Génie Civil, the Laboratoire de Mécanique in Lille, the Laboratoire de Mécanique des Solides, and the Laboratoire d'Étude des Transferts en Hydrologie et Environnement at Liege University. In addition, Andra takes part in the project devoted to gas migration in waste disposal (FORGE), which began in 2009 as part of the European 7th Framework Programme in Research and Development (FPRD), which includes experiments in 4 underground laboratories.

scientific work rests upon a growing number of experiments and modelling or demonstration operations, it is crucial that it be confirmed on a constant basis during construction and operations, through an efficient observation and monitoring system. By constantly integrating additional data corresponding to situations that are sometimes specific, and by reporting on periods of increasing duration, we shall possess an increasingly effective tool to manage the details of reversible operation.

Technological tests are also carried out in surface installations. In the framework of the ESDRED European project, Andra has built a demonstrator for testing the package emplacement/retrieval process for HLW. Tests covered an overall system (haulage and docking shuttle, radiation-protection cask, pusher robot) within a full-scale drift section. These tests aimed at assessing the system and defining more precisely its performance.

In order to assess the package-retrieval capability of the system within a pessimistic hypothesis involving heavy deferred deformations of the cell, the various tests simulated significant geometric alterations in the liner: jamming (gap between two liner sections), faulty angular alignment between sections (Figure 16) and faulty diagonal alignment. Those situations have not led to any special problems during package retrieval.

Figure 16 – Retrieval test of a HLW package from a heavily deformed cell

A specific complementary means of package retrieval could be developed so as to be able to apply significant traction, in the event a package was stuck to the lining under conditions of substantial corrosion stemming from abnormal progress in the cell. The placement procedure for intermediate-level, long-lived packages is under development and will be tested by 2013.

The technological tests programme calls for making a prototype of a HLW cell front at the Underground Research Laboratory in Meuse/Haute-Marne, and setting up a test to monitor cell behaviour over the long term when subjected to high temperatures. Surface technological tests will continue, especially to test a new capsule/HLW cell front docking system.

Repository observation and monitoring[21]

Observing/monitoring repository structures contributes to the security, the safety and the reversible management of the repository. It intervenes notably in support of the guidance of the disposal process and to its decision-making process. It was integrated as early as the upstream repository-design phases (Andra, 2005d).

Observing/monitoring is useful notably in following the evolution of the different structures in their environment in order to ensure their durability and to detect, if necessary, any need for intervention with a view to maintaining the different reversibility-management options: preservation of a structure as is for a certain time period, transition to the next step by sealing the structure or return to the previous step by restoring access to the structure. It also provides experience feedback on the completed structures in order to improve the design of future ones. The collected data also contribute in refining the models being used for describing the behaviour of the repository.

The needs in observation/monitoring are met through standard, tried and tested approaches, to be adapted to the geological disposal context[22]. The design of the observation/monitoring system takes into

21 The term "monitoring" here refers to a permanent control throughout the overall process of the sound state of devices and systems, and of the compliance with an operating range, whereas "observation" refers to the action of examining things, beings and events carefully. From a scientific standpoint, it is an investigation process consisting in reviewing closely a fact or process with a view to knowing it or grasping it better without acting on the phenomena under study. By observing the repository, it is therefore possible to collect a wealth of additional information. Observation and monitoring both rely on an "auscultation" system (or instrumentation/monitoring system), which includes an overall series of devices designed to record, to analyse and to interpret measurements. An "auscultation" device is rarely used alone; several sensors and non-destructive measurements are combined into an essential global system for drawing reliable interpretations, which makes it difficult to maintain the distinction between "observation" and "monitoring".

22 Andra's approach on this subject is similar to the *Structural Health Monitoring* approach developed in civil engineering for "smart structures".

account feedback from the monitoring of civil engineering works (tunnels, nuclear reactor vessels, dams, etc.). However, two specific characteristics of the examination systems used on geological disposal structures are worth highlighting:

- the longevity required is of the order of a century, a period that is both very long in view of the durability of examination systems, and very short in relation to some of the phenomena involved;
- the most sensitive structures, the disposal cells, will only be accessible through robotic means once the first package has been put in place, and then they will be inaccessible to instruments should one want to get additional measurements after sealing.

The observation/monitoring means required for in-depth cell monitoring must be able to function reliably, over several decades, in potentially aggressive environmental conditions (radiation, temperature) and with constraints in terms of accessibility. It is also desirable for those means to be "discrete", so as not to disrupt operational conditions, degrade the stability of the structures, compromise the safety functionalities assigned to structures or the favourable properties of the environment, or, insofar as it is possible, interfere with the phenomena being observed.

In order to provide solutions that are adapted to those specificities, a range of studies and discussions were conducted. The developments involve the following:

i. the examination strategy, particularly with regards to the distribution of monitored structures throughout the disposal facility;
ii. the design of examination units following an in-depth qualifying approach;
iii. a range of research and developments to adapt, complete and qualify the examination systems.

Setting up an observation/monitoring strategy[23]

The strategy must first of all meet the specificities of an observation/monitoring system meant to last at least for one century. Although this

23 In that regard, Andra coordinates the MoDeRn project, co-funded by the European Commission as part of the EURATOM (7th FPRD) programme, with the participation of 18 partners established in Europe, the United States and Japan (Andra, Aitemin, DBE TEC, Enresa, Euridice, Nagra, NDA, NRG, Posiva, Rawra, RWMC, Sandia, UA, UEA, UGOT, GSL, ETH Zurich).

period does not necessarily apply to a specific structure – it rather refers to an overall period prior to sealing-off the disposal facility – this nevertheless implies the need to design a sustainable observation/monitoring system. To that end, the strategy must first rest upon the implementation of complementary examination approaches: resident instrumentation completed by standard visual inspections and non-destructive assessment methods.

This redundant, complementary approach is also adapted to on-site instrumentation. Within the examination units, sensors will on the one hand be deployed in surplus amounts, and on the other combined according to how complementary they are with one another: standard technology side by side with innovative sensors, localised measurements combined with systems making measurements spread across substantial lengths. This combination of means and approaches will help reinforce confidence in the durability of the overall system.

The strategy must also find a balance between observation-monitoring needs, implementation constraints and accruing costs for structure monitoring. In that regard, it is important to consider the similarity of the structure types (IL-LLW cells, HLW cells, underground drifts, etc.) and the homogeneity of rock properties. By exploiting the similarity in certain expected phenomenological occurrences, the observation/monitoring strategy intends to look at a sequence of structures, referred to as pilot, reference, standard and instrument-free, whose on-site instrumentation density is gradually reduced. Each structure, so designated, has a precise function in the observation/monitoring plan. The "pilot" structure is selected within the first structures being built and shall fulfil exhaustively the technical monitoring objectives. Its vocation is to become a "reference" structure as soon as a series of identical structures would be built. Such "reference" structures are selected within characteristic locations allowing for relevant observation-monitoring operations to be conducted. Then the "standard" structure is less instrumented with regards to the "reference" one. Non-instrumented structures would contain only essential devices for operational safety's sake and could be subjected to inspections and spot controls, notably through non-destructive methods that would not require access to the structure itself. In the context of reversible management, the choices relating to the distribution of "reference", "standard" and non-instrumented structures shall be reassessed as more and more measurements are gathered on the first structures. Those decisions will concern both the choice to implement more or less "reference" or "standard" structures and the selection of phenomena to be monitored more or less intensively.

At this time, the Underground Research Laboratory in Meuse/Haute-Marne is already in a position to acquire operational feedback. It is equipped with over 2,000 sensors that can be monitored over the long term, and uses an efficient data acquisition and management system. It allows the on-site qualification of examination systems for the specific context of Callovo-Oxfordian argillite and it is a privileged place in which to test full demonstrators of monitoring devices.

The observation/monitoring system will be adapted to the various stages in the repository management. After sealing-off, safety is by nature totally passive. However, it is conceivable to extend monitoring beyond the sealing-off, by studying systems that would neither disrupt the repository, nor the Callovo-Oxfordian argillite layer.

Provisions under consideration for HLW cell observation/monitoring

HLW cells are identified by their small diameter, their exposure to radiation and their high temperature, which reduce the setting-up and the use of sensors inside the cell itself. Since the characteristics and expected progression of all cells are similar as a result of their design, observation/monitoring can take place using a representative sample of cells. The provisions under consideration at this point in the studies are shown in Figure 17.

Instrumented boreholes drilled from the access galleries will help perform near-field examinations of the rock. The boreholes can then be sealed. They will help monitor conditions in the lining's gradual mechanical loading through measurements in temperature, interstitial pressure and rock warping. Andra is also looking into the possibility of monitoring the loading directly by deploying instrumentation on the outer surface of a lining. In addition, it will be possible to monitor the physical-chemical environment within a cell by tapping into the cell front. This will allow monitoring of corrosion conditions for the lining and packages, as well as checking for possible water presence.

Tests are planned at the Underground Research Laboratory in Meuse/Haute-Marne. For instance, the lining examination system will be tested on site. Another test will be to study the technical possibility of using the sealing test of a cell to equip the metal plug with sensors and means of transmission, and then monitor their operation over time.

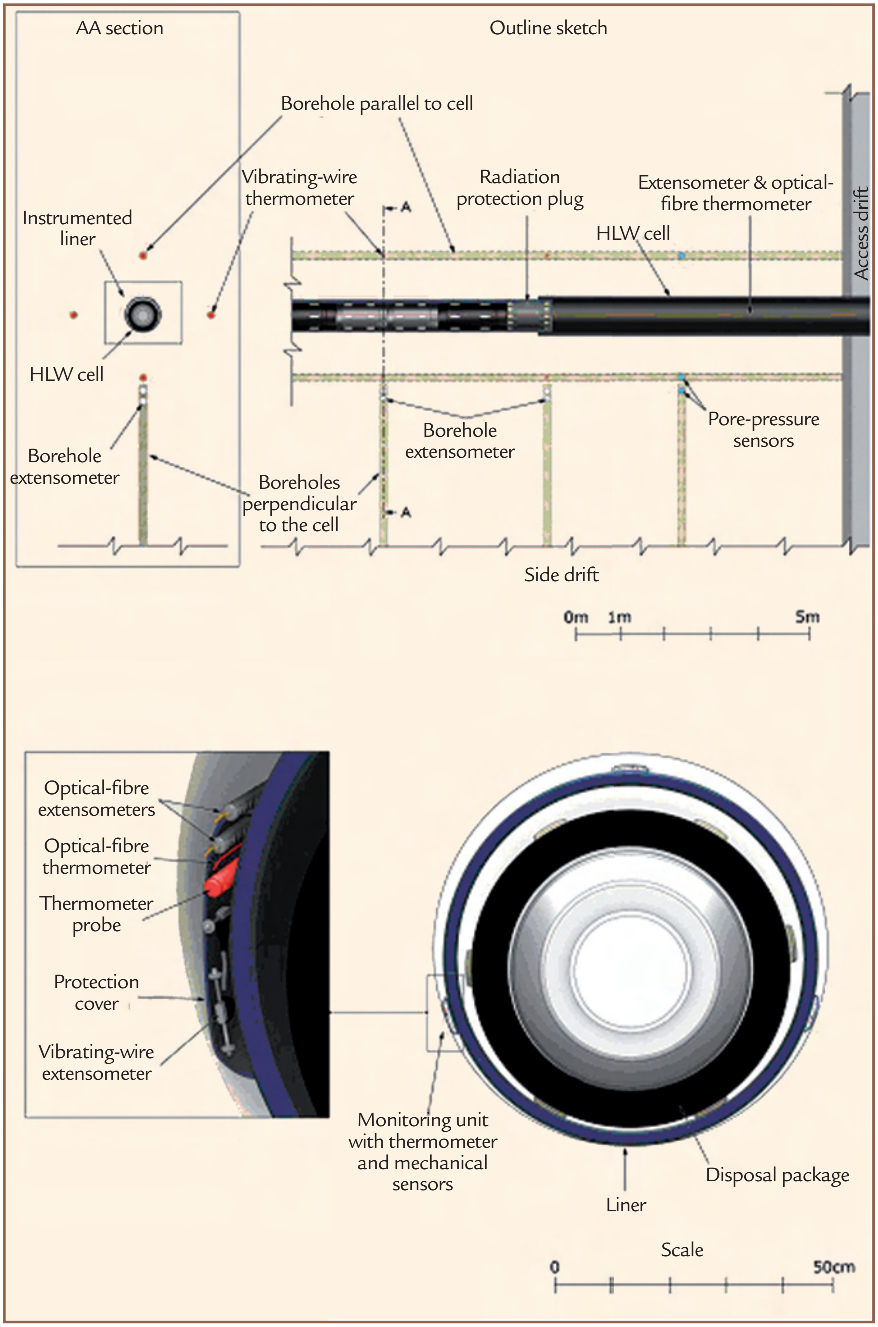

Figure 17 – Instrumentation on a control HLW cell

Provisions under consideration for ILW-LL cell observation/monitoring

Contrary to HLW cells, those for IL-LLW packages release little heat, have a cement environment (disposal packages and ground-support lining) and vary significantly in size (especially in diameter). Those data must be taken into account in order to adapt the observation-monitoring system, notably in the case of hydric and mechanical processes that will intervene during the reversible operation of the repository.

Sensors may be installed in the liner of IL-LLW cells during their construction (see Figure 18) in order to follow up the thermal evolution, deformations and hygrometry in the different sections of the cell. Those measurements may be completed, for instance, by additional recordings through optical-fibre devices interspersed longitudinally along the structure. Non-destructive monitoring devices mounted on robots, as well as a ventilation-air monitoring unit may also complete the observation-monitoring system.

This instrumentation will help verify the lack of deterioration to the structures and disposal packages during the operational phase. Any warping observed will be taken into account to assess conditions of retrievability.

Plans call for an in-situ qualification of the observation-monitoring system in the testing drift of a rigid lining in the Underground Research Laboratory in Meuse/Haute-Marne. The purpose of the ex periment is to compare the convergence measurements taken by traditional methods with innovating systems. In addition, an advanced monitoring method may be tested on concrete.

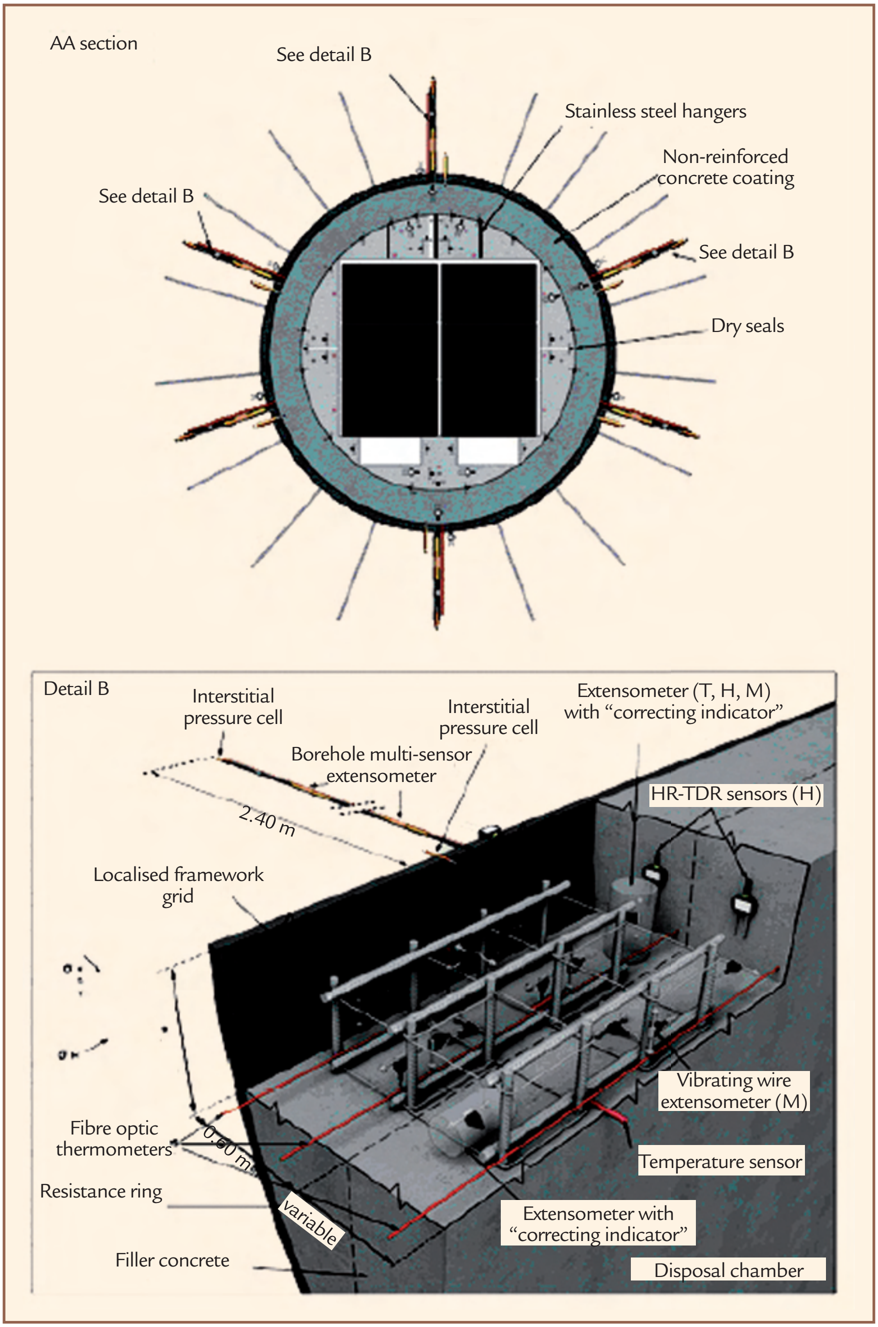

Figure 18 – Instrumentation on a ILW-LL cell

Research and development to procure appropriate tools

The developments being contemplated continue and complete those already committed. Several innovating instruments have been proposed as progress tracks for monitoring devices and constitute the subject of comprehensive studies within a group of laboratories (GL) associating universities, public establishments and companies on the topic of "monitoring means and strategies"[24].

Hence, it should be noted that for conventional spot measurements of temperature and deformation, the civil-engineering experience feedback shows the availability of particularly robust and durable means, since they have been functioning on certain structures, as dams, for more than 50 years. The availability of such durable means is not guaranteed by other types of instruments, especially in the case of chemical measurements. For instance since existing sensors for measuring hydrogen concentrations in the atmosphere of the cells require maintenance and/or regular calibrations, only a measurement through ventilation-air sampling with piping may be envisaged at this stage (and not a distributed monitoring system along the cell). Several studies on chemical sensors are under way, particularly the development of a miniature nanotechnological spectrometer that may perhaps resolve that limitation in the future. Other studies have been launched in order to combine proven technologies with elements likely to provide chemical measurements. Studies on the development of optical-fibre sensors for recording chemical measurements, as the model shown on Figure 19, are also under way.

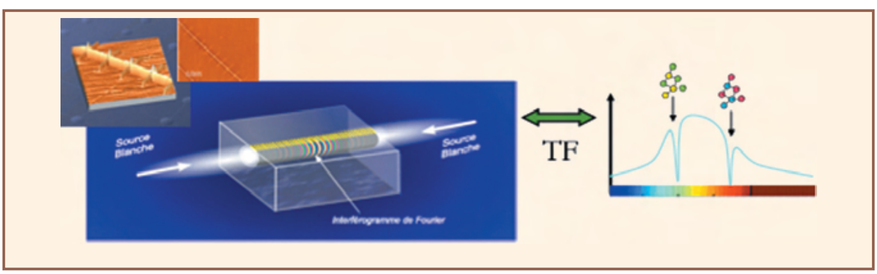

Figure 19 – Fibre optic sensor using light spectrum absorption to identify and quantify the presence of certain molecules

24 The Group of Laboratories (GL) also deals with topics in the early stages, from sensor miniaturisation to highly applicative themes already considering durability in the spirit of civil engineering work sites. GL partners (BRGM, EDF R&D, Inéris, LAAS-CNRS, LCPC, LNE, PACT, University of Saint-Étienne, UTT) are thus working according to complementary approaches.

Many technological qualification steps have been committed. Hence, a subject requiring targeted developments is associated with locating measurements of special interest. In fact, since the purpose of observation-monitoring is to provide information on the evolutions likely to have an impact on the behaviour of structures or packages, the issue is to identify the exact location where those evolutions are likely to become constraining, particularly in the context of reversible management. An especially interesting lead would be to develop distributed measurements along a single optical fibre. An implementation test was carried out for several fibres that were integrated in the concrete slab during the construction of Saudron's Exhibition Technological Facility (Figure 20). Optical-fibre sensors designed for conducting distributed measurements of the deformations were embedded in the slab and as well placed on the surface of a metal frame beam during the summer of 2008. Hence, analysing the signal crossing a fibre shows the temperature distribution over several tens of kilometres of fibre. The developments under way are designed to envisage with confidence such a distribution to measure local deformations. In September 2008, three devices were embedded in the shear walls of structure No. R04E15 at the CSFMA surface disposal facility (Aube district); more precisely, a complete concrete monitoring unit was set in place. Until 2015, two large demonstrators will be installed at the Underground Research Laboratory in Meuse/Haute-Marne: the instrumentation of the metal lining of a "HLW-cell" type structure in late 2010 and the instrumentation of a concrete-lined drift section of a "IL-LLW-cell" type in 2011. In addition, technologies to withstand radiation are being developed for both recent sensors with optical fibres and well-proven sensors, such as vibrating-wire extensometers.

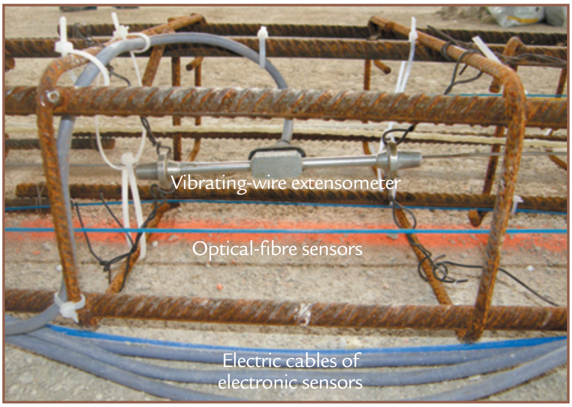

Figure 20 – Deployment of fibre optic sensors within a reinforced concrete structure, in order to supply distributed temperature and warping measurements

That type of development is carried out also for "discretion" in the implemented means and, consequently, may be better adapted in principle to safety functions preservations. In fact, a single optical fibre with its sheath, in the order of a few millimetres in diameter is clearly less intrusive than the large number of spot sensors that would need to be installed in order to ensure a distribution of comparable measurements.

Another lead being followed to improve device "discretion" concerns signal-transmission means. That issue would not be raised if the decision to close part of the repository (cell, module, etc.) were to induce the decision to abandon any measurement within the closed structures, but that is not expected to be the case: the measurements of the evolution of closed structures would provide interesting information for the decisions to be taken concerning management choices. Those would include notably ascertaining whether reverting to a previous step is possible while maintaining operational safety. Wireless transmission through the rock and the closure structures would then provide an alternative to wire transmission, although it includes several technical limitations, such as the actual transmission distance of the signal and the requirement to have enough stored energy to ensure operation in a closed zone (in the absence of power-supply cables). Developments under way are comparing two available technologies and assessing their performance over the transmission distance and the operating timescale, which is coupled with the management of the available energy.

Lastly, the advances of the observation-monitoring strategy will integrate the recent results from phenomenological analyses, notably in order to assess the relative significance of technical monitoring objectives of phenomenological evolutions with regard to safety and reversibility requirements.

The overall R&D work described above provides a general overview of the efforts made to achieve the required technological advances in order to provide the relevant information that will facilitate the reversible management of the disposal process and the decisions to be taken throughout the operation of the underground structures. The set objective is to implement sensitive, efficient, durable and discrete monitoring means with a view to informing the operator on the evolutions of the repository components.

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The argumentative trajectory of reversibility in radioactive waste management

by Pierrick Cézanne-Bert and Francis Chateauraynaud

Introduction

The nuclear issue in France has been marked by an ongoing succession of events, announcements, debates and controversies. This near-daily appearance of nuclear topics in public space is strongly related to the inception of a criticism-bent configuration in the late 90s, resulting from the forceful resurgence of radical protest and the birth of an actor-network possessing fairly substantial expression clout, the "Sortir du Nucléaire" (Nuclear Phase-out) network[1]. Although constantly being compared to the situation in Germany, the confrontations meeting the treatment of every event and project do not appear to be causing any major swaying in French nuclear policy, rather described as being extremely firm, especially in the foreign media. In the overall nuclear picture, the issue of radioactive waste remains at the heart of concerns for most of those involved, and despite the Law voted in 2006[2], the fate of the various options, like HLW (high-level) and ILW-LL (intermediate-level, long-lived) waste disposal

1 For an analysis of the resurgence of antinuclear protest in France, see F. Chateauraynaud, A. Bertrand & J.-P. Charriau, *For a computerised observatory of environmental alerts and crises. An application of concepts developed in the course of research on whistleblowers*, Paris. A report by the GSPR, CEMAGREF/GSPR-EHESS Symposium, February 2003; specifically regarding the nuclear-waste front, see Y. Barthe, *Le pouvoir d'indécision. La mise en politique des déchets nucléaires*, Paris, Economica, 2006.

2 Planning Act n° 2006-739 dated June 28th, 2006 on the sustainable management of radioactive waste and materials.

in deep geological layers, or the creation of a disposal facility for LLW-LL (low-level, long-lived waste) is still the subject of controversy, even though many actors believe that the decisions have already been made.

In the course of formalising the deep disposal project, introduced by the Law of December 1991 (known as the Bataille Law)[3], and which led to the creation of the Underground Laboratory in Bure, between the Meuse and Haute-Marne districts, legislators put forward the idea of reversibility, found in the expression "reversible disposal". In concert, this reversibility idea became the topic of many discussions, ranging from attempts to technically distinguish it from that of waste "retrievability" all the way to critical incriminations alleging a communication campaign motivated by purposes of "social acceptability".

Andra (the National Radioactive Waste Management Agency), which is responsible for the second venue of the Bataille Law regarding the possibilities of reversible or irreversible radioactive waste disposal in deep geological layers, is quite obviously right in the heart of the affair. Caught in the middle of opposing trends, brought to light during the public debate held by the National Public Debate Commission (CNDP) in 2005 and 2006[4], the Agency undertook a campaign of discussions, confronting the perspectives of engineers and those of social sciences researchers, about the concept of reversibility. As the dialogue progressed, especially during a day of study at Andra premises in early October 2008[5], it became apparent that the idea of reversibility, unlike that of irreversibility, involves the new relationship existing between science, technology and society, particularly in the nuclear field. This study will extend those discussions via the systematic analysis of the range of arguments used in discussing the concept of reversibility. To the Pragmatic and Reflexive Sociology Group (GSPR), the idea is to use the words used by players in the HLW and ILW-LL radioactive waste management issue to understand how they make use of the concept of reversibility: how do they define it (if at all)? What kinds of

3 Act n° 91-1381 dated December 30th, 1991 on radioactive waste management research.

4 See the public debate proceedings about general options in terms of high-level and intermediate-level, long-lived radioactive waste management (September 2005 to January 2006), established by Georges Mercadal, Chairman of the Public Debate Special Commission, and members of the Commission, January 27th, 2006: http://www.debatpublic.fr/docs//compte-rendu/compte-rendu_dechet.pdf.

5 *Réversibilité et sciences sociales*, Minutes, October 2nd, 2008, Andra, 2008.

arguments are used to justify one definition rather than another? Is the concept an argument used in order to legitimise a point of view[6]?

In terms of common sense, the initial use of the concept of reversibility involves first of all the possibility of reversing the course of a process: reversibility is the nature of that which is reversible, meaning that which can be performed or happen again in reverse. Accordingly, it is usually believed that a motion is reversible insofar as it is possible to travel the path followed in reverse, while time is by nature irreversible, in that it is accepted that we are never given a chance to relive an instant that has already been experienced. Within the context of a controversy about a public decision, the concept of reversibility involves the possibility of continuing a discussion without having to consider that things have "already been decided", "achieved", "wrapped", "enshrined", that "it is no longer possible to go back on it".

In the early 90s, in a collective work coming out of a symposium, economists looked into the issue of irreversibility, by studying the relationship between modelling, economic phenomena and historical time[7]. What came out of confronting the approaches was the multiple faces of irreversibility. As a counterpoint, the authors seem to share the same concern: how do we get out of the standard economic balance model, and how do we introduce into the models those non-linear dynamic formulae borrowed from the complexity paradigm which was making strong inroads into science at the time[8]? Confronted with the diversity of approaches, which tend to proliferate whenever complexity and non-linearity are involved, the coordinators of the work suggest singling out two main aspects:

- irreversibility seen as the inability for the players to change a status quo or modify the course of a process (given that custom differentiates between the inability to maintain a status quo – one cannot fight to maintain it – and the irrevocable nature of that which has already taken place);

6 The players we have met with may have wondered about the ultimate aim of our study. Let us therefore explain that the idea is not for us to take part in a work to define the concept of reversibility. Naturally, since Andra has commissioned this study, the Agency is perfectly entitled to use our report in its work; but since the report is to be published, different actors too have the possibility, and of course all legitimacy to use our work in their discussions, criticise the analyses developed therein, or even denounce the deceitful aspect of that concept.

7 R. Boyer, B. Chavance and O. Godard, Les figures de l'irréversibilité en économie, Paris, Éd. de l'EHESS, 1991.

8 See, among other works, M.M. Waldrop, *Complexity–The Emerging Science at the Edge of Chaos* (Touchstone Books, N.Y., 1993); D. Byrne, *Complexity Theory and the Social Science* (London, Routledge, 1998).

- irreversibility as the impossibility of returning to the starting point or of restoring the same position through the simple inversion of the action: a transformation is said to be irreversible if a symmetrical modification cannot restore the initial condition, including variations according to whether other forms of action make returning to the same point possible (for instance, by using force to cancel that which has been obtained by law), or if it absolutely is no longer possible to restore the same condition (however substantial and numerous the means used, as is often the case during restoration attempts in terms of political regimes).

In the face of those theoretical discussions, useful in providing a conceptual clarification, the use made of reversibility among nuclear engineers is closer to a technical definition in which "reversibility" means "retrievability". This understanding is separate from a definition involving the level of openness in the decision-making process. The way in which "reversibility" has been used in speeches and political writings concerning radioactive waste aims simultaneously at articulating both definitions and at asserting a determination for political decision-makers to control the process. Those aspects are clearly seen when analysing the range of arguments, which show an opposition between two definitions of reversibility, one that is minimalist and the other extended: on one side, players who defend geological disposal by expressing a preference for "trusting in geology" to confine the waste; on the other, players who favour surface or subsurface storage, preferring to "trust in society" in managing it. The opposition between two definitions of reversibility thus represents the backbone for an analysis of the controversy about the future of radioactive waste in France and throughout the world.

The comments developed in this article are based on a substantial corpus of writings and on dialogues with various players involved in the issue. On the basis of this twofold investigation material, we shall uphold the following assumption: while the construction of the concept of reversibility has indeed been the subject of controversy, the polemical aspect does not concern all players in the issue, since part of them are above all involved in a conflict focusing on siting a geological disposal facility in the Meuse/Haute-Marne region. It seems necessary in a pragmatic approach to take this conflictual aspect into account, which is inseparable from the power struggle affecting both the path of the issue and the arguments exchanged about reversibility.

Author-Actors[9] in the controversy

Actors behaviour is influenced by the dominant presence of assessment bodies who write reports about waste management or the concept of reversibility, like the National Assessment Board (CNE) or the Parliamentary Assessment Office for Scientific and Technological Choices (OPECST), of Andra, who is in charge of managing it, of public debate bodies like the CNDP, the Local Information and Oversight Committee (CLIS) for the Bure Underground Research Laboratory or the Entretiens Européens, of associations against burying waste like the AEMHM, and to a lesser extent antinuclear players like the Sortir du Nucléaire Network, or independent experts like the Association for radioactivity control in the West (ACRO).

The leading author in our corpus mobilising the concept of reversibility in these writings is Andra. While this result is not exactly a surprise, it does nevertheless demonstrate that the issue of reversibility remains for the most part confined to the organisations that manage and control radioactive waste management. The result is further confirmed by a relatively poor showing on the part of the media in this ranking of authors on reversibility: *Libération* and *Le Monde* only make it to 16th and 18th place respectively. The other two main authors on reversibility are the CNE and the Bure CLIS. The CNE has published several reports, including one that specifically deals with the concept of reversibility, in June 1998. The Bure CLIS penned a report for a symposium on reversibility and its limitations in March 2001, in which the main players in the issue were featured. Both those hefty documents play a large part in their dominant position as authors in our corpus. Both documents are also used as a work of reference by the various authors-actors in the corpus, who regularly quote excerpts from them to build their own argumentation.

Operators (among whom we mostly find Andra) are the ones who talk the most about reversibility, both in their absolute and relative score. They are followed by consultation bodies (mostly the Bure CLIS) and official rapporteurs (CNE, OPECST, Members of Parliament Christian Bataille and Claude Birraux, the Technological Risk Prevention Committee). However, consultation bodies and official rapporteurs have a relative score below expectations, given their presence within the corpus. Moreover, consultation bodies like the Bure CLIS have a relative score double that expected.

9 Author/players are the authors of documents in the corpus who also appear in the writings as players quoted by other authors.

Among authors obtaining a better relative score than expected, we note the Government and Members of Parliament: this is because the corpus includes the questions in Parliament prior to the Bataille Law, where reversibility was indeed one of the topics under discussion.

Other authors with a high score in absolute value are nuclear or burying opponents, and journalists; yet for both those author categories, the relative score is sharply lower than one would expect, given their relative weight within the corpus: opponents get a relative score twice as low[10]; journalists' score is three times as low. While reversibility is one of the opponents' cornerstone in denouncing the disposal project, it is not, however, their core argument against burying.

This table confirms once again a result that we have already observed: the topic of reversibility is a technical issue, mostly relayed by Andra engineers and local players taking part in the Bure CLIS. When mentioned by the other authors-actors, the concept is included into a wider context: for instance, to journalists it is radioactive waste management; to Bure laboratory opponents, it is the conflict surrounding the deep disposal project.

Status of authors on reversibility	*Score*	*Interval measurement**
Operators	1,264	1,079
Consultation bodies	782	225
Official bodies and rapporteurs	734	83
Nuclear or burying opponents	279	50
Journalists	246	32
Official control agencies	190	85
Public debate organisers	163	69
Independent experts	126	37
Social sciences researchers	122	43
Government	64	156
Political bodies or spokesmen	38	48
Press agencies	28	30
Local media	28	34
Members of Parliament	27	186
Foreign experts	10	24
Alternative media	5	119
Pronuclear scientists	4	2
Public players in nuclear matters	2	26
Doctors/Epidemiologists	1	1

* Figures are weighted to allow for the relative amount of pages assigned to each medium

10 Let us note however that opponents have frequently expressed themselves in the meetings held by the CLIS in Bure.

Type of medium	*Score*		*Type of medium*	*Score*	*Interval measurement*
Proceedings	1,115	591	Press agencies	24	30
Reports	738	132	News and magazines	19	10
Communications/ symposiums	336	528	Outlook reports	19	525
Hearings	210	705	Works	16	3
Public debate meetings	163	69	Public enquiries	13	311
Websites	140	148	Letters	12	717
Opposing periodicals	131	46	Parliamentary debates	12	358
Notes	130	1,771	Summaries	10	717
National daily press	107	29	Radio	9	124
Press releases	96	120	Nuclear press	8	159
Trade press	94	316	Legal texts	7	19
Scientific articles	69	280	Professional press	6	195
Technical notes	68	587	Open letters	6	69
Answers to parliamentary questions	61	231	Magazines	5	20
National press	57	148	Specialty magazines	4	119
Information letters	43	596	Conventions/ recommendations	4	21
Regional daily press	40	37	Information notes	3	179
Business press	39	90	Flyers	1	119
Working documents	39	1,564	Free press	1	89
Internet	38	50	Magazines about the environment	1	27
Parliamentary texts	29	135	Intermediary documents	1	8
Parliamentary questions	24	183	Opinions	1	39

This table shows once again how the issue of reversibility is confined to those spheres that include players who directly take part in the discussions about HLW and ILW-LL radioactive waste management. The main documents are communications made during symposiums or the proceedings from debates, reports or report summaries, public hearings or contributions to public enquiries. Opposing periodicals and the regional daily press are under-represented, which suggests that the concept of reversibility is poorly covered as such by opposing players and/or local players. We note that a similar phenomenon has been observed on an entirely different front, that of "low doses", whose language-game is still highly confined to the arena of specialists and official bodies, despite the many controversies they have raised.

If we take the relative weight of each writing into account, it becomes even clearer that the treatment of the issue of reversibility is confined to the expert's and decision-makers' sphere. The highest density is found in a CEA (the French Atomic Energy Commission) working document, *Contribution du CEA à la réflexion sur la réversibilité des stockages* (CEA contribution to discussions on disposal reversibility), a follow-up to the inter-ministerial council held on February 2nd, 1998. In the document, the CEA mentions the three venues in the Bataille Law, taking care to distinguish between the concepts of disposal and storage, a distinction that authors-actors in the issue are often confused about, and explaining that storage is a temporary solution, quite apart from the technical provisions being used, while disposal is a permanent solution. We note in passing that opponents to burying regularly take advantage of the vagueness that exists regarding certain core concepts in the issue to support their protest. This is well illustrated in the following excerpt from a communiqué released by the Association of Elected Officials in the Meuse opposed to the establishment of a laboratory for the burying of nuclear waste and favourable to sustainable development (AEM)[11], where they make ironic comments about the inter-ministerial decision dated December 9th, 1998:

> "The Government communiqué says the disposal is 'final with reversibility'. This would be worth a chuckle if the decision that has just been made were not so serious."

11 This association is expected to grow gradually, and become the AEMHM (Association of Elected Officials in the Meuse and Haute-Marne opposed to the establishment of a laboratory for the burying of nuclear waste and favourable to sustainable development) and then the EODRA (Association of Elected Officials in Lorraine and Champagne-Ardennes opposed to the establishment of a laboratory for the burying of nuclear waste and favourable to sustainable development).

The definitions (and motivations) given to the concept of reversibility

In the Anglo-Saxon world, there are three concepts indicating reversibility: *reversibility*, which is the reversibility of the decision, a managerial concept; *retrievability* (accessibility), which is the retrievability of waste packages; *recoverability* (valorisation), which is the retrievability of the waste itself. In our corpus, the distinction between those three definitions is much less clear. Statements most often refer to two meanings of the concept: retrievability, understood as the maintaining of accessibility to waste packages; and reversibility of the decision-making process, helping leave freedom of choice to future generations in their way of managing the issue. However, the distinction, while it is there, is not always that clear, since retrievability is perceived as the operational technical mode to keep the range of possible options open, meaning the decision is in effect reversible.

Several arguments are used in the statements, either as possible motivations for reversibility, or as obstacles to its implementation: the precautionary principle; future generations; scientific and technological progress; site memory; confidence in society as opposed to confidence in geology; the safety principle in disposal; the duration of reversibility.

When analysing the network of entities found in the corpus[12], we notice that the issue of reversibility is strongly related – which is no surprise – to the choice of the radioactive waste management mode (a strong presence of entities Choice and Management), including arbitration between disposal and/or storage techniques. Heading the network, we find disposal: most of the writings in the corpus arguing about the concept of reversibility do so about waste disposal; the presence of fictional-being[13] ANDRA@ is obviously in keeping with this. Safety is also part of the entities leading the network: assessment bodies and research agencies regularly mention in their documents that implementing reversibility must not be detrimental to waste disposal safety. We also note a strong presence of Politics through the existence of fictional-beings CENTRAL-STATE@ and PARLIAMENT@

12 An entity is a a topic, whether human or non-human, who is verbally represented in the corpus under study.

13 Fictional-beings in a corpus naturally group the entities around a relatively stable nucleus. A fictional-being gathers all of the ways of designating a player in the issue, whether human or non-human. The "@" symbol is added to separate fictional-beings from the other entities in the corpus when using Prospero text data analysis software.

as well as, inevitably, that of “Law”, since most of the corpus was developed between the passing of two acts (1991/2006).

To approach the way in which authors-actors conceptualise and analyse reversibility, let us look at the result from a formula such as: / ENTITY in reversibility. The table below shows the formulae that appear at least twice in the corpus.

ENTITY in reversibility	Score	ENTITY in reversibility	Score
Notion(s) of reversibility	150	Expectations in terms of reversibility	3
Level(s) of reversibility	85	Constraint for reversibility	3
Concept of reversibility	72	Reversibility rationale	3
Reversibility principle	67	Possibilities of reversibility	3
Condition(s) of reversibility	56	Retrievability and reversibility	3
Reversibility scenario(s)	34	Reversibility case	2
Period of reversibility	28	Reversibility aspect	2
Phase(s) of reversibility	25	Need for reversibility	2
Reversibility duration(s)	21	In terms of reversibility	2
Demand for reversibility	20	Concepts of reversibility	2
Scale of reversibility	18	Reversibility context	2
Term(s) of reversibility	18	Reversibility criteria	2
Degree of reversibility	17	Time limit of reversibility	2
Reversibility option(s)	12	Demonstration of reversibility	2
Obligation of reversibility	11	Distinction between reversibility	2
Idea about reversibility	8	State(s) of reversibility	2
Reversibility problem(s)	7	Irreversibility and reversibility	2
Reversibility study	6	Reversibility approach	2
Reversibility guarantee(s)	6	Reversibility standards	2
Request for reversibility	6	Reversibility objectives	2
Question of reversibility	6	Reversibility operations	2
Absence of reversibility	5	Reversibility perspective	2
Reversibility imperative	5	Perspectives in terms of reversibility	2
Reversibility situation	5	Search for reversibility	2
Nature of reversibility	4	Reversibility techniques	2
Reversibility system(s)	4	Type of reversibility	2
Implementing reversibility	4	Reversibility value	2
Safety and reversibility	4		

The above table is the translation of the data obtained in French documents and references.

Reversibility is above all a concept... to be defined

To authors-actors, reversibility is above all an idea ("notion", "concept", "term", or "an idea about reversibility"). The largest score was achieved by "notion of reversibility" with 150 occurrences in the corpus. Yet, if the word "notion" can be synonymous with "idea" or "concept", it is most often used to mean "intuitive knowledge". This highlights one of the corpus' properties: authors-actors mostly utilise the reversibility entity without precisely defining it, assuming the person they are talking to has an intuitive understanding of the word. This point is regularly stressed by corpus authors: the Bataille Law, which introduced the word, nevertheless failed to provide a definition for the notion; so it was Andra who would perform this work, especially in technical terms, while the CNE (or the NEA) would extend the notion to the decision-making process. In 1992, in a technical note analysing regulatory documents concerning reversibility in deep disposal, an Andra engineer commented:

> "The notion of reversibility is not explicitly defined in the text of the Act; it merely states that hazardous products should be removed when the licence expires."

There are different levels of reversibility

The second-ranking expression in the corpus is "level(s) of reversibility". We also find this idea of gradation when corpus authors talk about scale or degree of reversibility. Andra is the player who most uses the expression "level(s) of reversibility", the others being the CNE, the Bure CLIS and Local Information Commissions (CLIs). It is used during the "Reversibility and its Limitations" symposium held by the Bure CLIS in March 2001, for instance during a speech by then-Andra Chief Executive Officer François Jacq:

> "Before anything else, we must look at the issue of reversibility from the perspective of the duration and the degrees or levels of reversibility. (...) To put it extremely simplistically, one could say that the very first degree of reversibility is storage, while the ultimate level would be, even though it may itself remain reversible, the closure of a would-be disposal facility."

The reversibility principle established as a standard

In our /ENTITY in reversibility table, the expression "reversibility principle" comes 4th in the corpus in terms of occurrences. We also find this standardisation aspect in expressions like "ethics" or "reversibility value".

The expression is the most often quoted in a legal study on the reversibility principle in waste disposal[14], conducted for Andra in June 1998, from which we quote a lengthy excerpt below:

> "On the other hand, the principle of the study of reversibility is a must for operators of facilities for waste eradication through disposal. In other words, the application of the reversibility principle tends nowadays to ensure that any new waste eradication facility, including radioactive waste and subject to the special provisions they are under, should meet reversibility standards guaranteeing that waste valorisation could be performed satisfactorily, once such valorisation were decided. In addition, as of July 1st, 2002, the reversibility principle will guarantee that any waste which has been disposed of can be valorised, once appropriate techniques are available. Such an application of this principle to radioactive waste disposal cannot therefore be ruled out.
>
> Given current legislation, operators of disposal facilities are thus obligated to show that the chosen means of disposal will allow effective application of the reversibility principle. Consequently, operators must demonstrate that the treatment under consideration is closer to storage than to straight waste disposal. One should also consider the need, at the very least, to set down arguments to justify, if necessary, the impossibility of proceeding with the normally required reversible disposal."

Reversibility also expresses an imperative to be deployed: words are used such as demand, imperative, obligation, request and constraint for reversibility.

14 It should be explained that this study by Jean-Pierre Boivin concerns waste in the widest sense, and not just radioactive waste.

Conditions of reversibility are to be expected

Andra, then the Bure CLIS are also the main authors of "conditions of reversibility". These express the anticipation of the practical terms surrounding implementation, and the anticipation of various possible scenarios. The idea is found in a speech by an Andra engineer, during a meeting of the CLI in Gard in June 1995:

> "I will show you in a concrete way how Andra deals with the issue of reversibility. (…) The analysis conducted within the framework of research in the underground laboratory should precisely help to provide, at the end of this programme in 2006, satisfactory conditions of reversibility, meaning technically feasible and provable. It will be necessary to prove what one is saying."

Reversibility is a phase in the disposal option

The need to translate the notion of reversibility into technical terms and to determine the concrete terms of its implementation has led Andra to specify the timescales considered for reversibility. Reversibility is then related to a phase, a period, or a duration of reversibility. The idea that reversibility corresponds to a limited period in time quickly appears in Andra's works, for instance in a study dated March 1997, describing the main provisions in terms of reversibility for ILW-LL waste disposal concepts in the Gard:

> "Its two-hundred-year sustainability will guarantee the maintaining of functional looseness during the reversibility period (levels 1, 2 and 3). This will allow package removal during the period, whether the functional looseness is plugged or not."

This limited duration for reversibility, corresponding to a phase in disposal facility management, is the main angle of attack used by opponents to burying: if reversibility is only effective for a given time period, this indeed means that the ultimate result in burying packages is that their disposal will be irreversible. This is how the "Bure Stop" Collective sees an interview given by Andra's Chairman in the *Le Monde* newspaper in April 2000:

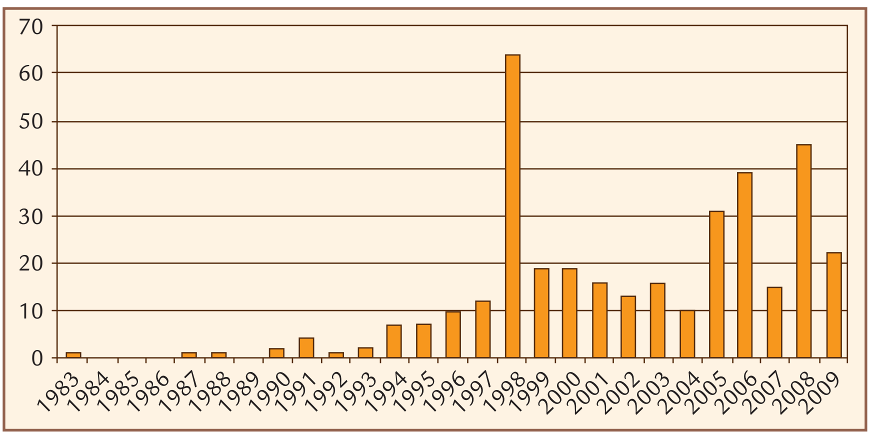
> "Deciphering the language used by Andra Chairman Yves Le Bars (…)
>
> But, as soon as the temporary period of reversibility (forced even in the operational phase) is over, we shall proceed, out of necessity, in an attempt to avoid water coming in, with total

filling-up, complete with a sealing off of the shafts and drifts. The CNE thus notes a *Post-sealing* phase, adding 'In the longer term, and especially if package confinement integrity is no longer guaranteed, the word reversibility loses its true meaning. We shall thus find ourselves in a situation of deep disposal characteristic irreversibility, for unavoidable technical reasons involving the very principle of disposal, even though we momentarily passed through a phase which one could describe as *very temporarily reversible deep disposal* and where one will of course forget about the *very temporarily*.'"

Development of the notion of reversibility in the corpus

The diagram below shows the chronological appearance of documents in the corpus mentioning the notion of reversibility, under one of the following lexical forms:

Reversibility(ies); reversible.



Timeframe of texts mentioning reversibility

A surprising stability in the arguments

The histogram of Reversibility[15] shows that the word is virtually absent from the writings in the corpus prior to 1990. A quick historical

15 Reversibility@ includes here the following entities: reversibility(ies), irreversibility(ies), reversible and irreversible. It thus indicates minimal use of the fictional-being tool; under review is sufficient to explain this. Geological surveys conducted from 1988 by Andra (still at the time part of the CEA), in view of the feasibility of an underground laboratory, provoked such strong and sometimes violent opposition locally that scientists had to cease their work. On February 9th, 1990, the Rocard Government decided on a moratorium on highly radioactive waste management, and passed the matter on to Parliament. Member of Parliament Christian Bataille was then mandated to write a report, suggesting the total rethinking of the decision-making process. The work ended with the passing of Law n° 91-1381 dated December 30th, 1991, which broke down radioactive waste management into three venues: separation/ transmutation; geological disposal; long-term storage. The second venue in the Act explicitly introduced the notion of reversibility, with Andra's research directed to focus on "the study of possibilities for reversible or irreversible disposal in deep geological formations, particularly through the completion of underground laboratories". So it was indeed the Bataille Law that introduced the notion into the public arena.

This brief historical reminder shows us that as of its public emergence into the issue, reversibility began tangling together a conflictual aspect and a controversial aspect. Conflictual, because the notion is introduced into an act that had put an end to three years of bitter opposition to a project vigorously rejected by the populations concerned; controversial, because the act made it one option among others regarding a given radioactive waste management mode, with scientific studies meant to decide on the appropriateness of reversible disposal.

To complete this historical part, let us mention that the first document in our corpus explicitly referring to the notion of reversibility is a CEA article dated March 1st, 1983, entitled "L'Andra, un service public pour une gestion sûre des déchets radioactifs" (Andra, a public service for the safe management of radioactive waste). The text presents Andra's mission: to design long-lived waste management. While the word "reversibility" is not expressly in there, the text presents the completion of an underground laboratory as a reversible facility. The CEA paper clearly states that engineers have built a solution to manage this waste; the idea is now to deploy it by establishing laboratories that will help

extended use, a term like "retrievability" should by rights be one of the representatives for Reversibility@, since most authors use the term when referring to the notion of reversibility. This loose writing has nevertheless been included, in that it has helped us measure in a simple way the presence of the reversibility entity in the corpus writings.

study the various types of rock likely to host the waste. The conception of the notion of reversibility is not specified in this short text, but it does not appear to concern the disposal mode per se, which is considered at the time as a final solution to the problem of long-lived waste, but the experimental phase that will help validate the choice of deep disposal.

> "Since technical options have been determined, we must now move on to a new stage by completing one or more underground laboratories. Those laboratories are intended to help in the analysis of the geological environment within which the waste can be placed over the long term.
>
> A pilot facility must then be built to qualify the technical solutions that will be deployed. Beyond the initial experimental phase, this facility, designed as reversible, could be turned into a final disposal facility if the experience acquired confirms the legitimacy of the option chosen to ensure that the disposal meets long-term protection objectives."

It is striking to realise that in this text, dated 1983, reversibility is already considered as a transitional phase prior to the facility closure and turning it into a final disposal facility. This point is still at this time the topic of many discussions around this idea: can one really speak of reversibility if the ultimate fate being considered for the disposal facility is final closure? Accordingly, the argument regarding the reality of the reversibility concept as developed in Andra works is regularly taken up by burying opponents.

The first document in the corpus to formally mention the reversibility entity is dated January 11th, 1988; it is an article published in *Geo* Magazine, entitled "The funeral of the atom". At the time, reversibility does not appear to be considered in Andra projects, given that its basic principle seems incompatible with the requirement for safety which the agency is obliged to meet. Yet the idea of burying radioactive waste is already causing worry: how to guarantee that radionuclides will not migrate up to the surface?

> "Reversibility? The word startles Andra's boss. 'Look, if we were to keep some access towards the packages, it would be harmful to site safety and watertightness.' So the undertakers will merely bury the sarcophagi, but they will backfill the mausoleum with special, highly-compact clay, bentonite. And what if the living dead came back to life? At the Curie Institute, Doctor Gongora assures that his establishment is totally able to handle another Chernobyl."

As with the previous excerpt, we notice a certain continuity in the arguments: reversibility's limited time span in the CEA text; the compatibility issue between safety principle and reversibility principle in *Geo* Magazine's article[16]. Argument stability is indeed an important result of our study: without going as far as to pretend that everything is immobile in this issue (for instance, in order to include the reversibility principle into its research, Andra has brought substantial changes to some aspects of technical design for geological disposal), the main controversies and debates around the notion of reversibility are structured by a number of questions or oppositions that barely ever vary: confidence in geology or in society; compatibility between disposal reversibility and safety; unlimited or time-limited reversibility etc.

Reversibility established as a principle

In the histogram of reversibility above, we see three main peaks: in 1998 (89 texts); in 2005 (63 texts) and 2006 (47 texts); in 2008 (67 texts). The 2008 peak can easily be explained by the impact of the enquiry, while for its part, the public debate in late 2005 about high-level and intermediate-level, long-lived waste management explains for a large part the peaks in 2005 and 2006. As for the year 1998, it is a pivotal year in the issue, if looked at in the light of the notion of reversibility.

In that year, the CNE answered a Government request made on February 2nd, 1998, asking for a report on reversibility, which was handed in June; to answer this request, the CNE had held hearings with the main players in the issue. By late 1998, the Government decided on the construction of a laboratory in Bure, in the clay of the Meuse (this is the Underground Laboratory in Meuse/Haute-Marne), and to pursue the search for a site with granite. The findings of the inter-ministerial meeting of December 9th, 1998, which held to "the reversibility rationale", confirmed that reversibility was from then on an incontrovertible requirement.

> "Therefore, for purposes of ethical imperative, the condition for acceptance of decisions made is subject to their reversibility.

16 Let us note that Andra has responded to the apparent contradiction between safety and reversibility by designing a reversibility concept that is limited in time. It is precisely because the disposal facility must one day be closed, with no intention of ever retrieving the packages, that geological disposal remains the safest management mode in assessments made by engineers.

> It is crucial that future generations should not be bound by decisions already made and should be in a position to change their strategy according to any technical and sociological changes that may have occurred in the meantime."

During that year, the issue of reversibility was also a frequent topic in parliamentary debates, particularly championed by Members like François Dosé, who made it a condition for acceptance of the project by local players. The MP and Mayor of Commercy, Meuse, restates in a interview given to the *La Croix* newspaper, "Those Meuse inhabitants who are accepting the idea do so with great precaution", the *sine qua non* condition for acceptance by the District Council, of the establishment of a future research laboratory:

> "The Meuse District Council has unanimously accepted the candidacy for the completion of a laboratory, with a clause which Meuse elected officials and myself will stand for firmly: reversibility."

So the year 1998 marks a turning point in the issue: with reversibility having become an imperative for geological disposal, opponents to burying would from then on tirelessly denounce the notion of reversibility as a deceitful argument intended to get approval from local players. It should be mentioned however that while critical objections became systematic as of that date, they existed well before 1998. Witness the following excerpt, which illustrates an argumentation technique which consists in interpreting the meaning of a notion or proposal without fully taking charge of it. Typically, opponents attempted to make the acceptance strategy used by Andra obvious and intelligible:

reversibility = credibility = public trust

> "As admitted by the Ministry for Industry and Town & Country Planning itself, 'easy reversibility is not desirable'. Clearly, disposal will be engaged with the idea of final burying. Besides, the Ministry does not conceal its intent very well when it asserts: 'Reversibility is de facto assured during the building of the facility (to be operational in 2010-2015) and the cooling period of the waste (several years) stored on the surface. In the event that a major technical advance should allow, tomorrow or fifty years from now, an improvement in waste processing, the possibility remains intact to retrieve the packages in order to process them again.' In other words, the notion of reversibility entirely disappears after fifty years, if it even ever existed beforehand.

Security or irreversibility

According to Mr Régent, reversibility can only be considered during the underground disposal's operational phase. 'At a certain point, we shall want to backfill the drifts where we have put packages. From there, reversibility becomes a little more difficult because we will have to remove what we put in to backfill the drifts. And that backfill we put in is also part of the security. There comes a time when one will have to choose between reversibility and security. Right at the start of the disposal operational period, we are still in the reversibility phase, and then the more we go forward, the more we shall have to play the security card.' Lastly, and this will be the final quote on the topic, let us not forget what Andra's Director himself told *Geo* Magazine in January 1988: 'If we were to keep some access towards the packages, it would be harmful to site safety and watertightness'. (…)

A sales argument

Reversibility looks like a sales argument, legally and scientifically groundless. Unless research undergoes dramatic progress in the years to come, it is obvious that radioactive waste disposal will be looking more and more like final burying. We should highlight the skill of public authorities who succeed in burying within the population's cerebral canyons the hope that nuclear waste may be retrieved, thus steering to their benefit the decisions that local elected officials will be making. There is a need for a major communication effort on this delicate topic."

> AEMHM, September 1996, *La Meuse face aux déchets radioactifs (The Meuse facing radioactive waste)*

An irreversible path?

In this same work, Yannick Barthe focuses on the three options under consideration in radioactive waste management (HLW and ILW-LL): irreversible geological disposal, reversible geological disposal, and long-term surface storage. His analysis can help us outline the path taken by the notion of reversibility throughout the issue.

Barthe shows that at first, irreversible deep disposal established itself as the reference solution designed by scientific experts, in response to the safety principle in disposal. This solution is meant to be final, it allows solving the problem right now: the responsibility for waste management is not transferred to future generations, the confidence in geology helps sidestep the problem of continuity in human society and its ability to manage and monitor the waste. The techno-scientific world has thus solved the problem by defining a project that is optimal in terms of HLW and ILW-LL waste management: irreversible deep disposal. The dangerousness of the waste to be managed, its long lifespan, even the consequences on future generations, all these are arguments in favour of that management mode. Jean-Claude Petit, who wrote a thesis on the topic in 1993[17], insists that irreversibility in disposal is a techno-scientific construct:

> "The notion of irreversibility is a patient, conscientious construct from the engineering world. One wants to make deep disposal irreversible, for one thinks that this reinforces safety."
>
> Jean-Claude Petit, CEA (phone interview).

Starting from 1987, this solution, founded on strictly scientific criteria, began facing opposition from local populations as the search for a site for the laboratory proceeded, and failed to establish itself. Responding to this opposition, the 1991 Law caused a turnaround in decision-making process timeframe: political criteria would from then on have precedence over scientific and geological criteria[18]. Little by little, this reversal led to the concept of a reversibility principle, which was officially established at the inter-ministerial meeting on December 2nd, 1998. Radioactive waste management would now be reversible, so as to leave the range of possibilities open. The fact that no assertive decisions are taken immediately has as a first consequence to improve the acceptability of the decisions that will have to be made. We have seen how this led Andra to develop a reversible deep disposal concept.

Irreversible geological disposal allowed us not to transfer to future generations a legacy (in this case a burden) they were not responsible for: thanks to this concept, present generations would themselves address a problem they had created; but they would deprive those same generations of the freedom of choice concerning a possibly

17 Jean-Claude Petit, *Le Stockage des déchets radioactifs : perspective historique et analyse sociotechnique*, ENSMP, 1993.

18 See Yannick Barthe, *Le pouvoir d'indécision. La mise en politique des déchets nucléaires*, Paris, Economica, coll. Études Politiques, 2006. In this work, Yannick Barthe speaks of "indecision-making" with respect to the Law of 1991.

better future option. With reversible geological disposal, future generations would regain that freedom of choice, at least for the – limited – period of reversibility, as well as the burden of continuing with the waste management. Yannick Barthe legitimately comments that this freedom of choice is not to be a legacy for all future generations, since reversibility has a limit in time of a few centuries. But the principle of reversibility also has a paradoxical consequence on the freedom of choice of successive future generations, which is rarely mentioned: it excludes the possibility of choosing irreversible geological disposal for present generations. In other words, the increase in the amount of possible world conditions implies a reduction in immediate possible world conditions.

While from a political perspective, reversibility appears to have become a prime condition for engineers in charge of waste management, it represents a constraint in terms of safety, one that is non-negotiable. Reversible disposal as designed by Andra is thus a mode of management that allows for the removal of packages during the reversible period, and that becomes irreversible once deep disposal meets its initial intent as a final solution to the problem of radioactive waste. So Andra provides reversibility that is limited in time, set up in stages, gradually leading to the facility closure; at every stage, a decision is made either to proceed onwards, to remain as is, or to return to the previous stage.

With the reversibility principle being an obligation, the Government requested in 1998 that some thought be given to the possibility of subsurface disposal. This management mode was supposed to facilitate waste package retrieval while protecting the disposal facility from human intrusion. The option was studied by the CEA, who redefined it as long-term subsurface storage. This is how a CEA engineer described the political request for subsurface storage:

> "In 1998, this pressure materialised in the shape of an order for a report on subsurface storage. To me, that request is to be considered as square one of the reversibility. Indeed, it expressed significant political pressure from the Green Party (Voynet, Rivasi) of the time. We see the Green Party forcibly demanding the establishment of surface disposal, a concept which of course puts reversibility at the heart of the concept. The request for a report on subsurface seems to me to be a highly tactical response to that political demand, with the following semantic shift:

i. they start with surface disposal;

ii. they convince themselves that it must *at least* be subsurface (a concept giving rise to some ambiguity about the depth);

iii. to protect standard disposal (Law of 1991), they go from subsurface disposal to subsurface storage;

iv. they launch a very substantial effort at the CEA on subsurface storage from 1998 to 2000 (it was important to protect the standard disposal concept by working on the technical aspects, which would lead to 'orthogonalise' the concepts, since the differentiation was valid technically);

v. as of 2001, they remerge all storage concepts, to ultimately conclude that existing industrial storage facilities are sufficient. This path has given new legitimacy to the Law of 1991 by treating the intermediary concept of subsurface technically and then dissolving it (reversible disposal or storage)."

Thus the main impact of the semantic shift described above is to assert that subsurface storage can in no way represent a final solution, since storage is temporary by definition: in other words, storage does not merely allow for waste retrieval, it demands it. The paradox in the case of subsurface storage is that the management mode makes waste retrieval compulsory (the technological containment will deteriorate before the waste becomes safe, and the burying is not deep enough for the geological barrier to prevent radionuclides from migrating up to the surface), while simultaneously making it complicated (the waste is buried beneath 40 to 60 metres of rock). Studying this option, which is supposed to be a potential alternative to deep burying, thus leads to confirm the latter as the reference solution.

The third option analysed by Yannick Barthe is long-term storage, on the surface. This option appeared to meet with the approval of the majority of participants in the public debate in late 2005, early 2006, held by the CNDP, to the extent that some speak of consensus for this solution. However, the June 2006 Act which followed it did, for its part, confirm that reversible deep disposal remains the reference solution. Long-term storage, as with subsurface storage, demands waste retrieval, but without making it complicated this time, since the packages remain handy. For those who promote this option, it features de facto reversibility that fully complies with the safety principle: if the packages are retrieved and repackaged before their technological containment deteriorates too much, then the containment obtained is lasting, safer than a geological barrier that is unpredictable over the very long term, despite laboratory studies. Every time the packages are retrieved, the decision may be made either to repackage the waste to extend storage, or to reprocess or transmute it if new technology has been developed, or even to bury it. Barthe then speaks of an iterative decision model, where the problem is left permanently open and subject to periodic reassessment. This process allows for full freedom of choice to successive generations (as long as the previous generation decides to extend storage, however); on the other hand, it forces future generations to manage nuclear waste they had no part in creating, and it assumes the long-term maintenance of nuclear competencies. Yannick Barthe then points out that this option, favoured by the antinuclear lobby, does not seem therefore very compatible with a fast abandonment of nuclear energy!

Certainly, the paradox is merely apparent. This option, at least to the antinuclear lobby, does not aim at answering the problem of waste, but to the contrary it aims at exposing a problem we have no answer for. Long-term surface storage would thus ultimately aim at ongoing publicising of the problem, with as an expected result to convince sceptics of the need to phase out nuclear energy. In other words, if this option were to be studied seriously by the authorities and engineers in charge of waste management, there is every chance that its current champions would turn into its prime opponents, via a "backfiring" debate, to use Yannick Barthe's own words. Moreover, this analysis is shared by the authorities, with the OPECST's Chairman believing for instance that the consensus is entirely illusory, given that long-term storage is merely brought up by opponents with the sole intent of disqualifying deep disposal:

> "– Mercadal came up to me and said, 'A consensus is forming.' I told him, 'Those who are proposing your consensual solution… If I were to propose it to them, have they signed on the dotted line that they would not demonstrate, that they would not seek to oppose it? No. Therefore it is not a consensual solution.' The consensual solution is a solution that can be implemented. So they were proposing a solution to avoid making a decision. This decision implied a number of adaptations which they were going to oppose: it was not a consensual solution (…), it as an argumentation, made precisely to prevent application. On that basis, it is no longer a solution."
>
> Interview with Claude Birraux, Chairman of the OPECST

In the above description, we observe a shift of the "power of indecision" described by Yannick Barthe in his thesis, from political authorities towards opponents to burying. The Law of 1991 provided an opportunity for politicians to gain renewed control in managing the issue, precisely because they apparently made no decisions in terms of management, but to the contrary they were reopening the issue, recommending initiating research along three venues. On this occasion, it was opponents who made a proposal that aimed, not at finding a solution to the problem, but at regaining a handle on the issue by encouraging the players not to decide anything final.

When studying the trajectory of reversibility, we see that controversy surrounding the notion concerns the junction between political objectives and techno-scientific objectives: by making the decision-making process more flexible, reversibility must facilitate its acceptance; from a technical standpoint, it forces engineers to amend a solution seen as optimal in terms of its safety. The notion of reversibility has therefore been built little by little by reference to deep geological disposal, which it has substantially contributed in changing. Yet this controversy is part of a bigger picture, that of the conflict surrounding the burying project. Thus it was possible for opponents to antinuclear players to promote the reversibility principle as long as it appeared to be weakening the project; but once the principle was appropriated by deep disposal supporters and included into the project, it was no longer acceptable. In other words, as was highlighted by a CEA engineer in the interview he granted us, the problem of HLW and ILW-LL waste management has long been resolved from a technical standpoint thanks to deep disposal, but that is not enough to validate the project.

> "There can be instances of rebounding in the arguments. In a socio-technical controversy, one is hindered by acceptance. The technical sphere is like a train speeding on its rails, never deviating from its path, while acceptance is a wall, which one either passes or not.
>
> In fact, from a technical perspective, the debate is very simple, everything has been said. Technique always pushes in the same direction, it is stupid and stubborn. But since there is no acceptance of the technical solution, one plans for downtime, for breaks."
>
> Interview with a CEA engineer

Jean-Luc Godard opens his "*Histoire(s) du Cinéma*" with a quote by Robert Bresson: "Don't change a thing, so that everything will be different"[19]. In the case of radioactive waste management, studying the path of the notion of reversibility could almost lead one to invert the formula: "Change everything, so that it all stays the same", recalling Tancredi Falconeri's notorious injunction in *The Leopard*: "If we want

19 Robert Bresson's precise quote was actually: "Without changing a thing, so everything is different", in *Notes sur le cinématographe*.

things to stay as they are, things will have to change"[20]. Indeed, while the Bataille Law helped reopen the issue by suggesting further research development, thus making room for the study of further options, it seems that ultimately, introducing the notion of reversibility has served to consolidate the deep disposal option, without fundamentally changing its basic principle: to trust geological layers to ultimately block any would-be migrating radionuclides. The confidence in society is thus only granted over a limited time. To opponents, whose "ideas are not reversible", the reversibility principle then becomes, in their view, a means of mystification to get the agreement of local players, since it helps validate an option that they reject. Ultimately, the HLW and ILW-LL waste management issue remains structured by a conflict that centres on a development project, disposal within deep geological layers: all arguments, notions, concepts, even alternative options, are brought in to either consolidate or weaken that project, with the reversibility principle being just one of those arguments.

Conclusion

The topic of reversibility has given rise to mobilisations relating to key moments in the nuclear waste issue (1998, 2005-2006). From time to time, Andra makes public a discursive scheme which, subject to legal constraints, takes the notion of reversibility seriously, turning it into a hybrid concept, featuring retrievability techniques at one end and the handling of a social demand at the other, understood as an opening of future choices and decisions – some refer here to reversibility in the "democratic sense". But most players in the issue believe that the studies and the research are converging towards a deep disposal facility project, de facto irreversible – even though the idea that the Bure laboratory itself would be the disposal facility in no longer alive. The emphasis on reversibility is thus interpreted as one of the means towards building social acceptance for the project. As a result, critics attempt to take public authorities literally by demanding genuine reversibility, based on the surface or subsurface storage option. The time span is clearly seen as the major constraint: reversibility over one hundred years[21] is thus considered as false reversibility, from a critical

20 *The Leopard* (*Il Gattopardo*), a novel by Giusepe Tomasi, published posthumously in 1958.

21 Andra has studied the possibility of package retrieval over a period of one to three hundred years, matching the filling-up phase of the potential disposal facility and beyond.

viewpoint. Yet the compulsory reference to future generations requires going beyond one century, a deadline which, besides, just about matches the end of package emplacement and of the site's operational phase.

To antinuclear critics, waste management is assuredly a problem that imperatively requires a solution and which does indeed deserve to be the concern of research, yet there is a non-negotiable precondition: stop producing it. Thus in the hierarchy of argumentation constraints, nuclear phasing-out has precedence over waste management. One of the rhetorical points of tensions here is that we should not seek a solution prior to nuclear phasing-out, for a solution would provide legitimacy to the nuclear cycle and to its ongoing development. While we await the choice of another waste management option, the Sortir du Nucléaire Network suggests extending the current situation, on the basis of a recurring argument: storage already exists; what is preventing us from continuing? Indeed, high-level (HLW) and intermediate-level, long-lived (ILW-LL) radioactive waste from the French electronuclear industry and from the activities of the French Atomic Energy Commission are stored in sites where this waste has been produced or transported. This is the "least bad" of solutions, according to the Network, for it has two benefits:

- it allows not establishing nuclear facilities in new sites;
- it avoids the transport of radioactive waste, deemed too hazardous.

Whenever one moves away from the core of the issue, meaning the interplay of players pushing their projects, their criticisms and their placing on a public forum (the pro-s, the anti-s, the CLIS, the sociologists etc.), one notices a fairly understandable kind of derealisation of timescales setting in. How can one interest new generations, branded by a form of obsession with the "now" and a highly restricted temporal horizon, - that of instant connections – to projects that not only bring up ghosts from the past (waste as a "nuclear nightmare"), but also involve a undetermined future in the phenomenological sense, ranging from one hundred to one million

The most frequent reference in the issue, recorded in the 2006 Act, is a duration of no less than one hundred years for that period. While the variations in duration for that initial phase may be relevant to the site's management and may have some technical impact, it is totally irrelevant to antinuclear opponents; indeed, to players opposed to deep disposal, reversibility should be effective throughout the lifespan of the waste placed under disposal, meaning well beyond three hundred years for long-lived waste.

years, that is to say timescales that are not suited to standard scales of action and judgement[22]? In addition, waste as a collection of inert, non-malleable objects clashes with a shared, ergonomic view of reversibility as interactivity with technical objects.

But as we all know, the problem is more fundamental: who has the right to speak on behalf of future generations[23]? Sometimes we grant them some freedom; sometimes we protect them from the consequences of present-day choices by planning to rid them of having to make a decision. Certainly, generations born between 1960 and 1990 are said to be less politicised than previous generations, and their mobilisations turn out to be fleeting and fragmented. Yet the close presence of objects that cannot be seized and are incompatible with any technical appropriation – such as that made possible by new technology – will continue providing opponents with convincing clout for years to come[24]. In effect, the antinuclear movement could very well operate on the basis of a handful of "activists" and score points in terms of collective representation – Simply look at the impact the PMO group (Pièces et Main d'Œuvre) had on the issue of nanotechnology, or the way in which anti-GMO groups succeeded in enlisting support well beyond their own networks with the "crop busters" or "voluntary mowers" movement[25].

As it is with "individual" impact on technology, players are lacking in "collective impact" on decision-making processes, causing either demobilisation and exit, or defiance and voice. Nowadays, participative democracy is a powerful constraint. Regarding nuclear waste, we are in fact managing the remnants of a process that was set up along purely technocratic lines. There is an overwhelming feeling that the debates have come too late, confirmed by the way in which the findings of the CNDP debate on waste were in effect contradicted by the Law of 2006. Ever since that debate, the various forms of discussion, especially at the CLIS, seem stamped by some kind of demobilisation, witness the latest CLIS newsletter's title and its surprising rhetorical approach: *Le Clis reste actif (The CLIS remains active)*. This movement is sustained by the

22 For timescales and their relation to the time of the action and of the project, see R. Duval, *Temps et Vigilance*, Paris, Vrin, 1990.

23 See H. Jonas, *Le principe responsabilité*, Paris, Cerf, 1992, and the discussion about it by Jean-Pierre Dupuy in *Le catastrophisme éclairé*, Paris, Seuil, 2002.

24 See F. Chateauraynaud, *Argumenter dans un champ de forces. Essai de balistique sociologique*, to be published in 2010.

25 See F. Chateauraynaud, M.-A Hermitte, A. de Raymond, G. Tetart, *Formes de mobilisation et épreuves juridiques autour des OGM en France et Europe*, Rapport ANR OBSOGM, 2010.

presence of protesting players who have no hesitation in denouncing institutional debate as an antidemocratic device prohibiting the occurrence of "genuine debate". This aspect can be seen in this excerpt from a PMO communiqué:

> "The CNDP is part of the array of tools to foster the acceptability of new technology, at the disposal of decision-makers to overcome the mistrust of consumer-citizens put off by too many techno-industrial scandals: asbestos, mad cow, GMOs. Its public debates perfectly match the recommendations of inventors of *technical democracy*. Scab sociologists, specialised in the acceptability of innovation, who provide decision-makers with systems to manage controversy. (…) Do you know the credo of those professionals in manipulation? 'Getting them to participate is to get them to accept'".

The increasingly frequent refusal on the part of opponents to enter the forums of discussion and consultation in order to take part in the debate is causing the issue to be split into two distinct arenas:

- an arena restricted to players in charge of managing the issue (assessment bodies, Andra, official rapporteurs, consultation bodies like the Bure CLIS and the ANCLI). Arguments here are structured by standard finality whose end is defined by the passing of an act on the conditions of reversibility;
- a wider arena, with more media coverage, where the presence of opponents and antinuclear players is felt much more acutely. Thus the statements are in large part structured by criticism denouncing a communication campaign meant to foster "social acceptability".

Accordingly, Andra has succeeded in substantially changing the operational terms of the concept of disposal, with reversibility designed as a possibility for gradual and evolving steering of the disposal process, leaving future generations with decision-making freedom on the process. However, those provisions get poor media coverage, with the media being in large part taken by opponents and players advocating the abandonment of nuclear energy. As a result, arguments developed in the public arena are mainly structured by polemical disputes around the deep disposal project, rather than by the controversy surrounding the definition of the reversibility concept.

To allow the arguments defended by authors-actors in the corpus to get a fair description, it appears to be necessary not to limit the analysis of the issue to its controversial aspect about defining the conditions of reversibility, but to regularly expand the lens towards the conflict about the disposal project. The fact that the media are structured by the critics can then explain for a large part the stability we have observed in the argumentation all along the path taken by the issue.

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