THE CHALLENGES FACING THE LONG TERM INTERIM STORAGE

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Key words: storage, radwaste, management, spent-fuel

INTRODUCTION

In France electricity generation by means of commercial nuclear power plants has come to a point where it contributes to the national demand at a level of 80%. The safety performance of the production system has also reached a high level of both maturity and reliability taking advantage of the cumulative effect of a 30 years long learning experience and ever more stringent safety requirements.

The policy to reprocess spent fuel has been overriding but no final decision has yet been made regarding the ultimate disposition of the waste streams. Although studies on deep geological disposal are ongoing, France is also looking at whether and under which conditions a long-term interim storage may provide an effective flexibility to the fuel cycle back-end.

We discuss thereafter the needs and the paramount objectives of this latter R&D program. Results are being framed as potential guiding criteria for decision makers and various stakeholders.

In first part, we propose a general analysis which emphasises that a long term interim storage is more than a classical nuclear facility because it explicitly requires long-lasting control and creates a burden for Society during many generations.

Present storage facilities are usually designed for 50 years; it may happen that the quality of the design allows for longer operations. Nevertheless, a systematic analysis of the life limiting factors clarifies the specifications required to improve and to guaranty the time-dependant robustness. Related scientific issues take into account what is specific in the interim storage, a secular nuclear facility under control[1], which also implies that scope and procedures for licensing have to look at the sustainability of Society and its intricacies.

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[1] Interim storage does not rely on geological containment and is not designed to become ultimate; at the opposite, deep geological disposal is technically able to become ultimate, beyond society control, to suit the multi-millenium requirement for the management of long lived high level waste.

Then, in second part, we offer an overview of the technical results from the R&D program as they stand at the time of writing. As an answer to the Government request, a strong emphasis has been put on this research for three years. Conclusion is an attempt to outline the societal context in which future decisions will have to be made.

LONG TERM INTERIM STORAGE: WHAT IS AT STAKE?

Let's make sure first that we share together a common understanding on what a long term interim storage is: it is neither a repository nor a disposal. The interim storage is designed to end its life at a time which is specified as part of its design criteria. As a result, the end goal of the design work is to guarantee that it will be safe to retrieve, handle or/and transport each and every nuclear material package stored to some other place at conditions affordable to future generations.

The century-long timescale envisaged for its lifetime is adding a particular and unusual dimension to the safety aspects and conditions usually encountered in nuclear facilities. Firstly, it impacts on our capacity to raise relevant questions and find proper answers regarding the effect that time might have on our decisions but also on harder components such as nuclear materials, metals, various natural or man-made materials, facility structures, processes. Secondly, it impacts also on the ability to predict the behaviour of what we design and the sustainability of the key assumptions, among them the structural societal aspects, made preliminary to the design work.

What does give this time-related very special nature to the long term interim storage? Uncertainty with regard to a number of questions. Here are just a few: for how long would a package be left there before being retrieved and handled back to a new destination? Which events could strike Society in the meantime and cause the storage to be left unattended for a certain period of time? Which environmental conditions could prevail during the lifetime of the facility and should be designed against?

Uncertainty is certainly something that Society has become more and more aware of during the 20th century marked by the tremendous technological developments and the correlative potential threats that they may represent.

In addition there is also the immaterial dimension of transferring today's problems to people in the future and the surrounding moral and ethical environments.

The safety of such a facility is therefore at stake and must be evaluated against new criteria to be identified and looked at carefully.

The current situation

What is the current situation with regard to nuclear spent fuel and waste to-day which must be considered as a start point for the design work? They are represented under multiple forms either placed in pools, already conditioned within packages or left in bulk in silos and are safely stored and managed according to scenarios designed to last a few decades. In a number of countries this situation has been regarded as acceptable as long as it was linked to a decision regarding the endpoint for these materials: i.e. deep geological storage in particular for the waste forms.

New considerations are being given worldwide to diversifying the management strategies for nuclear waste as the concept of deep geological disposal faces more and more public concerns.

New objectives for the management of the interim period, the wait period pending the final decision, must be explored now that uncertainty about when the final decision might be made is confronting us.

The long term interim storage paramount challenge: managing the ageing effects under unpredictable and varying conditions

One can easily realise that there is nothing like a unique technical solution which may work and meet the duration goal set for long term interim storage. The paramount challenge is with regard to the management of the ageing effects on materials, hardware, structural components under varying organisation schemes in Society.

The long term interim storage strategy is a response to that specific situation and is based on:

- The design of a packaging strategy which must encompass all forms of waste and spent fuels;
- Designs for technical installation providing safe storage conditions for nuclear materials for a duration set beyond 100 years to ensure that societal uncertainties which lie ahead are fully recognised and addressed;
- The demonstrated capability to handle back any nuclear material package at any given time and up to the end of the designed lifetime;
- Achieving reasonable economical and societal costs compared to current standards.

The long term interim storage can become a useful nuclear installation to fill the gap between the industrial decade-long storage options currently available and the final disposal and to organise the wait time in a well designed and controlled fashion under institutional control and the umbrella of Society as a whole since the final decision regarding the endpoint relies with it.

Such a facility must provide safe wait time for stored packages and guarantee their protection and retrieval at conditions affordable to future generations. We can see that these goals are all related to the long life nature of the facility. Therefore new guiding principles must enshrine this particular dimension through a specific ageing assessment process. Their definition have been central and essential to initiating the long term interim storage research work. Their consequences are far reaching. They will affect the facility design and operating procedures and supplement the list of traditional risks considered in the safety case and they may impact on the methodology used to address these risks.

At this point we would like to mention the major key principles which we arrived at. They are common to our different designs and maintain a strong guidance to our research work:

- The long term interim storage is an installation characterised by several management periods during its lifetime, (loading, waiting, re-handling...); for each, functions, risks, operating rules and safety conditions differ and must be known, evaluated and listed as part of the primary design criteria and objectives;
- To ensure safety during the wait period, the design criteria must set stringent goals for the components reliability; specs must not rely as much on criteria like preferred environmental conditions or human presence but should stress upon passiveness, simplicity, robustness (performance left unaltered under varying conditions);
- The burden left to future generations must be minimised, evaluated, known by the decision-makers;

- Understanding the ageing mechanisms is central to our ability to master their damaging effect. We must incorporate relevant strategies in the design work to acknowledge them and efficiently monitor their effect. The demonstration that we are able to safely cope with this risk must be made through proper technical provisions at the design stage and throughout the safety case;
- The long term interim storage is a facility under institutional control, subjected to unpredictable evolutions taking place in its natural and societal environments. No matter what provisions are made from the design stage to ensure that acceptable safety conditions will last during the lifetime of the facility they are not satisfactory enough without also considering a safety review on a scheduled basis and a thorough monitoring programme and proper means to facilitate its implementation now and in the future;
- The package must remain intact throughout the storage period to ensure safe re-handling and retrieval and to facilitate its eventual transport and/or disposal;
- Continued capability to safely re-handle any package any time must be available and demonstrated. Since the decision we could make to day would transfer the technical responsibility and the corresponding cost to future generations we must design cost-effective and technically flexible handling solutions;
- The safety case is essentially based on the principles and the methodology currently in use, including the defence in depth approach, but must also incorporate provisions against the ageing mechanisms, as indicated earlier. Societal risks must be addressed according to societal data and rules that we are experiencing to day and surrounding assumptions must be documented and traced to facilitate decisions to be made by others later on. The radiological impact must be evaluated for each management period of the facility. Off-normal scenarios under which technical and/or institutional controls of the facility are not performed for limited periods of time must be studied and their health consequences in terms of added impact quantified;
- In addition and/or to supplement the safety case an analysis of the reliability of the facility systems must be conducted and storage management protocols and criteria defining how and which packages are acceptable must be established at the very beginning. Such analysis and protocols are to become part of the operating procedures to be designed along with the facility itself;
- Since the long term interim storage is not a disposal option Society must be and remain organised as to keep all the information related to the facility and the packages which are in it and to sustain appropriate knowledge, competency and expertise in the relevant technical fields. The design work will have to accommodate this requirement as far as practicable.

These ageing management principles which are effective criteria to guide the design work naturally lead to technical and scientific questions regarding how damaging effects that time might have could be controlled through proper actions.

TECHNICAL RESULTS OVERVIEW

First part has highlighted the main guidelines set out to guarantee and maintain control of an interim storage over a secular timescale.

These general principles have to be translated into technical specifications. Thereafter, the main results concerning the storage of PWR spent fuel are outlined. Three levels (overall design, component technology, basic knowledge) are deeply interwoven and have to be addressed in a single approach:

- First of all, it is necessary to optimise the primary design to minimise the burden related to all facility life steps and operations: loading, monitoring, unloading;
- Secondly, technological processes have to be investigated to meet the design requirements; this is clearly a key point since satisfactory design has to be implemented through high-quality in manufacturing. Therefore, the purpose of technological studies is to find out relevant technologies and associated rules and to identify demonstrators for design and facility important components;
- Thirdly, some basic knowledge is required to select the relevant design. This need is related to the behaviour versus time and temperature for the following materials: i) the spent fuel, ii) the canister materials, iii) the concrete or the rock material of the facility structure. A fourth topic is related to the ability of forecasting the seism amplitude on the storage.

Here are important highlights:

Comprehensive design

The purpose of the CEA undertaking is to clarify what the concept of long term interim storage means and holds and to identify both its potentialities and its limitations in the overall waste management strategy. Interim storage has to be studied as a comprehensive multi-functions, multi-components system. Such a global approach is clearly required i) to evaluate key indicators for decision makers, i.e. safety, economical and ageing assessments, ii) to point out relevant questions and further R&D programs.

For spent fuel, most of the current interim storage are pool type facilities. This classical design is recognised as efficient for current buffer operations. Such a facility may last for a long period and allow a safe management [1]. Low temperature and monitoring capabilities are strong advantages for ageing management and working on water chemistry and on bottles devices improves reliability [2].

Nevertheless, for a very long term storage, the pool design presents limiting factors that has to be carefully investigated: i) active components like pumps, filters, etc, ii) common failure mode in the event of a loss of water, iii) maintenance requirements, iv) reliability of the recovery phase after a long wait period. As a result and after having conducted an ageing performance analysis of an optimised pool design, we now consider that a pool system cannot be recommended for a long term interim storage.

On the opposite, air cooled dry storage insures passiveness; storage canisters increase modularity which strongly reduces the occurrence of a common failure mode; robustness is enhanced since a maintenance shut-down for a limited period of time holds limited consequences.

Dry storage with a high degree of modularity is clearly recommended to insure the long term operating capability. Four complementary designs have been studied by CEA (to be published) to take into account different industrial strategies and public concerns: single or multiple –storing sites, surface or subsurface storage, strong or weak continuity from storage to disposal...

As a first result, it appears that the implementation of an efficient ageing management scheme is reasonably achievable from technical and economical viewpoints. But it requires that this goal be considered as a prime objective from the start of the design stage and throughout technical specifications when addressing, for example, redundancy of access, handling processes and water management (water table, seepage water, condensation). This also raises additional scientific questions, illustrated thereafter and related to i) the spent fuel package and ii) the temperature management.

Beyond the technical questioning, an additional area of uncertainty lies with future changes in the regulatory guidelines and framework and the potential for any storage facility to become one day obsolete as a result of their implementation. Indeed, it might happen (as it did) that a well run facility had to shut down because it could not meet changing regulatory requirements. We will illustrate our approach to deal with this point even if we cannot know today what future regulations could hold.

Screening economics

The study of different design combinations which illustrate various basic choices allows to also shed light on cost estimates. For each comprehensive design, we estimated costs for components and processes. This allows to quote available data and to offer a global overview for nuclear waste management.

Available data:

The following data only refers to orders of magnitude, either for existing facilities or for project, mainly because cost items and the relevant technical specifications are generally neither provided nor detailed. This gives a wide range for costs. Data is averaged over many sources and should not be read or interpreted as final or official information:

NUHOMS is a rather cheap storage system installed at existing nuclear sites. Neither operating nor installation costs are accounted for. Total cost estimate amounts to 0,4 MFRF/MTU, 55% of it is for the canister alone.

An alternative storage system relies on canisters fitted with biological shielding and licensed for transport, standing in a large centralised concrete shelter (Germany). The canister cost is around 0,8 MFRF/MTU which is half of 1,6 MFRF/MTU for the overall system. Cost for forthcoming disposal is minimised.

The factor 4 between these two systems is related to the operating cost and to the transport function.

The Yucca Mountain disposal project provides interesting references but one must keep in mind that the Yucca Mountain program mostly focuses on disposing UOX spent fuel. Recent data were released at the end of 1999 [3]. Unit costs for the Monitored Geologic Repository originating from this report are typically 2,5 MFRF/MTU, of which 0,5 MFRF/MTU is canister related.

Our approach takes into account ageing performance requirements, for both UOX and MOX fuels, for example through new components like the spent fuel holder. Moreover, we claim that, in order to reduce the capital cost component, biological shielding and the transport function should not be embodied in the canister design. The resulting average cost for waste conditioning and canister is estimated at 0,6 MFRF/MTU. The transport function is evaluated separately at less than 0,3 MFRF/MTU. The long term storage facility cost estimate ranges from 0,8 MFRF/MTU to 1 MFRF/MTU depending on the design, split roughly 50% for capital and 50% for a 60 years long operation.

Global analysis:

At this stage, tentative unit costs to figure out the cost and the economic sensitivity of possible strategies for spent fuels are suggested below:

- Canister cost is 0,5 MFRF/MTU;

- Transport cost is 0,3 MFRF/MTU;
- Storage facility (including operations) cost is 1 MFRF/MTU;
- To be compared to disposal facility (including operations) cost at 2 MFRF/MTU.

Even if one should be very careful when using these orders of magnitude, these unit costs are useful to put in perspective various steps and scenarios in the nuclear waste management schemes: transportation before storage and/or disposal, impacts of postponed decision on disposal, on re-conditioning between storage and disposal...

This also suggests that a low cost solution may result from disposal designs organised to be operated as a storage from the start and over a secular period (with a cooling system) since disposal costs can be further reduced by increasing package density at no extra cost (no extra storage facility, no extra re-conditioning, no extra transportation).

Of course, adding these costs together is not always relevant; for example, increasing the storage period decreases the disposal cost through heat management optimisation. But it provides a basis for a cursory global analysis.

Spent fuel package

One of the most important basic research program looks at the PWR spent fuel behaviour [4-6]. Part of this program focuses on the possible evolution of the spent fuel during a secular period; another part explores the post millennium period pertaining to the disposal concept. For periods less than 50 years and at cool temperatures as obtained in pool storage, we do not identify severe problems. For longer periods and at higher temperatures, one may question the mechanical behaviour of claddings and assemblies, the pellet stability and the gas generation.

Complex phenomena and intricate mechanisms are involved and lead to strong propositions for long term storage.

First, ageing analysis indicates that the use of a double static barrier is strongly recommended (the cladding is no longer considered as a long-lasting effective barrier); both barriers have to be monitored in some way (frequency, sampling strategy, etc to be determined). This monitoring is a prime technological challenge and constitutes a key R&D program because it has to be performed without weakening the confinement function and performance.

Secondly, for flexibility purpose, we propose that the first barrier be a bottle containing one assembly. This fuel holder is the elementary package insuring confinement and handling for any future operations. So its design and the manufacturing processes have to be reasonably well adapted – to suit these deferred operations which may include reprocessing as well as direct disposal. The second confinement barrier is the canister; it contains typically four bottles and is disposal compatible.

Thirdly, technological issues about industrial processes are also being looked at as part of the technological research program:

- The transition from the pool to dry storage relies on encasing the irradiated assemblies into the holder; it is of prime importance to guarantee the residual water volume within the holder for criticality and the corrosion of the holder and the spent fuel pellets;
- Subject to future decisions (reprocessing, re-conditioning...), it might be necessary to reopen the canisters; so, for a large number of canisters one has to investigate the technological capability and effectiveness i) to seal the canister, ii) to guaranty

its tightness during a secular period and iii) to reopen the canister under viable conditions afterwards.

Many of the existing processes and technologies can address these questions. The purpose of the R&D program is then to identify solutions and to produce guidelines for the design and the manufacturing of the canisters.

In support to this, the scientific research program on spent fuel behaviour will expand the knowledge base to help decide on two points for the PWR spent fuel long term interim storage strategy: i) which timing for the transfer of spent fuel from the buffer pool to the dry interim storage? ii) which operating temperature for the dry storage? Along with it two intricate scientific studies are ongoing regarding:

i) the gas release process; even if neutronic computations give relevant estimates for the maximum potential gas production, the velocity of the release is clearly important for the storage safety analysis,

ii) the state of the spent fuel matrix versus the duration and the temperature of the storage; it is clearly important for the safety analysis of a possible disposal.

Temperature and corrosion management

In this paragraph, we discuss the choice for the canister materials and a high operating temperature in the storage consistent with economical safety and ageing assessments.

An obvious purpose for long term interim storage is the preservation of the waste package. To minimise future burden the integrity of the package must be guaranteed and has to remain, in some sense, as good after the storage period as at start-up.

Failing that could imply that a possible re-conditioning of the spent fuel package before transportation or disposal might be needed which would represent a high burden for future generations.

Concerning canister materials, the following technical considerations are driving our approach:

- To manage the thermal power of the assembly and its irradiation, metallic canister materials are more suitable than concrete, ceramics…;
- Canisters manufacturing is very expensive, consumes materials and requires a heavy industrial organisation. Common materials like cast iron or steel are preferable compared with copper;
- Corrosion assessment for stainless steel is intricate due to pitting. To be able to guaranty the evolution of the canister materials, one has to choose conditions allowing generalised corrosion rather than passivation in the case of low allied steel;
- Atmospheric corrosion has to be avoided because i) it may lead to high velocity (a few mm per century) unacceptable with the purpose of integrity; and ii) it presents a high sensitivity to air pollution unacceptable from the point of view of robustness. As waste power decreases, potential for corrosion may exacerbate at the end of the storage process and ultimately impede the retrievability;
- An alternative is to design and establish conditions under which dry corrosion phenomena will prevail. In that case, there is no water condensation and the corrosion velocity slows down to a few microns per century, in line with the integrity objective.

We therefore suggest the use of low alloyed steel canister with a high operating temperature to guaranty the integrity at retrieval time. Concerning temperature management, the following technical considerations are driving our approach:

- Long term interim storage means long wait periods characterised by a very low human presence and activity mainly related to monitoring. These wait periods will be interrupted by many active periods required for loading or unloading packages, for scheduled periodic heavy control and/or maintenance operations;
- As an off-normal situation, we consider the breakdown of the thermal release systems during a limited period of time. The higher is the authorised operating temperature of the canister, the more robust the facility becomes since it requires less cooling power;
- Consistent with the ageing management principles as stated above, we define specific operating rules for the wait period. A storage design based on a high operating temperature can be used for the wait period since no human presence is required.

This is why, we investigate the possibility to establish operating procedures which accounts for wait periods during which the canister outside temperature is above 100°C as to guarantee a secular corrosion free period due to the absence of condensation. The result is a dramatic improvement in the corrosion assessment even for soft iron canister and in the robustness in off-normal situations. This choice is made possible by the assembly holder which allows a higher operating temperature for the spent fuel. This strategy is attractive but two issues have to be investigated:

- firstly, the global study of the transient regime between wait and active periods and;
- secondly, the behaviour versus time and temperature i) of the spent fuel (cited above) and ii) of the facility structural material (concrete or rock material).

Therefore, it appears that a key issue about long term storage lies with the secular behaviour of the concrete structure under temperature. This behaviour involves intricate mechanisms coupling thermal, hydraulic, mechanic and chemical phenomena. Even if a higher temperature operating scheme was not successful, this issue had to be addressed within the standard safety analysis. This explains why CEA has launched a large scientific program on the long term behaviour of porous media subjected to temperatures higher than the boiling water threshold.

Early results suggest that for current porous materials (either concrete or natural materials like granite and limestone) there is no structural discontinuities for temperatures ranging from ambient temperature up to 250°C and more. At this point it seems that the vaporisation of free water within the material has no dramatic effect from a mechanical point of view.

So far we expect a good large scale behaviour of the structural material surrounding the canisters even at temperatures higher than the currently authorised 80°C. An increase of say 50°C of this design threshold would present definitive advantage for ageing and safety assessments. At a smaller scale, say centrimetric, the behaviour is more questionable but can be probably overcome through proper engineering. Forthcoming studies will clarify the effect on chemistry[2].

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[2] We expect possible effects to have small consequences due to the weakness of the matter flux.

Seismic long term management

For the secular period involved in storage management, the seismicity does not evolve. So the problems are related to i) the site selection and the assessment of its maximum seism and ii) designing a facility to stand that maximum level. We consider that appropriate knowledge and technology are available to address the latter problem.

Is the risk for a long term interim storage higher than for a short term one? As a matter of fact, the seismic risk does not depend on the life time of the facility but only depends on the period during which packages are stored: the probability of a seismic event to occur at a given level is the same for a facility lasting 100 years or for a sequence of two facilities lasting 50 years each.

Nevertheless, knowledge and perception can significantly evolve within 20 years. Nuclear industry is facing a situation whereby an operating facility could not meet a new provision in the regulation based on complementary knowledge or social requirement.

It is clearly necessary to minimise this occurrence because such a situation may put a heavy burden on future generations.

The design of a facility relies on site data acquisition and knowledge. The goal is to render the information as robust as practicable in the following sense: the failure is with regard to acquiring a new information within 20 years or more which would lead to the conclusion that the facility had to be shut down. We call this risk of failure the "regulatory obsolescence" of the long term interim storage.

As a result, the purpose of the scientific program is to define the methodology for site characterisation, including local geography and depth effects in order to produce robust information on the selected site. To address that generic questions, we have chosen to investigate the variation of seismicity with depth.

It is well known that the effects of seismic waves are less pronounced underground than on the surface. This is confirmed by worldwide observations made within underground facilities such as tunnels and mines where significant damages are generally due to displacements along active faults intersecting the facility.

There are three main near surface effects for seismic waves, namely, the free surface effect, the impedance contrast amplification and the ray angle differences [7]. Basically, the free surface effect reflects that for P and SH waves at vertical incidence, waves moving up and down are constructively interfering at surface.

When a wave enters a slower velocity material, which is often the case near the surface, amplitude generally increases by conservation of energy (impedance contrast amplification) and waves coming upward travel more vertically (ray angle differences).

In a simple tabular structure, these different effects can be easily modelled [8]. Nevertheless, in more realistic cases, several other phenomena may have to be taken into account such as converted waves, possible lateral discontinuities in the velocity characteristics, non-linear effects in soil and topographic effects.

More realistic numerical models are under development and will be validated using seismic records obtained at several depths in areas known with well constrained characteristics. As a paradox, the experimental challenge comes from the overall low seismicity prevailing in France.

Hence, the goal of this program which is to enhance the quality and the robustness of the seismic maximum level forecast prior to establishing the facility design. We think that this approach, also focused at improving trust in the present state of the art, is relevant to prevent regulation obsolescence and can be generalised to other studies.

CONCLUSION: HOW TO INPUT AND FACILITATE THE DECISION-MAKING PROCESS?

Earlier we have tried to set and illustrate the technical environment and the relevant questions pertaining to the long term nature of the interim storage in order to better apprehend what is at stake on technical and scientific grounds. We also have shed some light on the current results and on how they could impact on storage facility design and management strategies.

But there is more to it. A decision is needed as to which nuclear materials management strategy Society is ready for and before this decision is made careful steps must be considered to achieve consensus building among various stakeholders.

One usual way of doing it is through information sharing, discussions and ownership building.

This is a long term goal as illustrated through the outcome of the Consensus Conference on Nuclear Waste [9] which took place in UK in 1999 and the subsequent steps taken by the House of Lords [10] and the UK Government. Another recent initiative by the EC, *TRUSTNET* [11], looking at how to improve trust in the decision making process, has led to the conclusion that such a decision making process should involve the public and benefit from public input to gain public support.

Public at large is not likely interested to discuss technical issues. For instance, the UK Citizens involved in the Consensus Conference cited above selected a number of questions formulated after what they had perceived to be the meaningful issues. Here follow some of the questions raised [9]:

- regarding nuclear waste management options or alternatives: what are the advantages and disadvantages of deep disposal and of shallow/surface storage?
- regarding informing the public on nuclear waste issues: what is the current/future policy with regard to informing the public about radioactive waste? Currently, what Research and Development is there into nuclear waste treatment?
- regarding the regulatory control: what is the current/future policy with regard to monitoring companies who produce radioactive waste?

For the scientists and the technical people this is a radical change. They must produce the best knowledge and design possible but also clearly identify flexibilities, alternatives as well as limiting factors.

The public is no longer to accept a ready for use package under the statement *"this is what we believe is the best technical solution".* They want to be listened to, participate in the assessment process and feel ownership in the subsequent decision to be made.

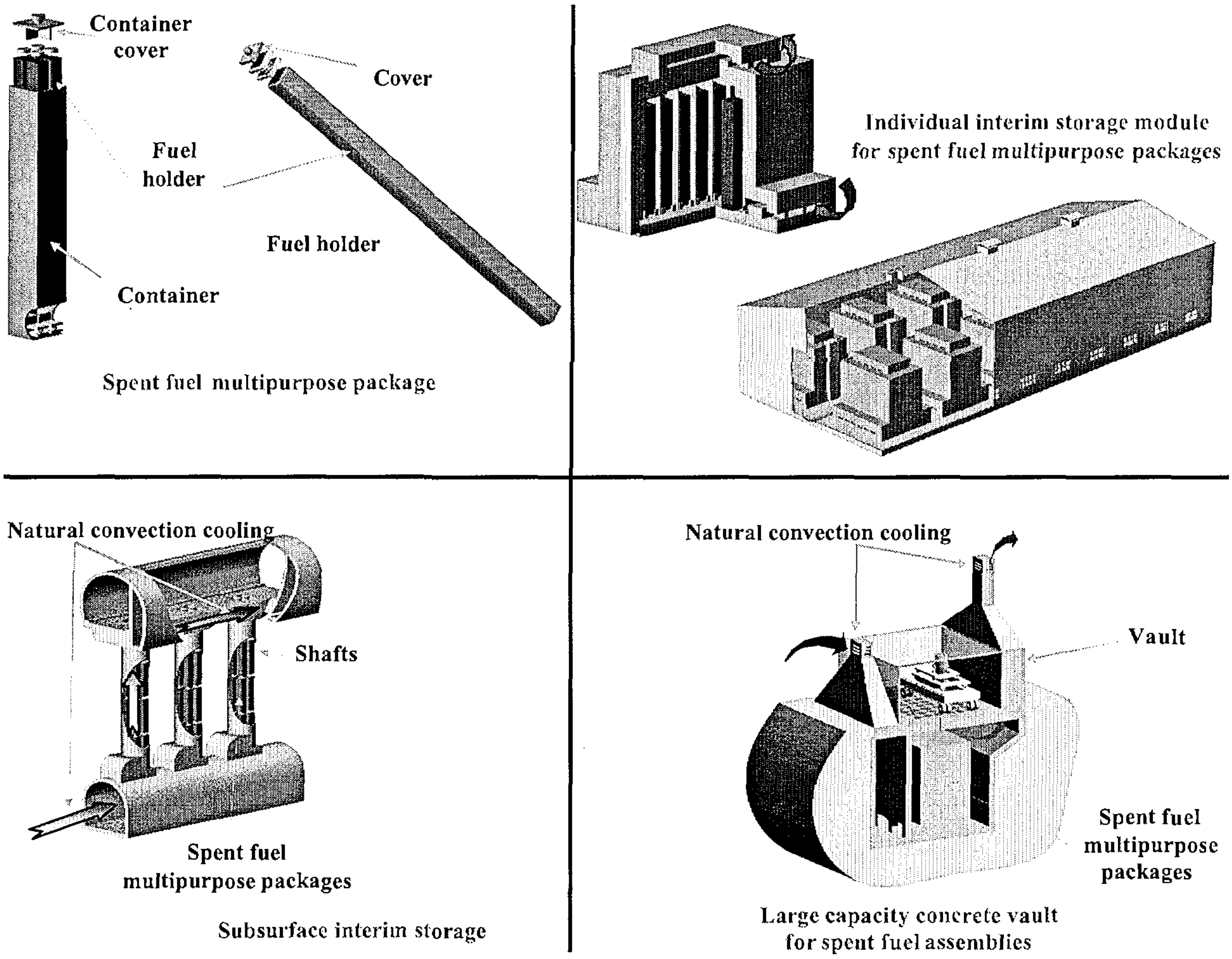

Figure 1: Example of alternative comprehensive designs

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