Proceedings of the Fifth Annual International Conference
Las Vegas, Nevada, May 22-26, 1994

A COMPARATIVE STUDY OF U.S. AND RUSSIAN HIGH-LEVEL WASTE REPOSITORY DESIGN CONCEPTS

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BSTRACT

A comprehensive study, including site visits, was ade of the high-level radioactive waste disposal programs in the USA and in the Russian Federation. Siting and xploration procedures for site characterization, repository esign concepts and the overall systems design methodologies were investigated and compared with the m of identifying those areas where the two countries can arn from each other. No other American - Russian omparative studies could be traced. It is shown that the SA can benefit by paying more attention to the Russian rogram of waste disposal in addition to the interest shown n the European waste storage activities.

INTRODUCTION

The world's first high-level radioactive waste storage repository, currently planned at the Yucca Mountain site in Nevada, represents one of the greatest design endeavors of he present time, at a cost of over $40 billion when completed around the year 2010. Yet, at this stage, there s no clear design strategy for this project and progress has been limited, in spite of some $2.5 billion already spent in he past ten years.

While the American program of high-level radioactive waste disposal has suffered from many indecisions and completion target date postponements, the Russian program is also in disarray with little planning directed toward the permanent disposal of the nuclear waste.

It is considered appropriate at this time of historical changes to compare the status of the programs in both countries, to point out the differences and similarities, and to suggest how one nation can benefit from the other.

II. ISSUES IN HLW DISPOSAL IN THE USA

Long-term storage of high-level radioactive waste presents formidable challenges throughout the world. In the USA, the design of an underground repository for high-level nuclear waste (HLW) was mandated by a 1982 act of Congress to provide safe underground storage for a period of 10,000 years, a criterion without precedence in rock engineering! One of the major problems encountered to date was the lack of a comprehensive and systems-integrating design methodology for the whole waste storage process which could contribute to the resolution of design and construction issues arising out of complex licensing criteria and strict environmental standards.

A. Environmental Requirements

The U.S. underground storage facility is to isolate an estimated 87,000 tonnes of high-level nuclear waste. Construction is to start by the year 2004 and be ready to receive the waste by 2010. The overall objective is to minimize cumulative release of radionuclides, such that:

1. The total system (natural geologic system, the repository, and the waste package, must isolate the waste for at least 10,000 years.
2. The package is to contain the waste for at least 300 to 1,000 years.
3. The rates of radionuclide release from the engineered system are not to exceed one part in 100,000 per year for each radionuclide, after the containment period.
4. The pre-emplacement ground water travel times from the repository to the accessible environment, over a distance of 10 km, are to exceed 1,000 years.
5. The engineered barrier system must be so designed that the waste can be retrieved for a period of 50 years after initial placement.

B. Current Status

The National Academy of Sciences (NAS) pointed out[1] that the US program is unique in its rigid schedule, in its insistence on defining in advance the technical requirements for every part of the multibarrier system, and in its major emphasis on the geological component of the barrier as detailed in the NRC regulations. In essence, nuclear waste management is a tightly regulated activity, hedged with laws and regulations, criteria and standards. Some of these rules call for detailed predictions of rock behavior for tens of thousands of years, longer than recorded human history.

NAS stated further that the US program as conceived and implemented over the past decade, *is unlikely to succeed because it is poorly matched to the technical task at hand.* This is because the program assumes that the properties and future behavior of a geologic repository can be determined and specified with a high degree of certainty. In reality, the inherent variability of the geologic environment will necessitate frequent changes in the specifications.

Another independent body, established by Congress in 1987, is the Nuclear Waste Technical Review Board (NWTRB). Its purpose is to evaluate the technical and scientific validity of activities undertaken by the DOE and, in the process, comment on the appropriateness of NRC regulations and EPA standards. In its reports[2], this Board also expressed many concerns and made far-reaching recommendations which could significantly improve the US nuclear waste disposal program. It pointed out that the standards should not impose restrictions that would *foreclose at the outset a candidate site subsequently shown to be suitable based on sound scientific considerations.* Moreover, an urgent need was identified to develop a comprehensive methodology for performance assessment of the overall repository concept.

Since the advent of the 1982 Nuclear Waste Policy Act, nine potential sites have been identified for the first geologic repository, of which three were selected for detailed site characterization at a price tag of $1,000 million each: Hanford, Washington, in basalt; Deaf Smith, Texas, in bedded salt; and Yucca Mountain, Nevada, in welded tuff. At that stage, the deadline for acceptance of waste for disposal was January 31, 1998. Extensive site exploration and design studies were performed for the Hanford site, known as the Basalt Waste Isolation Project. The other two sites also had major investigations and studies in progress or planned when the whole approach was changed in 1987 with the designation by Congress of only one site, Yucca Mountain, for full site characterization.

The ten-year task of characterizing the Yucca Mountain site at a cost of $6 billion has only just started, due to severe delays when the state of Nevada denied air-qual permits for dry drilling at the site. The result: the 20 deadline could be in jeopardy. In March 1993, excavati has begun at Yucca Mountain with machine boring 24 of exploratory tunnels (7.6 m diameter). It will take fr three to four years before this Exploratory Studies Facil and the site characterization phase are completed.

Site characterization at Yucca Mountain included Exploratory Shaft Facility (ESF) originally featuring t drill-and-blast vertical shafts accessing the reposito horizon in the most favorable welded tuff zone. T concept of shafts was abandoned in 1990 after an alternati investigation of 34 options for the ESF (renam Exploratory *Studies* Facility). The top option now featur TBM excavated ramps.

C. Geologic Aspects of the Candidate Site

The repository horizon, approximately 335 m bel the surface of the Yucca Mountain, is to lie within t Topopah Spring welded tuff, 290-370 m thick and near flat, which is bounded above by the Paintbrush nonweld tuff and below by the Calico Hills nonwelded tuff. T distance below the repository to the regional water tab ranges from 170 to 400 m. The Topopah Spring dense welded tuff, called the TSw-2 unit (27-50 m thick), will used as the host rock.

Evidence exists that geologically recent faulting (i. within about the past million years) in the Yuc Mountain region is relatively widespread. A major faul the Ghost Dance Fault, crosses the proposed repository ar but shows no recent activity. On June 29, 1992, a earthquake measuring 5.6 on the Richter scale took plac only 20 km southeast of Yucca Mountain. Currently, conceptual repository design calls for withstanding groun accelerations of 0.5g to 0.6g which is equal to a earthquake magnitude of 6.5 on a nearby fault[3] (th January, 1994, earthquake in Los Angeles measured 6.6).

Some rock engineering information is available which provides the preliminary data for conceptual desig purposes. The design of rock excavations at the Yucc Mountain Project is directed to overcome two possibl types of rock mass failure: failure due to stress and failur due to gravity driven movement of discrete blocks. Thus the stresses as well as the rock mass strength have to b determined. However, the assessment of the rock mas strength is particularly problematic. The determination o the rock mass strength is based mainly on rock mas strength criteria involving rock mass classifications, such as the Rock Mass Rating (RMR) system or the Q-system[4].

Using these data, the material constants for the rock mass strength criteria by Hoek-Brown and by Yudhbir-

years, and perhaps more, would be unattainable in the United States program." In this case, the required redundancy can be directed to the design of the repository, the main role of which will be to maintain retrievability of the waste for 85 years (including the time for repository construction, waste placement and decommissioning).

A conceptual design for a nuclear waste repository, currently contemplated in the USA, will feature a network of tunnels (drifts) - similar to an underground mine - in which waste packages will be placed either in horizontal or vertical boreholes drilled in the drift floor or sides, or the waste packages will be placed directly on the drift floor for easy retrieval. The drifts will be excavated by tunnel boring machines (TBMs). An improvement in rock mass quality of about one to two classes was estimated by numerous engineers and researchers if TBMs are used[4].

In essence, the Systems Design Methodology serves as a guiding reference of where we are, where we ought to be, and what the next step should be within the overall workplan. But the SDM is not just a flow chart for step-by-step action. To be effective, this design methodology incorporates specific design principles which can be used to evaluate design and to select the optimum one fulfilling the perceived objectives. This assists in effective decision-making and promotes design innovation commensurate with safety and economy.

An overall systems design methodology (SDM) for the whole process of high-level waste disposal in the USA is yet to be undertaken along the lines discussed above. In principle, just as an engineering *structure* (e.g. a repository) requires a design methodology, so does a *process* - such as HLW disposal - requires a comprehensive and integrating systems design methodology which serves as a management plan to ensure that all the performance objectives are fully achieved.

For the United States, three challenges have been listed as critical concerns for an acceptable systems design[2]: (i) the need to establish realistic target dates for achieving important interim goals, such as determining the suitability of the Yucca Mountain site, (ii) development of a comprehensive, well-integrated plan for the management of all spent fuel and high-level defense waste, and (iii) undertaking independent evaluation of the organization and management of the Office of Civilian Radioactive Waste Management which now controls too many organizations and this restricts program effectiveness.

E. Repository Design Concepts

Currently, about 22,000 tons of waste sit at 60 utilities and will double by the year 2010. Additional waste from US defense facilities, also intended for the repository at Yucca Mountain, should be up to 8,800 tons by then. NAS[1] reported that on-site storage systems are safe for at least 100 years while NWTRB[2] pointed out that research conducted in Sweden since 1977 has suggested that containers can provide at least 10,000 years of isolation for 40-year-old spent nuclear fuel. Some of the design challenges are:

1. Selection of the repository thermal-loading strategy which affects the design of both the waste package and the repository.
2. Developing a comprehensive strategy that integrates exploration and testing priorities with the design and excavation approach for the exploratory facility.
3. Resolving the issue of coupled effects: thermal-hydrologic-geochemical-mechanical.
4. Defining the 'reasonable assurance' criterion and answering the question of 'what is enough?' for explolatory testing.
5. Analyzing, before repository design decisions are made, the pros and cons associated with long-term retrievability options (beyond the current 50-year retrieval requirement).

III. HLW STORAGE CONCEPTS IN RUSSIA

The former Soviet Union derived 12% of its electricity needs from 46 nuclear plants located at 17 sites, with an additional 25 plants being under construction in 1990. By comparison, the United States produces 22% of its electricity from 111 nuclear plants (at 70 sites) with only 3 plants under construction (no new reactors have been ordered in the USA since 1978).

After the break up of the USSR, the Russian Federation (population 155 million) comprises 76% of the area of the former Soviet Union and on its territory are 10 of the 17 sites at which the nuclear power plants are constructed.

Spent nuclear fuel was not classified as waste in the Soviet Union. It had to be reprocessed at radiochemical plants to extract uranium and plutonium. The same procedure continues in present-day Russia. This reprocessing of spent nuclear fuel results in the generation of high-level liquid radioactive waste.

Apart from discharging some liquid nuclear waste at sea, three approaches are used or planned in Russia for land-based storage operations. One is to solidify (vitrify) the waste and place it in a shallow lake, Lake Karachaj (near Chelyabinsk in the south Ural mountains), which is in the vicinity of the Mayak radiochemical plant where the first Soviet plutonium was produced weapons[7]. This area is already heavily contaminated and was the scene of a major nuclear accident on September 29, 1957. Large amounts of liquid waste have already been discharged into this lake. In 1967, a severe drought shrank the lake exposing nuclear waste sediments on its bottom. A tornado picked up the radioactive dust and scattered it over a large area. In 1987, a vitrification facility was put into operation at the Mayak plant. The process is based on radionuclide introduction into phosphate glass, prepared in a ceramic melting pot made of high-alumina zirconium refractory material with molybdenum electrodes. Vitrified wastes are poured into $0.2m^3$ canisters. After cooling, three such canisters are placed into metal containers of 0.6m diameter and 3.4m high. About 1,000 m^3 of nuclear waste has been stored in this fashion but the facility is being reconstructed at present and this form of storage is suspended. The waste so stored was declared safe for 20-30 years.

The second storage approach involves underground disposal of liquid radioactive wastes by "controlled discharge" into deep aquifers "isolated from other formations" using a system of injection wells[7].

The third approach is long-term storage of solidified high-level nuclear waste in geologic formations "below the zone of active water movement"[8]. For this purpose, during the times of the Soviet Union, a technique of "high-level waste *fractionation*" was developed to isolate the most hazardous (long-lived) radionuclides into separate fractions. This technique is based on the utilization of an extracting agent to separate 99% of cesium, strontium and plutonium elements into different fractions which are then solidified for placement in an underground rock formation. Investigations were performed in different rock strata which could host an underground storage facility. While no locality has been selected, one possibility studied was construction of such a repository directly on the site of the Mayak radiochemical plant because this would avoid transportation of large quantities of radioactive waste to another, perhaps far distant, permanent storage facility.

A. Site Selection Procedures

Initially, salt and potassium mines in the Caspian sea region were singled out as possible candidate sites, followed by sites in Belarus and Ukraine. This was followed by consideration of crystalline rock formations in Siberia and tuff and tuff-breccia formations in the south Urals, some 200-300 m below the surface. Moreover, vast permafrost territories in the Kola peninsula were investigated as particularly suitable since they could be expected to remain climatically unchanged for at least 10,000 years. They are characterized by the presence of very thick permafrost rock formations containing crystalline and sedimentary rocks. A specific feature of permafrost is its unique tectonic stability and virtually no permeability but heat generation effects would have to be carefully considered.

In essence, three major candidate sites are under investigation in Russia for deep underground, long-term, permanent storage of HLW : (1) Krasnoyarsk site in Siberia; (2) Mayak site, near Chelyabinsk, in south Urals, and (3) Kola site, in the Murmansk region in the Kola peninsula. No specific site characterization and final location selection programs are as yet in place.

B. Repository Design Concepts

An interesting consideration in developing conceptual repository designs in Russia is the possibile utilization of the stored nuclear waste in the future. Safe retrieval of waste packages after a long period (hundreds of years) is considered.

A conceptual repository design was published[8] depicting a multi-level storage concept in which solidified high-level waste is to be placed in underground tunnels, some of which are provided with a cooling system featuring natural ventilation.

Future work is to be directed to three aspects: (1) development of waste preparation methods to minimize the volume of high-level waste to be stored (e.g. "fractionation" technique), (2) development of reliable models for waste behavior in geologic environments over a long-term storage period; and (3) development of repository designs with an optimal combination of the geologic system and engineered system barriers.

It is not clear how repository design activities are coordinated in Russia and how the latest conceptual design is being evaluated. It seems that, as a result of severe economic constraints, permanent storage of high-level nuclear waste in Russia is quite behind its counterpart in the USA.

Most of all, a process design methodology for the waste disposal program is either vague or missing. Nevertheless, Russian scientists and engineers are known to have a wealth of experience and scientific knowledge about the construction of extensive and safe underground excavations in mining and civil engineering and it is probably only a matter of concentrated effort and funding to develop a comprehensive HLW disposal program.

IV. DISCUSSION OF THE HLW DISPOSAL PROGRAMS IN RUSSIA AND IN THE USA

There is no question that both the United States and the Russian Federation are determined to provide safe storage of high level nuclear waste generated in their countries. During the author's visit to Russia in 1992 he had the opportunity for detailed discussions at the Russian Ministry of Ecology/Environment and he was amazed at the complete openness and freedom of information in present-day Russia and at the determination of the Russian officials and the environmental community for safe disposal of nuclear waste and for clean up of the contaminated sites.

Both countries have made considerable progress in identifying the issues involved in nuclear waste storage, and in taking distinct action to solve them. However, in both countries progress is very slow, often indecisive, and the delays and turnarounds are considerable.

In the case of the United States, the search for a permanent waste disposal site has continued for 37 years (!) and since the advent of the 1982 Act of Congress mandating a comprehensive program to solve the problem, there were numerous deadline changes. Sites were selected and studied for site characterization, only to be abandoned (e.g. Hanford site) after large expenditures. The latest deadline, a repository opening in the year 2010, is in doubt and even the program objectives are under revision.

In the Russian Federation, no deadlines exist and there is no coordinated effort as yet directed specifically to site selection, characterization and systems design. Primarily activity is directed to the clean-up of contaminated areas and to providing broad planning for long-term disposal.

A mitigating reason for this unfortunate situation is that Russia has far more complex HLW problems to solve than the United States. For example, the USA is only responsible for nuclear waste generated within its territorial boundaries and nuclear waste generated by military sources is only 1/7 that from the commercial utilities. The Russian Federation is responsible for waste disposal not only from its own industry but also from nuclear plants in the former Soviet republics and even in the former Warsaw pact countries where Russian reactors are still in operation. Moreover, the issue of military nuclear waste in Russia is a major concern.

In summary, Russian challenges for long-term disposal of high level nuclear waste stem from three unique sources: (i) responsibility for the waste produced by nuclear plants in other countries such as the former Soviet republics and former Warsaw pact nations; (ii) a large proportion of military-produced waste and severe contamination of certain rivers, lakes, seas and land areas by the dumping of liquid and solid waste, and (iii) large volumes of reprocessed weapons-grade plutonium and enriched uranium having half-lives of 24,000 years.

For the United States, three challenges have been listed as critical concerns[2]: (i) the need to establish realistic target dates for achieving important interim goals, such as determining the suitability of the Yucca Mountain site, (ii) development of a comprehensive, well-integrated plan for the management of all spent fuel and high-level defense waste, and (iii) undertaking independent evaluation of the organization and management of the Office of Civilian Radioactive Waste Management.

It was also found[2] that, besides Germany, the USA is the only country characterizing a specific side for potential repository construction, and that all other countries, except the USA, are planning a repository below the water table.

It may be concluded that both the United States and the Russian Federation would benefit by relying more extensively on the engineered barrier system for long-term waste isolation (waste packages for over 10,000 years) with geologic barriers providing secondary but essential protection.

Finally, both the USA and Russia might benefit by adopting the regulatory criteria used in Europe where design and construction of a repository are based on radiation dose limits to individuals. Performance criteria involving individual radiation dose rates are consistent with the guidelines of the International Commission on Radiological Protection. By contrast, the United States is using rigid regulatory criteria in which specific containment standards must be met: the system performance criteria are based on a total cumulative release from the repository and the waste package lifetime and groundwater travel time are regulated. This may not be consistent with the overall system criteria[2].

V. CONCLUSIONS - RECOMMENDATIONS

It is concluded that lack of a comprehensive, systems-integrating process methodology has hampered HLW waste isolation programs in the USA and in the Russian Federation. The organization and management of the programs in both countries leaves much to be desired in spite of the availability of extensive knowledge and experience among technical experts in these nations. In spite of massive amounts of money and time spent, particularly in the United States, progress has been very slow and some decisions are very confusing and wasteful. During the author's twelve years of involvement in the program, first with the Brasalt Waste Isolation Project and subsequently with the Yucca Mountain Project, he witnessed only small improvements in site characterization procedures and repository design approaches.

Realizing the complex issues involved, a few recommendations are singled out based on this comparative study which could improve the effectiveness of the HLW storage programs in the USA and in Russia:

1. It is in the national interest of the United States to help Russia, technically and financially, to plan and execute a comprehensive program for its HLW disposal. U.S. interest stems from the fact that the contaminated areas in Russia and its territorial waters are a direct hazard to the United States and countries in Europe. It is necessary to help Russia because, at present, HLW disposal there is not receiving the necessary attention due to a lack of funds and because it is conceived of such long-term duration as to be beyond the current politicians' responsibility.

2. The United States can learn from Russia concerning the effects of radiation on excavation stability and on human health. Experiments performed in Russia since the 1960s with underground nuclear excavations for civilian purposes have provided a wealth of scientific data waiting to be analyzed.

3. In the United States, the duplication of effort, so wasteful and costly, should be eliminated. The DOE, NRC, EPA, nuclear utilities and the states concerned, have now reached a total of nearly 2,000 people on a full-time basis. As a result, the U.S. program is the least cost effective of all the nations working on HLW disposal.

4. The United States should consider the Russian approach to repository design involving the concept of an unlimited waste retrieval period. Russia argues that the potential value of spent fuel is not yet known. The future may bring vastly efficient and safe technologies necessitating nuclear power. Combined with the risks involved in burying radioactive waste, this means that the retrieval option should be kept open. The U.S. current approach, based on cost considerations mainly, stipulates a 50-year retrieval period.

5. A comprehensive systems design methodology (SDM) for the overall process of HLW disposal in the USA and Russia should be applied along the lines of the SDM for rock engineering. In principle, just as an engineering *structure* requires a design methodology, so does a *process* - HLW disposal - requires a comprehensive and integrating systems design methodology which serves as a management plan to ensure that all the performance objectives are fully achieved.

ACKNOWLEDGMENTS

This research was partially funded by the U.S. National Science Foundation, Design Theory and Methodology Program, under Grant No. DDM-91-13241. The author also wishes to thank Prof. E.V. Kuzmin for his hospitality and assistance during his study visit to Russia.

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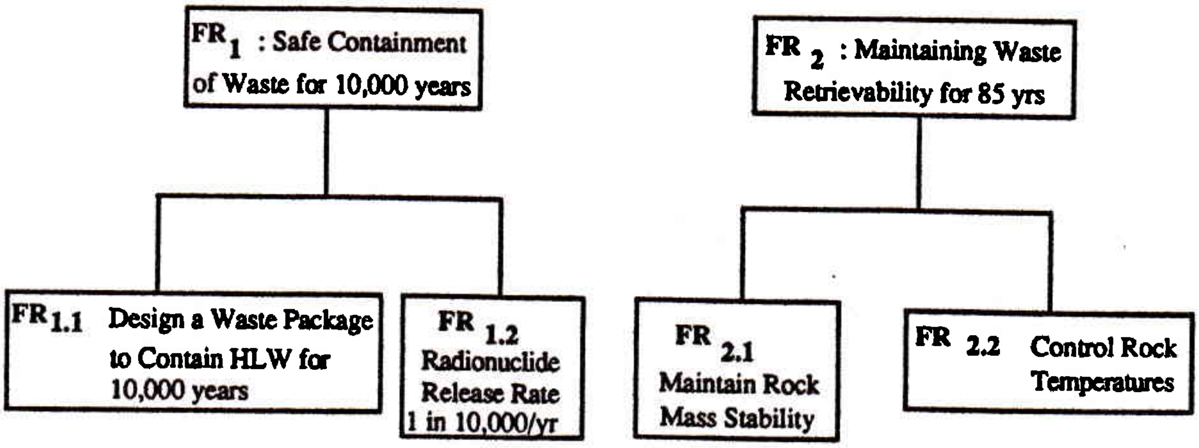

FIGURE 2: An example of Functional Requirements hierarchy for the Yucca Mountain Project