The Waste Isolation Pilot Plant Deep Geological Repository: A Domestic and Global Blueprint for Safe Disposal of High-Level Radioactive Waste - 12081

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ABSTRACT

At the end of 2011, the world's first used/spent nuclear fuel and other long-lived high-level radioactive waste (HLW) repository is projected to open in 2020, followed by two more in 2025. The related pre-opening periods will be at least 40 years, as it also would be if USA's candidate HLW-repository is resurrected by 2013. If abandoned, a new HLW-repository site would be needed. On 26 March 1999, USA began disposing long-lived radioactive waste in a deep geological repository in salt at the Waste Isolation Pilot Plant (WIPP) site. The related pre-opening period was less than 30 years. WIPP has since been recertified twice. It thus stands to reason the WIPP repository is the global proof of principle for safe deep geological disposal of long-lived radioactive waste. It also stands to reason that the lessons learned since 1971 at the WIPP site provide a unique, continually-updated, blueprint for how the pre-opening period for a new HLW repository could be shortened both in the USA and abroad.

INTRODUCTION

At the end of 2011, following more than 70 years of global efforts and 14,713 operating nuclear reactor years, the projected 2020 opening in Finland of the world's first man-made deep geological disposal system/solution (repository) for used/spent nuclear fuel and other long-lived highly-radioactive wastes (HLW) is still at least nine years away. The projected pre-opening periods for this as well as the world's other first three HLW repositories exceed 40 years.

Based on our active involvement and monitoring of a broad range of radioactive-waste-disposal programs and proposed disposal solutions since 1973 [e.g., 1], as elaborated upon in this paper, we believe the Waste Isolation Pilot Plant (WIPP) deep geological disposal system (repository) for long-lived transuranic radioactive waste (TRUW) in New Mexico (Figure 1) provides a globally-unique blueprint for how the pre-opening period for new HLW repositories can be significantly shortened, particularly in salt. WIPP opened in March 1999 following a pre-opening period of less than 30 years and it is still the world's only operating, man-made, deep geological disposal system for long-lived radioactive waste and materials (LLRMs) at the end of 2011.

The focus herein is on the 1971 to 1999 WIPP pre-opening period. Since the pre-opening period for the other repositories described herein remains to be completed, this term is explained on a case-by-case basis in the Background section, which contains "tip-of-the-iceberg" information on the three European radioactive waste management programs currently projected to open their respective HLW repository no later than in 2025. The Background section also touches upon the "re-born" German HLW-repository program, USA's "currently-hibernating" HLW and "safely-operating" TRUW repository programs, and select milestones, stratagems, and main tests conducted at the WIPP site during the pre-opening period. The Background section is followed by a summary of our Main Observations and Recommendations.

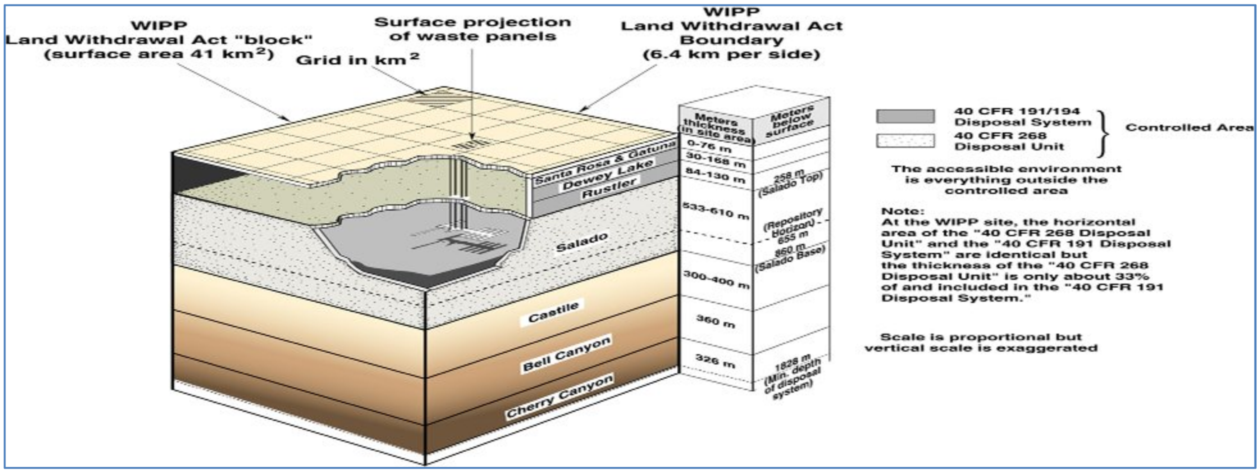

Fig. 1. Schematic illustration of the 75.1 km^3 WIPP disposal system (please note the reference to "Min. depth of disposal system" should read "Max depth …").

Key words and concepts are highlighted in *italics* throughout the text, and references to where additional information is available are denoted by numbers within brackets [1-30]. The full listing of these references is provided in the Reference section following the Main Observations and Recommendations section. However, it is acknowledged from the outset that the information and the related references presented herein are dated, incomplete, and biased. Consequently*, in order to derive the optimal benefit from the partial WIPP blueprint described herein, it needs to be updated, augmented, and modified to applicable conditions on a case-by-case basis*.

BACKGROUND

HLW Generation, Management and Disposal in Finland

At the end of 2011, Finland had four operating nuclear reactors, one new nuclear reactor being under construction, and two more being pursued. The two operating nuclear reactors at the *Loviisa* site commenced operations in 1977 and 1980, respectively, (www.fortum.com) and the two operating nuclear reactors at the *Olkiluoto* site commenced operations in 1978 and 1980, respectively. (www.TVO.fi) HLW is currently safely stored at the Loviisa and Olkiluoto sites pending the projected opening of a HLW repository in Pre-Cambrian crystalline/granitic/igneous ("granite") rocks adjacent to the Olkiluoto site in 2020. If opened in 2020, the related pre-opening period would be 40 years counted from 1980.

The studies and analyses leading to and required in the future for the Olkiluoto HLW repository have been and continue to be conducted by Posiva (www.posiva.fi), a subsidiary of TVO (60%) and Fortum (40%) established in 1995. For example, Posiva is currently evaluating the Swedish KBS-3H concept, i.e., multiple-canister disposal in horizontal boreholes. The Finnish and Swedish HLW-disposal programs have several commonalities, including lacking suitable salt deposits, having fully integrated national radioactive waste disposal programs, and pursuing similar HLW-repository host rocks ("granite"), canister designs, and disposal concepts (KBS-3V). They have also collaborated closely since the 1990s. Indeed, Finland significantly shortened its pre-opening period by adapting suitable components of the Swedish KBS-3V disposal concept and taking advantage of other lessons learned by SKB since the mid 1970s, demonstrating the benefits of *taking advantage of existing information and tailoring it to prevailing conditions*.

HLW Generation, Management and Disposal in France

At the end of 2011, France had the second largest number of operating nuclear reactors in the world with 58 operating reactors. All domestic nuclear reactors are operated by Électricité de France (EdF), with around 85% of EdF's shares being owned by the French government. France's first nuclear reactor commenced operations in 1963. All long-lived radioactive waste destined for disposal is currently stored pending the 2025 projected opening of a HLW and long-lived intermediate-level radioactive waste (ILW-LL) repository *in argillite* in the Meuse/Haute Marne area. The suitability of the chosen host rock has been and continues to be verified in the adjacent underground research laboratory (URL) at Bure. The related pre-opening period would be 40 years counted from 1985, at which time 34 domestic nuclear reactors were operating.

The studies and analyses leading to the siting and design of both the Bure URL and the pending HLW/ILW-LL repository have been and continue to be conducted by the French National Agency for Radioactive Waste Management (Andra). Andra, first created in 1979 within the French Atomic Energy Commission (CEA), was established by the December 1991 Waste Act as a public body in charge of the long-term management of all radioactive waste under the supervision of the Ministry of Ecology, Energy, Sustainable Development and the Sea (formerly the Ministry of Industry and the Ministry of Environment), and the Ministry of Research.

HLW Generation, Management and Disposal in Sweden

At the end of 2011, Sweden had 10 operating nuclear reactors located at the *Forsmark, Oskarshamn,* and *Ringhals* sites, and two pre-maturely-closed nuclear reactors at the *Barsebäck* site. The three nuclear reactors at the *Forsmark* site commenced operations in 1980, 1981, and 1985, respectively. The four nuclear reactors at the *Ringhals* site commenced operations in 1975, 1976, 1981, and 1983, respectively. The two nuclear reactors at the *Barsebäck* site commenced operations in 1975 and 1977, respectively, but they were closed prematurely in 1999 and 2005, respectively, in response to Danish protests. In 2011, nuclear power in Sweden got a new lease on life beyond 2012 in that the Swedish government modified the law to allow up to 10 commercial nuclear reactors to continue operations beyond 2012, including the replacement of the 10 currently operating nuclear reactors. As follows, *HLW will continue to be generated in Sweden well beyond 2012*.

In the 1970s, the nuclear utilities established the Swedish Nuclear Fuel and Waste Management Company (SKB) (www.skb.se) to manage and dispose of all radioactive waste from the Swedish nuclear power plants in such a way as to secure maximum safety for human beings and the environment.[2] A long-standing core component of the *fully-integrated Swedish HLW-management policy* shown on Figure 2 is to store the HLW for at least 30 years to let it cool down before disposing of it. The main two related benefits are *significant reductions in both the magnitude and spatial extent of thermal pulse induced by the disposed HLW; and the uncertainty in long-term (post-closure) performance/safety assessments (P/SAs)*.[e.g., 2] Pending the opening of the HLW repository, HLW is currently either stored at the "generating" sites or shipped to the central storage facility (Clab) that opened in 1985.

In June 2009, Sweden decided to build its first HLW repository (Figure 2) in "granite" adjacent to the Forsmark site. Up until then, Sweden had two candidate HLW-repository sites. The other site was located adjacent to the Oskarshamn site, Clab and the Äspö URL. The license application for the Forsmark HLW repository was submitted in 2010 and it is currently projected to commence operations in 2025. In the event it opens in 2025, the related pre-opening period would be 40 years counted from the 1985 start of Sweden's youngest operating nuclear reactor.

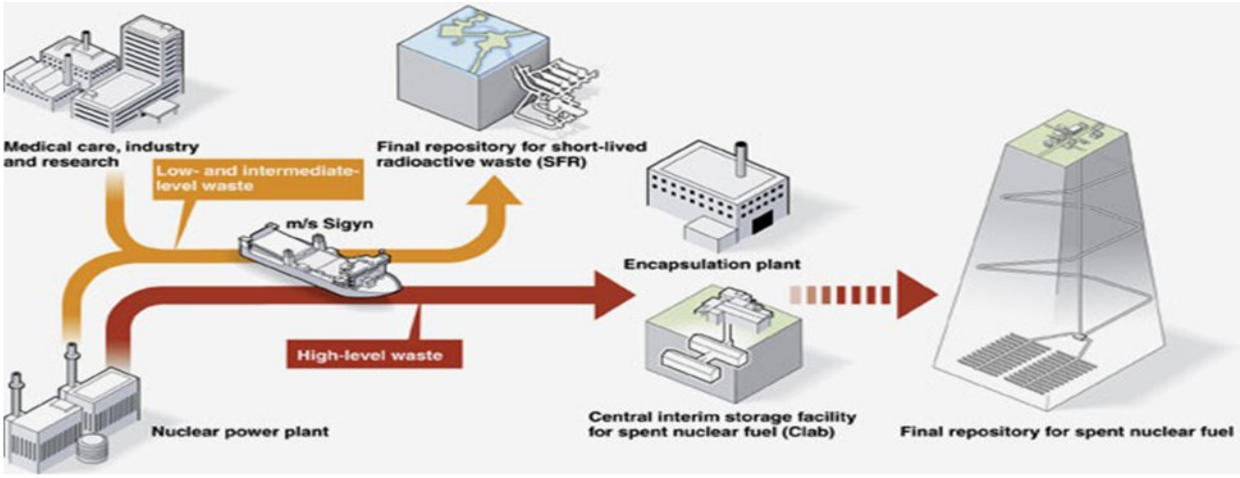

Fig. 2. Schematic illustration of the fully integrated Swedish nuclear waste management policy/program (the SFR opened 1988, encapsulation plant and repository remain to open - www.skb.se)

HLW Generation, Management and Disposal in USA

USA's first commercial nuclear reactor commenced operations on 26 May 1958. Prior to that, the US government had engaged in research- and defense-related activities generating HLW. There are thus two main HLW-categories in the USA with distinctly different characteristics; defense-generated (DHLW) and commercially-generated (CHLW). At the end of 2011, there were 104 operating commercial nuclear reactors located at 65 sites in the USA. In addition, there are both decommissioned nuclear reactors and research reactors bringing the total number of sites with operating and decommissioned/mothballed nuclear reactors above 100.

The Nuclear Waste Policy Act of 1982 (NWPA) [3] directed the then Secretary of Energy (SoE) to develop at least two deep geological repositories for safe disposal of CHLW of which the first was to open no later than 31 January 1998 and its disposal capacity could not exceed 70,000 metric tons of heavy metals or an equivalent amount of uranium (MTU) until a second HLW repository had opened. In 1987, an amendment to the NWPA (NWPAA) directed the then SoE to only investigate the Yucca Mountain (YM) site in Nevada for the nation's HLW-disposal needs.[4] Between the enactments of the NWPA and the NWPAA, an agreement was made in 1985 to accommodate 7,000 MTU of DHLW in the first HLW repository, limiting the amount of CHLW that could be disposed in it to 63,000 MTU. The related license application to construct (CLA) the YM HLW repository was submitted in June 2008.

In December 2008, the then SoE advised the US Congress that in 2010 the legal capacity of the YM HLW repository was smaller than the nation's projected stockpiles of HLW.[5] He also announced that the YM HLW repository would open no earlier than 2017 but more likely in 2020. However, in February 2009, President Obama inserted his new administration into the HLW-repository process and halted the YM HLW-repository program.[6] The related US Department of Energy's (DOE's) Office of Civilian Radioactive Waste Management (OCRWM) was subsequently stripped of virtually all personnel and all funding. In March 2009, the new/current SoE filed a motion with the U.S. Nuclear Regulatory Commission (NRC) for withdrawal of the 2008 CLA and a stay on the licensing proceedings, which the Atomic Safety and Licensing Board of the NRC declined. The SoE's motion also triggered several, *currently-unresolved*, legal challenges but it was rewarded with a stay by NRC on the licensing proceedings in 2011.

In January 2010, the SoE announced the establishment of a politically-selected 15-member Blue Ribbon Commission on America's Nuclear Future (BRC) chartered/directed *"to conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle, including all alternatives for the storage, processing, and disposal of civilian and defense used nuclear fuel, high-level waste, and materials derived from nuclear activities"* (www.brc.gov). The related draft and final reports were due no later than in July 2011 and in January 2012, respectively. The July 2011 BRC draft report [7] contained a blueprint for a fully-integrated domestic nuclear waste management policy that addressed the following seven key elements:

1. A new, consent-based approach to siting future nuclear waste management facilities.
2. A new organization dedicated solely to implementing the waste management program and empowered with the authority and resources to succeed.
3. Access to the funds nuclear utility ratepayers are providing for the purpose of nuclear waste management.
4. Prompt efforts to develop one or more geologic disposal facilities.
5. Prompt efforts to develop one or more consolidated interim storage facilities.
6. Support for continued U.S. innovation in nuclear energy technology and for workforce development.
7. Active U.S. leadership in international efforts to address safety, waste management, non-proliferation, and security concerns.

In our opinion, *key element 4 is imperative to achieving key element 7.*

In summation, the February 1983 enactment of the NWPA [3] started the current HLW-repository siting process in the USA but the 1987 NWPAA [4] legally terminated the related multi-siting programs in salt and "granite". As follows*, the only HLW-disposal site investigated in the USA since 1987 is the YM site in Nevada*. The related repository host rock is a welded tuff formation. However, the site characterization activities that began in 1976 were stopped by the Obama administration in 2009 and are still on hold at the end of 2011 pending the outcome of hitherto unresolved legal challenges. In the meantime, summarized below are two main scenarios for the related projected pre-opening periods of the YM HLW repository.

In the event the YM HLW-repository program a) is restarted, b) its capacity is not increased or c) *new legislation is not required*, based on previous official projections [5] and accounting for an additional up to five-year-long-delay of the opening of the YM HLW repository, *mathematically*, the YM HLW repository should still be able to open by the end of 2025. The related pre-opening period counted from the beginning of the site characterization activities would then be 49 years.

In the event the YM HLW repository program is not re-started, a new HLW-repository site would have to be identified, developed, and licensed, which in turn *would require either an amendment or a replacement of the NWPA and the NWPAA*. Based on past domestic events and depending upon when the new HLW-repository-siting process is started and how it is implemented, staffed, and funded, the pre-opening period for the nation's first HLW repository would likely be extended another 35-50 years. As elaborated upon in the subsequent text and in other documents,[e.g., 8-12] taking advantage of the lessons learned at the WIPP site since 1971 could shorten the aforementioned pre-opening period more than 10 years if salt is the selected repository host rock. Suffice it to mention here that salt is the only alternative repository host rock to welded tuff benefitting from domestic state-of-the-art LLRM-repository-siting and -design experience. Furthermore, in addition to the WIPP site, as illustrated on Figure 3, thick and laterally extensive salt deposits are abundant in the USA, many of which have a considerable relevant database from the pre-1997 HLW-repository-siting efforts in salt.

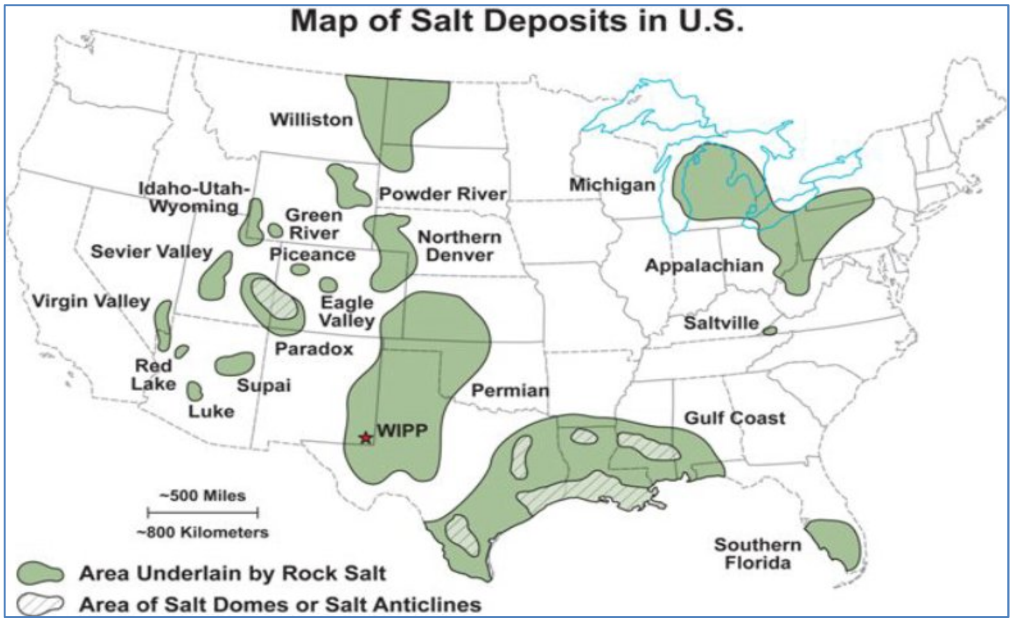

Fig. 3. Schematic illustration of US areas and regions with substantial salt deposits.[e.g., 13]

The WIPP TRUW Repository

The WIPP TRUW disposal system shown on Figure 1 was certified in May 1998 [14] to be in compliance with all applicable laws [15] and regulations [16,17] It opened on 26 March 1999 following the resolution of all related legal challenges. As illustrated on Figure 1 and to the left on Figure 4, the WIPP repository is located about 650 meters (m) below the ground surface in the lower half of the 610-m-thick Salado bedded salt formation. At the end of 2011, six (1-6) of the eight panels (1-8) shown to the right on Figure 4 had been excavated, five (1-5) had been filled, one (6) was being filled, one (7) was being excavated, and one (8) remained to be excavated. Each panel contains -seven disposal rooms measuring 4 m in height, 10 m in width, and 91 m in length. In addition to the eight numbered panels on Figure 4, the transportation and ventilation tunnels located between the two repository portions containing four panels each will also be used for TRUW disposal, i.e., *the current layout accommodates 10 disposal panels*.

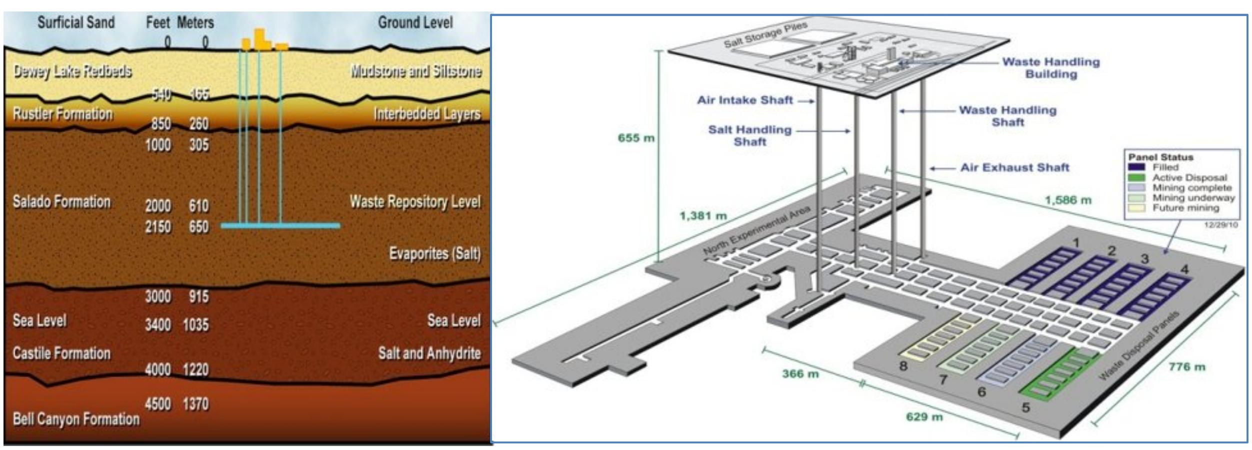

Fig. 4. Schematic illustrations of the stratigraphic column and the related location of the WIPP repository (left), and the layouts of the WIPP repository and the adjacent URL (right).

The current legal capacity of the WIPP repository is 175,584 cubic meters (m^3) [15] but there are also other limits, including on how much of the two activity-based categories of TRUW, i.e., contact-handled (CH) and remote-handled (RH), that may be disposed of. The RH-TRUW (2-10 Sieverts per hour) has higher canister-surface dose activity than the CH-TRUW but *both categories contain radioisotopes with half-lives longer than 6,000 years*. Figure 5 illustrates the different disposal concepts for CH- and RH-TRUW. Actually, the transport, handling and disposal techniques required for RH-TRUW are very similar to those required for HLW.

Fig. 5. Photos of equipment used for emplacing RH-TRUW (left top photo) and CH-TRUW (top right photo) and a portion of a disposal room with emplaced TRUW (bottom photo).

At the end of 2011, *the WIPP site had safely received, handled, and disposed of 79,660 m^3 of TRUW in salt. This TRUW had been safely transported by trucks on more than 19,700,000 kilometers (km) of public roads in more than 10,200 shipments* (www.wipp.energy.gov). Following is a summary of select milestone events deemed particularly significant *to: a) the WIPP pre-opening period; and b) the current statuses of the WIPP databases, and models*:

1971 - Eddy County representatives suggested to the Atomic Energy Commission (AEC) that the New Mexico portion of the Delaware Basin should be considered for HLW disposal.

1975 - Surface-based site investigations commenced in the WIPP region (Figure 3) with Sandia National Laboratories (SNL) serving as the DOE's Science Advisor.

1981 - The construction of the four shafts connecting the surface facilities with the pending URL and the repository in the Salado Formation (Figures 1 and 4) commenced.

1992 - The WIPP Land Withdrawal Act (LWA) was enacted.[15] It set aside the 41.6 square kilometers (km^2) WIPP surface area shown on Figure 1 from public use. (In 1982, DOE had agreed with the state of New Mexico to limit the depth of the WIPP disposal system to 1,828 m.) The LWA also established the US Environmental Protection Agency (EPA) as the sole regulator for disposal of TRUW at the WIPP site.

1993 EPA re-promulgated portions of the applicable environmental radiation protection standards (40 CFR 191) (December).[16]
1994 The then Carlsbad Area Office (CAO), now the DOE Carlsbad Area Field Office (CBFO), published *the WIPP Disposal Decision Plan (DDP)* (April).[18]
1995 SNL completed the *System Prioritization Method* (SPM).[19]
1996 - EPA re-promulgated criteria [17] for compliance with of 40 CFR 191 (40 CFR 194) (February) and CBFO submitted the approximately 70,000-page-long WIPP Compliance Certification Application (CCA) to EPA (October).[14]
1998 **EPA approved the CCA and certified WIPP** (18 May) following the receipt of an additional 20,000 pages of information, including a second set of 300 P/SAs based on parameter values defined by the EPA.[20]
1999 DOE won two court cases removing all legal challenges preventing the opening of WIPP (22 March) and **WIPP received the first shipment of CH TRUW** (26 March).
2004 CBFO submitted the first re-certification application for WIPP to EPA (26 March).
2006 EPA approved the first re-certification application for WIPP (29 March).
2009 CBFO submitted the second re-certification application for WIPP (24 March).
2010 EPA approved the second re-certification application for WIPP (18 November).

The third re-certification application is due by 26 March 2014. An integral component of the aforementioned re-certification process [15] is the five-year updates and EPA reviews of the long-term (10,000-year) post-closure P/SAs based on then "*current*" information. As follows, notwithstanding the WIPP repository was certified in 1998 [20] and has operated safely since March 1999, the related WIPP databases and 54 analytical and calculating tools used by SNL to perform the critical P/SAs listed in Table I are continually being "updated".

Looking back in time, ***three stratagems*** deemed particularly important to the 1998 certification of the WIPP disposal system that also could be used "generically/conceptually" by others were:

1. The 1994 WIPP DDP shown on Figure 6.[18]
2. The SPM.[19]
3. The seven domestic [21] and one international [22] peer reviews.

However, we wish to preface descriptions of these stratagems by recognizing the inspiring support provided by the then SoE, the honorable Ms. Hazel O'Leary, and her staff. It was probably more instrumental to the successful advancement and certification of the WIPP project in the 1990s than any of the three stratagems. The key point embodied in this recognition is that *without political support, even the best designed stratagems may fail*.

The WIPP DDP shown on Figure 6 served during the final 4½-year-long pre-certification period as the CBFO's, baseline schedule for maintaining a continuous, transparent, dialogue with the main federal and state regulators, i.e., the EPA and the New Mexico Environment Department (NMED), respectively, and other affected and interested parties. The "Stakeholders/Oversight" portion of the DDP listed in advance 47 different opportunities for affected, interested, and opposing parties to attend meetings between the CBFO and the WIPP regulators where CBFO reported and answered questions on the status of the WIPP program and related issues at a given point in time, and where it was heading from thereon. During this period, the CBFO also maintained a pro-active domestic and international outreach and information-exchange program.[e.g.,8,23]

Table I. Listing of computer software and codes used in support of the 1996 WIPP CCA.[14]

PA SES[a] (9)	PA NON-SES[b] (31)		NON-PA SES[c] (14)
BRAGFLO	ALGEBRACDB	POSTBRAG	COLUMN
CCDFGF	BLOTCDB	POSTGENII	EPAUNI
CUTTINGS_S	CAMCON_LIB	POSTLHS	***EQ3/EQ6***
BRAGFLO_DBR	CAMDAT_LIB	POSTSECOFL2D	***FMT***
GENII_A	CAMSUPES_LIB	POSTSECOTP2D	GRASP-INV
NUTS	CCD2STEP	PREBRAG	GTFM-PC
PANEL	CCDFSUM	PREGENII	NONLIN
SECOFL2D	GENMESH	PRELLHS	ORIGEN2
SECOTP2D	GROPECDB	PRESECOFL2D	SANTOS
	ICSET	PRESECOTP2D	SPECTROM-32
	LHS	RELATE	SPECTROM-41
	LHS2STEP	SDBREAD_LIB	***SWIFT II***
	MATSET	SPLAT	THEMM
	NUCPLOT	STEPWISE	***TOUGH28W***
	PCCSRC	SUMMARIZE	
	PLT_LIB		

[a] PA SES = PA scientific and engineering software that simulates (models) physical processes that describe the behavior of the repository system.
[b] PA NON-SES = PA nonscientific and engineering software that performs supplementary calculations.
[c] NON-PA SES = Non-PA scientific and engineering software that provides parameters used in the calculations. Most NON-PA SES codes provide their parameters to the PA database; however, GRASP_INV and SANTOS provide output directly to the PA codes.

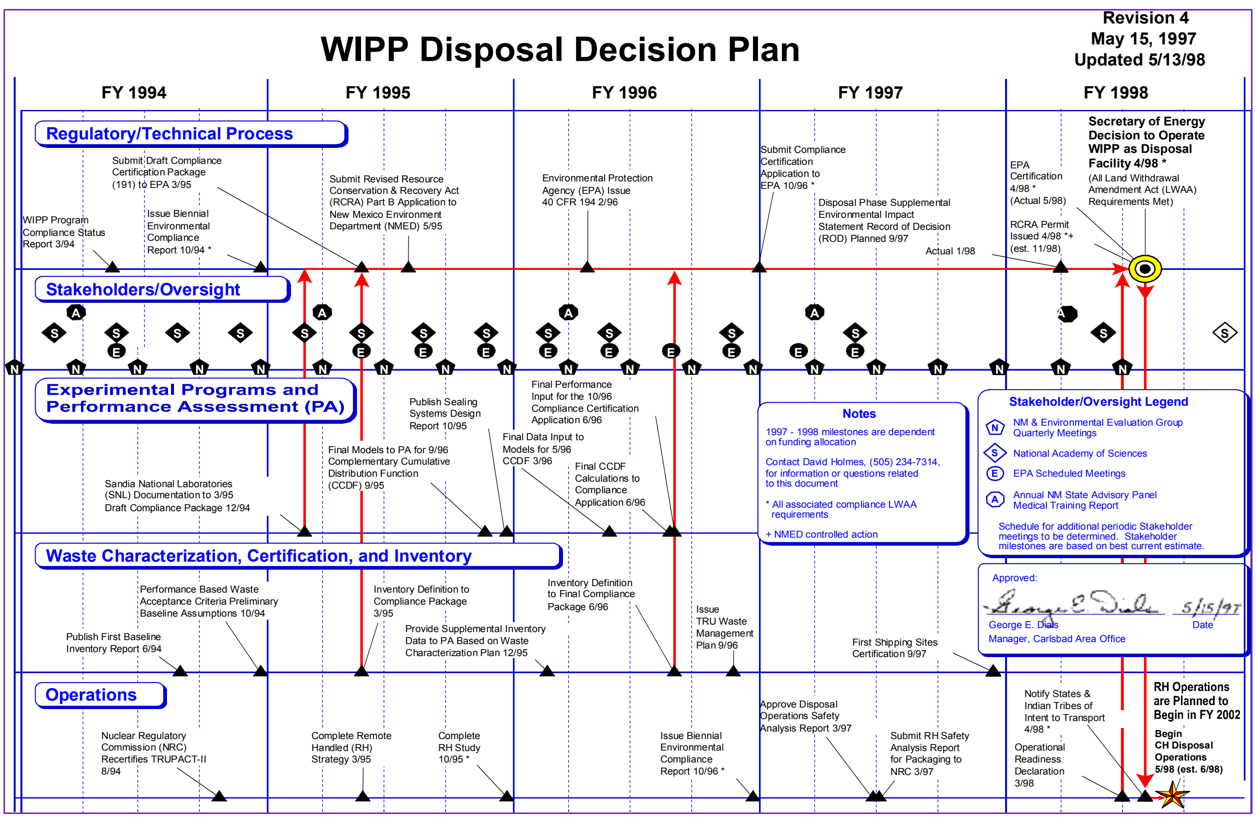

Fig. 6. The WIPP 1994-1998 Disposal Decision Plan.[18]

Following the EPA's December 1993 re-promulgation of 40 CFR 191,[16] the CBFO and SNL promptly devised and implemented the CBFO's most significant time- and cost-saving stratagem; the SPM. Prior to the conduct of the SPM, 116 scientific activities were considered needed to collect the information required to certify the WIPP TRUW repository. The SPM process evaluated all 116 activities in more than 46,000 combinations by some 1,300,000 P/SAs in terms of their individual and supplementary contribution to demonstrating compliance with 40 CFR 191. It identified eight scientific activity combinations/sets that, if performed as designed and with results being within the projected ranges, they would provide a 0.96 probability that compliance with 40 CFR 191 would be demonstrated.[19] Two key measures enhancing the acceptance and credibility of the SPM process/results and the CBFO were:

1. The CBFO's solicitation of periodic input on the format and interactive communications on the progress of the SPM in eight public meetings, including 11 topical white papers.[19,23]
2. The resulting transparency of the August 1995 decision by the CBFO manager to focus the experimental program on the eight scientific activity sets identified by the SPM.[19]

Seven domestic [21] and one international [22] peer reviews of the WIPP CCA verified that the data, codes, and models used were traceable and of highest quality and that the designs were compliant with applicable regulations. These reviews also greatly contributed to a credible and a continually forward-moving dialogue with the EPA and other affected and interested parties.

EPA's May 1998 certification of the WIPP repository [20] clearly demonstrated the success of both the SPM strategy and the peer reviews. They also greatly contributed to the almost three-year advancement of the EPA's certification of the WIPP repository, representing a cost saving on the order of 500 million US dollars and evidencing the value of a focused, regulatory-driven, scientific program. Indeed, the strategies and measures used by a government organization historically encumbered by inherent bureaucracy and territorial power struggles to advance the certification and opening of the WIPP repository almost three years within a six-year period is a remarkable feat deserving recognition and serious attention both in the USA and abroad.

As illustrated on Figures 1 and 5, the WIPP disposal concept primarily relies upon the ability of salt to creep and encapsulate the emplaced/disposed waste within a virtually impermeable salt monolith.[e.g.,13,24] The 600 CCA-related P/SAs projected a very safe disposal system.[14] Indeed, that the then projected "worst-case" releases of radionuclides under very-low-probability (10^{-8}), hypothetical, disturbed conditions were all less than 1/32 of the related EPA limit. Deemed of particular relevance to the *global use of the WIPP databases and facilities* in support of HLW-repository developments is the fact that the WIPP site was initially considered for safe disposal of both TRUW and HLW. During this period, SNL planned, designed and conducted a broad suite of HLW-related laboratory and on-site surface and subsurface test.[e.g.,25-27] Figure 7 shows the locations of the large-scale in-situ tests conducted in the WIPP URL but only the following three are summarized below: (A) The 18 Watts-per-square-meter (W/m^2) HLW Mock Up Tests; (B) The DHLW Overtest; and (H) The Heated Pillar Test.

The 18-W/m² DHLW Mockup Tests were conducted in Rooms A1, A2 and A3 shown on Figures 7 and 8. The primary objectives of these tests were to:

- Determine the rates of salt creep and room closure;
- Determine the effects of heat transfer to the host rock;
- Determine the validity of predictive methods and techniques; and
- Demonstrate the suitability of a reference DHLW room.

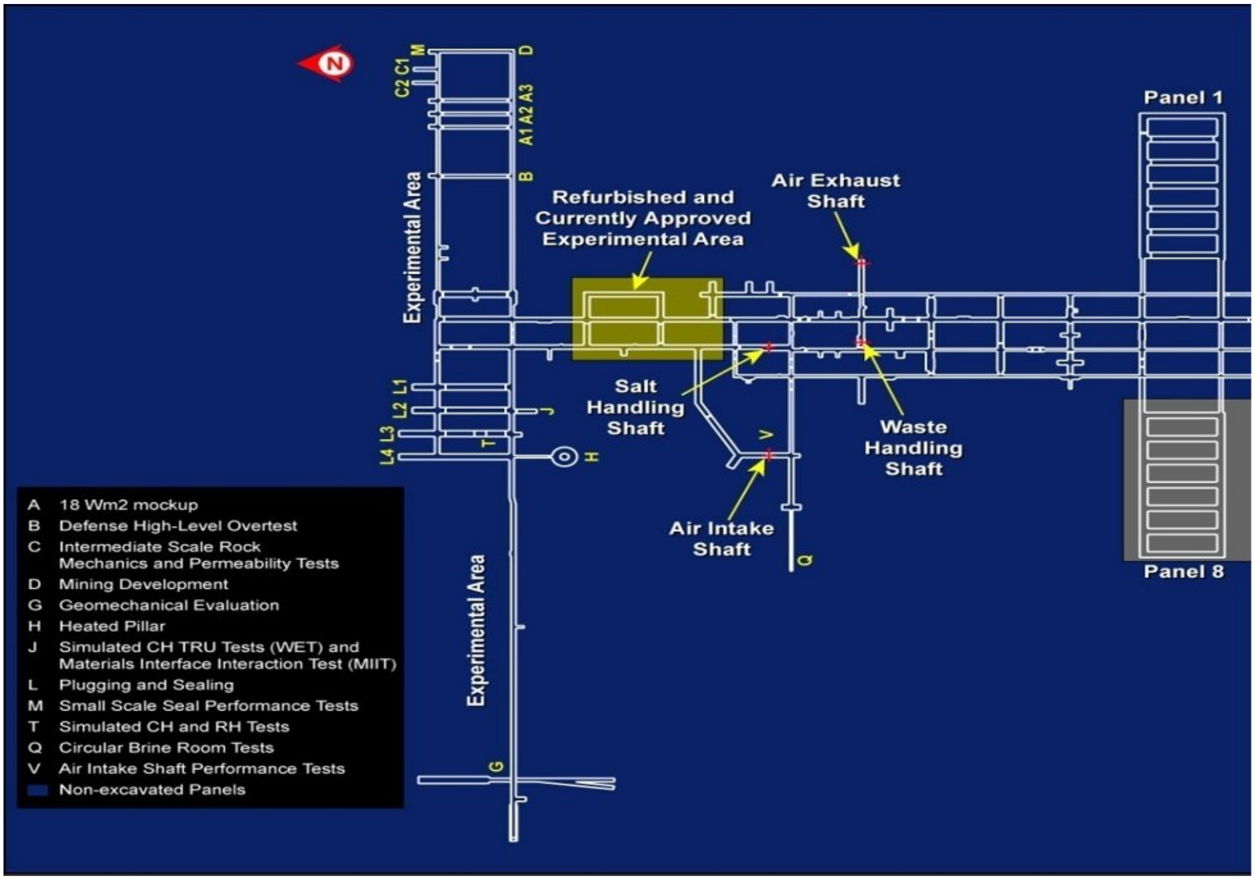

Fig. 7. Schematic illustration of the layout of the WIPP URL and the locations of the main in-situ tests conducted in it by the end of 1998 (see also Figures 1, 4, 8-10).[e.g., 24,25]

The test layout/design shown on Figure 8 was based on the exact thermal and structural matches of the Reference Repository Configuration (RRC) for DHLW in bedded salt within the limitation of presenting the fields of a large array of rooms with a three-room configuration. Room A2 was an exact match of the thermal and structural configuration, including the canister size, heat load, and spacing. It contained 28 0.47-kW heater canisters in two rows guarded by two 1.41 kW heaters at each end. A single row of 1.41-kW heaters in each of Rooms A1 and A3 provided the thermal and structural boundary conditions on Room A2 that would be experienced by an interior room in a large array of rooms. In addition to the main test objectives defined above for the 18-W/m^2 DHLW Mockup tests, they also provided valuable data on the effects of excavating adjacent rooms (mine-by experiment).

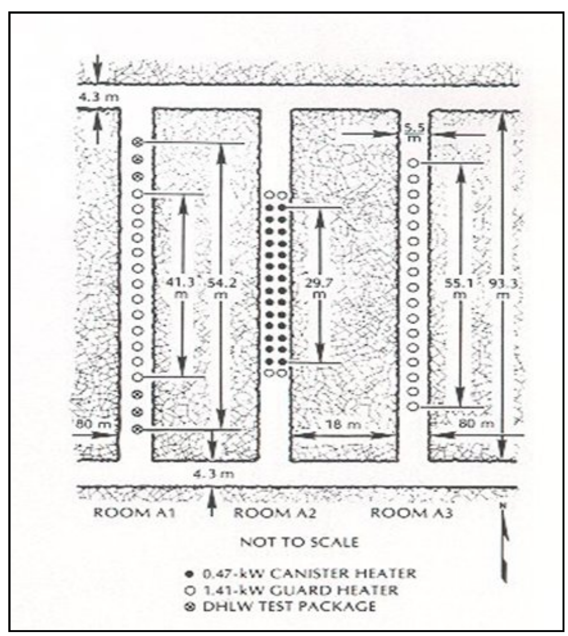

Fig. 8. Layout of the 18-W/m^2 Mockup Tests.

The DHLW Overtest was an accelerated version of the aforementioned 18-W/m^2 DHLW Mockup tests.[24,25] The primary objectives of this test were to:

- Determine room closure rate and heat transfer at temperatures higher than the reference case;
- Validate predictive techniques; and
- Evaluate long-term effects of heat and room closure.

The test was conducted in Room B shown on Figures 7 and 9 and, as for the *DHLW Overtest* reference case described above, the installed instruments measured:

- Vertical and horizontal room closures;
- Deformation of the salt mass surrounding the room, and
- Stresses in the salt mass surrounding the room.

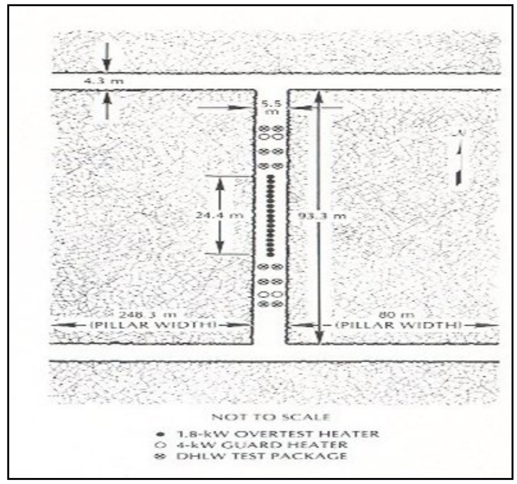

Fig. 9. Layout of the DHLW Overtest.

The geometry of Room B was the same as the disposal rooms of the reference repository design, i.e., 5.5-m in height, 5.5-m in width, and 93.3-m in length. However, as illustrated on Figure 9, only one single row of 17 1.8-kW heater canisters was emplaced at 1.5-m-spacing in the floor along the centerline of the room, rather than the 24 0.47-kW heater canisters placed in two rows of boreholes spaced 3.44-m apart in Room A2 (Figure 8). This experiment used about four times the reference thermal load to drive the room to failure more quickly to provide additional information on the creep constitutive model verification and structural data on canister response and room failure mechanisms. Canister/salt interface temperatures were about 250 degrees centigrade (^{o}C).

The Heated Axisymmetric Pillar Experiment in Room H shown on Figures 7 and 10 was designed to:

- Determine the behavior of room and pillar in response to (accelerated) creep;
- Compare actual 3-D response versus 2-D models;
- Determine the mechanical properties and failure modes of salt and other constituents in the testing envelope;
- Compare *in situ* data from laboratory-model pillar tests and from other salt mines to assist in model evaluation; and
- Determine the validity of the models and computer codes used in predicting the response of heated rock-salt mass.

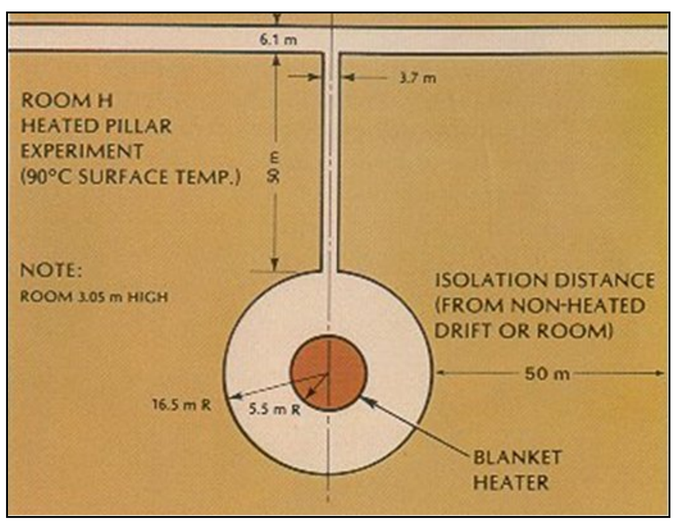

Fig. 10. Layout of the Heated Axisymmetric Pillar Test Room.

Room H was constructed to provide as good a match as possible between the 2-D modeling capability and the excavation geometry. Except for the necessary, 50-m-long, access drift, the concentric annular room around the 190 m^3 central cylindrical pillar of salt conformed to the 2-D, axisymmetric geometry, which can be modeled by 2-D codes without resorting to any geometric abstractions or approximations. After acquiring creep information on the pillar and room at ambient temperature for one year, the pillar was covered with an insulating blanket and heated with strip heaters to about 70^{o}C. This heating continued until one year before decommissioning to allow a one-year cool down period. A total of 10 years of active data were acquired from this test. Installed instruments measured:

- Vertical and horizontal room closure;
- Deformation of the salt mass bordering the room; and
- Stresses in the rock mass bordering the room.

Thermocouples were installed to measure the temperature of the salt surrounding the annulus and pillar. Deformation and pillar fractures were monitored by visual observations.

MAIN OBSERVATIONS AND RECOMMENDATIONS

At the end of 2011, the world's first three HLW repositories are projected to open in Finland, France, and Sweden by the end of 2025.[2,12] In each case, the pre-opening period would be at least 40 years. In addition, following the expiration in 2010 of the 10-year moratorium imposed upon Germany's partially-developed HLW-repository at the Gorleben site, it may also be able to open by the end of 2025 contingent upon pending domestic political agendas. In any event, the pre-opening period for the Gorleben HLW repository would also be in excess of 40 years. Notwithstanding the aforementioned 10-year hold on the Gorleben HLW repository, German scientists and engineers continued to conduct HLW-disposal-related research in salt during the moratorium period and are now promptly moving forward, including having signed collaborative agreements in September 2011 with the DOE CBFO and its Science Advisor since 1975, SNL. As follows, at the end of 2011, USA and Germany have a framework in place for collaborations, including the opportunity of conducting in situ tests in salt in the WIPP URL.

Following a less than 30-year-long pre-opening period, the WIPP TRUW repository opened in March 1999. Furthermore, the databases, software and codes used to project the post-closure performance and safety of the WIPP TRUW repository are being reviewed and certified at least every fifth year by the EPA. In other words, the WIPP databases, software, and codes are continually being updated and they represent the state-of-the-art in salt-repository sciences and engineering in the USA. Used fuel disposition activities and SNL research and development (R&D) are also reviewing, benchmarking and validating the computational tools, which allows application of massively parallel hardware and updated software.

At the end of 2011, the WIPP TRUW repository has safely operated almost 13 years. It thus stands to reason that *WIPP offers a global proof of principle for safe deep geological disposal of LLRMs*.[11] Furthermore, *the actual pre-opening period* for the WIPP TRUW repository was more than 10 years shorter than *the currently projected pre-opening periods* for the world's four most advanced (mature) HLW repositories located in "granite" in Finland, argillite in France, "granite" in Sweden, and welded tuff in USA, respectively. Both TRUW and HLW contain very-long-lived, highly-active, radioisotopes that require similar handling, transportation, and radionuclide-containment and -isolation conditions. It thus also stands to reason that the host-rock at the WIPP TRUW-repository, i.e., salt, offers the by far shortest pre-opening period relative to any of the other three LLRM-repository host rock pursued to date. Indeed, although all LLRM-disposal systems are unique, based on our active involvement in and monitoring of a broad range of radioactive waste disposal programs in the USA and abroad since 1973, and as illustrated in Finland, the pre-opening period can be shortened several years by a timely adaptation of applicable existing natural and man-made analogues and related lessons learned. Specifically, we believe the stratagems and lessons learned at the WIPP site since 1971 [e.g., 10,11,27-30] offer a unique blueprint for shortening the pre-opening period for new LLRM repositories in the USA at least 10 years and abroad at least five years. Two reasons for the projected shorter pre-opening period in salt in USA are:

1. The abundance of potential domestic salt deposits (Figure 3).
2. The availability of domestic state-of-the-art salt-repository sciences and engineering expertise and experience.[e.g., 13,26,27, 30]

However, the unique potential time- and cost-savings offered by salt, one long-standing observation is that *all programs attempting to site and develop national, not to mention international, LLRM-repositories, will experience delays and cost-increases*. Although the reasons for these delays have and will continue to vary both geographically and with time, there appear to be several "manageable" common core reasons affecting the acceptance, schedule, and cost of LLRM-disposal facilities around the world. Briefly described and discussed below are thus some select globally-common challenges, related reactions, and potential solutions deemed to affect the schedule, cost, and political acceptance of LLRM-disposal projects that can be and were successfully planned for and managed at the WIPP site.

One globally-common challenge is that all LLRM-disposal systems involve unprecedented spatial and temporal scales, and state-of-the-art scientific and engineering concepts beyond the comprehension of those not directly involved in or monitoring the project on a continuous basis. In simple terms, the related human understandings and perceptions may be divided into the following six main categories:

1. Things we know we understand/know.
2. Things we think we understand/know.
3. Things we know we don't understand/know.
4. Things we think we don't understand/know.
5. Things we don't know we don't understand/know.
6. Things we think we know but are not so.[29,30]

Also simplistically categorized, one related challenge common to all LLRM-disposal programs is that less than 1% of the human population, i.e., mainly the scientific and engineering "elite" actively involved in or closely monitoring the project on a continuous basis, grasps the underpinnings of the long-term P/SAs. Most politicians and other laypeople are thus left with the following three options when facing the challenge of having to pass judgment on an LLRM-disposal facility:

1. To reject/oppose the project due to fear of the unknown or pre-set agendas.
2. To reject/oppose the project based on the information presented by opponents to the project.
3. To accept/support the project based on the information presented by the "applicant" or other sources deemed *more trustworthy* than the opponents' sources. Unfortunately, this is not a level playing field. Whereas the "applicant" has to prove its points, the opponents typically only have to verbalize them, passing the burden of proof to the "applicant".

As stated above and in other articles [e.g., 2,30] and papers,[e.g., 9,10,18,21,29] communicating in terms the audience understands is *imperative to achieving and sustaining public trust in, and acceptance and support of, a LLRM-disposal system, which, in turn, affects the duration of the related pre-opening period and, in some cases, the viability of the project.* A related lesson learned was that *the interactions and communications between the implementer, regulator(s) and other interested and affected parties have to be a two-way street where the language used is understood by all parties and questions are promptly and truthfully responded to, if schedule and cost projections were to be met.*[e.g., 9,10,18,19,21,23,27-30]

In addition to trust and active communication, the level to which the following "ideal conditions" were present also had a profound impact on the duration of the pre-opening periods described and discussed herein:

1. Initial and sustained majority local public and political acceptance and support of
   a. the proposed disposal concept,
   b. the applicable laws and regulation(s), and
   c. the key parties involved.
2. Timely-availability of adequate financial resources.
3. The prevailing national political will to address and support the proposed solution(s).

However, even if a safe disposal concept is imperative for gaining and sustaining majority public support and surviving the regulatory and legal processes, a strong (majority) national political will and support from start to finish is the ultimate governing condition and the surrounding envelope for a timely-advanced HLW-repository program. For example, whereas WIPP has benefitted from a high level of these "ideal conditions" from the outset and onwards, the YM HLW repository has not.[e.g., 2,29] At the end of 2011, the US HLW-disposal program has been on hold for more than two years and its future hinges upon the outcome of currently unresolved legal challenges and/or ongoing and future political changes and actions. Pursuing more than one repository site until the site suitability has been established may thus safeguard against the inevitable fluctuations embodied in time-dependent political agendas.

A related observation is that all nations generating or planning on generating LLRMs likely would benefit from having a fully integrated waste management policy [11] in place plan from the outset that outlines how the resulting waste is to be safely managed until rendered harmless. Following are our main recommendations for the makings of a robust, defensible, and cost-effective national HLW-disposal policy/program:

1. Enact nationally uniform laws.
2. Enact nationally uniform regulations.
3. Co-locate facilities whenever possible, i.e., minimize transportation distances.
4. Secure majority residential and political support before selecting a site and nurture it carefully from thereon.
5. Expect and plan for schedule delays and cost-increases.
6. Staff the implementing organization with qualified managers, scientists and engineers, and provide it adequate funding to be able to execute its assigned mission.
7. Establish and conduct collaborative Research, Development and Demonstration (RD&D) programs with other nations and/or organizations with *relevant resident* expertise pursuing the same repository host-rock(s) but ensure the requisite experts and facilities are still available, i.e., trust but verify.
8. If available, focus on salt as the repository host rock.

Although the final BRC report was still pending at the time this paper was written, following are a couple of concluding preliminary observations and comments based on the July 2011 draft BRC report.[7] In our opinion, it outlined a long-overdue*, fully-integrated*, very robust, and well underpinned *approach to safe nuclear waste management and disposal*. However, based on Congress' a) past and current "secondary" uses of the Nuclear Waste Fund (NWF) and b) unwillingness hitherto to amend the since February 1999 overdue NWPA schedule, key elements 2, 3, and 4 of the draft BRC report are likely very challenging to it. Furthermore, due to the pending national elections in late 2012, Congress may not develop any related Bill(s) until 2013. However, regardless of when Congress addresses the HLW-disposal program again, which it ultimately has to do, at the end of 2011 and for a foreseeable future ***salt and welded tuff are the only two potential LLRM-repository host rocks with relevant domestic state-of-the-art expertise***. ***If time, cost, and a proven disposal concept became governing criteria for a future HLW repository in the USA, salt is the optimal domestic repository host-rock solution.***[30] Conceivably, "domestically-tailor-made" versions of the lessons-learned at WIPP could also be the optimal solution for other countries considering or planning new LLRM-disposal solutions that benefit from adequate salt deposits and time- and cost-saving blueprints to countries not benefitting from adequate salt deposits.

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