A Feasibility Study On The Horizontal Emplacement Concept In Terms Of Operational Aspects

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ABSTRACT

Based on the H12 study, two emplacement variants were initially considered - namely, vertical (in pits) and horizontal emplacement (in tunnels) in the Japanese HLW disposal programme. The horizontal emplacement design may possibly be more economical than the vertical design due to smaller excavation volume, however, several aspects such as quality assurance (QA), operational safety and logistics have been questioned. In this paper, the feasibility of the operation system for horizontal emplacement with several buffer options (e.g. bentonite block, pellets, in-situ compaction and prefabricated engineered barrier system module) is reported in terms of operational practicality, particularly logistics. The results show that the prefabricated engineered barrier system module (PEM) option could be advantageous and implemented more easily due to the much simpler emplacement process in an underground facility.

INTRODUCTION

The current engineered barrier system (EBS) design for vitrified high-level waste (HLW) disposal in Japan features a thick steel overpack surrounded by a highly compacted bentonite / sand buffer. Based on the H12 study [1], two emplacement variants were initially considered - namely, vertical (in pits) and horizontal emplacement (in tunnels). Also, the fundamental feasibility of safe disposal has been demonstrated in the generic H12 study.

NUMO, established in October 2000, was given the responsibility of implementing a disposal programme for vitrified HLW. Considering that the site selection is based on a volunteering process, NUMO is required to tailor the repository design to the volunteer sites’ characteristics and has accordingly shown a wide range of concepts for the repository structures and layout [2]. Repository concepts suitable to the site characteristics will be developed in response to increasing site understanding at each stage of site investigation in an iterative process. Although NUMO is still waiting for volunteers, considerable efforts have already been invested to the establishment of a methodology for developing repository concepts in an iterative manner [3].

The generic H12 designs that form the basis for initial repository design options are very robust, but may be extremely over-conservative with regard to long-term safety in a particular setting. On the other hand, neither operational safety nor practicality has been much studied in the Japanese HLW programme to date. It is worth noting that although exclusion criteria are defined to ensure that unsuitable locations are avoided - especially those associated with geological instability, which is a particular concern in Japan -, potential host rocks may need to be considered which are less than optimal in terms of construction and operational conditions. Therefore, the refinement of generic repository concepts in terms of practicality has been a focus of work for NUMO, and this study is one of them, which focuses on the feasibility of the horizontal emplacement concept.

The horizontal emplacement concept has been shown to be simpler, and significantly cheaper in terms of construction requirements due to smaller excavation volume, than the vertical one. However, several concerns, including the following aspects, have been discussed in terms of practicality:

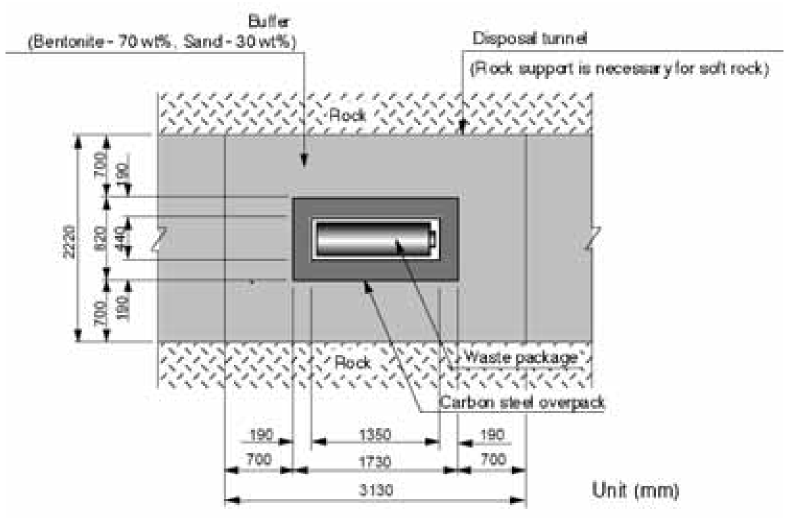
(a) QA of the EBS under the difficult operational conditions experienced underground, such as high humidity, water dropping, and relative high temperature;
(b) operational safety due to handling of large size, heavy weight, heat output and radiation from the waste package in the space-restricted area with remote-handling process; and
(c) operational schedule due to low flexibility of the logistics. In reference case, 40,000 packages need to be emplaced at a rate of 5 per day in the Japanese programme.[2]

In this study, the operational practicality of the horizontal emplacement concept in conjunction with several buffer options - e.g. bentonite block, pellets, in-situ compaction and PEM - has been examined. Particularly, the schedule per day has been examined quantitatively utilizing a simple logistics simulator which was initially developed. The premise, 40,000 packages to be emplaced at a rate of 5 per day, inevitably raises logistical challenges, which might involve continuous 24-hour operation of the facility or several emplacement operations running in parallel. This may be more challenging for tele-handled transportation / emplacement, which will tend to be slower than an equivalent manual operation, owing to the difficulty of positioning EBS materials in the dark underground condition. This may be more serious for horizontal concept than vertical one because it will require more tele-handled works in a narrower space.

Buffer Emplacement Options Considered in This Study

Fig. 1(a) shows an example of basic EBS specification for the horizontal concept. The buffer emplacement options considered in this study are shown in Fig. 1(b). The in-situ buffer emplacement design, including bentonite block, cold isostatically pressed (CIP) units, in-situ compaction and pellets, has been the main design option considered in the H12 study. In addition, the PEM is also included in this study. The PEM involves simultaneously emplacing the overpack, surrounded by a bentonite buffer, within a steel handling shell.

(a) Example of EBS specification [1]



(b) Buffer options considered in this study

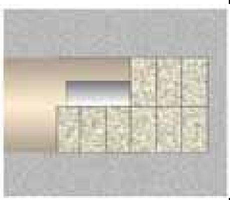
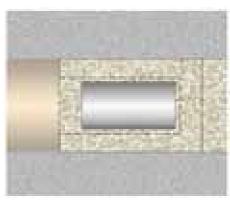
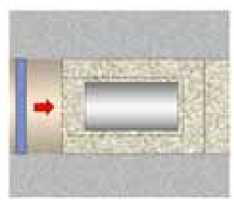
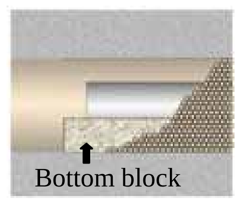
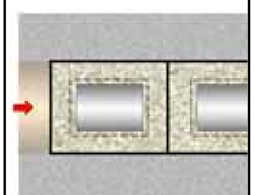
	Bentonite Block	CIP	In-situ compaction	Pellets	PEM
Bentonite Horizontal					

Fig.1. Example of EBS specification and buffer options considered in this study [2]

QUALITY ASSURANCE OF EBS

Hydraulic Conditions in the HLW Repository in Japan

In past studies, the high relative humidity (RH) and water dropping in tunnels have been acknowledged as problems for ensuring the required quality of the buffer during emplacement. The swelling of the buffer material due to the high RH in the air leads to eventual degradation of the buffer. Once water drips on the buffer, it will immediately swell at the contact point, absorb water and then erode. The buffer degradation will then cause difficulty for emplacement work and adversely affect the density of the emplaced bentonite.

Based on the literature, the RH in tunnels in Japan is within 70 % to 90 % [4] However, these data are provided as the general working condition based on the premise that air ventilation is present. In the case of the horizontal design, the space in the disposal tunnel is restricted during emplacement work, such that the disposal tunnels may not be ventilated. Therefore, the RH in the disposal tunnel during emplacement work can actually reach 100 %.

An average rate of water inflow, which results in water dropping, is as follows based on the literature [5,6]:

(a) sedimentary rock : 0 ~ 0.3 liters / min / meter; and
(b) crystalline rock : ~ 0.6 liters / min / meter.

These values are given as an average rate from the calculation, which divided the total inflow volume by the entire tunnel length. Therefore, the hydraulic conditions at emplacement positions will vary between no inflow at all (e.g., fracture free rock) and a large inflow from several fractured zones of several liters per minute. In fact, the total length of disposal tunnels is planned to be about 160,000 meters and the rock condition is non-homogeneous in general, therefore, the inflow rate will be large in some places.

Where the permeability of host rock is very small and the air ventilation is provided, it is assumed that neither leaching nor water dropping is possible due to balance of evapotranspiration rate. However, as previously mentioned, there may be no ventilation systems provided in horizontal case, and therefore leaching and water dropping is expected to occur in disposal tunnel during emplacement work. In addition, the repository will be located at a more considerable depth (more than 300m) relative to road tunnels such that a higher hydraulic gradient is assumed to possibly cause more leaching.

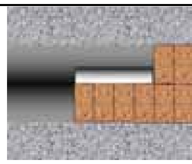
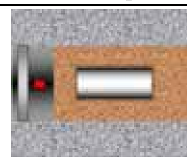
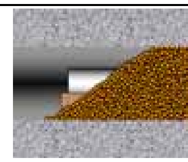
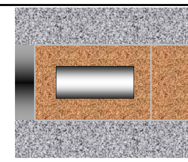
Quality Assurance of EBS Under the ‘wet’ Condition

Given the conditions of 100% RH and occurrence of water dropping (‘wet’ condition), the emplaced blocks will inevitably swell, and eventually transform or crack. This degradation will prevent the next block or overpack to be emplaced at the planned position. This ‘wet’ condition also renders the powder bentonite entirely useless for compaction. In the case of pellets, the bottom block is weak against wet condition, but measures to protect it from water dropping may be easy. Filling pellets around the overpack is not a particularly hard task.

In addition, there is a common concern regarding the swelling pressure of the entire emplaced ‘unit’. As the previously emplaced units have continued to swell, they may occupy the assigned position for the new unit. It will cause a decrease of the amount of bentonite to be emplaced, and the planned bentonite density will not be achieved. Considering that this behavior is a common concern, in-situ compaction, pellets, and density control needs to be tested in the underground research laboratories.

The PEM is the optimal option being forwarded for ‘wet’ rocks for various reasons. The steel handling shell prevents bentonite to come in contact with high-humidity and water inflow. A further advantage of PEM is the better QA provided by prefabrication in a surface facility with a controlled environment. Table I shows the feasibility study of emplacement under the 100% RH and water dropping condition.

Table I. Feasibility Study of Emplacement under the Assumed Hydraulic Condition

	Bentonite Block		In-situ Compaction		Pellets		PEM	
								
High humidity	D[a]	Difficult to emplace an overpack and next blocks at planned positions due to swelling of previously emplaced blocks	D	Difficult to compact due to water absorption of bentonite powder	C[a]	Possible to emplace an overpack, but presence of crack in the emplaced bottom block	F[a]	No problem
Inflow	D	Difficult to emplace next blocks and an overpack at planned positions due to swelling and erosion of previously emplaced blocks	D	Difficult to compact due to water absorption of bentonite powder	D	Difficult to emplace an overpack at an exact position due to swelling and erosion of the bottom block	F	No problem
Swelling pressure	D	- Difficult to emplace new blocks because the swollen blocks occupy the space assigned for the new blocks - Bentonite density control should be considered.	C	- Possible to fill the next unit with bentonite powder - Bentonite density control should be considered.	C	- Possible to fill the next unit with pellets - Bentonite density control should be considered.	F	No problem

[a] F: feasible, C: possible but there are some concerns, D: difficult (maybe infeasible)

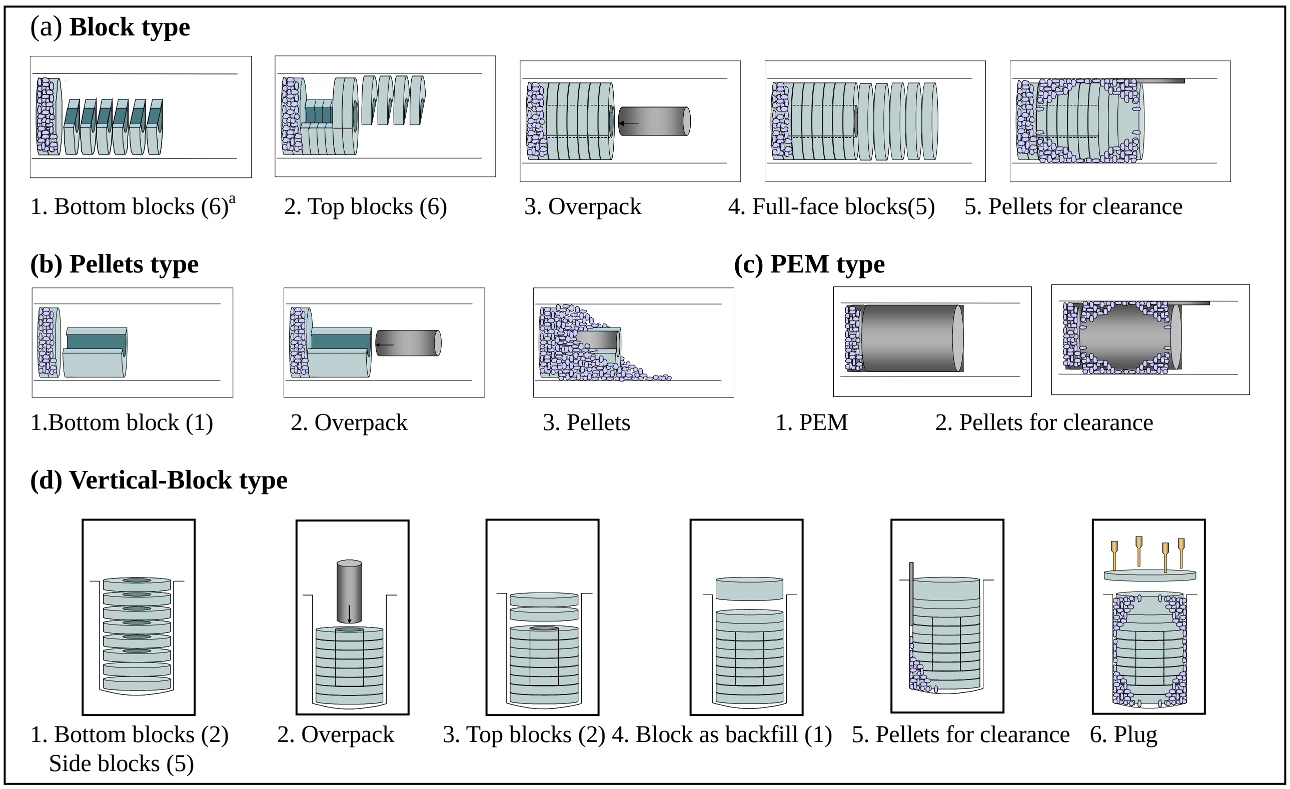
LOGISTICS ANALYSIS

As described above, the premise is that 5 HLW units should be emplaced per day in Japanese programme. In this study, a logistics simulator was used to evaluate different design options. The evaluation criterion determines whether or not the emplacement of 5 HLW units can be completed within 16 hours (2 shifts per day). The logistics simulator can provide a Gantt chart for the emplacement of 5 HLW units, which makes it easy to find rate-limiting factors.

Emplacement Procedures and Cycle Time

The block, pellets and PEM options were considered for the logistics analysis in this study. In addition, the vertical block option was likewise considered for comparison with the horizontal case. Fig. 2 shows the emplacement procedures for each buffer option.

The cycle time for each material in the horizontal case was set in reference to the cycle time in the vertical case.[7] In the vertical design, even though perfect alignment of a block is not achieved, the block can be emplaced along the pit wall. Furthermore, the straightness accuracy of a block is attained by gravity and this enables easier positioning of blocks with hardly no effort required to maintain straightness. For the horizontal design, on the other hand, the straightness accuracy of the desired path along the horizontal direction during emplacement must be strictly achieved. Moreover, during the emplacement of the upper blocks, consideration of the relative error of already emplaced bottom blocks is necessary. Therefore, positioning blocks in the horizontal direction requires longer time compared to placing them in the vertical direction. The cycle time for the vertical case was set relying on engineering judgment based on previous experience of using similar technologies.[7] However, the realistic cycle time for emplacement work cannot be attained at present due to few experiences with similar horizontal emplacement machines. In this study, the positioning time per block is supposedly set at 10 minutes. In addition, the cycle time for the works affected by or affecting the positioning accuracy is set twice longer than the corresponding works in the vertical case. Here, 'twice' is provided as an indication of the work's difficulty. The filling pellets time is based on the Obayashi's full-scale testing of filling pellets.[8] Table II shows an example of cycle time for block emplacement works regarding both cases.



[a] Numbers in parentheses means the number of blocks

Fig. 2 Emplacement procedures for each buffer option

Table II. Example of comparative cycle time of various emplacement works for both vertical and horizontal cases

Emplacement works	Cycle time (min)	
	Vertical	Horizontal
Emplacement of block		
Positioning of machine	5	**10**
Preparation for emplacement	30	30
Grasping one block	1	**2**
Positioning of one block (horizontal only)	N/A[a]	**10**
emplacement of one block	4	**8**
Preparation for machine movement	15	15
Emplacement of overpack or PEM		
Positioning of machine	5	**10**
Preparation for emplacement	30	30
emplacement of overpack	10	**20**
Preparation for machine movement	20	20
Filling pellets		
Positioning of filling machine	5	5
Preparation for filling	20	20
Filling for clearance (except pellets option)	30	**60**
Filling (pellets option)	N/A	**100**
Preparation for machine movement	15	15
Installation of plug	40	N/A[a]

[a] N/A = not applicable

Transportation Route and Speed

As this simulation process addresses the schedule and logistics per 5 HLW units emplacement, the transportation route was set for only one panel and simplified in reference to the standard layout in the past study. Fig. 3 shows the layout set including the assumptions of tunnel length in this simulation.

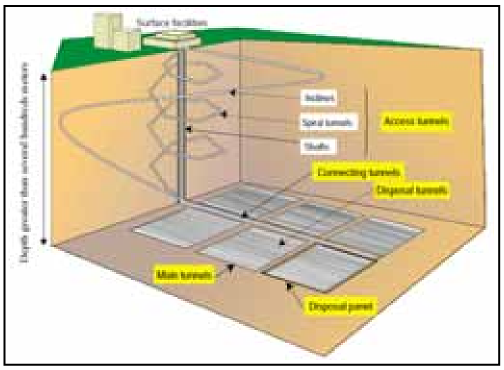
It is assumed that the schedule might be tight as the emplacement works need a relatively long time. Therefore, the following assumptions were considered to avoid "occurrence of waiting time" due to emplacement bottlenecks:

(a) There are sufficient numbers of transportation vehicles in the repository; and
(b) The emplacement work can proceed in parallel at five disposal tunnels.

Moreover, it was assumed that utilization of multiple transportation vehicles should not be done in one tunnel to avoid traffic conflict. This means that within the reloading facility, the next vehicle will have to wait for the previous vehicle to completely depart from the tunnel before coming in. However, this simplification is based on the layout for the current simulation, where connecting tunnels and main tunnels are assumed to be short.

The depth of the repository is assumed to be 1,000 meters in the simulation. For an access tunnel, a spiral tunnel (ramp) was selected from the perspective of safety and practicality considering the shaft case requiring the use of high-speed lift. Other assumptions include:

(a) The transportation vehicle leaves an entrance of ramp for underground facility continuously at ten-minute intervals;
(b) Ramp inclination is 10% and the total length is 10,000 meters;
(c) The vehicle speed is 5km/hour for ramp, connecting tunnels and main tunnels; and
(d) The speed of emplacement machine is 1 km/h, which moves in the disposal tunnel.



Standard layout for the underground facilities[1]

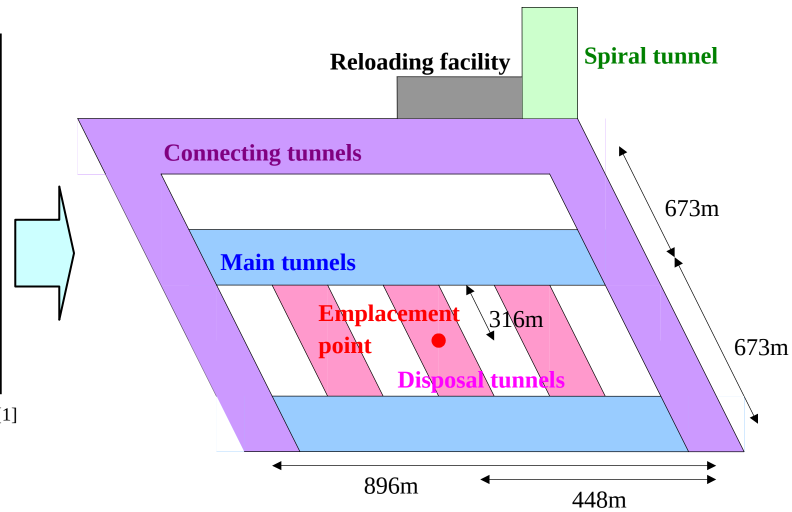


Fig. 3 Simplified layout of the underground facility for simulation

Simulation Results

Fig. 4(a) shows a Gantt chart output for the block option from the logistics simulation. It takes about 20 hours for even the first HLW unit to be completely emplaced in spite of the assumptions of the transportation design mentioned beforehand. The time for the emplacement of one HLW unit is composed mainly of the transportation time through the ramp and the emplacement time. There is no rate-limiting factor which may delay the progress of emplacement. Only the 10-minute interval of starting time at the ramp affects the time difference among each waste package. Even if the cycle times set in Table II are reduced to a certain degree, it is still impossible to implement the emplacement of 5 HLW units in 16 hours of working time.

The result of simulation for the PEM is shown in Fig. 4(b). The required time for 5 waste packages is 9.4 hours for the PEM and 13.2 hours for the pellets. For comparison, the time for the vertical block option is 15.6 hours (Fig. 4(c)). As clearly seen from these Gantt charts, the PEM option requires fewer emplacement materials and shorter schedule.

The Gantt charts do not show the time for the transportation vehicle to return to the surface. If the spaces for passing a vehicle from the opposite direction are located at 500-meter intervals in the ramp, the schedule is not affected.

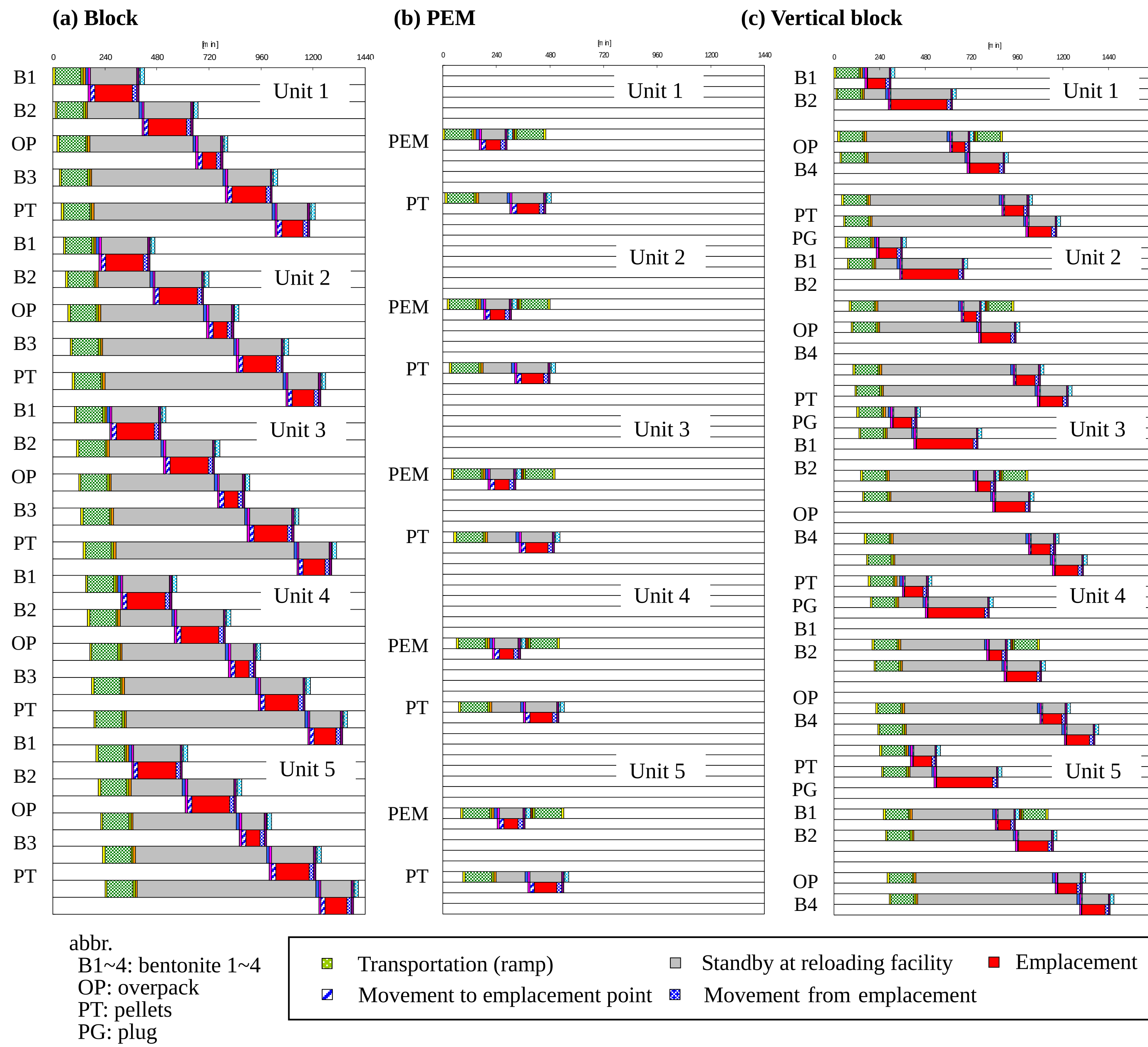


Fig. 4 Gantt chart outputs

OPERATIONAL SAFETY

The operational safety of each buffer option can be conceptually compared by considering the difficulty level of recovery from the assumed major disruption. Scenarios causing major disruptions during emplacement work could arise from mainly external perturbations as follows:

(a) Partial tunnel collapse;
(b) Eventual large transformation of rock;
(c) Vibration caused by a major earthquake;

(d) Fall of a large concrete fragment used as lining;
(e) Abnormal flooding;
(f) Fire;
(g) Power unit failure;
(h) Emplacement equipment breakdown;
(i) Drainage equipment breakdown; and
(j) Ventilating installation breakdown.

In case of vertical emplacement, considering the emplacement process shown in Fig. 2, direct access of workers to the disposal pit is possible prior to overpack emplacement, thereby making counter measures easy to implement. Also, the radiation shielding is available after the emplacement of a block as backfill. Therefore, the process requiring tele-handled technology, which may be difficult, is limited to the emplacement of overpack and backfill blocks. In addition, the space for emplacement equipment is large, and a two-way access is provided within the disposal tunnel making it possible to have two emergency exits in case of accidents. Meanwhile, in the case of horizontal emplacement, all emplacement work in the disposal tunnel is implemented with tele-handled technology because any particular measure for radiation shielding is not considered at present. Moreover, the limited space in the disposal tunnel can lead to higher risks of being stuck, and unfortunately, there is only one exit. As it seems, there are more difficulties associated with the horizontal concept than with the vertical. Particularly, recovery from the breakdown or entrapment of emplacement equipment will be considerably more difficult and a rescue system needs to be developed. The recovery from the damage of overpacks or blocks caused by rock or concrete fragment falls will also be problematic. However, it will be not particularly a hard task for the PEM due to the protection provided by the handling shell. The PEM will also be an optimal option to other perturbations, such as abnormal flooding and drainage/ventilation equipment breakdown. The simplicity of the emplacement process for PEM must be advantageous in operational safety even though the PEM concept requires handling a much larger and heavier package.

CONCLUSION

The operational practicality, particularly the logistics aspect, of a Japanese HLW programme has been systematically studied considering a reference case of 40,000 packages needing to be emplaced. The large reference inventory and emplacement rate of 5 waste packages per day is challenging to implement in the horizontal emplacement concept. However, this study indicates that PEM could be advantageous from this point of view. The advantage of PEM is also clear based on general project management studies, which evaluated the influence of potential operational disturbances under the assumed ‘wet’ condition. Such designs allow more flexibility to recover from a wide range of perturbations. Even though the PEM concept requires handling a much larger and heavier package, aspects, such as simplicity of QA, robustness to perturbations and ease of reversal, make a convincing case for focusing future efforts on such designs. A key step required to advance further from such conceptual analysis is to gain practical experience by full-scale demonstration experiments carried out under realistic underground conditions. Such experiments will not only serve as proof of concept, they will also examine the robustness of the system to a range of different perturbations.

REFERENCES

1. JNC, “H12: Project to establish the scientific and technical basis for HLW disposal in Japan”, JNC TN 1410 2000-001 (2000).
2. NUMO, “Development of Repository Concepts for Volunteer Siting Environment”, NUMO-TR-04-03 (2004).
3. Kitayama et al, “A structured approach for stepwise tailoring of repository concepts to volunteer sites”, Proceedings of ICEM’05 (2005).
4. Japan Construction Safety and Health Association, “Guideline for tunnel ventilation technology (design and maintenance)” (1992) (in Japanese).
5. Japan Tunneling Association, “Study on the phenomenon of water inflow and drought during tunnel excavation (version 2)” (1983) (in Japanese).
6. Japan Railway Construction Public Corporation, “Study on the investigation and countermeasures for drought” (1987) (in Japanese).
7. Federation of Electric Power Companies of Japan and Central Research Institute of Electric Power Industry, “Report on the technology for a HLW repository toward commercialization” (1999) (in Japanese).
8. Masuda et al, “Buffer Construction Technique by means of Granular Bentonite”, Proceedings of GLOBAL 2005 (2005)