Decommissioning and Environmental Remediation Scenario Development for Fukushima Daiichi

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ABSTRACT

Although the general approach to reactor decommissioning is well established, there is no direct precedent for managing the 6 units of the Fukushima Daiichi Nuclear Power Plant. Apart from damaged reactors, challenges include extensive contamination of the entire reactor site and a huge tank farm currently storing contaminated cooling water. In order to move forward with planning decommissioning, it is important to decide on the desired end state of the site and understand the impact of such a decision on the costs, hazards and environmental impact of the project. A decommissioning roadmap and reference dismantling concept provide a basis for short-term planning, but the potential for technological optimisation should be carefully considered because of the potentially large benefits to this long, complex and costly project.

1. Introduction

The general approach to nuclear power plant decommissioning is well established, based on experience with a diverse range of different kinds of reactors (e.g. IAEA, 2007). There is, however, no direct precedent for managing the 6 units of the Fukushima Daiichi Nuclear Power Plant (referred to in Japan as “1F”). As extensively documented elsewhere (e.g. current information on METI homepage: http://www.meti.go.jp/english/earthquake/nuclear/decommissioning/), these include undamaged and defueled reactors (units 5 and 6), a defueled reactor that has suffered extensive explosion damage (unit 4) and 3 reactors that have suffered extensive core melting (units 1-3), including at least some degree of melt through the reactor pressure vessel.

Figure 1 overviews the current status of units 1 to 4, indicating the various degrees of hydrogen explosion damage within the primary and / or secondary containment (especially units 1, 3 and 4) and progress with clearing rubble, placing weather covers over reactor buildings and removal of fuel from storage ponds (presently only Unit 4 completed fuel removal). As also indicated in Figure 1, the primary containment vessel (PCV) is flooded with water in the case of units 1-3, which is circulated for temperature control of fuel and fuel debris (“corium”), either remaining in the reactor pressure vessel (RPV) or melted through onto the concrete base of the PCV.

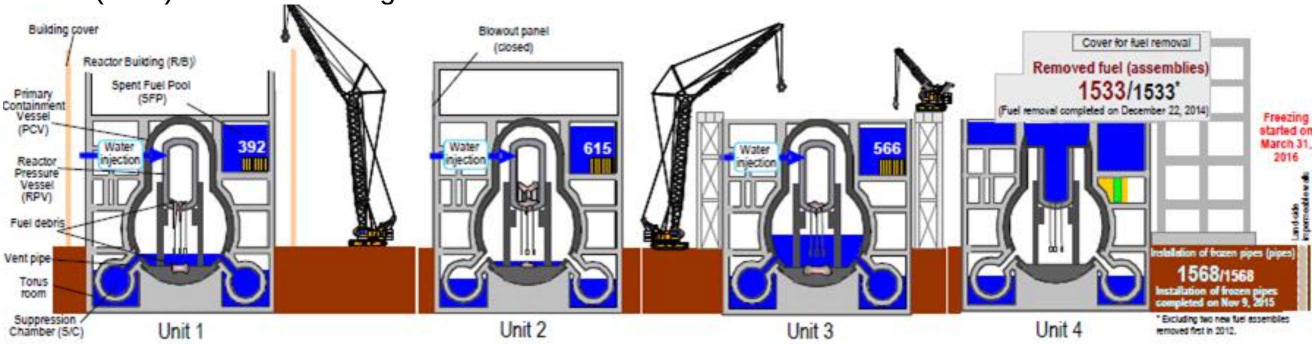

Figure 1 Status overview for 1F Units 1 to 4

Further challenges include extensive contamination of the entire reactor site, due to fallout from both pressure venting of containment and hydrogen explosions, and a huge tank farm storing contaminated cooling water. Currently leakage into cooling water circulation amounts to about 400 m^3 / day and groundwater inflow rate was 400m^3/day, which caused a major site management challenge. (TEPCO would reduce ground water inflow rate 400m^3 to 100m^3/day after completion of frozen soil wall around damaged reactor buildings within FY2016)

Due to a lack of relevant international experience, the Japanese site recovery team needs to develop decommissioning strategies tailored to 1F boundary conditions, with particular emphasis on operator safety and cost performance.

2. The “Road Map”

As a starting point, the Japanese Government and TEPCO established the “Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1-4” in 2012 (hereafter “Road map”: a recent revised “Road Map” available as METI, 2015). Key aspects of the Road map are summarised in Figure 2. The main focus is defining how to remove spent fuel from damaged storage pools and fuel debris from damaged reactor cores. The road map also presents milestones and decision-making points in this 40 year project.

However, the roadmap does not specify either the “end state” of the site or the waste management strategy, hence leaving 2 very important boundary conditions undefined. Indeed, a holistic approach to decommissioning requires that removal of highly radioactive fuel debris and damaged core is seen in the context of associated demolition of a range of other highly contaminated and damaged buildings and infrastructure on site, together with treatment and disposal of the huge amount of resulting waste.

It is also important to note that the time plan is very optimistic compared to international experience from major accidents such as Three Mile Island (TMI) in the US in 1979, Chernobyl in the Ukraine in 1986 and Windscale in the UK in 1957 (e.g. McKinley et al. 2011). Damaged core has not yet been removed from either Chernobyl or Windscale and debris removal from the much less damaged RPV of TMI (no melt through experienced) took 20 years.

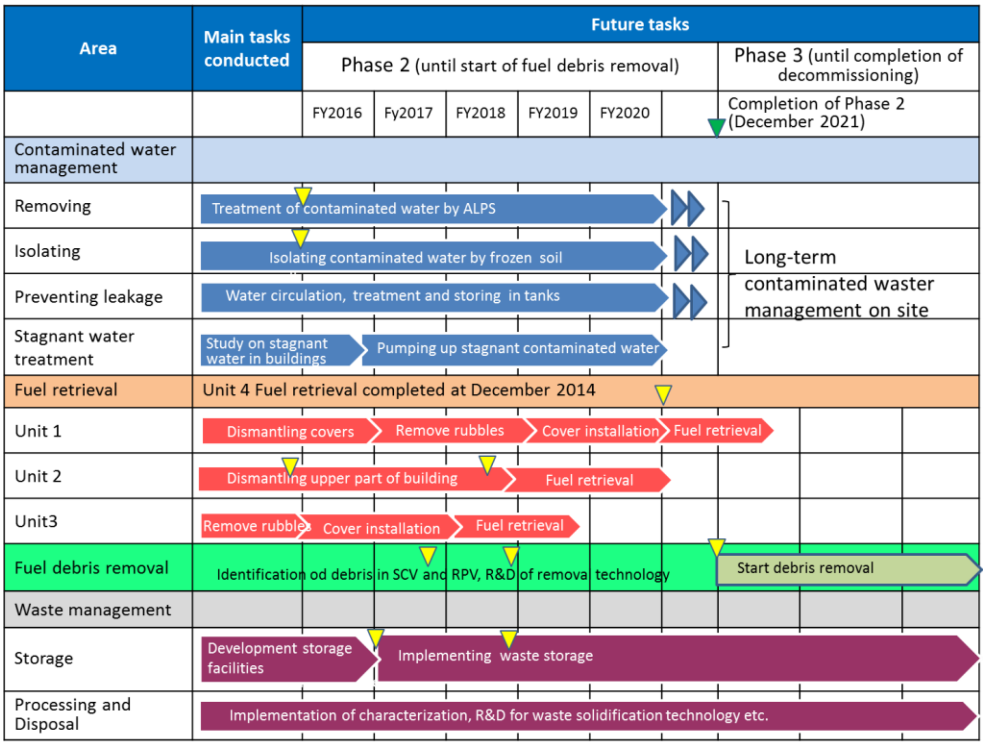

Figure 2 Mid- and Long-term Road map (rearrangement of 1F Road Map revised in June 2015)

3. “End state” Concepts

It is not possible to rigorously assess decommissioning without considering the final “End state” of the site. In principle, there are three fundamental variants, here termed Green field, Brown field and Entombment, which are used as the basis for defining a reference scenario and 4 alternatives (Figure 3).

These scenarios are grouped as:

A. Green field (Reference, Alternative-1): Shipping out all radioactive waste from 1F with decontamination of the site to below 0.3 mSv/year, allowing unrestricted land use and human activities.
B. Brown field (Alternatives-2 and-3): Storing waste on site, with long term institutional control
C. Entombment (Alternative-4): Disposing all waste underground on site.

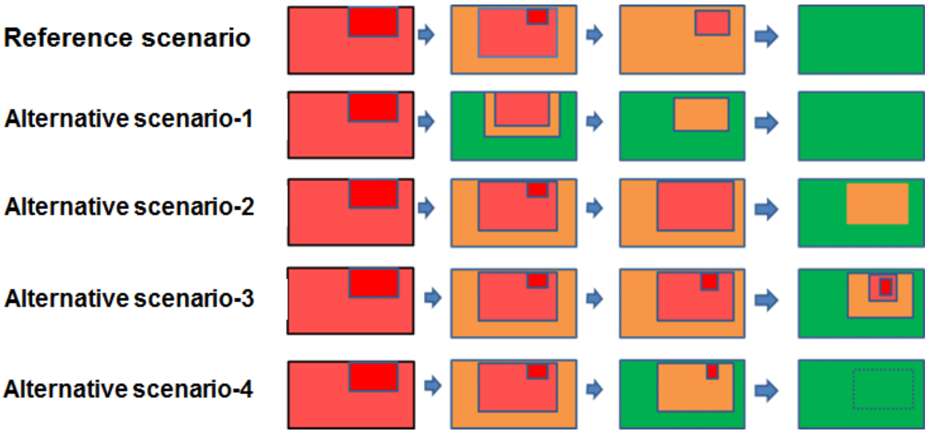

Figure 3 Reference and alternative scenarios (schematic: colours are an indication of the level of surface contamination at different times)

For each scenario, a particular focus is on its impact on resultant procedures, costs and risks of removal and treatment / storage / disposal of fuel debris and the damaged RPVs / PCVs.

4. Reference Scenario (Green field)

Moving toward “no restriction” on future site access provides many challenges, given the extent and complexity of contamination. Assumed constraints and boundary conditions for quantitative analysis are that, within 40 years, complete removal of units 1 to 6 along with all other facilities and extensive land clean up. This would proceed via a series of defined tasks:

(1) Dismantling reactor buildings after fuel debris removal
(2) Dismantling other site facilities
(3) Decommissioning contaminated water treatment facilities, plants, tanks (currently increasing with time)
(4) Decommissioning waste treatment and storage facilities (non-existent at present)
(5) Environmental remediation

Task breakdown for unit-3 dismantling programme

In order to highlight the issues involved, a detailed work breakdown for Unit-3 dismantling procedure is specified for the reference scenario (Figure 3). This is based on the current debris removal strategy outline in the road map (termed “wet”). Figure 3 shows the “level-1” work breakdown. Level-2 and 3 Work Breakdown System (WBS) has also been prepared, together with a task dictionary, which describes technologies, produced waste volumes, durations and cost estimations.

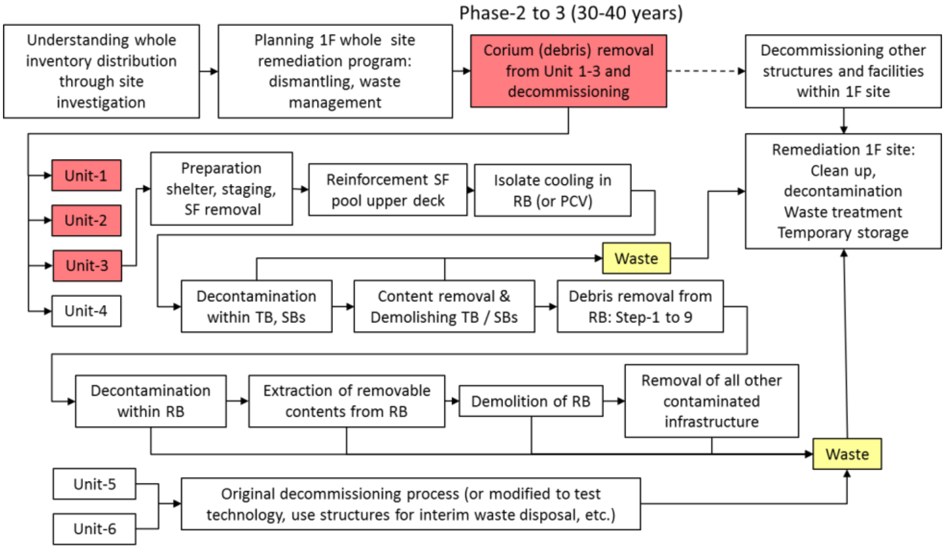

Figure 4 Dismantling Scenario outline for Unit-3

Waste management (on site treatment and storage)

For this scenario, after separation and treatment / packaging, storage of the produced waste will require a huge area (about 40% of the entire 1F site – Figure 5). Despite this huge inventory, it is assumed that, after 30 years, all waste will be shipped out to an off-site disposal facility and the storage facilities themselves decommissioned.

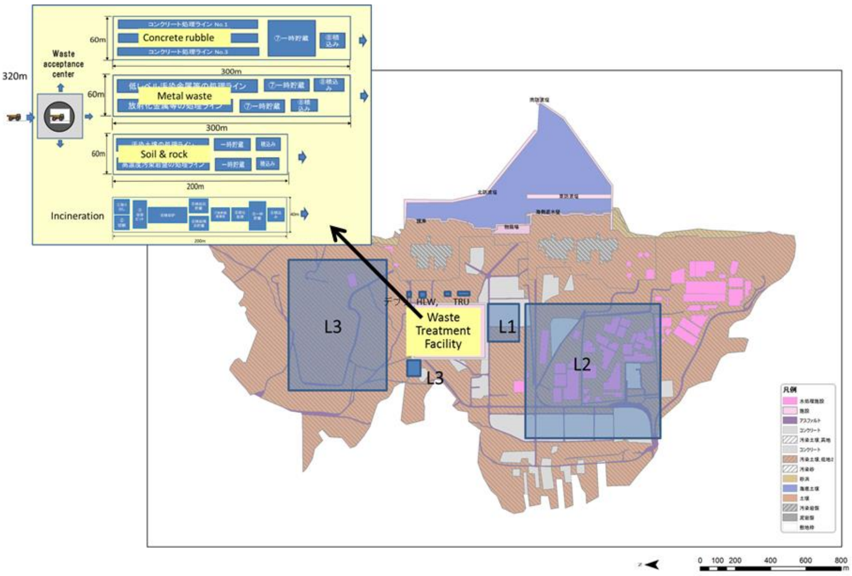

Figure 5 Layout of waste treatment and storage facilities (L1, L2, L3 refer to categories of waste with decreasing contamination levels – see Table 1 and Figure 10)

Environmental Remediation programme

After decommissioning all 1F facilities, remediation actions will cover forest, bare ground, paved surfaces, harbour and foreshore, together with contaminated subsurface rocks and groundwater, including material within the frozen soil wall surrounding damaged reactors (Figure 6). The target of such remediation is to reduce radiation exposure to future populations to a value below 0.3 mSv/year, which will be a very difficult goal to meet, based on experience to date with off-site decontamination (e.g. http://c-navi.jaea.go.jp/en/). In particular, subsurface clean-up of contaminated groundwater and removal of contaminated rocks could require a tremendous remediation effort.

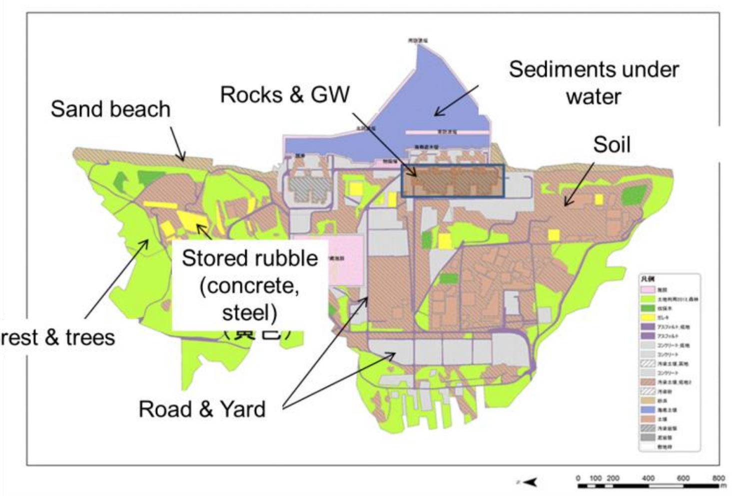

Figure 6 Targeting environment on 1F site

Project schedule
Based on the road map, the decontamination will be completed within 40 years of the accident (Figure 7). This target is set on the basis of a political decision, without any consideration of technical feasibility. Some of the scheduling has been based on TMI experience, although this does not account for either the much greater complexity of 1F units 1-3 or the particular difficulties caused by damage / contamination of infrastructure. However, there are potential synergies from parallel work on 6 units at the one site, although this is not directly reflected in this plan.

A particular uncertainty involves development of the novel technology required to handle corium that has melted through into the PCV (the extent of which is still not completely defined). Nevertheless, if units 4-6 are dismantled before 1-3, it could allow for development and testing of technology under less challenging conditions than those to be found in units 1-3. This would, however, require some modification of the schedule shown in Figure 7.

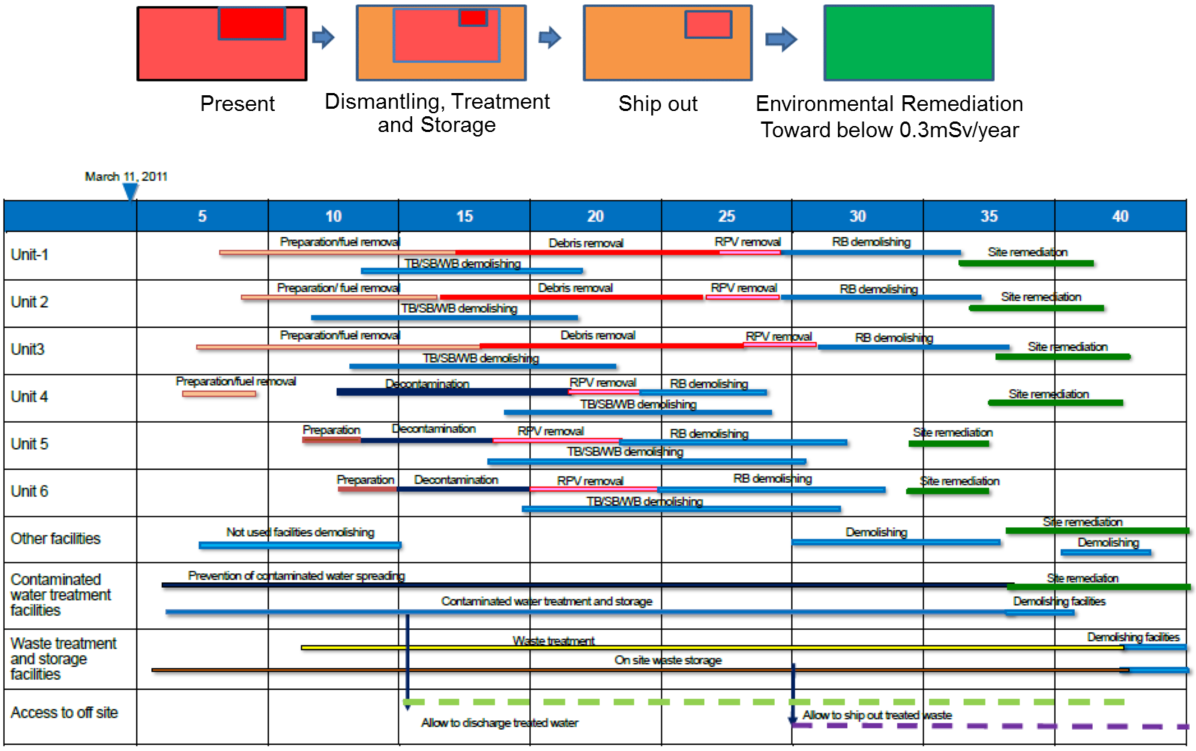

Figure 7 Project schedule from the “Road map”

Waste volume

Estimated waste production from the reference scenario is summarised in Table 1. Waste here is classified in terms of contamination level (based on both alpha and beta-gamma activity – see Figure 10, left). The highest activity waste ("HLW") is damaged fuel and fuel debris from the cores of units 1-3, which has significant heat output and for which criticality control could be an issue. Undamaged spent fuel from the various storage pools and central store is not included in this inventory. The volume of fuel debris is estimated assuming 100% fuel melting in unit-1 and 70% for units 2 and 3. The estimated volume of TRU (a term applied here for high alpha / long-lived L/ILW) and other categories of L/ILW have been derived from open documents. Note that, as illustrated in Figure 10 (left), "TRU" as generally used is a rather odd classification that relates to source of waste (reprocessing and MOX fabrication) rather than its composition: for the waste classification in Table 1, therefore, focus is on disposal option and hence "TRU" here is the component specified for deep geological disposal. All other waste is categorised in terms of disposal facility (termed L1/L2/L3 LLW in Japan – see Figure 10, right).

Unlike normal decommissioning, for 1F there is no waste assumed to be below clearance level or non-radioactive in terms of current waste classification rules, because of contamination throughout the site. As a result, low level waste (L2, L3) from dismantling site infrastructure and environmental remediation dominate the total volume (Figure 8). Reducing the volume of these waste is a critical issue.

Table 1 Waste volume from the reference scenario

Waste Category	Unit	Dismantling Unit 1 to 6	Demolishing other NPP facilities	Decommissioning water treatment facilities	Decommissioning waste treatment and storage facilities	Environmental remediation	Total
Debris	t	644	0	0	0	0	644
HLW		2,042	0	0	0	83	2,125
TRU		0	0	16	0	830	846
L1		100,135	104,543	310	1,050	76,030	282,069
L2		429,462	329,364	38,174	200	1,424,600	2,221,800
L3		951,309	2,825,634	151,320	26,325	1,375,000	5,329,587
Total		1,483,592	3,259,541	189,820	27,575	2,876,543	7,864,646
debris	m^3	107	0	0	0	0	107
HLW		338	0	0	0	62	400
TRU		0	0	3	0	623	625
L1		57,463	55,511	51	174	74,538	187,736
L2		251,063	194,916	6,322	33	1,164,764	1,617,098
L3		555,901	1,813,403	98,045	16,752	1,303,846	3,787,947
Total		864,872	2,063,829	104,421	16,959	2,543,833	5,593,914

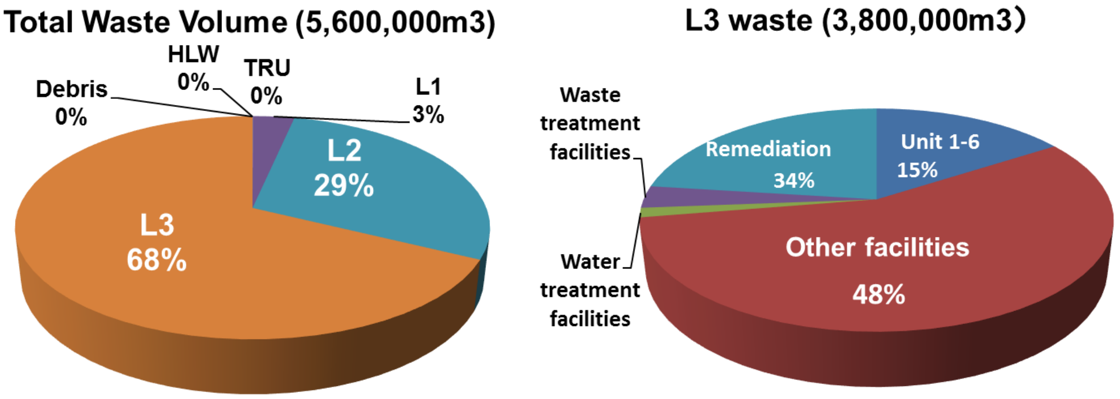

Figure 8 Breakdown of waste arising

Cost analysis

The total cost for the defined reference scenario (shipping out all waste) is estimated to be around 14 T Yen (about 130 B US$), based on information available in open documents. This cost does not include contaminated water treatment or any other activities associated with current efforts to manage water on site. It is notable that the cost of waste management (characterisation, segregation, conditioning, packaging, storage, transportation and disposal) dominates (86%) the entire project cost (Figure 9).

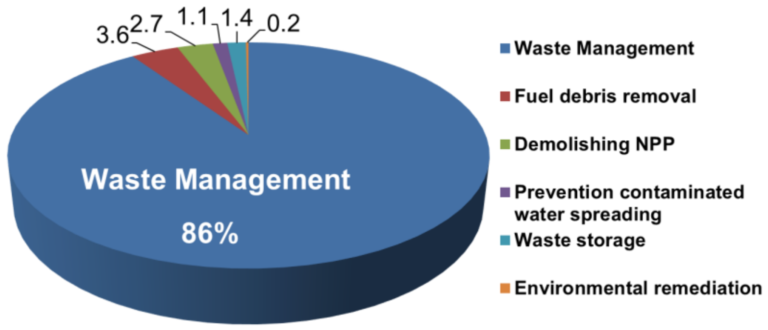

Figure 9 Breakdown of estimated cost components

The main reasons that waste treatment and disposal dominate total project costs are:

- There are no wastes below clearance level, thus even materials with very low levels of contamination have to treated as radioactive waste
- Waste management cost includes transportation of huge volumes of material to an unspecified location off site
- Fuel debris and other material with significant fissile nuclide component will be reprocessed and resulting high activity waste vitrified (as required by existing rules)
- All other wastes are also conditioning, packaged and disposed of in facilities that are equivalent to those currently employed for the measured level of contamination (Figure 10, right).

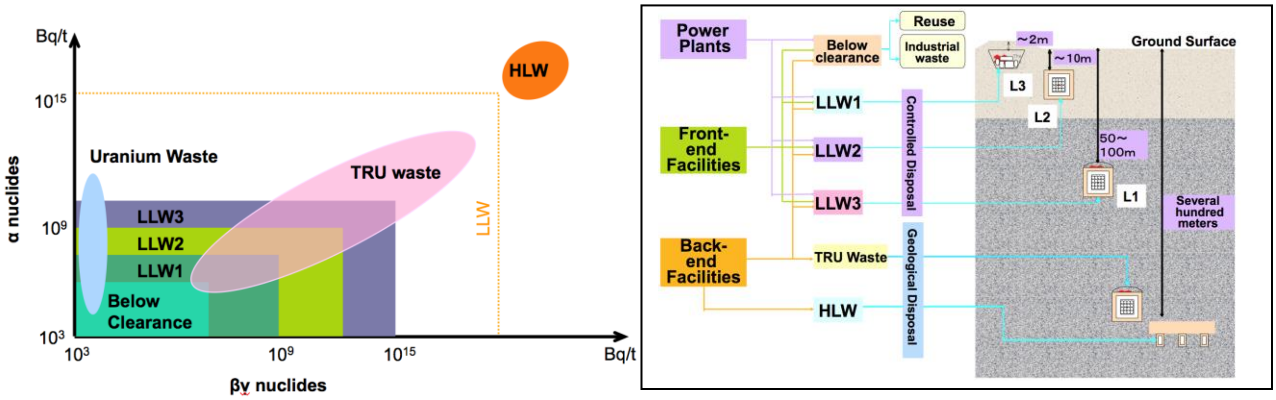

Figure 10 Waste classification and disposal concepts for nuclear fuel cycle wastes in Japan

5. Comparison with alternative scenarios

Alternative Scenario 3: On-site long-term storage

As the decommissioning approach is fundamentally the same, the waste volume is same as in the reference scenario. In this option, however, waste is stored on the site (Figure 11), which remains under institutional control for an indefinite period of time (about 300 years, say). Assessment of longevity of facilities over such a period results in a requirement for refurbishment every 50 to 60 years (based on existing technology). For this case, robust, long-lived waste packages are needed, to allow removal / re-emplacement every 50 to 60 years. In any case, such waste movement would include inspection and reconditioning / repackaging as required. It is estimated that such long-term storage on site could increase the waste management cost by about 120%, predominantly due to long-term storage and maintenance.

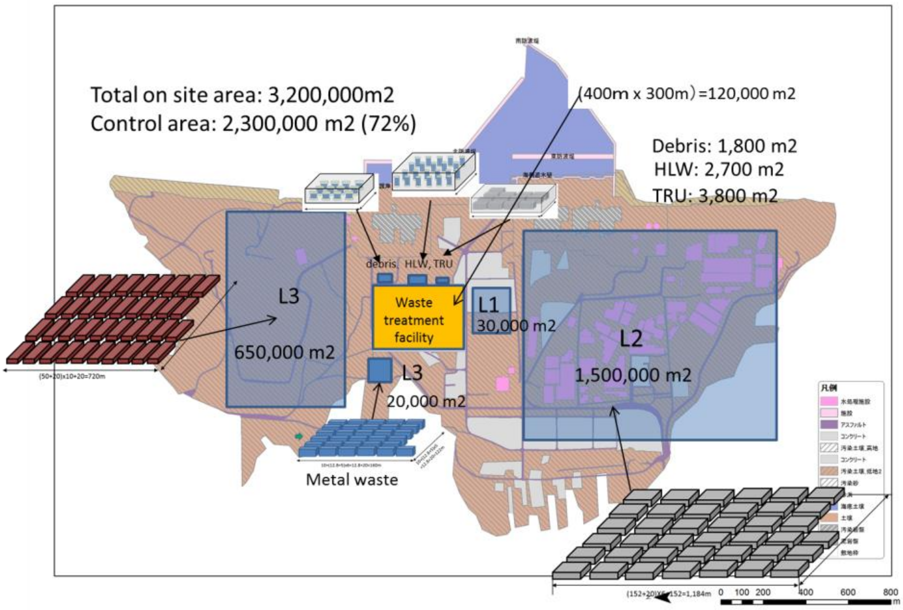

Figure 10 Layout of on-site long-term storage facilities (Alternative scenario 3)

Alternative scenario 4: On site disposal concept

Again the waste volume is same as for the reference scenario, but this goes directly for disposal in a facility located below the site. The basic concept is that all waste would be disposed of at significant depths below surface, basically providing more robust safety than conventional L1/L2/L3 disposal. This can be justified as construction and operation of these facilities utilises infrastructure required for the deeper disposal of fuel debris, HLW and TRU (Figure 11).

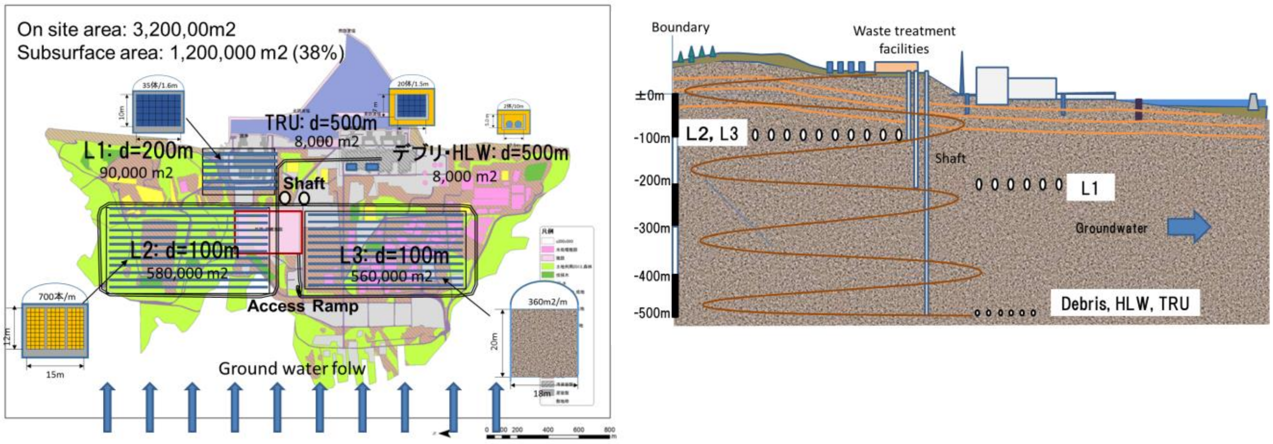

Figure 11 On-site disposal concept (left showing footprint, right depth profile of facilities)

In terms of geological disposal, fundamental construction and operation technologies are reasonably well developed, although confirmation of site suitability and optimisation of layout and implementation would be key factors if the project is to be completed within 40 years.

In addition to avoiding off-site transportation, storage requirements can be reduced and waste packaged directly for disposal, resulting in a net reduction of the waste management cost of about 50 % compared to the reference scenario.

When disposal occurs on site, additional options arise to reduce waste handling, pre-treatment and packaging costs (discussed further below), increasing the net reduction of budget to about 50 to 70 %.

6. Comparison of scenarios

Comparison of the reference and alternative scenarios has involved expert elicitation of input for both technical and socio-political aspects of decommissioning. These included:

[Technical aspect]
(1) Technical feasibility
(2) Operational safety (on site only)
(3) Treatment and disposal
(4) Secondary waste production
(5) Environmental Impact (to the 1F site)
(6) Cost
[Social and institutional aspect]
(7) Public acceptance
(8) Consistency with existing rules
(9) Ensure containment of radioactive material
(10 Institutional control

The results of this assessment are summarised in Table 2.

In the table, a score of 5 represents the best performance with respect to the attribute considered and 1 the worst. Thus the reference scenario scores very well for site safety, because all waste will be shipped out. Local people would support such a scenario, but cost and risks of possible release of nuclear material are negative attributes. Note, however, that this assessment treats safety, environmental impact and acceptance only from the perspective of 1F site: moving the waste transfers risks, environmental impacts and acceptance problems to another, undefined location. In terms of feasibility, a special issue is cleaning the site to a level that would allow free access. The degree to which the subterranean environment is contaminated is still unclear and there is no precedent anywhere for such an effective decontamination, so feasibility must be considered uncertain on the basis of existing technology.

Table 2 Qualitative comparison of scenarios

	Technical aspect							Social aspect					
Scenario	(1)	(2)	(3)	(4)	(5)	(6)	Sub-Total	(7)	(8)	(9)	(10)	Sub-Total	Total
Reference Scenario	5	4	4	2	5	2	22	5	4	2	4	15	36
Alternative-1	5	4	4	2	5	2	22	5	4	2	4	15	36
Alternative-2	4	3	3	3	3	1	18	4	3	2	4	13	31
Alternative-3 On-site storage	3	3	3	2	2	1	14	3	2	4	3	12	26
Alternative-4 On-site disposal	4	5	5	4	4	4	26	1	4	5	4	14	40

On-site, long-term storage is certainly technically feasible, but the inventory of waste contains very long-lived components, so storage cannot be considered a final solution, but more a stopgap until better technology or alternative disposal options are developed. In addition, very long-term storage raises questions on how the required longevity of waste packages and storage facilities can be managed. For this option, a critical social aspect is local public acceptance, providing assurance that the required level of institutional control can be guaranteed and that, in the event of perturbations (natural or anthropogenic), risks of loss of radionuclide containment can be precluded.

On-site disposal clearly provides many technical benefits and is cost effective. Although it is the only option that fully defines final disposal of waste, it goes against existing political commitments to remove waste from site and thus would have difficulties gaining required local public acceptance.

If new rules for damaged waste classification and treatment/disposal are established in future, these may provide major advantages in terms of:

- Waste volume reduction (e.g. if a central decontamination / recycling facility allowed material to be free released or recycled for nuclear applications – including waste disposal structures)
- Improved waste treatment within a holistic disposal concept (e.g. avoiding separate consideration of conditioning / packaging for storage and disposal)
- Cost reduction (which could certainly exceed 8 T JPY for an optimised approach)
- Much safer working conditions (for both expected conditions and also in case of any unexpected perturbations).

However, it will still be very difficult to complete all decommissioning activities within 40 years. Such a tight time schedule precludes benefiting from synergies, which make best use of expert staff, equipment and infrastructure. Time pressure requires also a sophisticated management system, which may be less robust in case of perturbations, which is a special consideration for 1F, due to high media interest and the importance of rebuilding public confidence in the safe operation of this site.

7. CONCLUSIONS AND FUTURE PERSPECTIVE

The decommissioning of the 1F site presents unique challenges and requires a plan that is tailored to the specific boundary conditions of this project. The road map provides basic goals, but specifies an extremely ambitious implementation schedule and leaves key constraints undefined – in particular the site end state and waste disposal concepts.

Development and assessment of different end state and implementation scenarios has highlighted the huge cost of the reference option and the potential savings and other benefits of alternatives. To date, however, this assessment has been technically superficial with only qualitative evaluation. As a next step, the more favourable options need to be described in detail and the basis developed for a more quantitative evaluation of specific pros and cons of variants. For the on-site disposal option, this requires better characterisation of the geological environments accessible and assessing their potential for hosting an appropriately designed repository.

Because waste management is such a large proportion of the total cost – and also a likely focus of public concern – it is critical that the safety, environmental impact and socio-economic issues involved are communicated to all key stakeholders, so that they can participate in the decision-making process and fully buy into the option selected. Based on past experience, this may be as difficult as any of the technical aspects of this challenging project.

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