2.4 DEEP BOREHOLE ALTERNATIVES

Two alternatives are described in this section. Each can be defined as the entire sequence of processes and facilities necessary to convert stable stored weapons-usable plutonium forms into forms to be disposed ultimately in a government-owned deep borehole. The disposal form is not spiked with radioactive waste to provide a radiation barrier; the geologic barrier by itself provides a level of proliferation resistance.

In the deep borehole concept for geologic disposal of surplus fissile materials, the material will be emplaced in the lower part of one or more deep boreholes drilled in tectonically, hydrologically, thermally and geochemically stable rock formations. The borehole site facilities are presumed to be sited on non-DOE sites, unlike all other alternatives which are accomplished on DOE sites with greater or lesser amounts of infrastructure. Once the emplacement zone of the borehole is filled with materials, the “isolation zone” extending from the top of the emplacement zone to the ground surface is filled and sealed with appropriate materials. At emplacement depths, the groundwater is expected to be relatively stagnant, highly saline, hot (75-150^{O} C), and under high pressure. In deep boreholes there is a large barrier to transport posed by the isolation zone because of its low permeability and high sorptivity, the stability and low-solubility of the disposal form, and high salinity and the lack of driving forces for fluid flow. Thus the disposed material is expected to remain, for all practical purposes, permanently isolated from the biosphere.

The Deep Borehole Alternative team analyzed the alternatives in Table 2-6. Both borehole alternatives assume a disposition rate of five MT/year over a ten year operational period, although accelerated cases could allow emplacement in three years with simultaneous rather than sequential drilling of boreholes. The processing operations of the beginning-to-end direct and immobilized deep borehole alternatives are presented in Figures 2-11.

2.4.1 Direct Emplacement Alternative

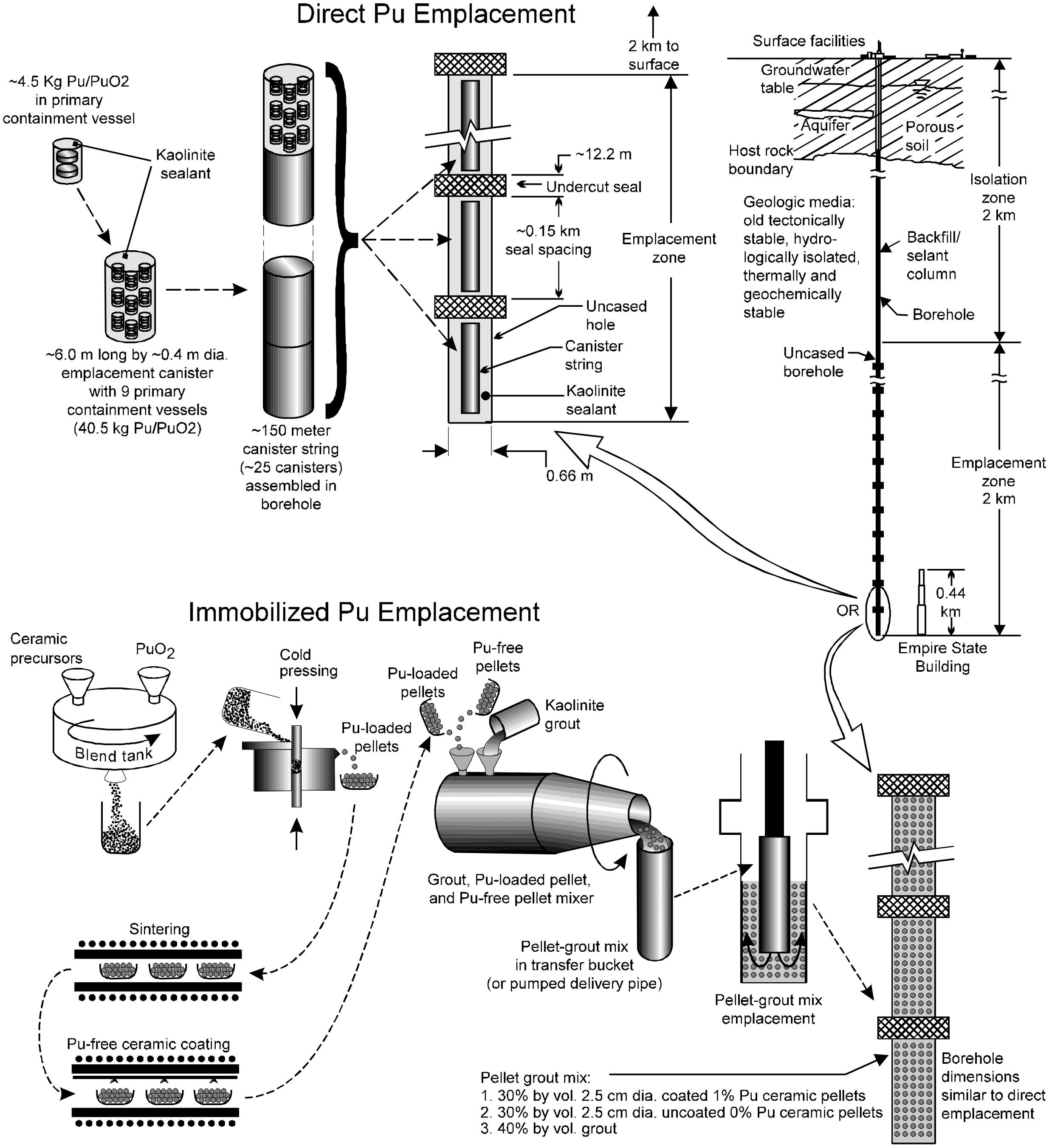
As shown in Figure 2-11, the direct emplacement alternative receives plutonium metal and oxide; and without further purification, this product is packed in metal product cans which are then sealed in primary containment vessels and delivered by SSTs to the deep borehole disposal facility. The product cans are placed in a container which holds plutonium product cans containing approximately 4.5 kg of plutonium with double containment. These transportation containers are directly encapsulated in large (0.4 meter diameter, 6.1 meter long) emplacement canisters with filler material mixture without reopening. Each emplacement canister contains 40.5 kg of plutonium. The emplacement canisters are then assembled into 152 meters long canister strings with 25 canisters per canister string. The canister strings are lowered into the emplacement zone of the boreholes (2 km deep) and are grouted in place with kaolinite clay. Finally, the isolation zone is sealed from the top of the emplacement zone to the surface with appropriate sealing materials.

Table 2-6. ***Deep Borehole Alternatives***

Alternative	***Description***
Direct Emplacement	• Disposal form is plutonium metal or plutonium oxide • Emplaced at 2 km depth in four 4 km deep 0.66 to 0.91 meter diameter uncased boreholes • Emplaced in containment vessels (with void filling) within 0.4 meter diameter 6.1 meter long emplacement canisters • No radiation barrier
Immobilized Emplacement	• Disposal form is plutonium immobilized in SYNROC-like titanate ceramic pellet with thin plutonium-free coating • Ceramic pellets containing plutonium have 1% plutonium-loading • Plutonium pellets mixed with equal volume of plutonium-free ceramic pellets and kaolinite grout and emplaced directly without any canisters (mixing plutonium loaded and plutonium-free pellets creates an average plutonium loading of 0.5% by weight) • Emplaced at 2-4 km depth in four 4 km deep 0.66 to 0.91 meter diameter uncased boreholes • No radiation barrier

In the direct deep borehole alternative, the criticality safety of the plutonium-loaded product cans and the transportation containers during intra-site transportation, processing, emplacement, and post-emplacement performance will be ensured by spatial dispersal (i.e., spatial separation). The low solubility of the plutonium metal/plutonium oxide disposal forms and the very slow flow velocities expected at depth appear to provide sufficient resistance to mobilization by flowing groundwater. The heat generated by the plutonium is so small that the temperature rise due to alpha decay of the plutonium is negligible. The high salinity of the groundwater completely suppresses any buoyancy-related fluid flow due to temperature changes arising from both the heat generated by plutonium decay as well as due to geothermal heat. Estimates of fluid flow velocities due to water level fluctuations at the surface and earthquake generated fluid pressure fluctuations appear to be negligible as a result of the great distance from the surface, the low permeabilities of fractured rocks at depth, and stabilizing effect of the high salinity gradients.

Figure 2-11. ***Deep Borehole Alternatives***



2.4.2 Immobilized Emplacement Alternative

As shown in Figure 2-11, the immobilized emplacement alternative receives plutonium oxide from the front-end facility which is then transferred to the immobilization process of the front-end facility for forming plutonium-loaded ceramic pellets by a cold press and high temperature sintering process. The plutonium loading of the ceramic pellets is kept at the very low level of 1% by weight to assure criticality safety during processing and after emplacement. To provide a barrier to contamination during handling, the sintered ceramic pellets are subsequently coated with a thin impervious layer of ceramic that is free of plutonium. The ceramic material is a tailored, SYNROC-like titanate-based ceramic with the mineral phases zirconolite and perovskite as the primary constituents. The pellets will contain 98% ceramic and will be about approximately 4 g/cc in density. The ceramic pellets fabricated at the disassembly, conversion and immobilization facility are then transported by SSTs to the deep borehole disposal facility. At the emplacing facility, the plutonium-loaded ceramic pellets are uniformly mixed with an equal volume of plutonium-free ceramic pellets (to yield a pellet mixture with an average plutonium loading of 0.5% by weight) and ‘grout’ (i.e., kaolinite clay). This additional dilution of the plutonium-loaded pellets with plutonium-free pellets increases the criticality safety margin. The mix is then directly emplaced in the uncased emplacement zone of the borehole. No metal canisters, packaging materials, or borehole casings that could compromise the hydraulic sealing are left in the emplacement zone of the borehole, providing superior sealing compared to the direct emplacement alternative. Finally, as in the case of direct disposition, the isolation zone of the borehole is sealed from the top of the emplacement zone to the surface with appropriate materials.

The very low solubility and high thermodynamic stability of the ceramic disposition form is expected to provide superior long-term performance as compared to the direct emplacement form. The low solubility of the ceramic pellet disposal forms and the very slow flow velocities expected at depth indicate that many millions of years would be required to mobilize even one millionth of the emplaced plutonium.

2.5 HYBRID ALTERNATIVES

The alternatives described above dispose of all 50 MT of surplus plutonium using a single technology approach. Alternatives which use combinations of reactors, immobilization, and borehole approaches could be devised. Two of the more likely hybrid alternatives are presented here to indicate the potential impacts on technical, cost, and schedule. These two hybrids alternatives are the combination of immobilization can-in-canister with either existing LWRs or CANDU reactors. Both hybrids assume the use of modified existing facilities. Hybrid alternatives provide flexibility to the decision-making processes. Specifically, flexibility is retained in that a decision to utilize a hybrid approach preserves the option to go exclusively with either disposition technology at a later date and flexibility is retained in operations in that one technology is the back up for the other. Furthermore, a higher confidence of timely start-up of the disposition mission is achieved with the potential of a more rapid completion.

In the two cases considered, high-purity, weapons-grade plutonium from pits, metal, and oxides (approximately 32.5 MT) will be used as feed materials for the fabrication of MOX to be used in the reactors. The balance of the surplus plutonium (approximately 17.5 MT) will be used as feed materials for immobilization (either glass or ceramic) can-in-canister. For the LWR hybrid alternative, three existing LWRs without neutron absorbers are assumed. For the CANDU hybrid alternative, two CANDU reactors with reference fuel are assumed. The number of reactors deployed is limited by the capacity of the plutonium processing facility which provides materials for both the reactors and the immobilization plant. Although vitrification can-in-canister was costed in the hybrid, no distinction is made here regarding the selection of either a ceramic or vitrified can-in-canister approach since the cost and schedule differences between the two are small.

The hybrids considered here are illustrative, and others could be presented. No preference is intended by the cases chosen for discussion in this report. Moreover, cost and schedule improvements may be realized with further design optimization.