" Benefits of an Integrated Fuel Cycle on repository effective capacity"

D. DAVIDSON, I. HUNTER,
COGEMA Inc, 4800 Hampden LA, Suite 1100 Bethesda, MD 20814, USA

R. VINOCHE, J. BRUYERE*, G. CLEMENT, T. LOUVET,
COGEMA, 2 rue Paul Dautier BP 4 78141 Vélizy Cedex, France
*SGN, 1 Rue des Herons, Montigny le Bretonneux, 78182 st. Quentin en Yvelines, France

Abstract

Today, the Yucca Mountain repository is limited by legislation to a maximum capacity of 70,000 metric tons of initial heavy metal (MTiHM), of which 63,000 MTiHM is reserved for civilian nuclear used fuel. Various sources have estimated the "real" or "technical" capacity of Yucca Mountain could be around 125,000 MTiHM. Whatever the actual number is, it will be significantly less than the anticipated total volume of used fuel expected to be generated in the US by 2100. This paper briefly reviews the design constraints of the Yucca Mountain repository and shows the potential gains in capacity by early recycling of used fuel from US commercial reactors using an evolutionary COEX process (co-extraction of uranium and plutonium) design.

To optimize the Yucca Mountain loading, two important constraints need to be addressed: heat load and physical volume. For heat load there is a long-term issue with actinides (primarily plutonium and americium) and a short-term issue with fission products (primarily cesium and strontium). We present a new way to increase the capacity of Yucca Mountain by increasing the unit loading of the repository - early recycling approach. For the once-through option and the early recycling solution, drift loading factors are calculated, looking at both volume and heat. The resulting densification factor (ratio of drift loading factor of treatment high level waste residues to used fuel) is 4 using COEX technology. In simple terms, the total length of Yucca Mountain tunnels needed to dispose of 63,000 MTHM of used fuel (legal limit) could be used to dispose of the residues from the treatment of 252,000 MTHM of used fuel.

1. Yucca Mountain capacity Limitations

There are two ways to increase the capacity of Yucca Mountain: 1) increase the number of waste emplacement tunnels (which would require additional underground area that has not yet been characterized), or 2) increase the unit loading of the repository – that is, the amount of waste placed per unit length of repository tunnel.

Increasing the number of waste emplacement tunnels is limited by the sub-surface area of Yucca Mountain. Today, the repository is limited by legislation to a maximum capacity of 70,000 metric tons of initial heavy metal (MTiHM), of which 63,000 MTiHM is reserved for civilian nuclear waste. Various sources have estimated the "real" or "technical" capacity of Yucca Mountain could be around 125,000 MTiHM. Whatever the actual number is, it will be significantly less than the anticipated total volume of used fuel expected to be generated in the US by 2100. Making better use of the available space for disposal will not only increase the life of the repository but it will significantly postpone the cost of any further repository space.

Increasing the reference "unit" loading capacity of Yucca Mountain can increase capacity without requiring adding tunnels. Unit loading is defined as the amount of MTiHM placed per meter of repository tunnel. Today, the reference unit loading is based on what is currently accepted as the reference repository design, whereby waste packages containing PWR and BWR used nuclear fuel and others containing defense waste are placed back-to-back in repository tunnels with only ~10 cm of space between them.[1] Roald Wigeland and his associates have published results of analysis showing the maximum loading of repository tunnels for reference PWR fuel (burnup rate of 50 GWd/MTHM) is on the order of 1.1 MTiHM of used nuclear fuel per meter of tunnel, under reference operating conditions.

Increasing this unit loading requires reducing waste volumes and then packing wastes closer together. Under the reference repository design, waste packages are lined up with little space between them. Thus, there is no possibility to squeeze untreated used nuclear fuel closer together, without extensive changes to tunnel and waste package design. Increasing the unit loading of Yucca Mountain requires some reduction in waste volumes such that wastes can be packed more densely (e.g., replacing untreated used nuclear fuel by vitrified residue canisters). However, this "increased packing" of the waste stream must also respect the Yucca Mountain design temperature limits.

The current reference configuration and operating mode of Yucca Mountain imposes two important thermal constraints, as shown in Figure 1 below:

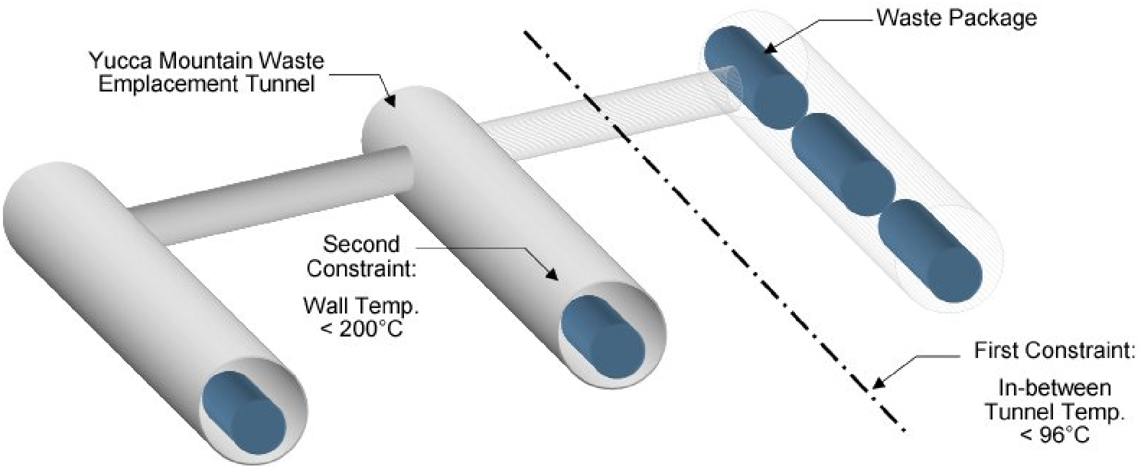
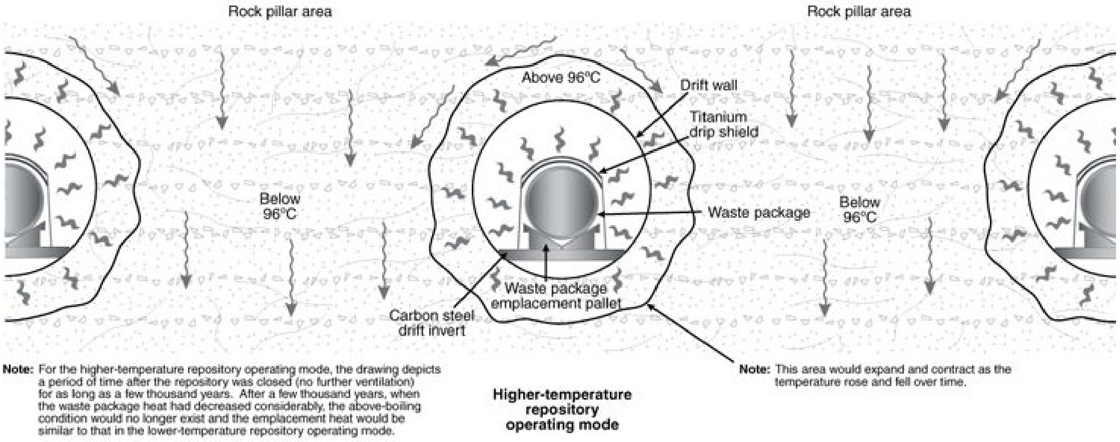


Figure 1, Tunnel and waste package configuration at Yucca Mountain

---

[1] The reference design is sometimes called the "hot" repository operating mode, because the rock around the tunnels exceeds 100°C. The Nuclear Waste Technical Review Board (NWTRB) has raised concerns about the corrosion of waste packages in a "hot" environment. At the recommendation of the NWTRB, a "cold" operating mode has also been considered by DOE, where waste packages are spaced considerably further apart and rock temperatures around the tunnels remain under 100°C. This "cold" design would require considerably more tunnel space. A final decision on hot versus cold has not been made by DOE.

First, the temperature in between used nuclear fuel placement tunnels must remain below 96°C (the local boiling point) to permit water to percolate in between tunnels, avoiding any accumulation of water above the repository (see Figure 2 below)
Second, temperature of the surrounding rock must remain below 200°C (the maximum temperature must occur at the repository wall). This avoids inducing changes to the mechanical properties of the rock.



Note: For the higher-temperature repository operating mode, the drawing depicts a period of time after the repository was closed (no further ventilation) for as long as a few thousand years. After a few thousand years, when the waste package heat had decreased considerably, the above-boiling condition would no longer exist and the emplacement heat would be similar to that in the lower-temperature repository operating mode.

Note: This area would expand and contract as the temperature rose and fell over time.

Figure 2. Temperature distribution in Yucca Mountain

The first constraint is specific to the currently accepted design of Yucca Mountain. The second is specific to the rock at the Yucca Mountain site. Thus, the first might no longer apply if the design of Yucca Mountain is changed, and the second may not be applicable to sites other than Yucca Mountain, where the surrounding geological medium would have different physical characteristics.

The temperature in-between tunnels is driven primarily by the long-lived heat emitting isotopes of Pu and Am contained in waste. These actinides emit heat for an extremely long time. This heat diffuses through the rock and gradually causes the temperature in-between repository tunnels to increase. Figure 3 below shows the contribution of various elements to the heat output of used nuclear fuel over time. It can be seen that ^{241}Am, ^{239}Pu and ^{240}Pu emit heat for thousands of years.

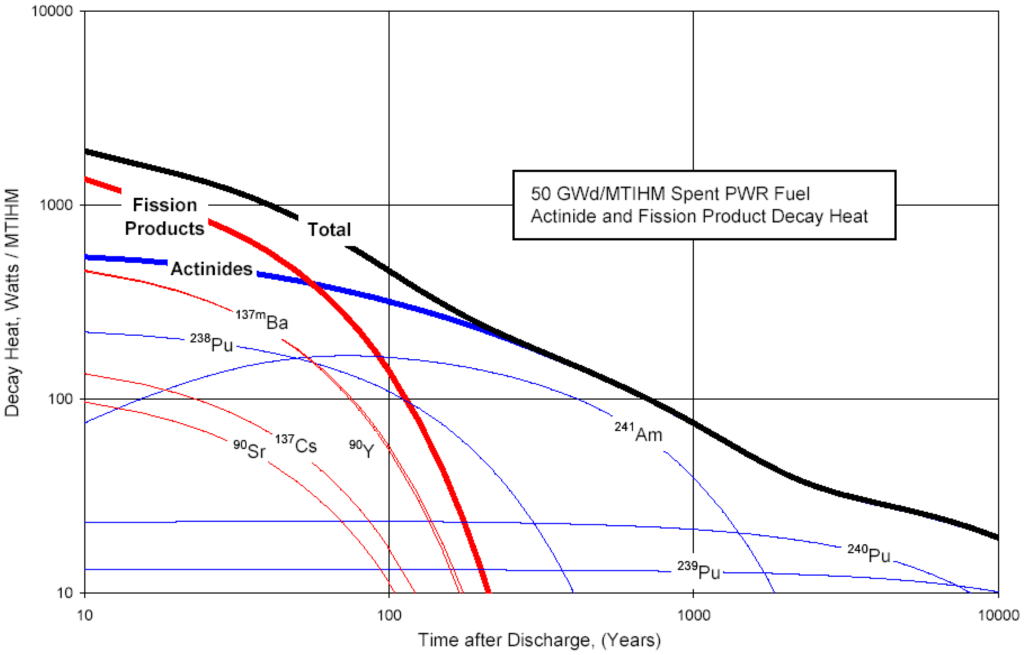


Figure 3. Contribution of elements to heat output over time

The temperature of the repository tunnel wall is driven by short-lived, very "hot" isotopes contained in spent fuel or other wastes, notably ^{90}Sr and ^{137}Cs and their decay products ^{90}Y and ^{137m}Ba. The Cs and Sr isotopes have half-lives on the order of 30 years, while the Y and Ba isotopes have much shorter half-lives on the order of several hours and several minutes, respectively. The figure above shows the contribution of these isotopes to overall used nuclear fuel decay heat. Once the planned 75 year ventilation period of the tunnels at Yucca Mountain is finished, these isotopes emit enough heat to cause a short-term spike in the wall temperature.

In the reference Yucca Mountain design, the in-between tunnel temperature limit is the first limiting factor. In other words, the long term heating of the Pu and Am contained in the used nuclear fuel causes the in-between tunnel temperature to peak close to 96° between 1,000-1,500 years after repository closing in the reference loading condition.

Figure 4 illustrates the phenomenon described above for the current Yucca Mountain reference case. The curve highlighted in red is the in-between tunnel wall temperature, while the curve in yellow is the tunnel wall temperature. From the curves, it can be seen that somewhere between 1,000 and 1,500 years after disposal, the in-between tunnel temperature, driven by the Am and Pu contained in used fuel, reaches its limit (96°C), while the wall temperature does not come close to attaining its 200°C limit. If Pu and Am are removed, the heat limiting factor becomes the tunnel wall temperature, driven by Cs and Sr.

It is therefore clear that the specific heat generating capacity of the waste must be reduced if the capacity is to be increased by denser packing. However, and this is often an overlooked fact, a volume reduction must also be achieved in similar proportions to achieve a true densification.

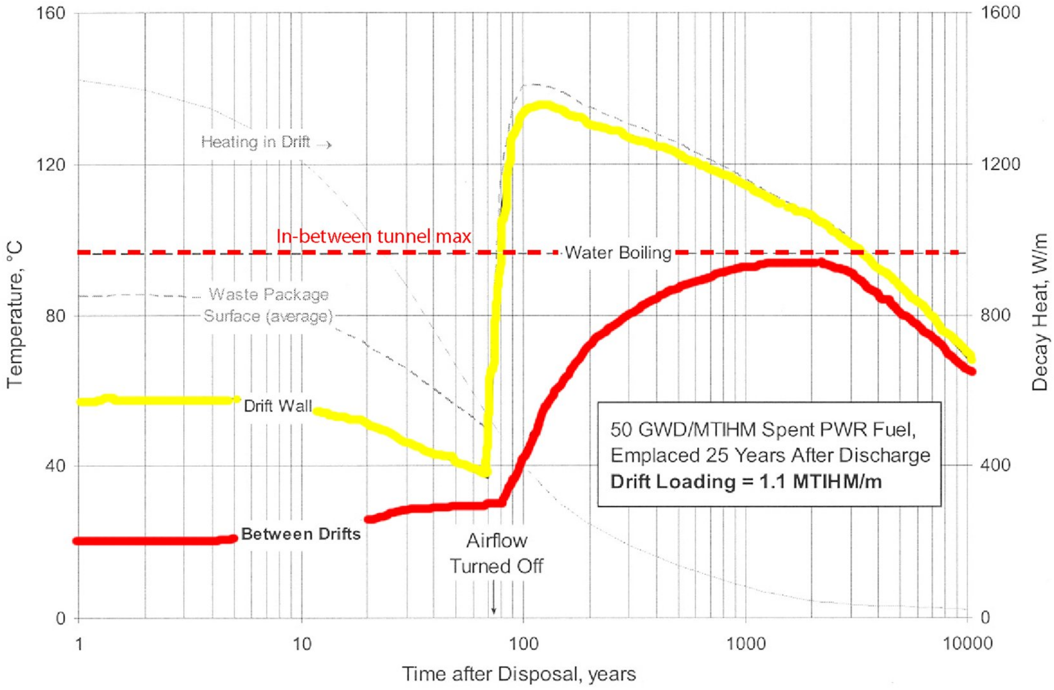


Figure 4. In-between tunnel and tunnel wall temperature in Yucca Mountain [2]

2. Potential improvements in Yucca Mountain capacity

As indicated previously any YM densification strategy will have to successfully reduce both

- Heat generation due to:
    - Am and Pu (1st limiting factor)
    - Cs/Sr (2 nd limiting factor)
- Volume of ultimate waste being disposed of

For the once-through option and the early recycling solution, drift loading factors are calculated, looking at both constraints (volume and heat). There is, therefore, a “densification factor” which is the ratio of the *drift loading factor* of high-level waste from recycling to the *drift loading factor* of used fuel.

The decay heat of a used fuel element decreases rapidly after reactor discharge, being dominated in the first 60 years by the decay products (barium and yttrium) of the fission products cesium and strontium respectively. After this period, the decay heat is produced predominantly by the actinides plutonium and americium up to at least 10000 years (illustrated in figure 3). It is precisely this long-lived thermal output from the plutonium and americium isotopes that constrains the unit loading in the current configuration at Yucca Mountain in the case of directly disposed used fuel. While cooling the used fuel for several decades prior to disposal reduces considerably the thermal contribution from the fission products, it is ineffective against the actinides as the plutonium and americium isotopes emit heat for thousands of years.

Removing the heat-emitting plutonium and americium isotopes would thus significantly reduce the thermal output of the waste bound for final disposal. The separation of plutonium (and uranium) from used fuel is an industrially proven and well-established technology. In contrast, the removal of americium, while technically possible, is yet to be developed at an industrial level. However, given that the majority of the heat-emitting americium isotope contained in used fuel originates from plutonium radioactive decay, early treatment of used fuel to remove plutonium also prevents the long-term accumulation of americium. The unit loading of Yucca Mountain could thus be increased by a factor of *four* (as compared to the present strategy of direct disposal) using currently available technologies to remove the uranium (for volume reduction) and plutonium from the used fuel approximately three years after reactor discharge, and then storing the resulting vitrified treatment residues before final disposal in order to minimize the fission product contribution to the thermal output.

Therefore, two figures need to be calculated:

a) Volume constraints

Volume constraints for recycling solution: Assuming that the HLW canisters are loaded into the current waste packages to be disposed in the tunnels (same for both canisters or used fuel) - 5.2 m long, including a 0.1 m spacing - the quantity of high-level waste that can be disposed per linear meter of Yucca Mountain, or drift loading factor, is in the order of 4 MTHM/meter. This figure takes into account both vitrified waste (for fission products) and compacted waste (hulls and end pieces which represent significant volumes but limited heat contribution) from recycling.
Volume constraints for "once-through" option: The same assumption - 5.2 meters for the length of a waste package- results in a drift loading factor for used fuel of ~1.6 MTHM/meter.

b) Heat constraints

Analyses using AREVA models demonstrate that removing the Uranium and Plutonium from used nuclear fuel and then disposing the remaining actinides and fission products (in vitrified glass) can increase the unit loading of the repository by a factor of ~ 5 if fuel is treated 3 years after discharge and waste products (canisters of vitrified waste) are stored for 25 years before final disposal in Yucca Mountain.[2] An illustration of this model is presented below (figure 5). As illustrated before, ^{241}Am is a major contributor to the total heat that causes the increased in-between tunnel temperature. Therefore, by limiting the amount of ^{241}Am contained in the ultimate waste form, early treatment has a positive impact on the unit loading factor. Increasing the storage period for vitrified wastes to 50 or 100 years could increase by 7 to 8 fold the loading capacity of Yucca Mountain.
Figure 5 shows repository loading curves when U and Pu are removed from waste bound for disposal.

---

[2] Wigeland's publications do not contain results of analyses where only Pu and U are separated.

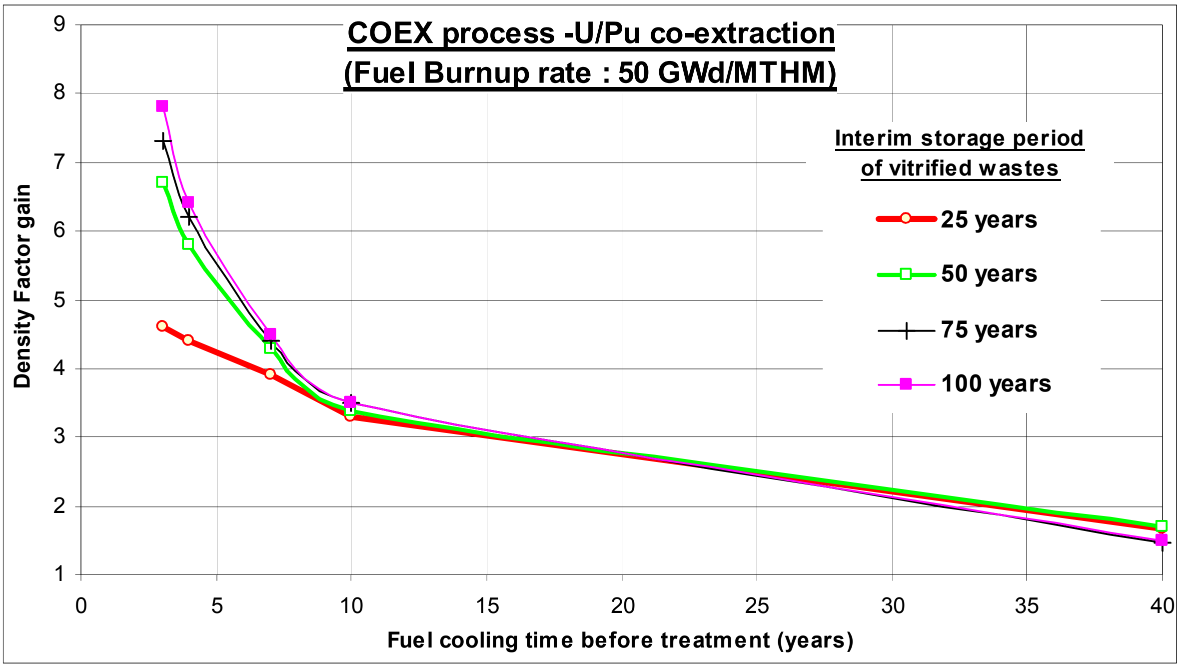


Figure 5. Repository loading curves for early treatment of used nuclear fuel cooled for 3 years

. Heat constraints for "once-through" option: Due to the long-term heat peak, the maximum quantity of fuel equivalent per linear meter of tunnel is in the order of 1.1 MTHM/meter. Compared with volume considerations, this is a lower value.

. Heat constraints for recycling solution: In the case of high-level waste from recycling operations, Pu and Am are present only in small quantities. A 3 year cooling time of coupled with an interim storage duration of 25 years results in a drift loading factor of 4.8 MTHM/m. Compared with volume considerations, this is a higher value.

The results show that the disposal of used fuel ("once-through" option) is constrained by heat, while the disposal of high-level waste (recycling solution) is constrained by volume. The ratio of the HLW volume-constrained to the used fuel heat-constrained drift loading factors is ~4.

Conclusion

Early recycling approach can provide in the short-term a 75% increase in Yucca Mountain through the following strategy:

- Early removal of uranium from used fuel (volume reduction) and plutonium (hence avoiding americium build-up, leading to long-term thermal output reduction)
- Through a plutonium-uranium mixture, plutonium is recycled as MOX in Gen III/III+ reactors
- Interim storage/cooling of vitrified waste before disposal
- Treatment of low burn-up legacy fuel by dilution
- Used MOX stored and saved for recycling in Gen IV fast reactors

This approach provides a "bridge" to the ultimate goal of advanced recycling in fast reactors for optimal use of Yucca Mountain.

References

[1] Carter, C.D; *Impact of Partitioning and Transmutation on Repository Design*; Proceeding of Atalante 2004, June 21-24, Nîmes, France
[2] Wigeland, R.A.; Bauer, T.H.; Fanning, T.H.; Morris, E.E.; *Spent Fuel Separations and Transmutation Criteria for Benefit to a Geological Repository*; Proceedings of Waste Management 2004, Feb. 29 – Mar. 4, 2004, Tucson, AZ
[3] Wigeland, R.A.; *Heat Load Benefits – Report to Richter*, AFCI Semi-Annual Review Meeting, Sandia-Califoria Feb. 26 2004, Livermore, CA
[4] Wigeland, R.A..; Bauer, T.H.; Fanning, T.H.; Morris, E.E.; *Repository Impact of LWR MOX and Fast Reactor Recycling Options*; Proceedings of Global 2003, November 16-20, New Orleans, LA
[5] Wigeland, R.A.; *Separations Criteria for Repository Benefits*; Presentation to COGEMA Visitors to Argonne National Laboratory; July 15, 2003, Argonne National Laboratory, Argonne, IL