KNS Workshop on the Safe Management of Spent Fuel

Deep Isolation's storage and disposal solution for nuclear waste

Richard Muller CTO (m) +1 510 735 6877 rich@deepisolation.com
https://deepisolation.com

DEEP ISOLATION

Waste per year from a 1 GW PWR Nuclear Power Plant

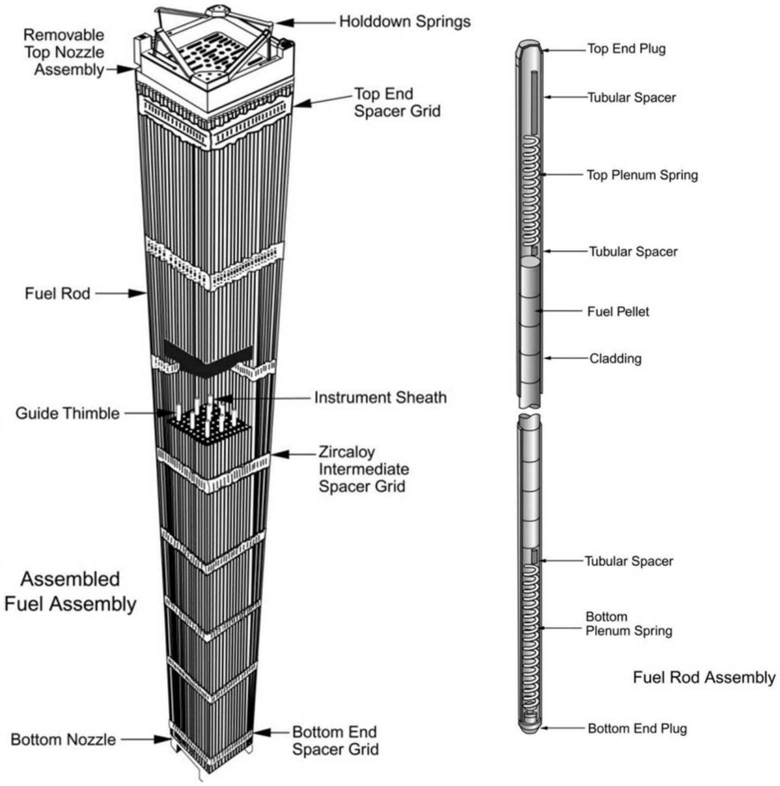
35 Metric tons/year

→ 3.5 m^3/year

→ 70 fuel assemblies/year

→ 350 meters/year (70 assemblies)

→ 50 GW-years of waste end-to-end needs only 17.5 km (6 to 12 boreholes)

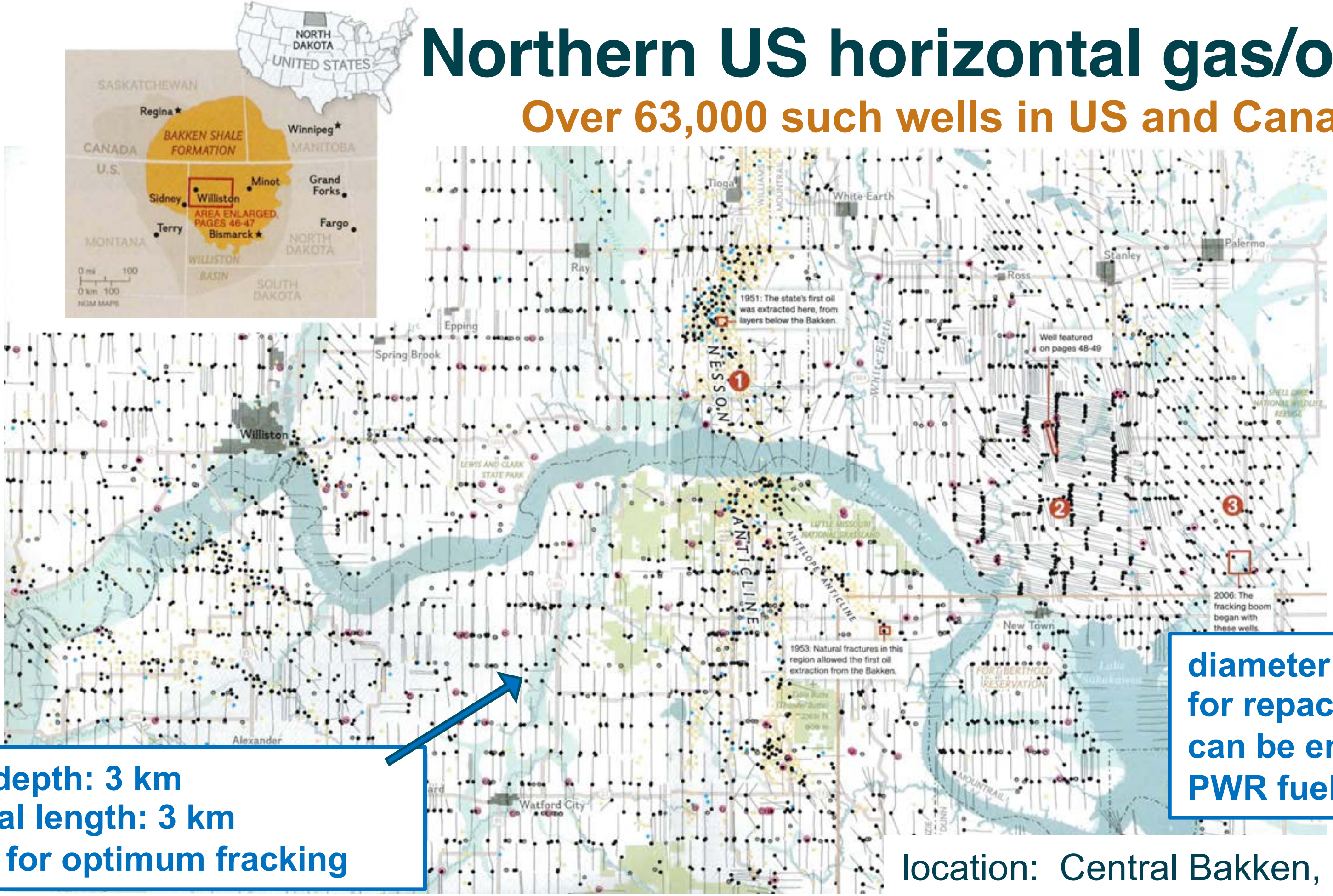


30 cm diameter

1 cm diameter

Northern US horizontal gas/oil wells

Over 63,000 such wells in US and Canada



typical: depth: 3 km
horizontal length: 3 km
oriented for optimum fracking

diameter sufficient for repackaged;
can be enlarged for PWR fuel assemblies

location: Central Bakken, North Dakota

National Geographic March 2013

DEEPISOLATION

Directional Drilling

Optimum depth 1-2 km

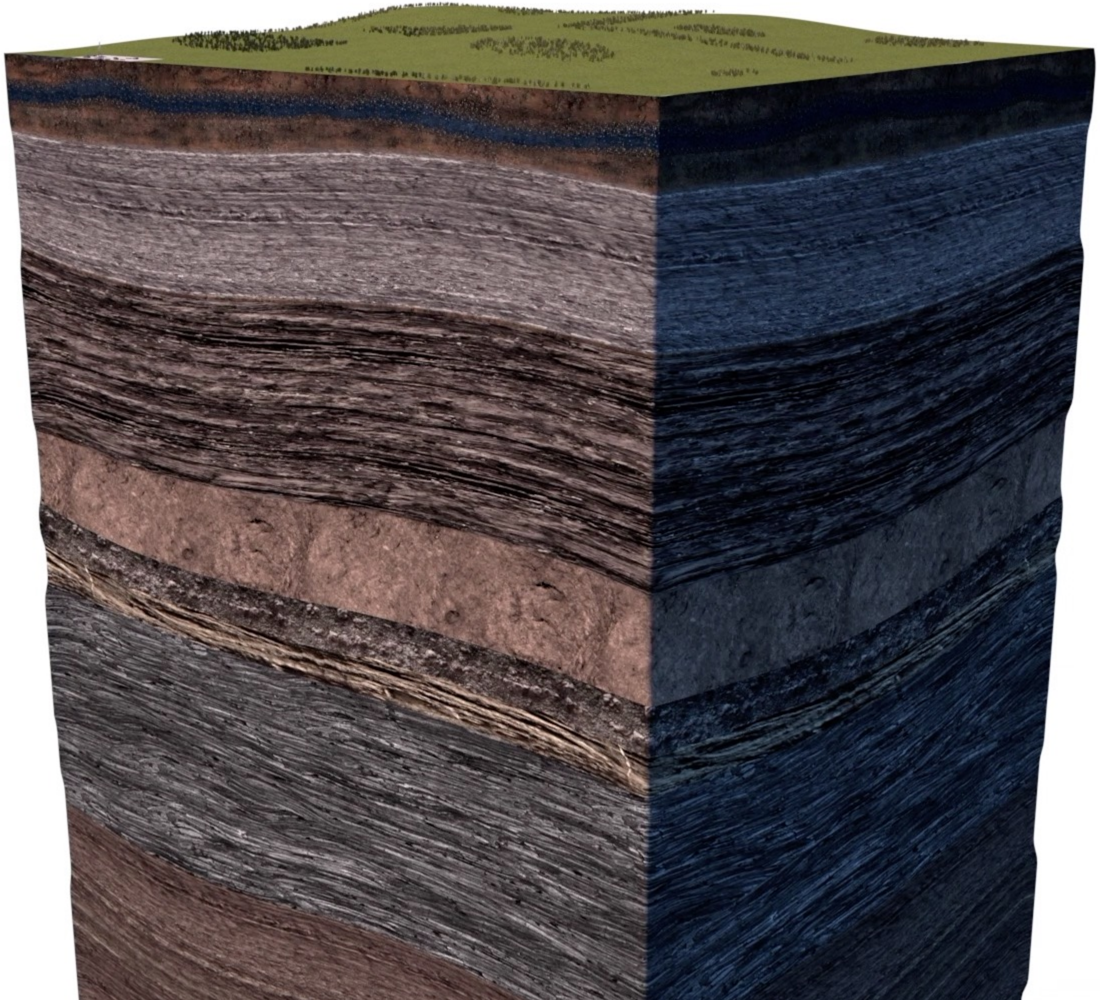
Directional drilling is *not* fracking.

***No* earthquakes; *no* water pollution**

Directional drilling pre-dated fracking.

DEEP ISOLATION

4-minute video:www.youtube.com/watch?v=IQx5zFUUIn0&t=11s

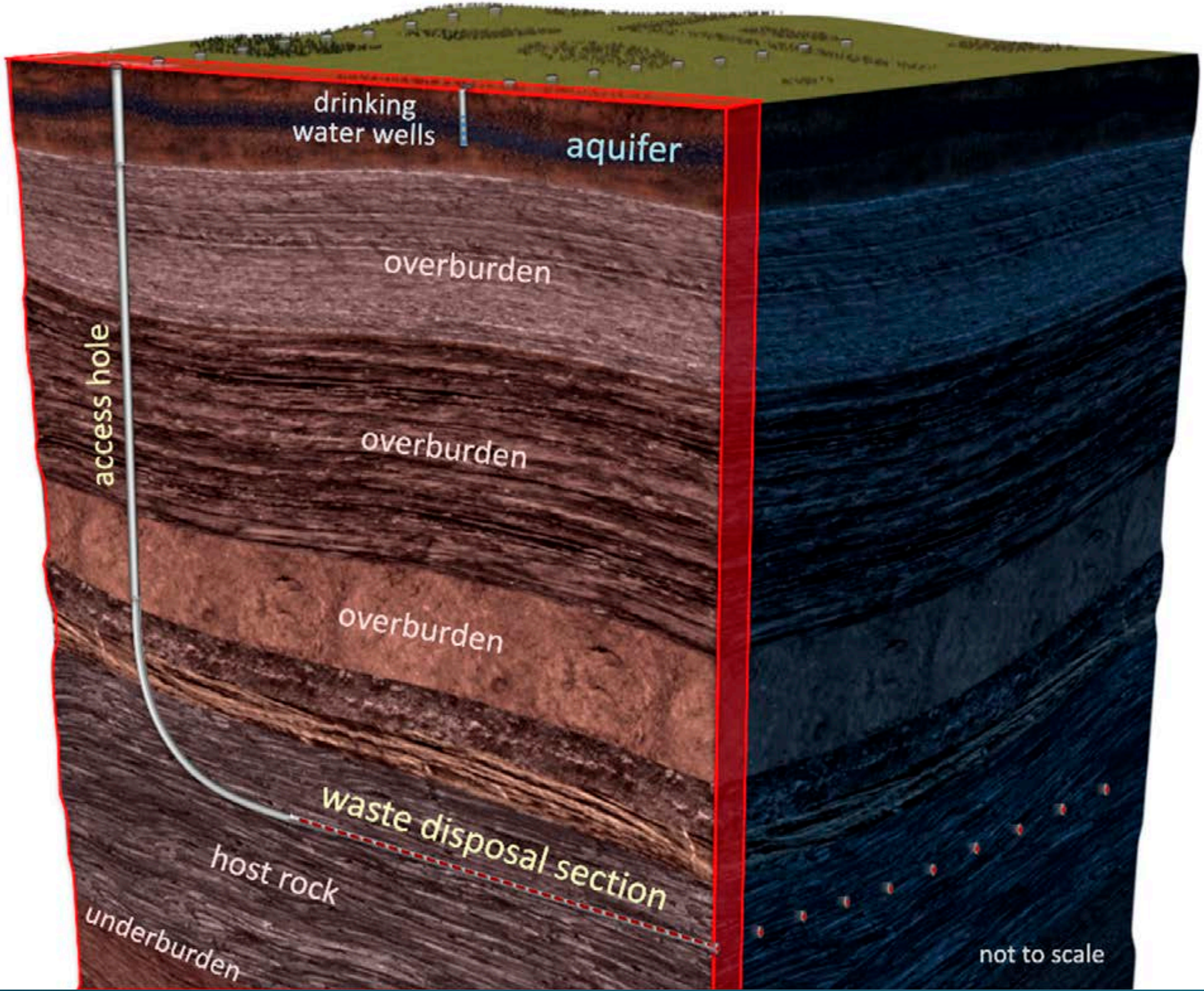


Borehole Storage vs Borehole Disposal

- **0 yr Cost:** Initial cost of borehole > initial cost of dry cask
- **12 yr Cost:** Actual cost spent (guns, guards, etc) → competitive after 12 years
- **Recoverability** can be monitored at low cost
- **Storage→ disposal**: seal the access borehole (when regulations allow). Risk that site will not pass disposal requirement is minimal
- **Guards and Guns:** Surface storage must pay the additional cost of disposal, when the time comes. ("Kick down the road – our grandchildren can take care of it")

DEEP ISOLATION

Safety


drinking
water wells
aquifer
overburden
overburden
overburden
access hole
waste disposal section
host rock
underburden
not to scale

Peer-reviewed publications

energies

Article

Disposal of High-Level Nuclear Waste in Deep Horizontal Drillholes

Richard A. Muller [1,*], Stefan Finsterle [2], John Grimsich [1], Rod Baltzer [1], Elizabeth A. Muller [1], James W. Rector [3], Joe Payer [4] and John Apps [5]

energies MDPI

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energies

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Stefan Finsterle [1,*], Cal Cooper [2], Richard A. Muller [2], John Grimsich [2] and John Apps [3]

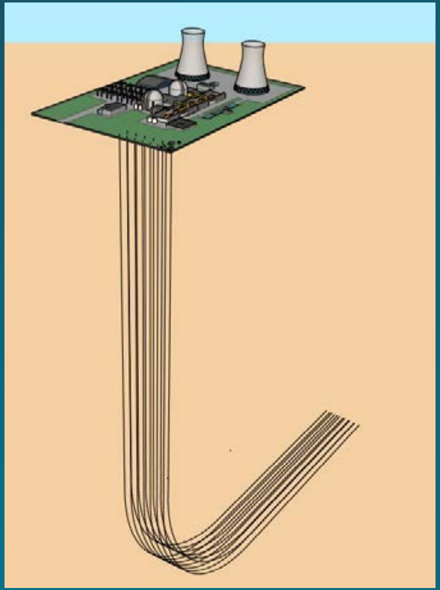
energies

Article

Post-Closure Safety Analysis of Nuclear Waste Disposal in Deep Vertical Boreholes

Stefan Finsterle [1,*], Richard A. Muller [2], John Grimsich [2], Ethan A. Bates [2] and John Midgley [2]

Siting requirements



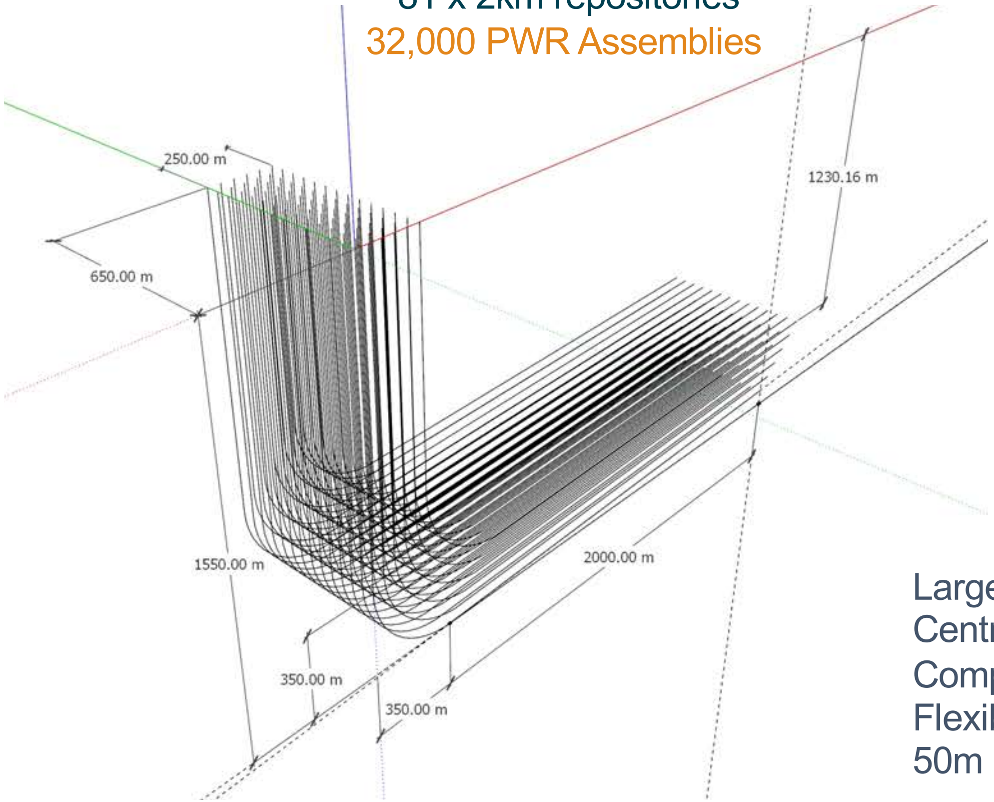
- Stakeholder informed consent
- Drillable, accessible geologic formation, likely depth 1-2 km
- Low permeability formation at or above (cap layer) deposition depth
- Brine saturated rock
- Brine stratified
- Reducing environment
- No deep fresh-water human-exploitable aquifer close to or below formation
- Any of the above can be ignored if the formation passes a “strong isolation” qualifying test

By going deep, the availability of acceptable sites is vastly increased.

Large Centralized Array of boreholes alternative to modular

81 x 2km repositories

32,000 PWR Assemblies



Large Capacity
Centralized infrastructure
Compact Surface Footprint
Flexible – Incremental Approach
50m Offset Repositories

Informed Consent: US Survey leads to optimism

Question	National	AL	AR	AZ	CA	ID	IL	KS	LA	MI	MN	MS	NE	NM	NV	NY	OH	OR	PA	TN	TX	UT	WA	WI
Finding a permanent solution for the nuclear waste currently stored above ground in our state should be a priority.	**89%**	85%	96%	93%	90%	89%	95%	95%	84%	91%	90%	92%	93%	92%	88%	88%	94%	90%	93%	94%	90%	88%	94%	91%
TRANSPORTATION																								
It is a bad idea to transport nuclear waste across the country.	**82%**	81%	77%	85%	86%	74%	78%	81%	85%	77%	79%	81%	82%	56/37	87%	79%	79%	79%	78%	80%	85%	80%	74%	81%
Nuclear waste should be put into storage outside of our state, even if that means transporting it long distances.	**33%**	38%	44%	27%	28%	38%	38%	37%	47%	44%	45%	40%	34%	29%	36%	34%	38%	32%	38%	34%	32%	32%	31%	38%
Our state SHOULD NOT move the waste long distances to another temporary storage site, and then move it again when an out-of-state underground solution becomes available.	**78%**	73%	70%	82%	78%	71%	76%	80%	78%	76%	70%	74%	88%	76%	84%	72%	83%	78%	73%	81%	83%	83%	81%	79%
OUR SOLUTION																								
Nuclear waste should be put into permanent disposal below ground.	**79%**	80%	85%	77%	75%	83%	83%	85%	81%	80%	82%	74%	84%	81%	78%	79%	83%	86%	82%	82%	79%	92%	87%	87%
Our state should consider the new option to safely dispose of the waste deep underground without having to move it long distances.	**82%**	82%	79%	81%	81%	78%	85%	82%	76%	84%	74%	76%	82%	81%	93%	84%	85%	84%	83%	82%	83%	87%	87%	80%
DO NOTHING																								
Nuclear waste should be kept where it is now, above ground in temporary containers.	**Agree/Disagree 33/64**	26/69	31/63	30/69	36/62	24/73	32/67	32/65	22/75	29/69	35/62	32/63	27/71	24/73	30/67	30/67	28/70	25/72	31/68	28/67	29/68	27/71	23/75	34/63
Our state SHOULD leave the waste above ground at each power plant and wait for a permanent solution to remove it.	**53%**	48%	44%	52%	60%	47%	50%	63%	49%	49%	47%	53%	50%	34%	53%	47%	51%	44%	50%	49%	53%	51%	43%	56%
Our state SHOULD NOT leave the waste above ground at each power plan and wait for a permanent solution to remove it.	**44%**	47%	52%	46%	39%	50%	49%	34%	47%	49%	47%	43%	50%	63%	45%	47%	47%	52%	48%	49%	46%	48%	54%	43%

82% say "bury it where it is"

Stakeholder Engagement?

- Building trust with genuine partnership
  - Incorporates stakeholder input into design elements
- Transparency and dialogue reduce risk of wrong steps
  - Improves program success (lessens the chances of obstruction, delay and outright program failure)
- Creates a better outcome
  - Engaging with, appreciating values of, and receiving input from the public, partners, and stakeholders allows for a smoother implementation and project future
- Created through a purposeful plan
  - Requires **best-in-class** design and implementation

- Informed Concent (Informed Enthusiasm)

Watch 7 minute video:
www.youtube.com/watch?v=3GZ4TC8ttbE&t=10s

DEEP ISOLATION

Technology demonstration on 16 January 2019

We emplaced and retrieved prototype disposal canister sized for cesium/strontium capsules. Borehole total length was 823 metres – 670m vertical and 153m horizontal. Local community participated, as well as stakeholders from government, NGOs, environmentalists, etc.

Watch 7 minute video: www.youtube.com/watch?v=3GZ4TC8ttbE&t=10s

Proven

Technical ability, program management efficacy (on time, on budget), partnering ability, and model for community and stakeholder engagement

Strong Isolation –

This method is established and accepted

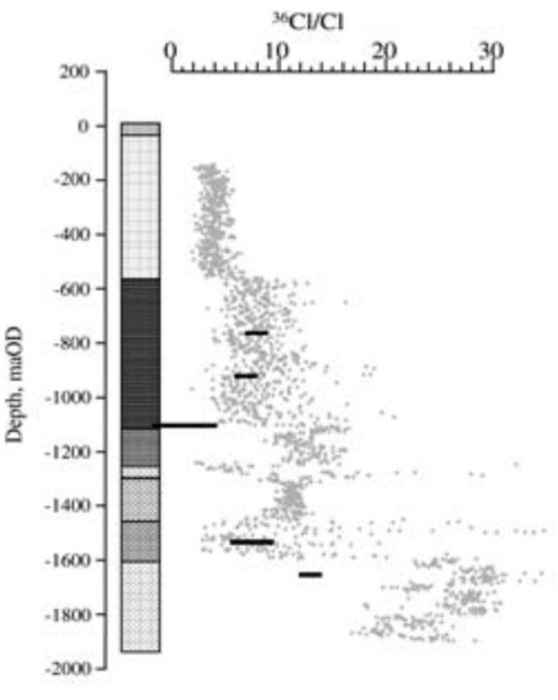
used primarily for carbon dioxide capture and storage

Determine stagnation in 4 different ways:

helium-4	(stable, produced from U, Th))
neon-21	(stable; produced by neutrons)
chlorine-36	(301,000 year half-life)
iodine-129	(15.7 million year half-life)

Readily accepted by public (environmental groups) and by experts (e.g. NRC)

Strong Isolation



Age date deep brines

"Strong Isolation" refers to ages of 100,000 to 1,000,000 years

Expected when saline stratification

More compelling than geologic modeling

Measurements of natural Cl-36, I-129, He-4, others vs depth

Analogous to radiocarbon dating

Accepted by stakeholder

DEEP ISOLATION
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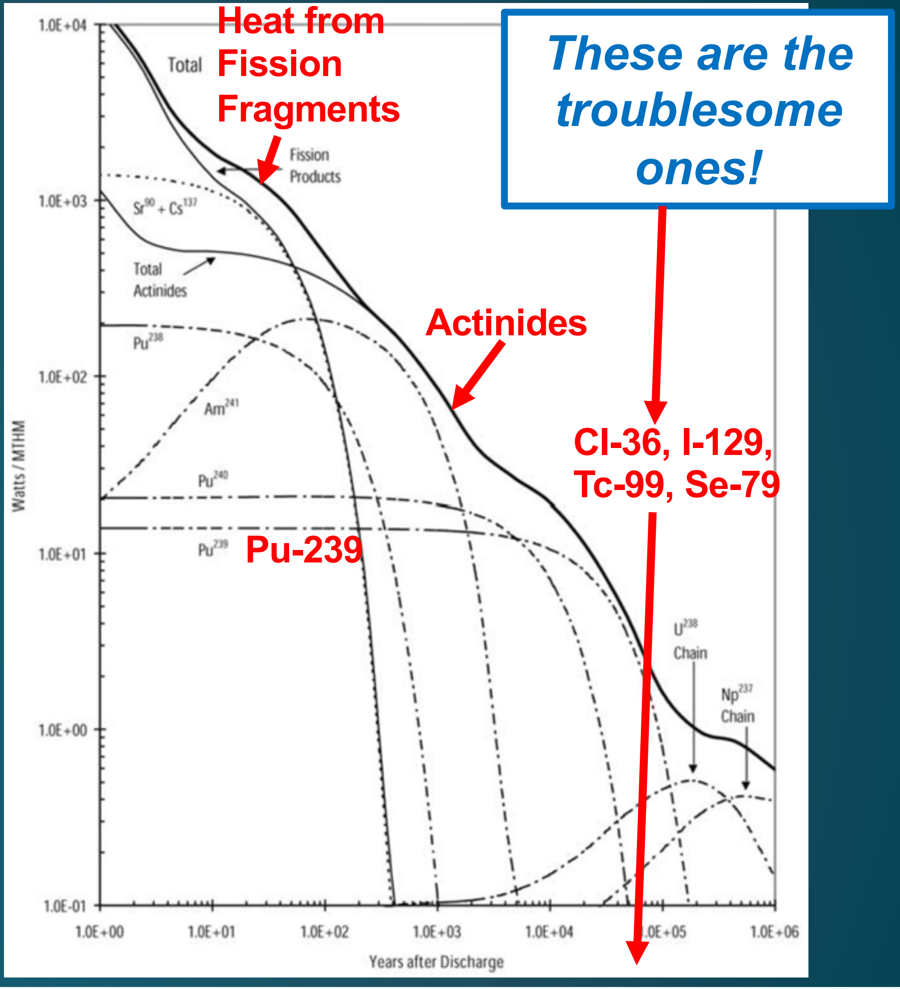
At 1.5 km depth, diffusion and advection of long-lived radioisotopes are the greatest safety concern

Table 1. Initial inventory, specific activity, and dose coefficient of selected radionuclides.

Isotope	Half-Life (Years)	Inventory [1] (g/MTIHM)	Inventory [2] (g/Canister)	Activity [3] (Bq/Canister)	Specific Activity (Bq kg^{-1})	Dose Coefficient [4] (Sv Bq^{-1})
^{129}I	1.57×10^{7}	313.	136.	8.88×10^{8}	6.53×10^{9}	1.10×10^{-7}
^{36}Cl	3.01×10^{5}	0.501	0.218	2.66×10^{8}	1.22×10^{12}	9.30×10^{-10}
^{79}Se	2.95×10^{5}	10.5	4.57	2.59×10^{9}	5.68×10^{11}	2.90×10^{-9}
^{99}Tc	2.11×10^{5}	1280.	556.	3.52×10^{11}	6.33×10^{11}	6.40×10^{-10}

[1] Source: [12] (Table C-1). [2] For 0.435 metric tons of initial heavy metals (MTIHM) per pressurized water reactor (PWR) assembly [27], (Appendix E-1). [3] Activity A (Bq) is calculated as $A = \lambda N = \frac{m}{MW} \cdot \frac{\ln(2)}{t_{1/2}} \cdot N_A$, where $\lambda = \ln(2)/t_{1/2}$ (s^{-1}) is the decay constant, N is the number of decaying particles, m (g) is the inventory mass, MW (g mol^{-1}) is the molecular weight, $t_{1/2}$ (s) is the half-life, and $N_A = 6.022 \times 10^{23}$ (mol^{-1}) is the Avogadro number; 1 Ci = 3.7×10^{10} Bq; [4] Source: [28, Table C5; Example Reference Biosphere 1A]; unit conversion factor: 1 rem = 0.01 Sv.



DEEP ISOLATION

Safety estimation by TOUGH2 Numerical Modelling

horizontal storage/ disposal

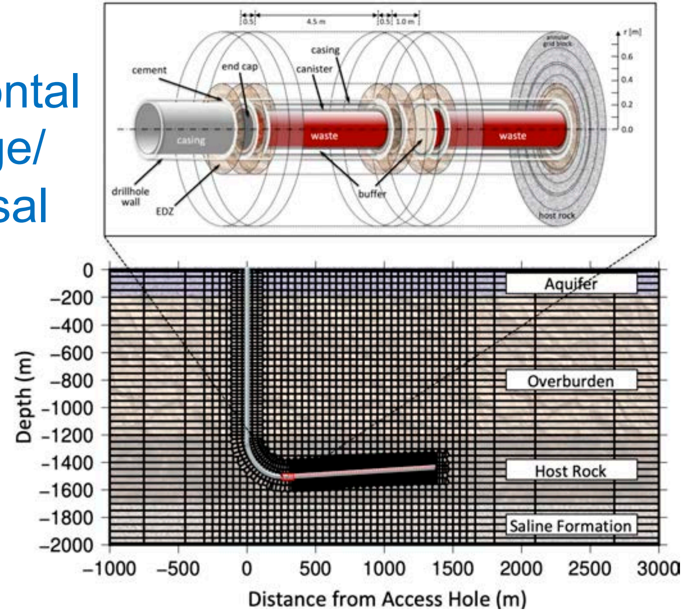


Figure 3. Computational grid: (top) excerpt of the radial–axial grid of the near-field model, which follows the trajectory of the directionally drilled borehole and is embedded in the three-dimensional Voronoi grid of the geosphere model (bottom). A total of 153 waste canisters are individually represented in the sub-horizontal disposal section, which is at a depth of 1.5 km. A detailed description of the grid can be found in [46].

vertical storage/disposal

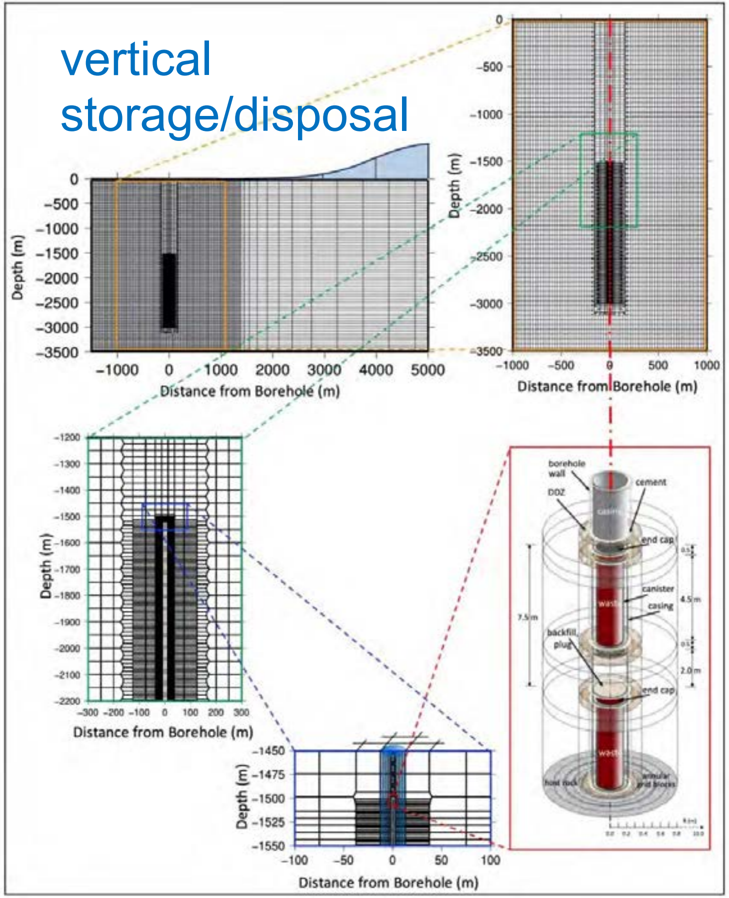
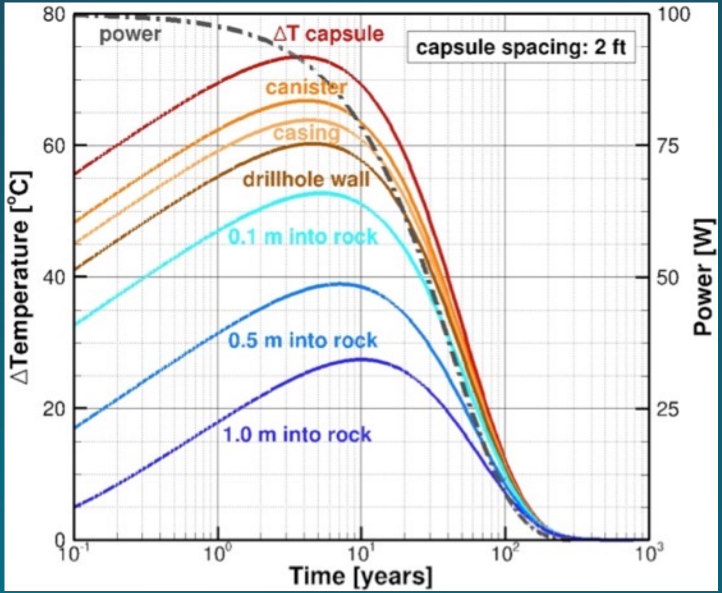


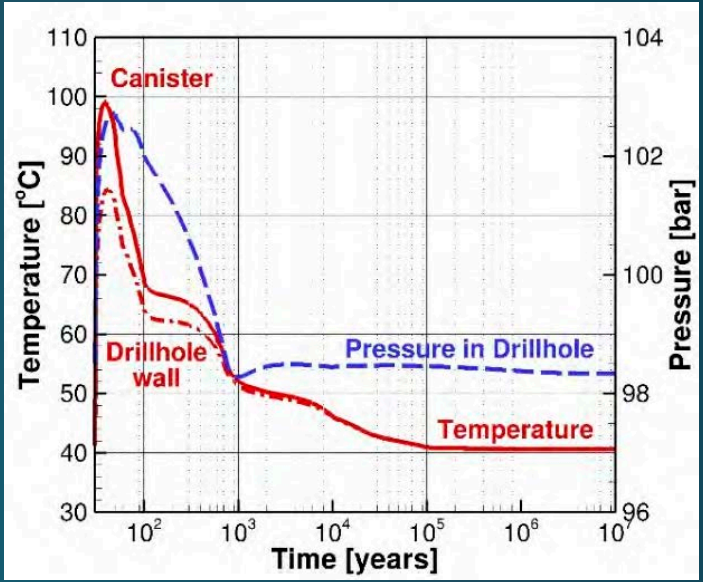
Figure 2. Cross sections through unstructured computational grid, showing nested mesh refinement; a two-dimensional, radial-axial subgrid representing the borehole, engineered barrier system, and near field is integrated into the three-dimensional Cartesian mesh of the far field.

DEEP ISOLATION

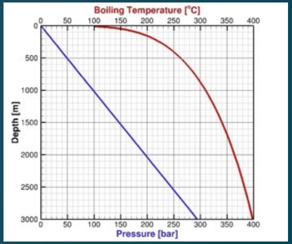
Separated Cesium-137 & Strontium-90



Spent Nuclear Fuel



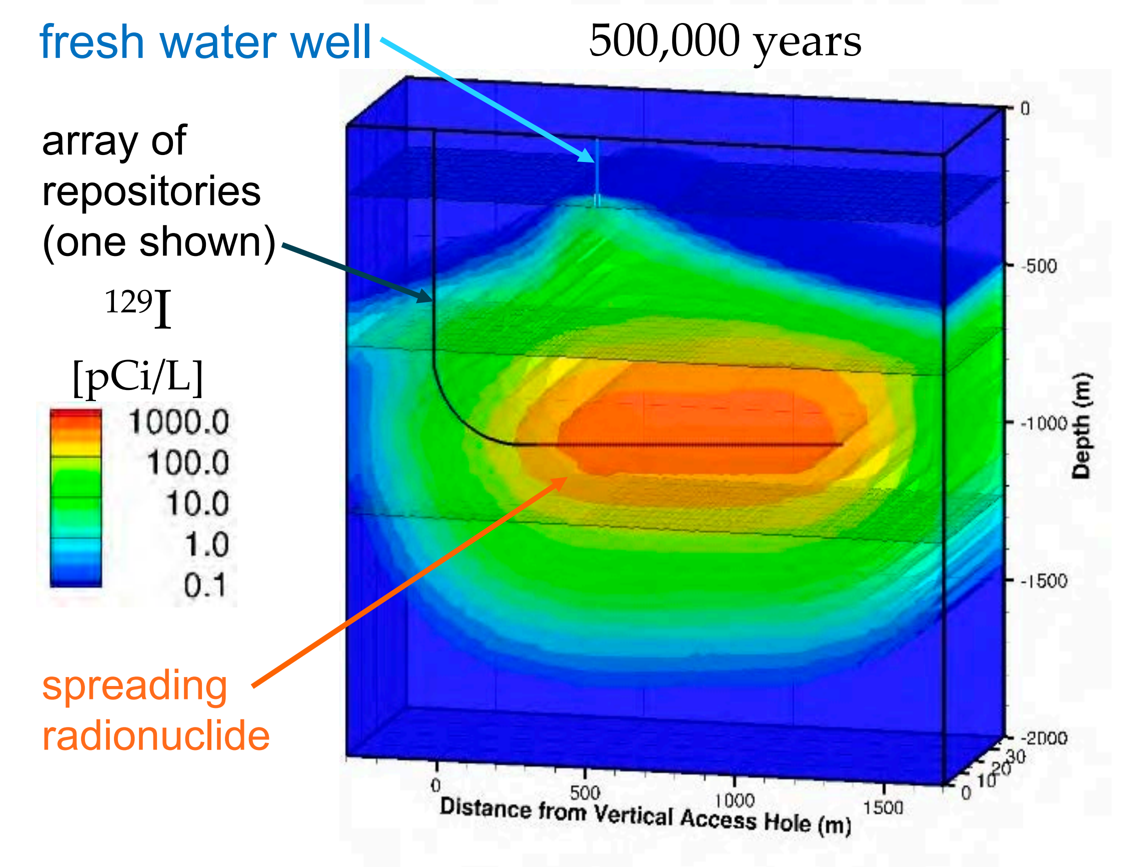
Temperature vs time: water never boils



Boiling point at 1.5 km
is > 300 C

sedimentary rock

Typical simulation result

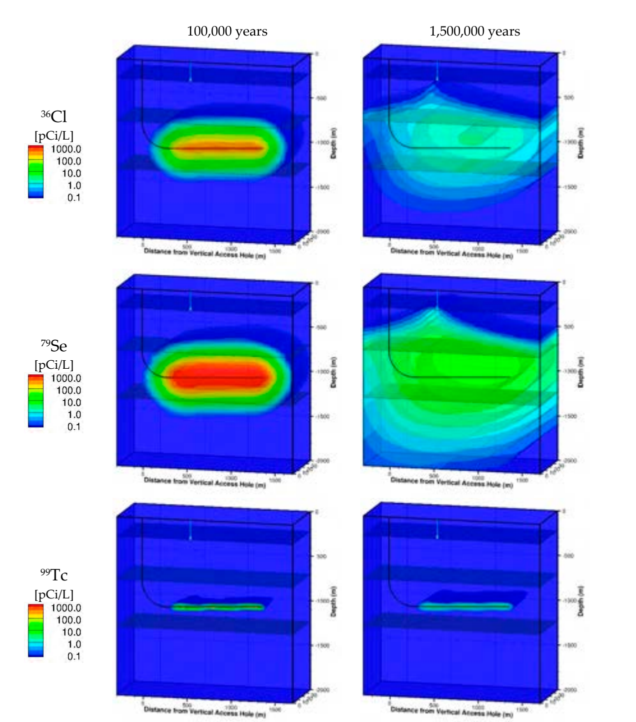


Radionuclide transport, sedimentary scenario

Cl-36

Se-79

Tc-99



I-129

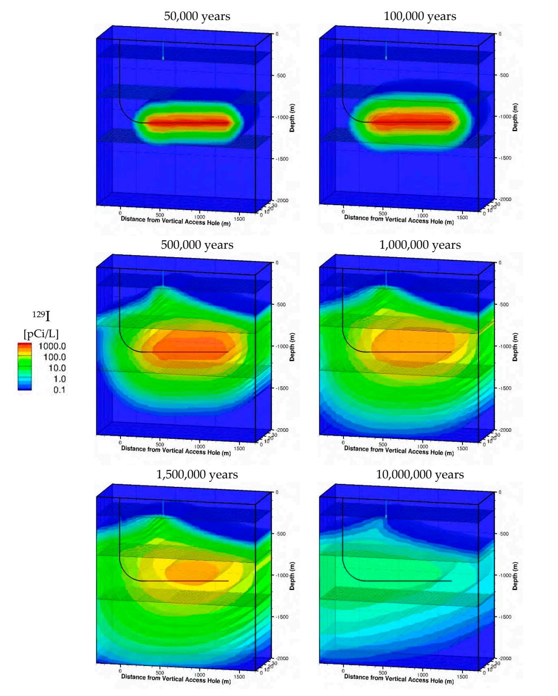


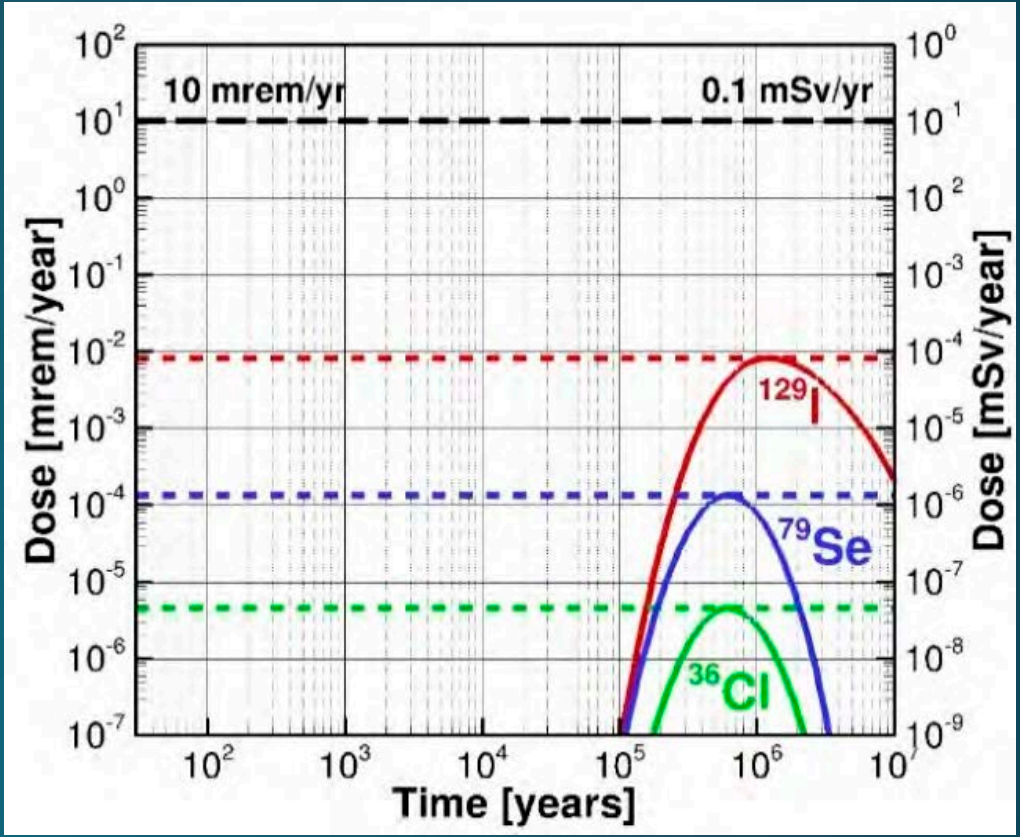
Figure 6. Simulated ^{129}I activity distribution throughout the repository system.

DEEP ISOLATION

Calculated dose to human using surface well above the repository

Nominal result for Sedimentary rock

1 cancer dose is 250,000 mrem



DEEP ISOLATION
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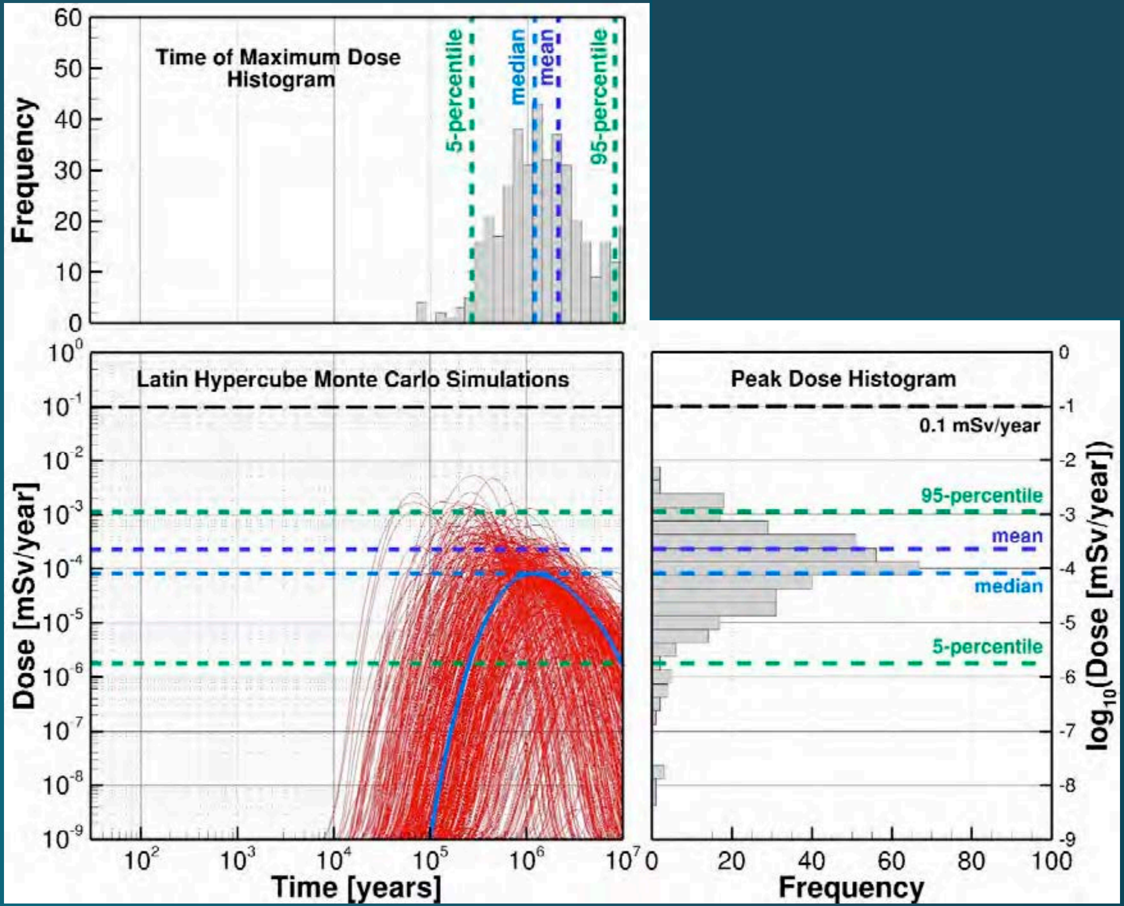
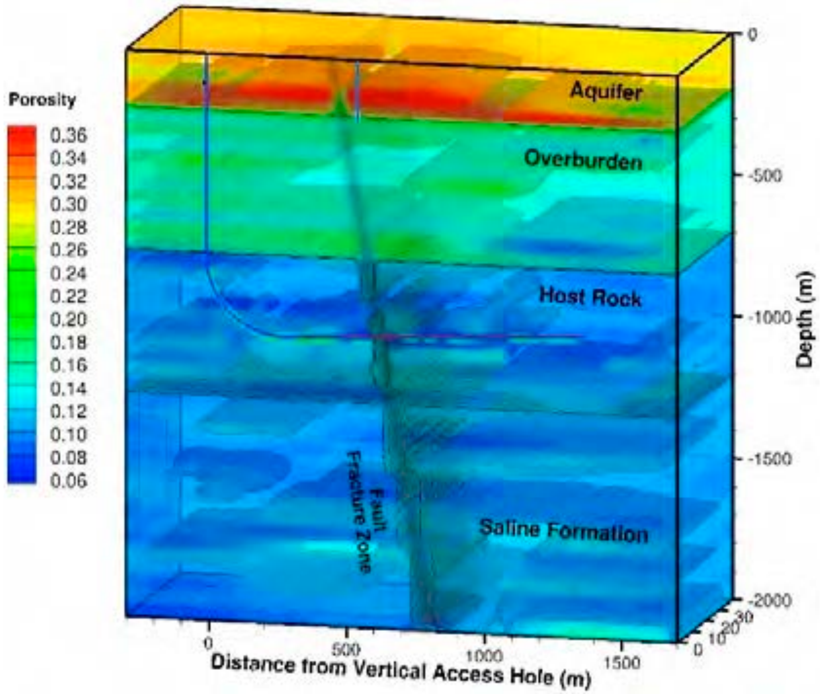
Probabilistic Uncertainty Analysis

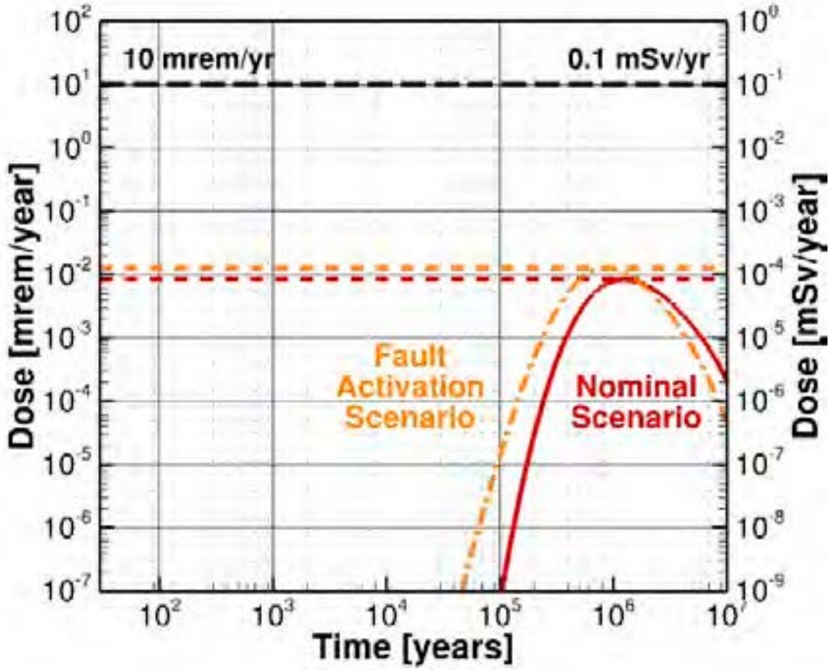


400 Monte-Carlo simulations of rock porosity structure

Fault vs No-Fault



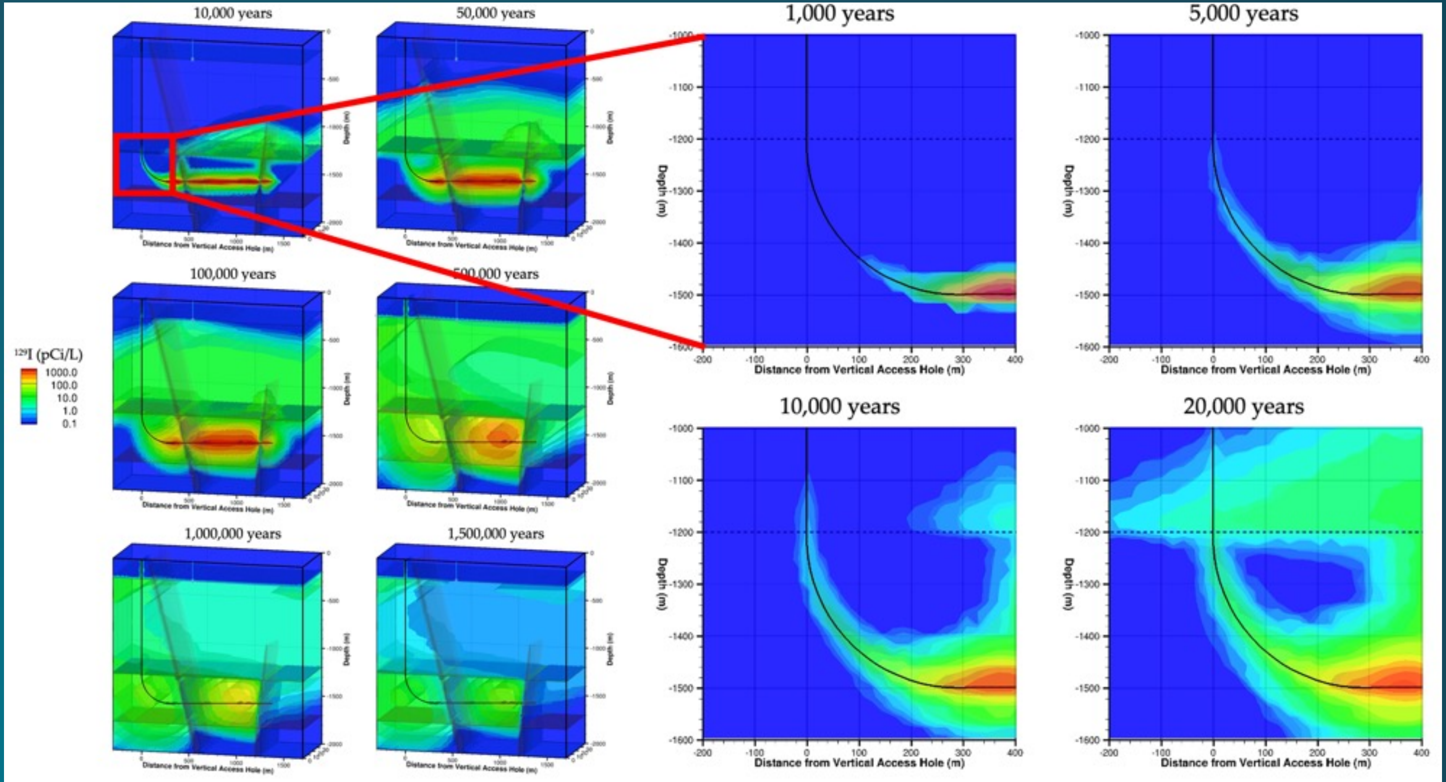
(a)



(b)

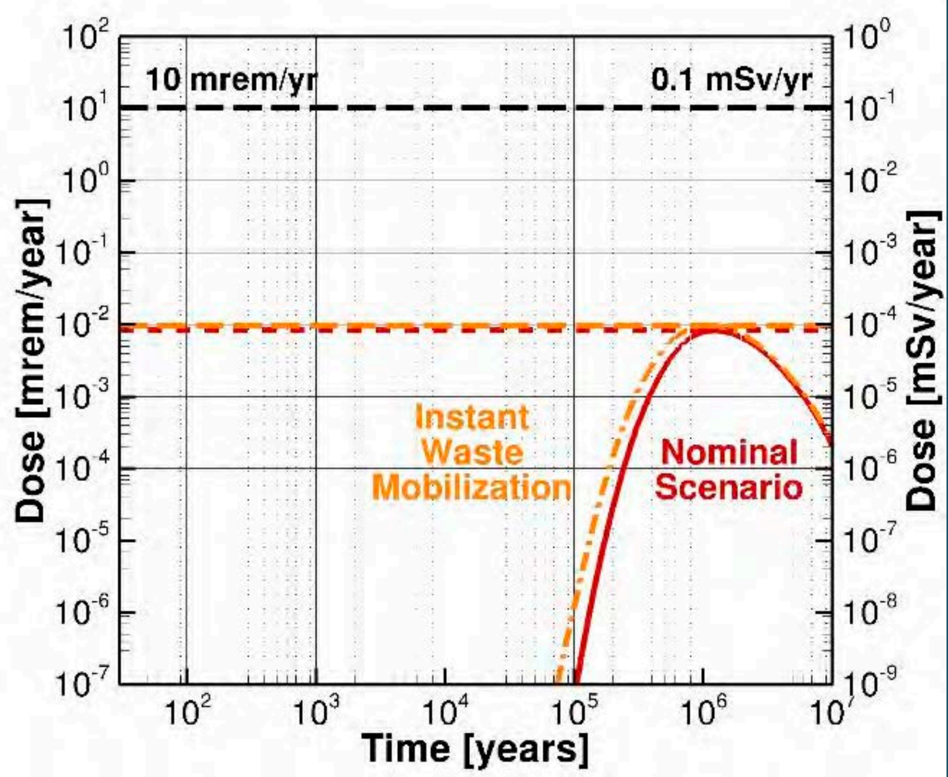
DEEP ISOLATION

One fault pushes fluid up poorly-sealed access hole



DEEP ISOLATION

Instant waste mobilization



(no or failed engineered barrier)

DEEP ISOLATION

Peer-reviewed publications

energies

Article

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Richard A. Muller [1,*], Stefan Finsterle [2], John Grimsich [1], Rod Baltzer [1], Elizabeth A. Muller [1], James W. Rector [3], Joe Payer [4] and John Apps [5]

energies MDPI

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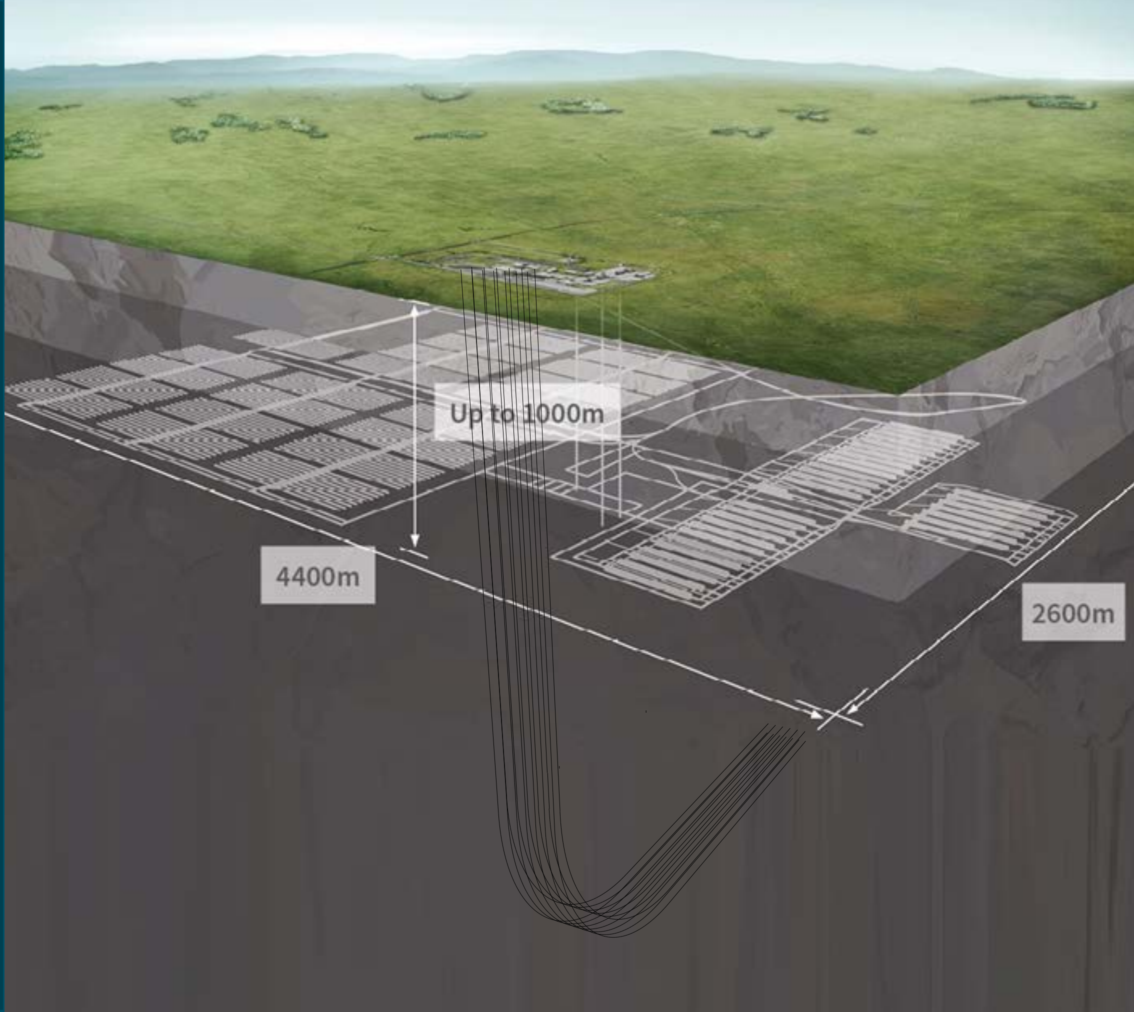
Siting:

stacked boreholes for reduced footprint

"mined repository +"



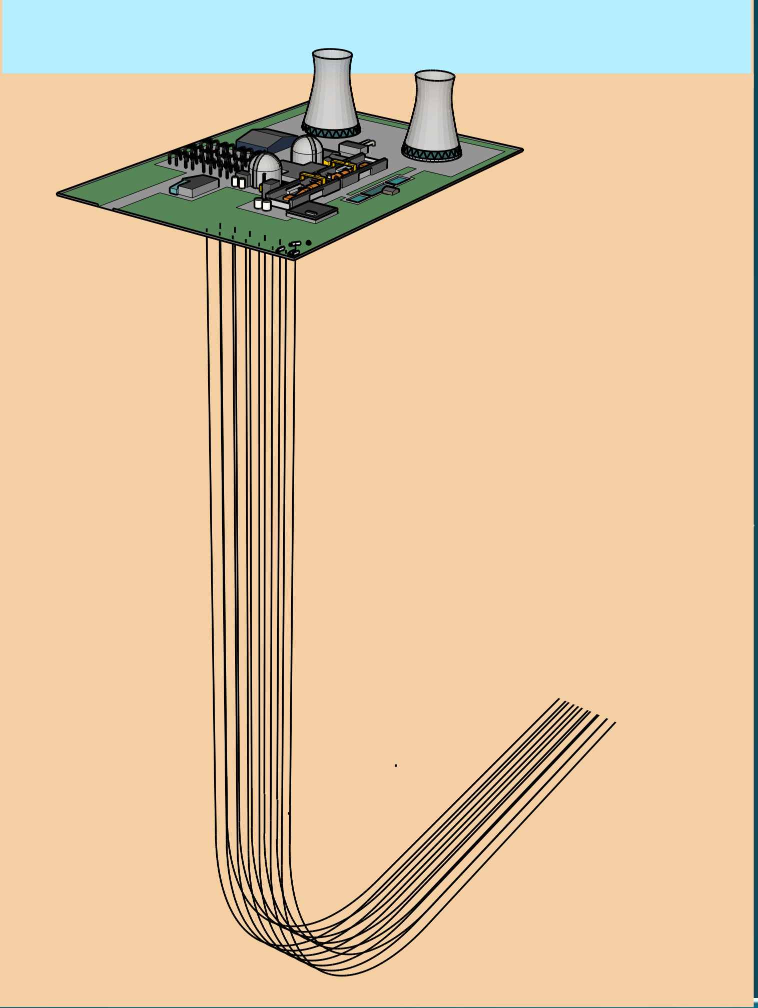
DEEP ISOLATION

Modular disposal –
(vs centralized disposal)

If "strong isolation" criterion satisfied

Avoids transportation challenges

Preferred by the public!



DEEP ISOLATION

Waste forms suitable for horizontal storage/disposal

Small Forms

Sealed Sources (7 x 53cm)

Spent Fuel (30cm x 450cm)

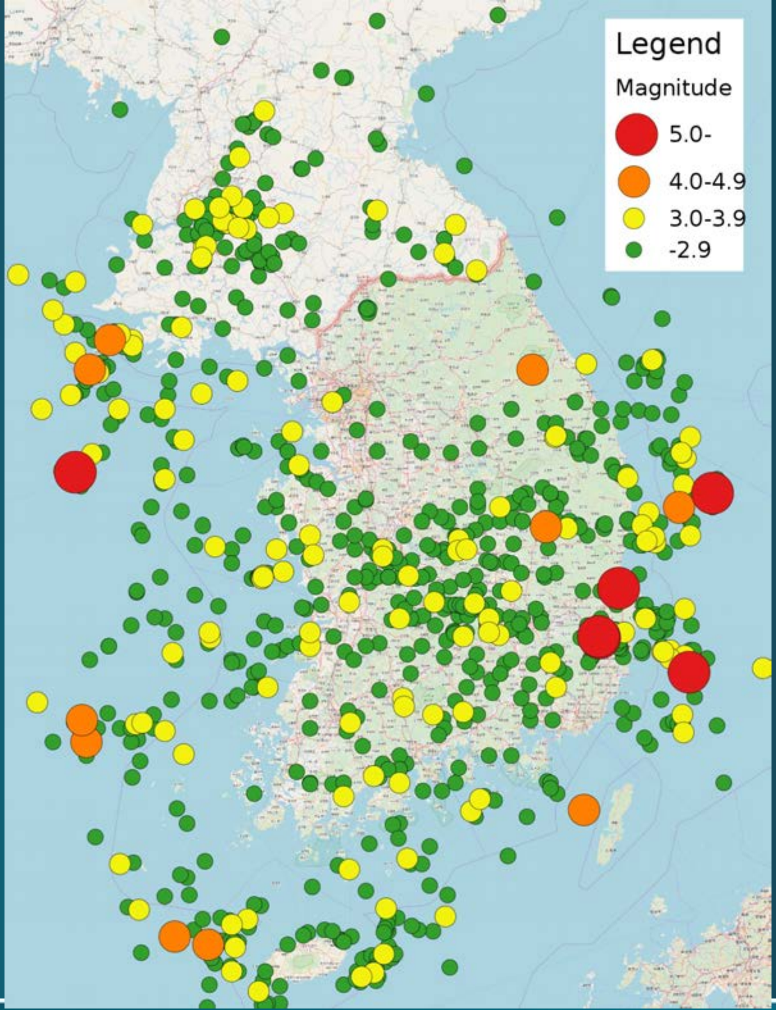
US ultra-large vitrified waste canisters (61cm x 450cm)

Deep Isolation /NAC PWR Canister

(3D Printer model)

DEEP ISOLATION

Earthquakes in Korea



DEEP ISOLATION

Pohang earthquake

15 November 2016

magnitude 5.4

peak acceleration 0.58g

depth 9 km

82 injured

1,124 people displaced

52 homes damaged

EGS water injection (Enhanced Geothermal System)

For boehole storage/disposal, no pressurized water is pumped into the ground

Gyeongju earthquake

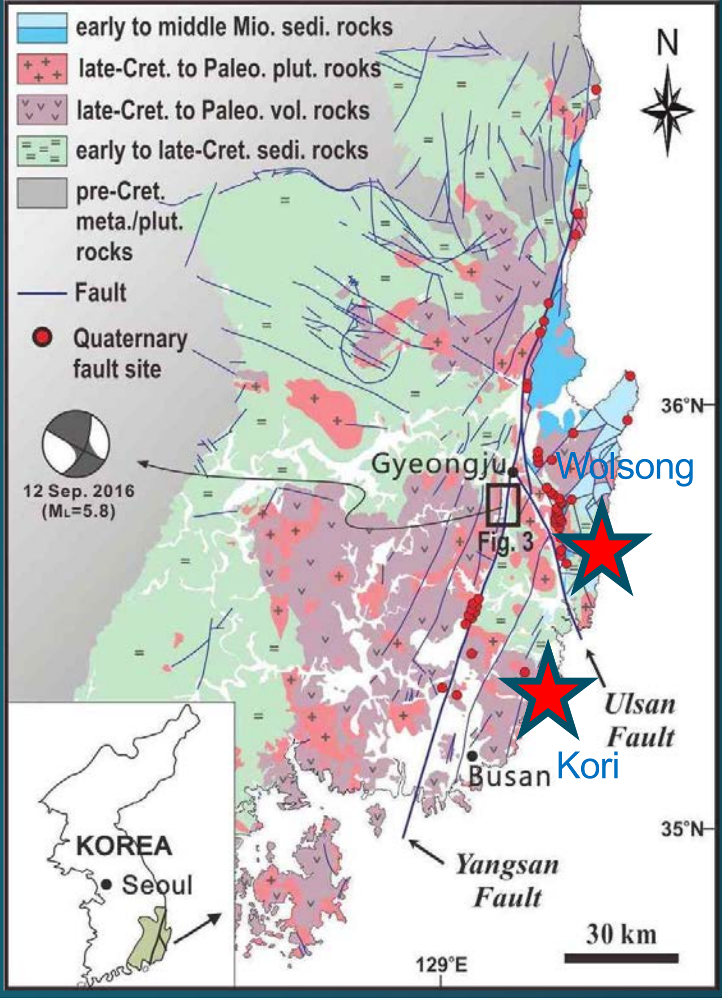
September 12, 2016

Magnitude 5.8
(strongest known in Korea)

13 km deep

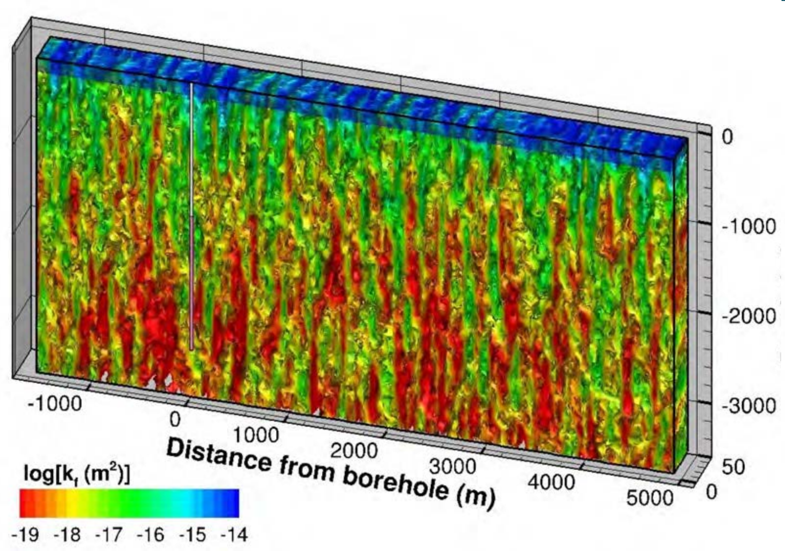
8 injured

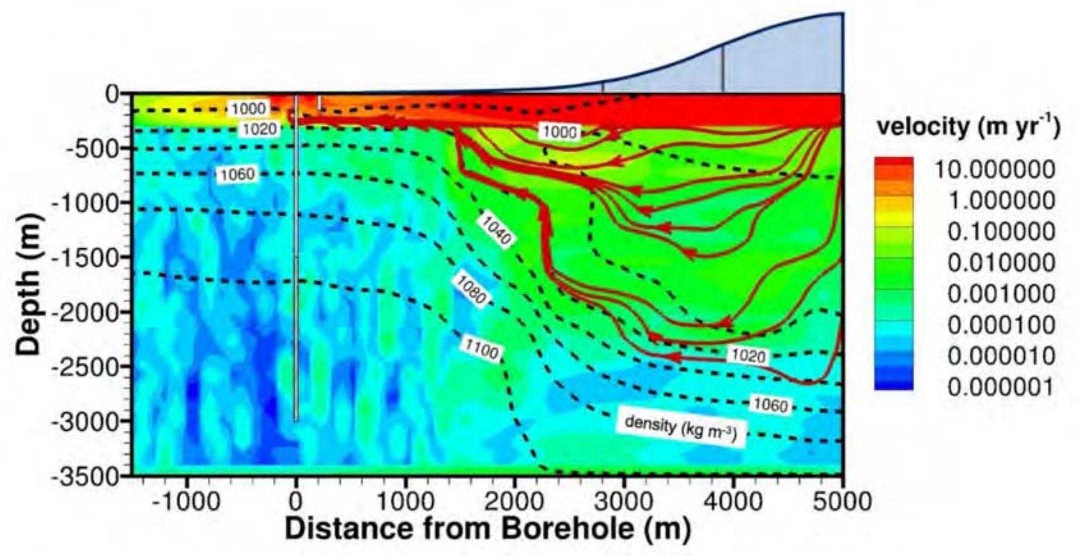
In a strong earthquake, hazardous waste is safer deep underground



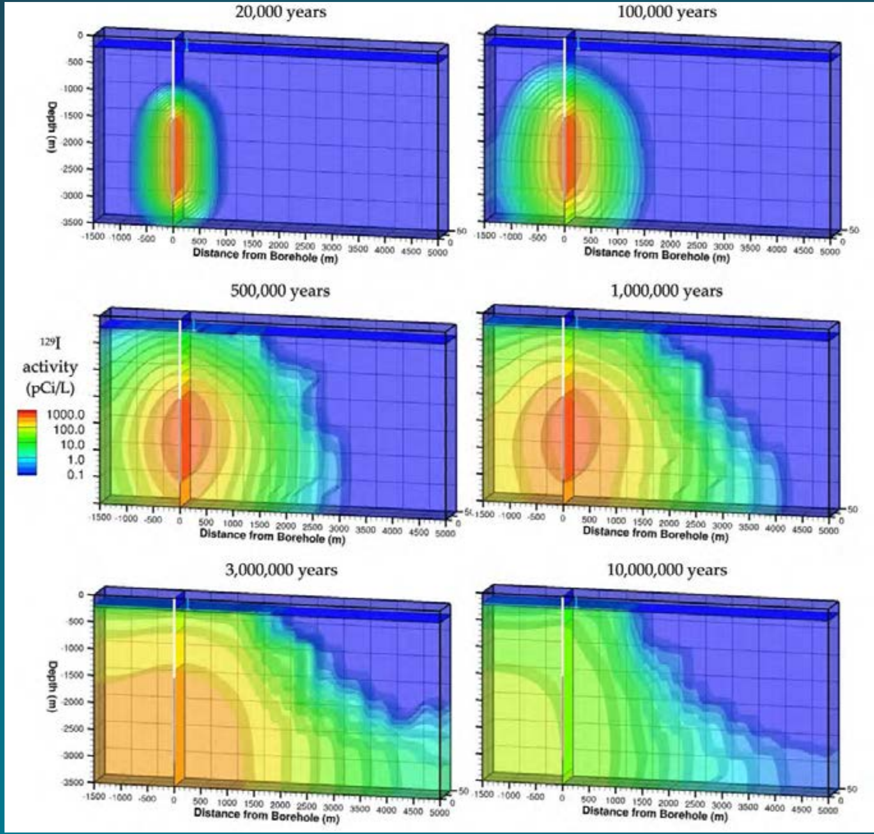
DEEP ISOLATION

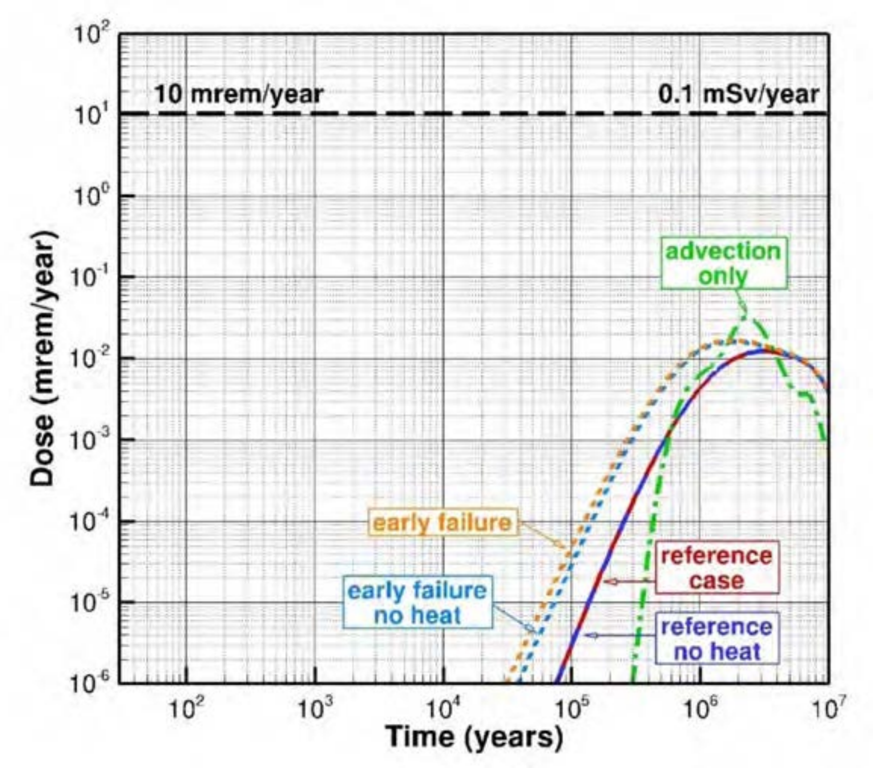
Vertical hole in crystalline basement rock (1)





Vertical hole in crystalline basement rock (2)





DEEP ISOLATION

sealing (1)

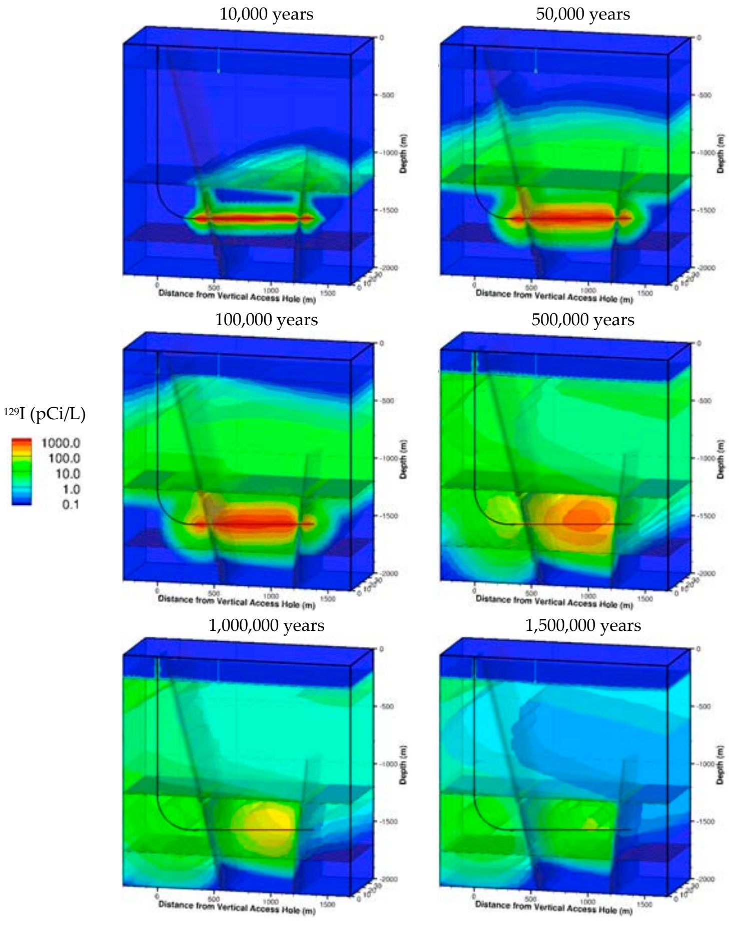


Figure 6. Distribution of ^{129}I activity at different times for a two-fault scenario with well-sealing backfill.

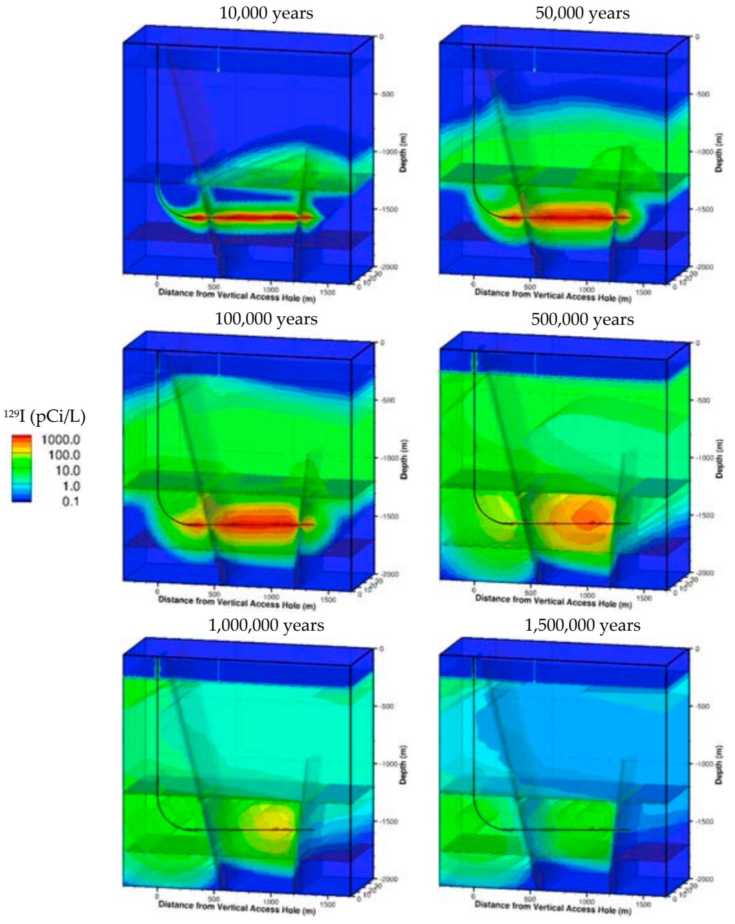
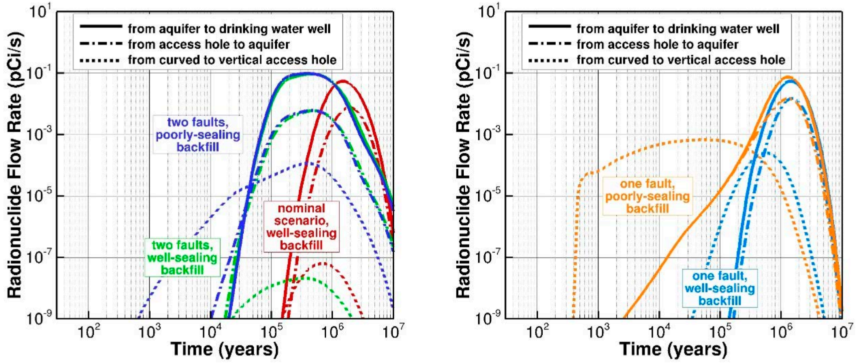


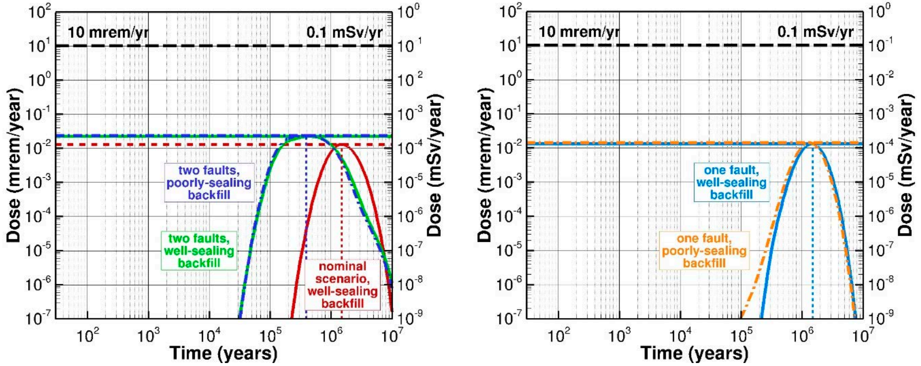
Figure 7. Distribution of ^{129}I activity at different times for two-fault scenario with poorly-sealing backfill.

sealing (2)



(a) (b)

Figure 11. ^{129}I activity flow rates along vertical access hole with sealing and poorly-sealing backfill for (**a**) reference and two-fault scenario, and (**b**) one-fault scenario.



(a) (b)

Figure 12. Annual exposure dose with well-sealing and poorly-sealing backfill for (**a**) reference and two-fault scenarios, and (**b**) one fault scenario.

sealing (2)

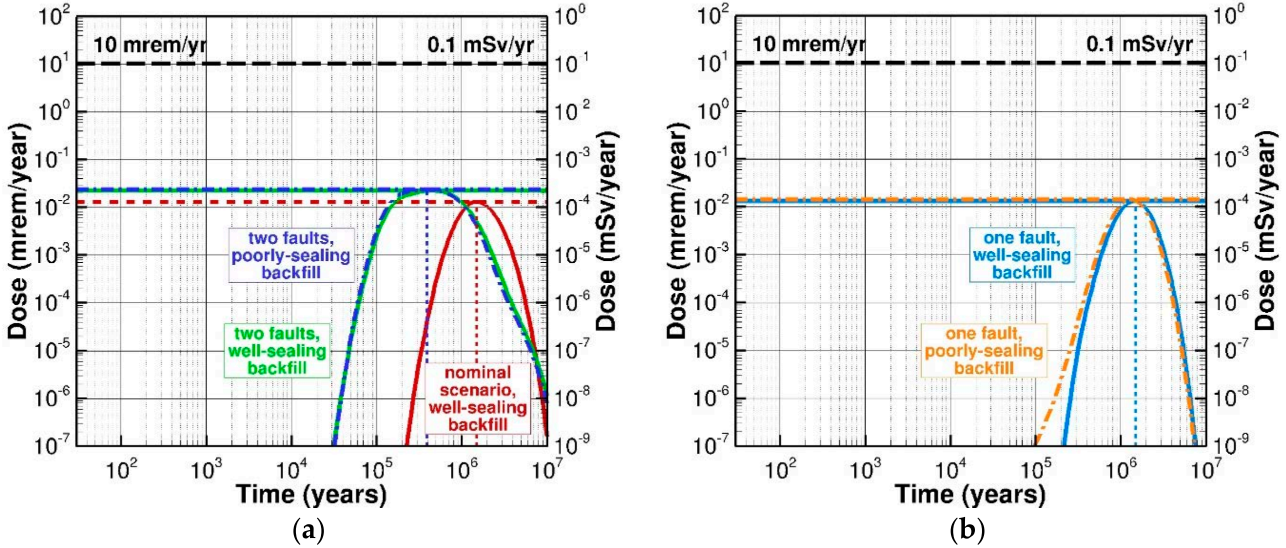
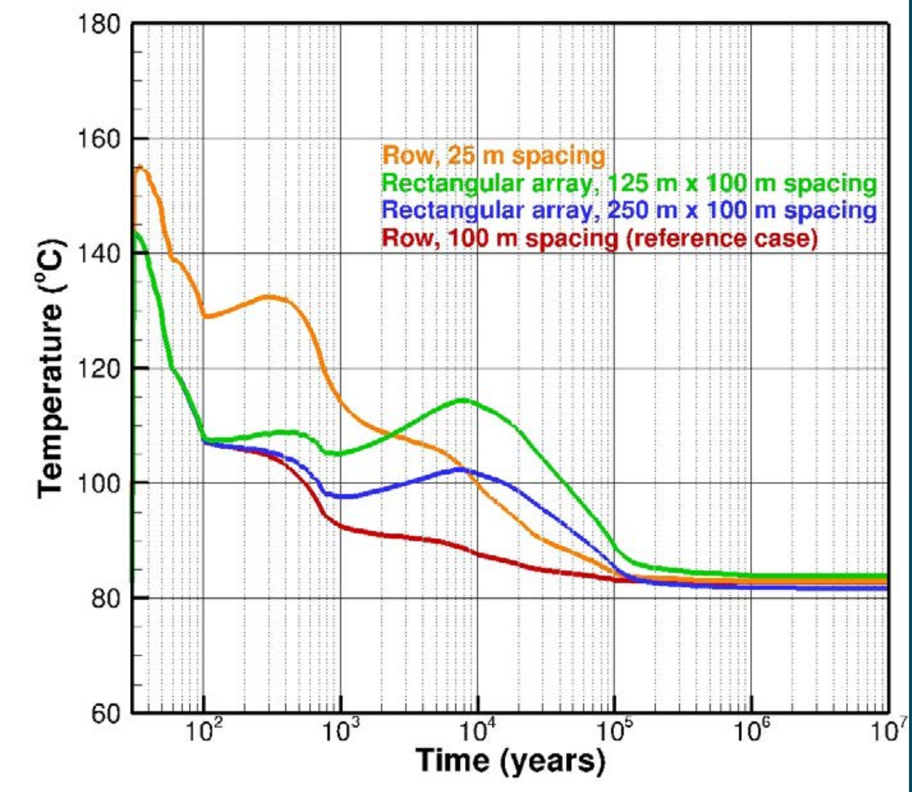


Figure 12. Annual exposure dose with well-sealing and poorly-sealing backfill for (**a**) reference and two-fault scenarios, and (**b**) one fault scenario.

Multiple borehole spacing & temperature

- Early temperature peak determined by heat release curve and cylindrical heat dissipation rate
- Not affected by borehole spacing *s* except if *s* is small (e.g., 25 m)
- Second peak determined by proximity to symmetry boundary
- Long-term temperature determined by rock volume in symmetry cell available to absorb total amount of heat released
- Consistent with Bates (2015)



DEEP ISOLATION

Borehole Storage vs Borehole Disposal

- **0 yr Cost:** Initial cost of borehole > initial cost of dry cask
- **12 yr Cost:** Actual cost spent (guns, guards, etc) → competitive after 12 years
- **Recoverability** can be monitored at low cost
- **Storage→ disposal**: seal the access borehole (when regulations allow). Risk that site will not pass disposal requirement is minimal
- **Guards and Guns:** Surface storage must pay the additional cost of disposal, when the time comes. (”Kick down the road – our grandchildren can take care of it”)

All aspects have been demonstrated

- Spent nuclear fuel and other wastes are routinely handled, packaged, transported and stored
- Wells are routinely drilled horizontally
- Costs are a fraction of a traditional mined repository
- Deep Isolation is using a proven approach to stakeholder and community outreach

Waiting only for regulations to catch up

Why is the cost so much lower?

no humans underground

much less rock removed

drilling technology well established

modular

faster time scale than mined repositories

can be used in *mined*+ combination

Discussion

Richard Muller
CTO Deep Isolation Inc.

(m) +1 510 735 6877
rich@deepisolation.com
https://deepisolation.com

4-minute tech video:
www.youtube.com/watch?v=IQx5zFUUIn0&t=11s

7 minute demo/stakeholder engagement video:www.youtube.com/watch?v=3GZ4TC8ttbE&t=10s

DEEP ISOLATION