Concepts for Siting Underground Nuclear Power Plants in Abandoned Limestone Mines

Mines to Megawatts Symposium
Missouri University of Science and Technology
Rolla, Missouri

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C. W. Myers
Retired: Los Alamos National Laboratory

Abandoned Limestone Mines

Existing Underground Space

Some Suitable for Siting Nuclear Power Plants and Data Centers

Several Probable Benefits Compared to Above-Ground Nuclear Power Plants

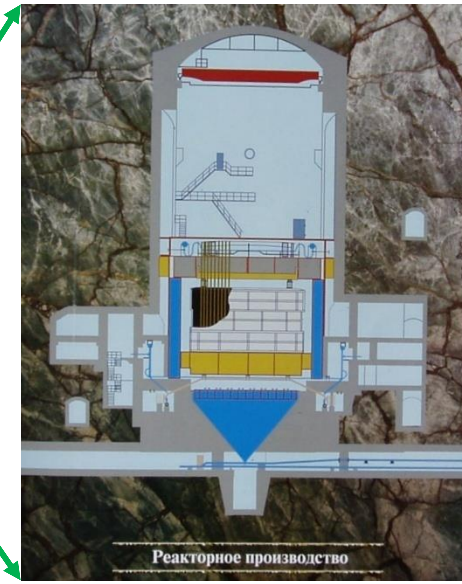
Life-Cycle Cost Will Be Reduced

Topics

Underground Nuclear Power Plants
Prior Studies and Experience

Underground Nuclear Power Plants (UNPPs) were Constructed and Operated Successfully, beginning in the Mid-20th Century.

Example 1. Central Siberia, Russia



Reactor

Uranium-graphite, Water-Cooled

Reactors commissioned in 1958, 1961, and 1964

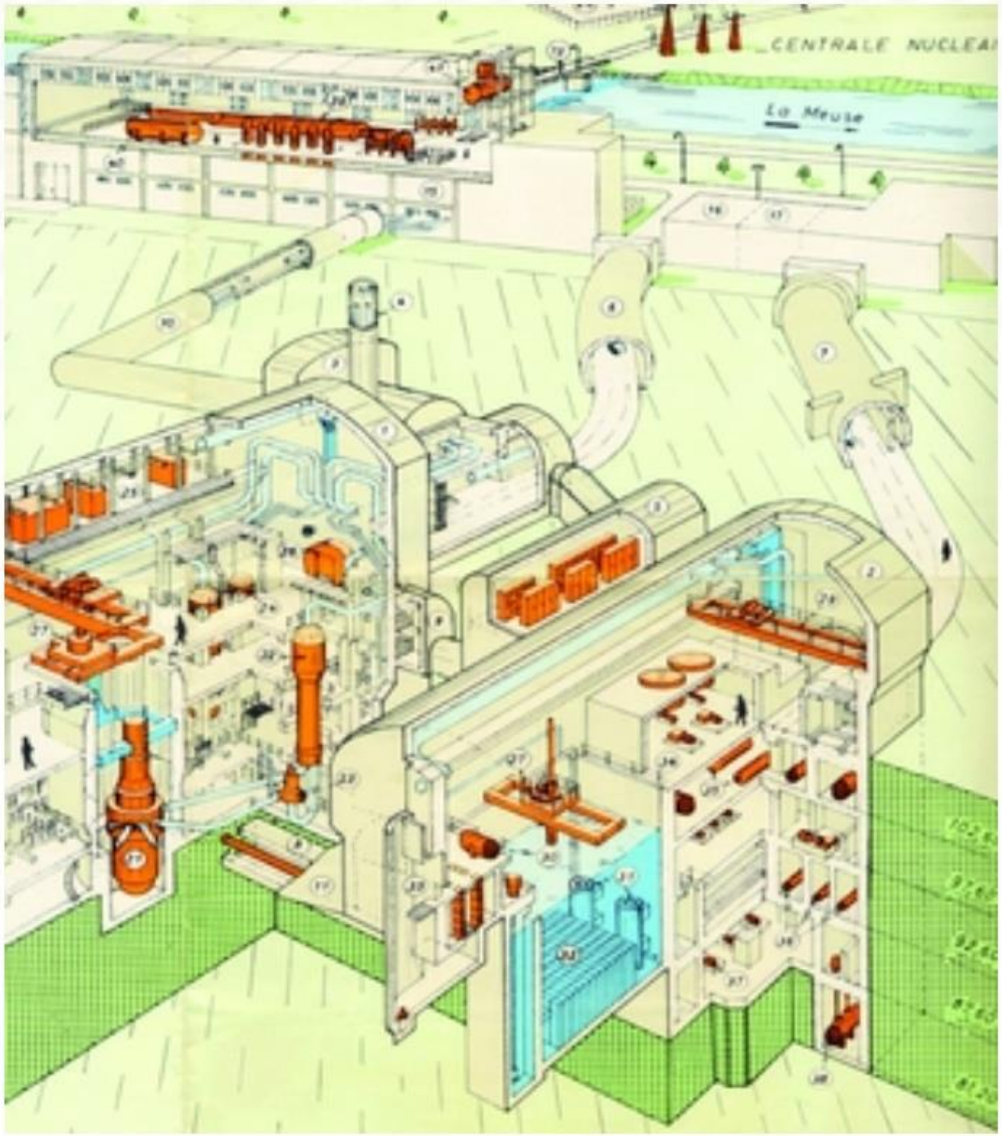
Radiochemical Plant

Turbine Room

Images Source: Mining and Chemical Combine, Zheleznogorsk, Krasnoyarsk, Kray)

Example 2. Chooz A, Northern France

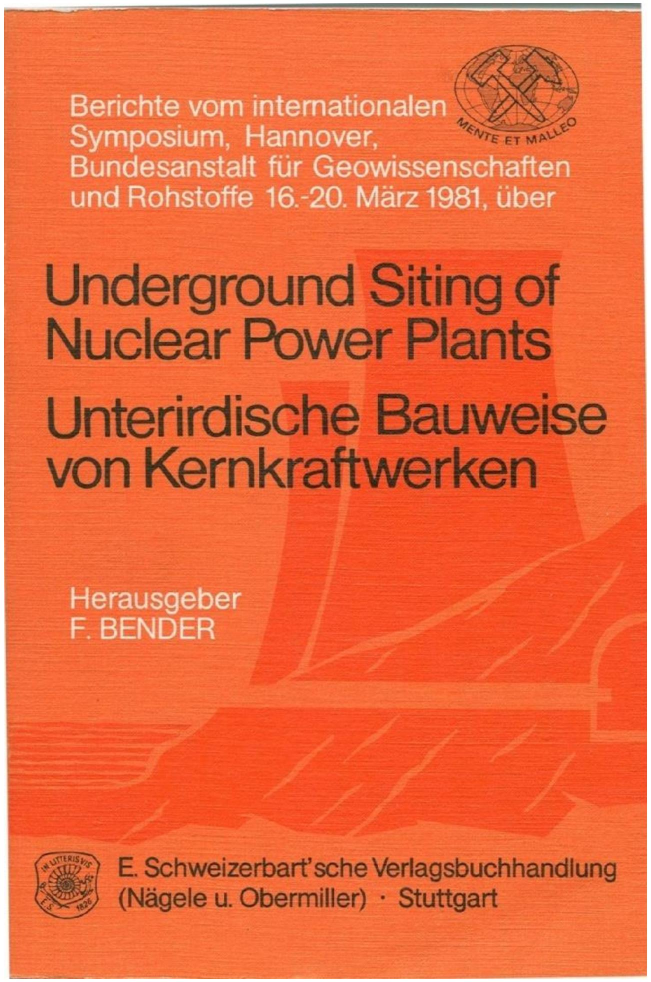
- Prototype PWR 305MWe capacity
- Operated 1967-1991
- Partially underground:
  turbine-generators were sited at the surface near the Meuse River
- Current status:
  Being decommissioned, the final phase is underway.
- **Significance:**
  First full-scale demonstration of an underground nuclear power plant with significant generation capacity



Source: (Duffaut, P., 2007 and Hitchin, P., 2010)

Detailed Studies of UNPPs in the1970s and Early 1980s:

Hannover Symposium (1981)



Conclusions related to **UNPPs in Bedrock Caverns**

Benefits:

- **improved containment under severe accident conditions,**
- **greater physical security**
- **greater earthquake protection**

Engineering conclusions

"...concept is practically feasible..."

"...within the current state of the art... no technological restrictions"

- **Construction cost penalty was the issue...**

Study Sponsor	Depth (meters)	Construction Cost Penalty
Swiss Federal Institute for Reactor Research	--	**11-15%**
Japanese Ministry of Trade and Industry	150	**20%**
Canada--Ontario Hydro	450	**31-36%**
U.S.--California Energy Commission	100	**50-60%(FOAK)** **<10% (Nth plant)**

RESULT: Interest in UNPPs declined

But.....Resurfaced 20 Years Later

Beginning with the September 11, 2001, Terrorist Attacks on the World Trade Center in New York City and the Pentagon in Washington, D.C.

Source: 911review.com

" Since the Sept. 11 terrorist attacks, growing anxiety over the safety of nuclear power plants has transformed Indian Point from a fringe issue that only antinuclear crusaders care about to a mainstream concern... "

New York Times, April 24, 2002

"...September 11 has implications for specific nuclear energy choices...The concept of underground nuclear reactors should be explored again..."

Bunn and Bunn, *Journal of Nuclear Materials Management,* Spring 2002

My Response: A New Study is Needed

RESULT

Underground Nuclear Park Concept

Nuclear Power Plant(s) + Spent Fuel Storage + Geologic Disposal

(All Co-located) at the same site

--**Enable on-site closure of the back-end of the nuclear fuel cycle**
--**Better promote environmental justice by eliminating the NIMBY issue**
--**Better withstand certain types beyond-design-basis events**

However, the foremost issue seemed to be the widespread and continuing perception that **underground construction costs would be excessive**. Therefore, I decided to study how to reduce underground construction costs for UNPs.

Example 1: Bedded Salt, GT-MHR Reactors (288MWe), Air-Cooled Spent Fuel Storage, Salt Repository, and Open Fuel Cycle

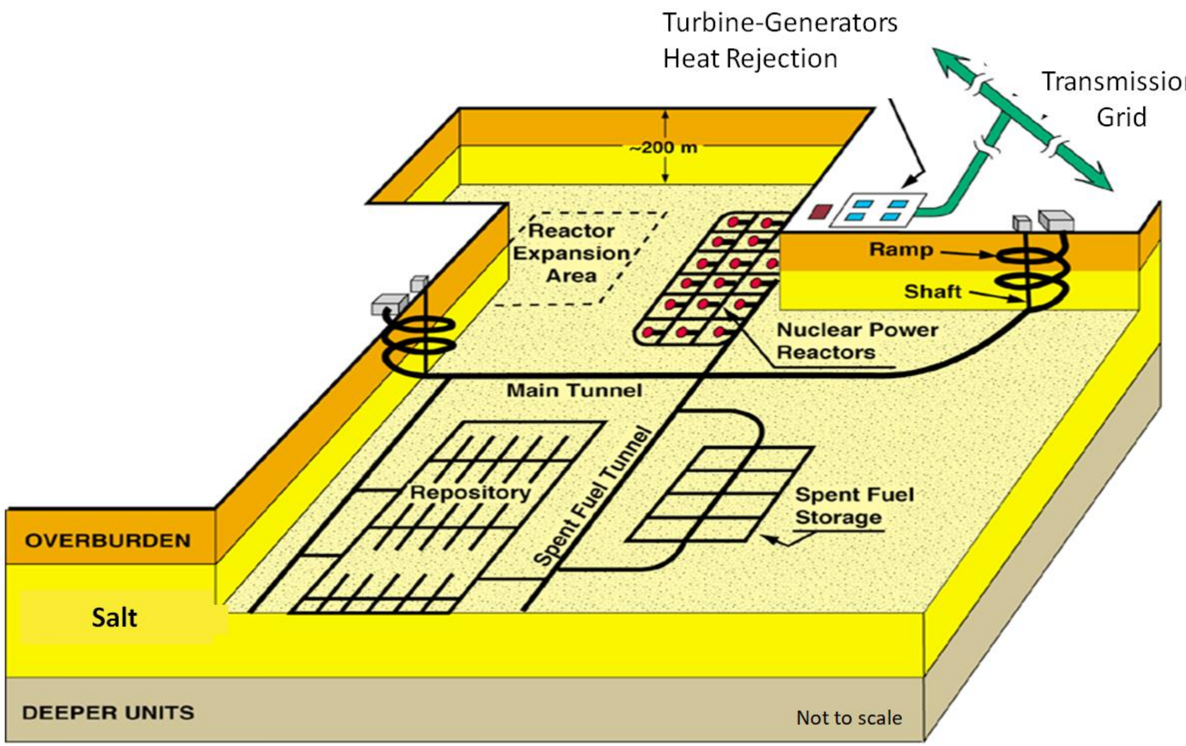
Concept based on the WIPP site in New Mexico, USA. (WIPP is a geologic repository for US DOE defense-related nuclear waste)

Motivation

1. **The WIPP repository is in a massive, well-studied salt layer**

2. **Favorable properties**
   - **--impermeable**
   - **--laterally extensive**
   - **--homogeneous**
   - **--predictable properties**

3. **Bedded salt is common in many sedimentary basins**



Not shown: Control rooms and other support facilities, isolation bulkheads and airlocks in tunnels, shafts for ventilation and emergency egress, etc

4. **Salt creep under heat loading can be controlled**

5. **Low-Cost Excavation**

Source: Myers and Elkins, 2004, 2009

Est. Capacity ~ 5.2GWe

Outcome

--Colleagues and I developed concepts for UNPPs in granite sited in TBM-excavated tunnels

--Publications: 2004-2011 16 articles,1 book chapter

--Numerous presentations given at conferences and technical society meetings

Noteworthy Feedback

--Some positive, some not: ”concept might work but is too far in the future to make a difference…” …. “for the present, don’t put nuclear new-build at risk”

Significance

--Understand who benefits? Who does not? And over what time frame?

--Do UNPPs and UNPs represent a threat or opportunity to me or my institution?

Then!

--Fukushima Accident and Explosion (2011), Impacted the “Nuclear Renaissance”

--Result: Continued research, but at a reduced pace

Recently

--Became aware of the opportunity presented by abandoned limestone mines

Topics

Underground Nuclear Power Plants

Prior Studies and Experience

Underground Nuclear Power Plants in Abandoned Limestone Mines

The Resource

Assumptions and Terminology:

--reactors are SMRs unless stated otherwise

--open fuel cycle

--follows the UNP concept

-- “Mine” = Abandoned Limestone Mine

Abandoned Limestone Mine Resource

- Likely 1,000 to 5,000 in the US, based on historical mining activity and limited data.

- Exact numbers are uncertain due to the lack of a large, centralized database for industrial mineral mines like limestone.

- The evidence leans toward there being a significant portion in states like Missouri and Kentucky.

Conclusion: Even if one assumes that only 1% of the resource is potentially suitable for siting underground nuclear power plants, then that part of **resource is approximately 10 to 50 mines.**

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*The above bulleted statements are derived from 1) a GROK 3, Artificial Intelligence, DeepSearch, in response to the question: "What is the approximate number of abandoned underground limestone mines in the US?".

Preliminary Mine Selection Criteria (work in progress)

Limestone Rock

- --High-strength and leak-tight

Room-and-Pillar Portion of the Mine

- --Overlain by ~50m to ~300m of bedrock
- --Geographic location includes a water supply suitable for cooling and heat rejection.
- --Deep subsurface geology is suitable for borehole disposal of spent fuel.
- --Location is favorable for grid connection and other infrastructure needed for construction and operations.

Rooms

- --Room dimensions, geometry, and orientation are suitable for siting and operation of the reactor system + turbine-generator system and the facilities for spent fuel cooling and storage--or can be made so with new excavations.
- --Enclosing limestone rock mass will be stable during the operational lifetime
- --Rooms are suitable for the installation of data centers and related facilities.

Reactor-System Locations

- --Accessible only by access-controlled tunnels and rooms
- --To control access, individual reactor locations can be isolated by bulkheads/airlocks, or equivalent structures.

Ultra-Secure Chip Manufacturing

"Our wafer fab is to be built deep inside a Swiss mountain. Perfect mechanical isolation from the outside world guarantee a **vibration free cocoon** for the highest quality standards in IC manufacturing. A **constant climate** and **total radiation shielding** allows us to control operation of the facilities inside in an efficient and cost effective way."

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https://www.linkedin.com/company/espros-photonics-ag/about/

Topics

Underground Nuclear Power Plants

Prior Studies and Experience

Underground Nuclear Power Plants in Abandoned Limestone Mines

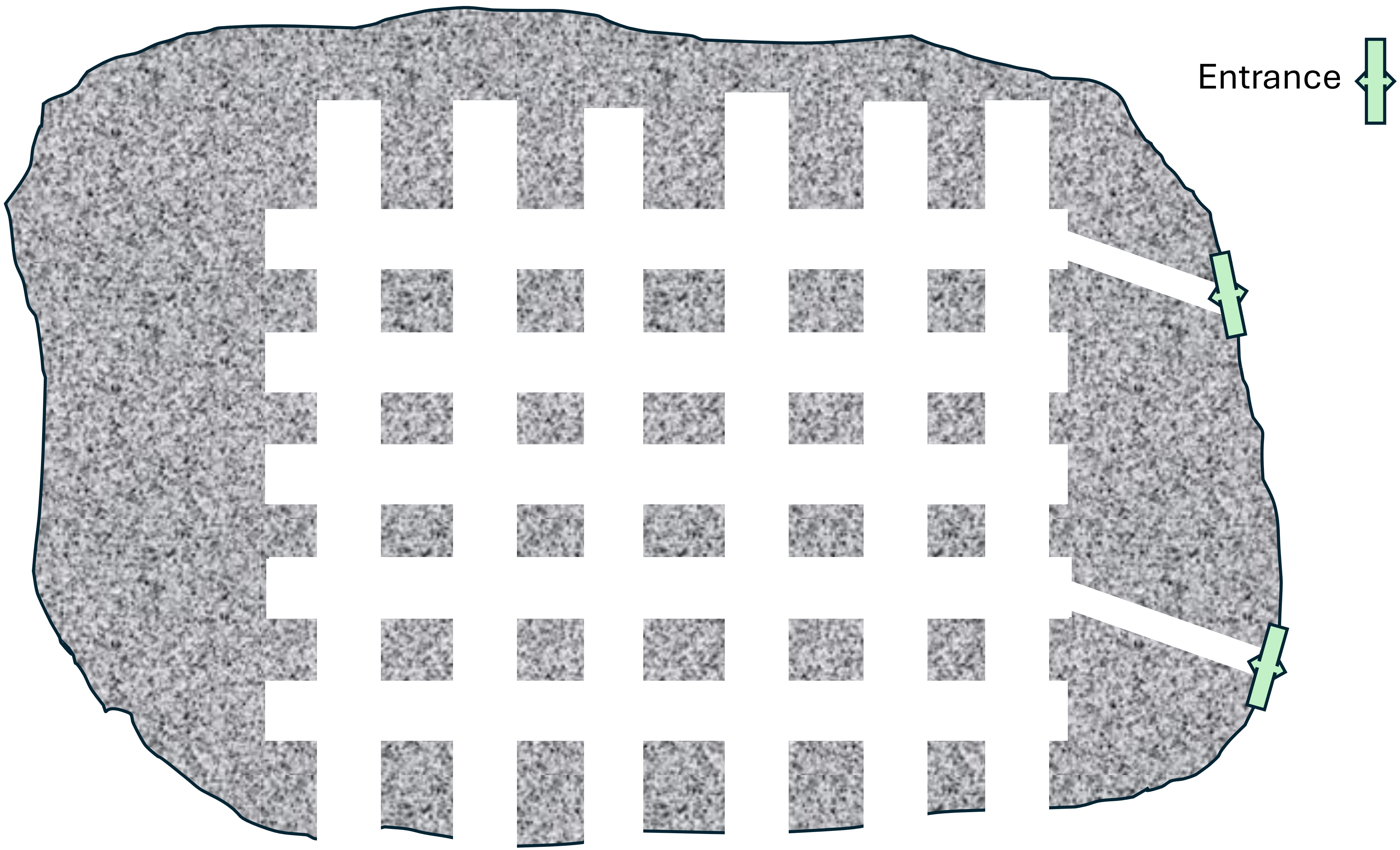
The Resource

Siting Concepts

Underground Nuclear Power Plants + Data Centers

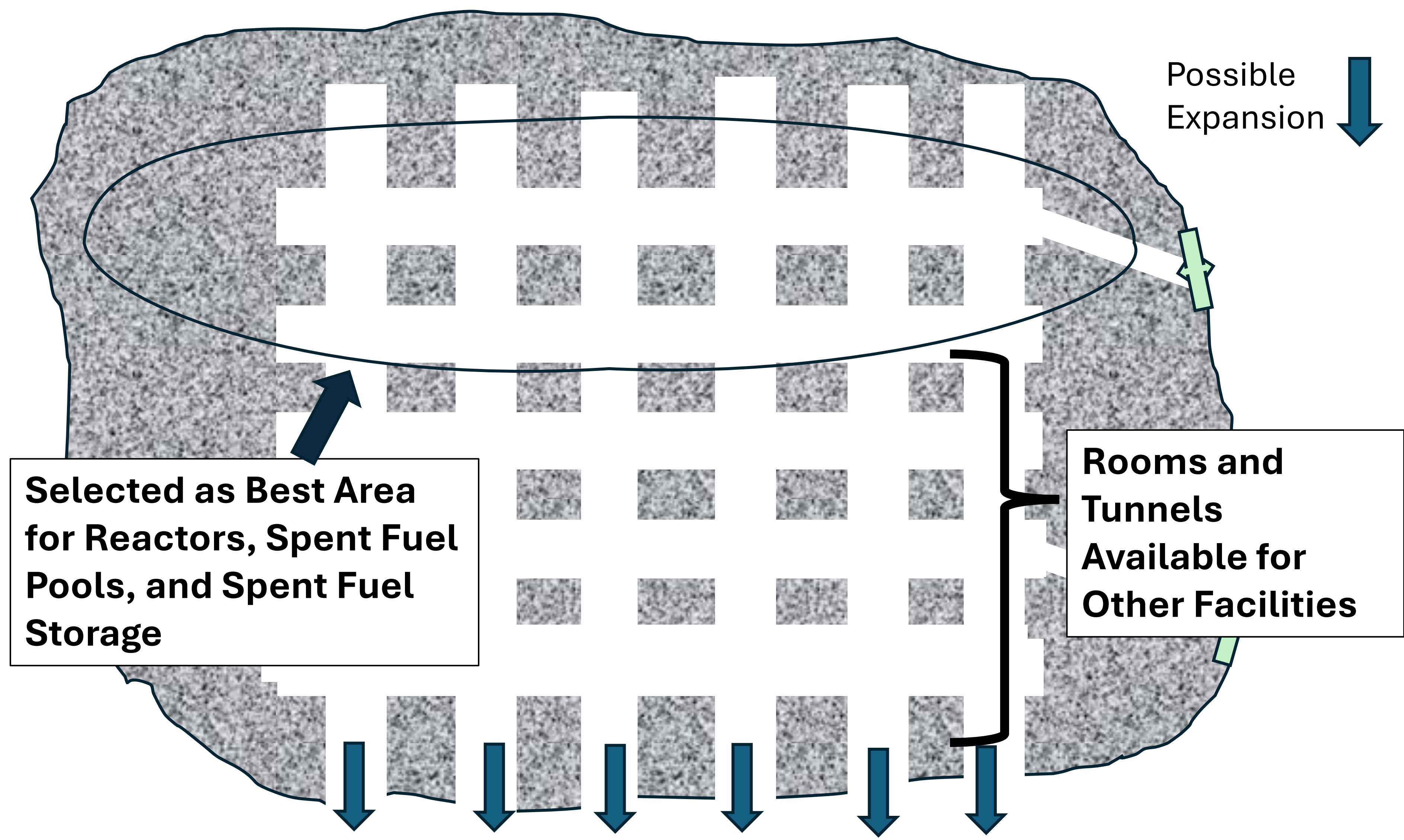
-Hypothetical
-Conceptual
-Simplified

Mine #1, Upper Portion, Original State



Mine #1, Upper Portion After Site Exploration:

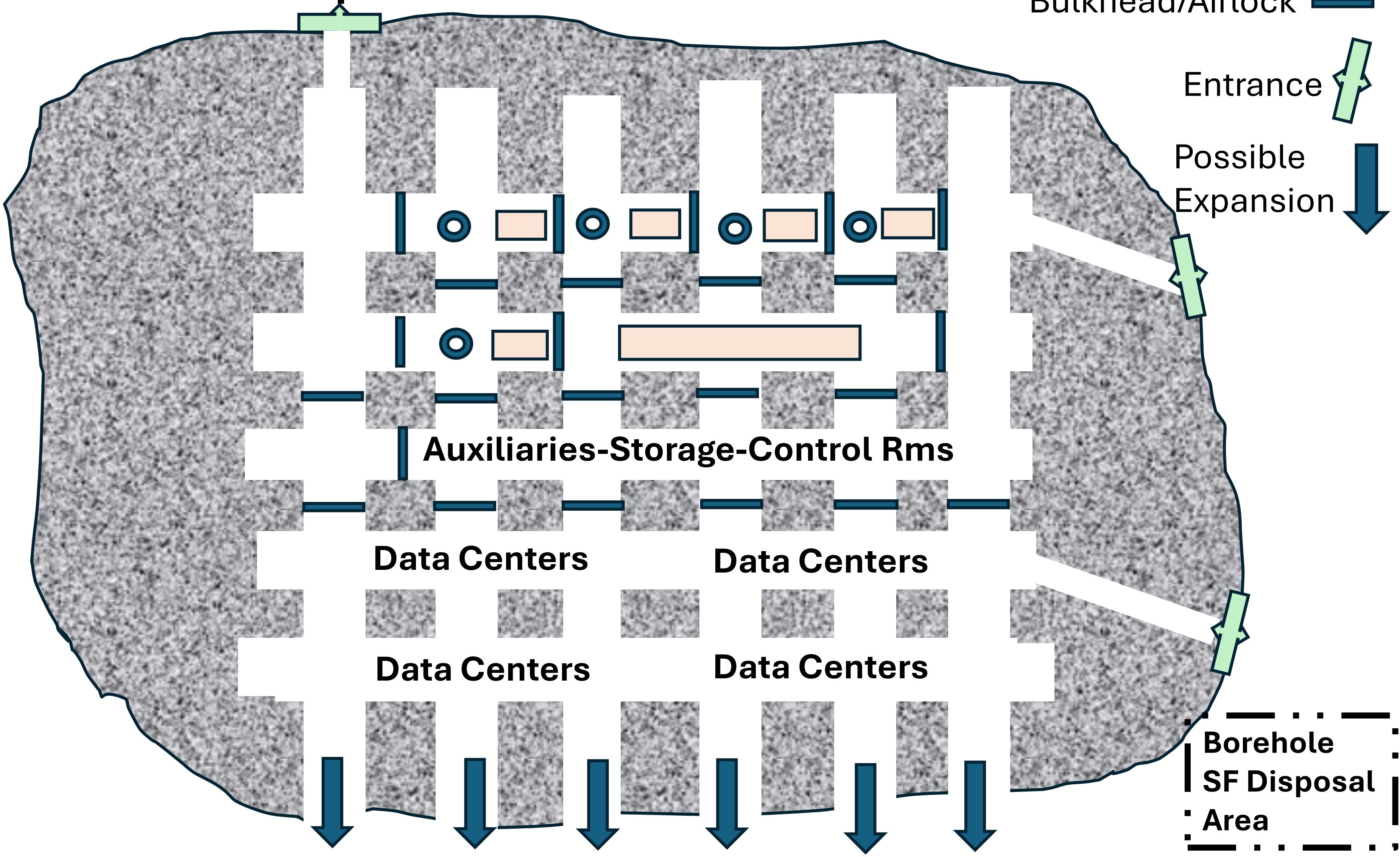
(Existing Information, New Boreholes. Geophysics, Hydro-Testing, Rock Mechanics…)



-Hypothetical
-Conceptual
-Simplified

Mine #1

-Suitable for Siting Reactor System + T-G and Data Centers, and Spent Fuel Facilities



Topics

Underground Nuclear Power Plants

- Prior Studies and Experience

Underground Nuclear Power Plants in Abandoned Limestone Mines

- The Resource
- Siting Concepts
  - Underground Nuclear Power Plants + Data Centers
- Licensability
  - Safety and Security Risks
  - Preliminary Siting Criteria
  - Layout Examples

Begin with the End Goal in Mind:
LICENSABILITY

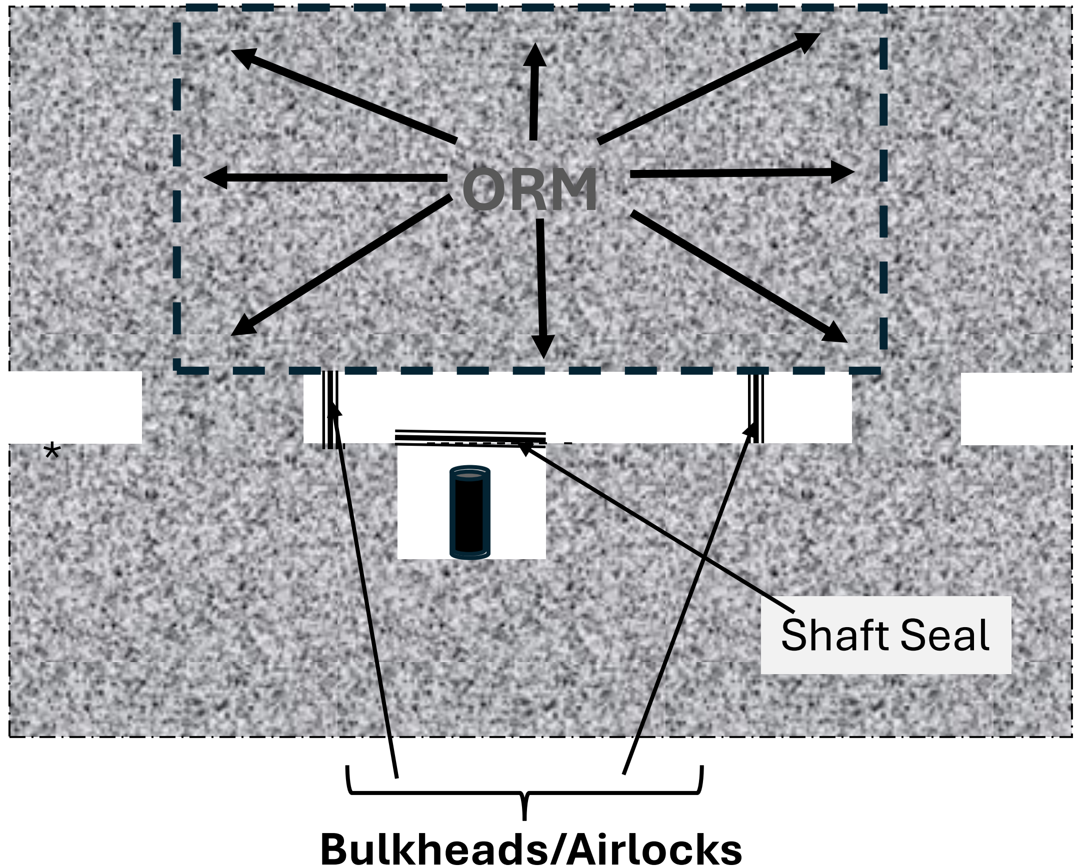
What will be the NRC regulatory requirements?
They are unknown, but anticipate the need to develop a "Safety Case".

Safety Case will require documented evidence that the design, construction, and operations of the Mine's UNPPs are safe in terms of radiological risks.

An important element will be the safety and security provided by the Mine's "containment envelopes".

The "containment envelope" in a Mine should serve the same safety and security function as the containment structure for conventional, above-ground NPPs.

Example 1. Reactor Containment Envelope = SMR* + Sealed SMR Shafts + Bulkheads/Airlocks + Overlying Rock Mass (ORM)



Licenseability: Probable

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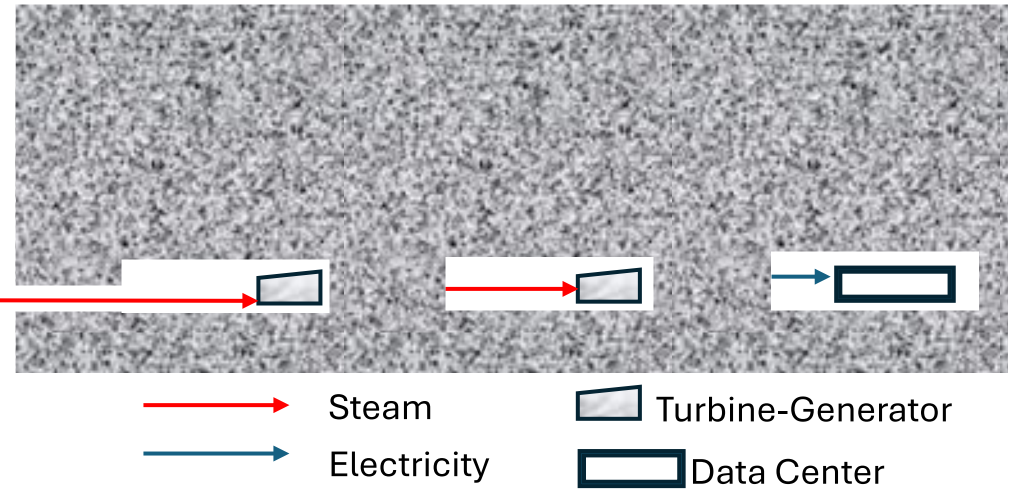
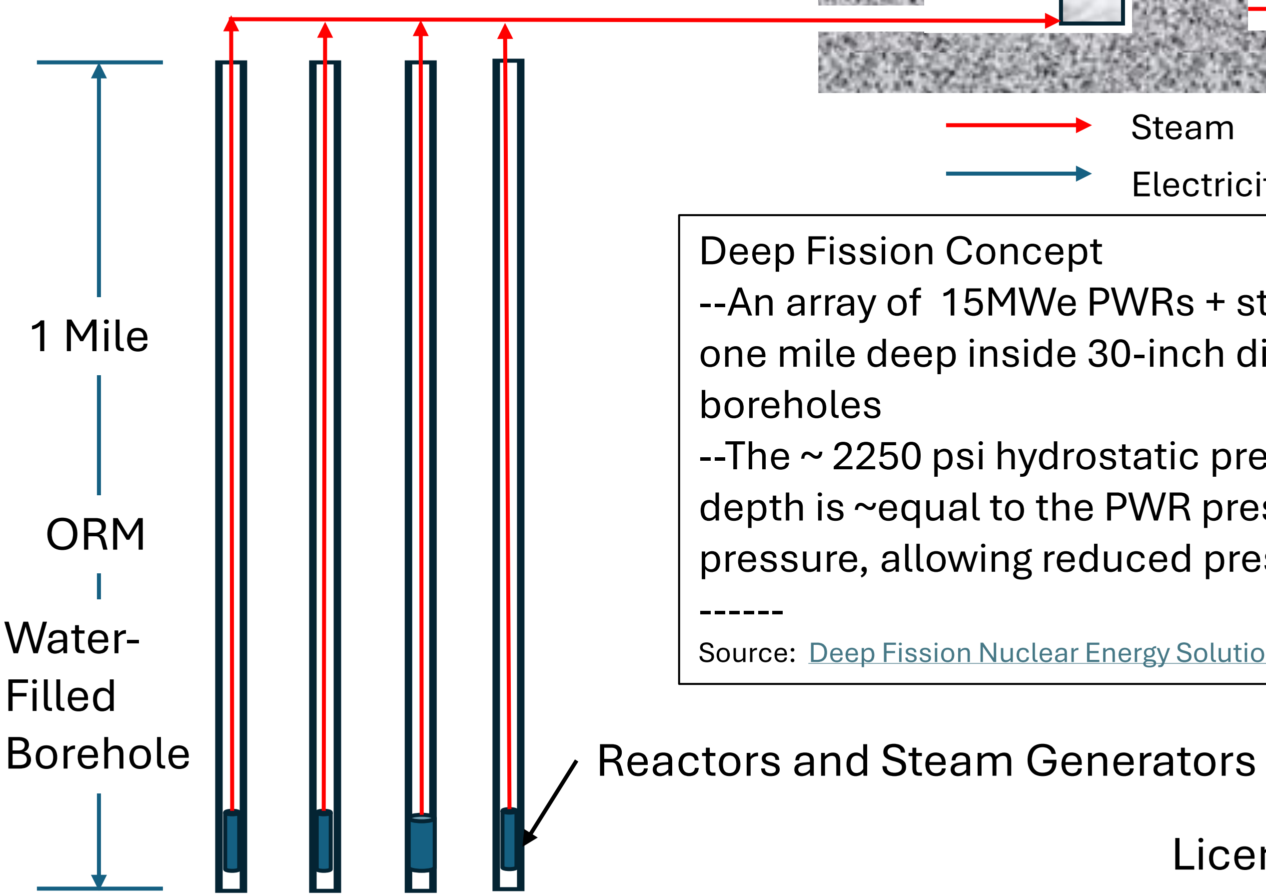
*The SMR pressure vessel and other components that provide containment

Example 2. (Based on Deep Fission Reactors) Containment Envelope = Reactor PV + ORM + Water Filled Boreholes

Produced steam rises to the surface and is delivered to turbine-generators. The produced power is supplied to, for example, data centers, which are securely sited underground.





Deep Fission Concept

--An array of 15MWe PWRs + steam generators is installed one mile deep inside 30-inch diameter, water-filled, cased boreholes

--The ~ 2250 psi hydrostatic pressure at one mile depth is ~equal to the PWR pressure vessel's internal pressure, allowing reduced pressure vessel wall thickness.

Source: Deep Fission Nuclear Energy Solutions

Licenseability: Highly Probable

Topics

- Underground Nuclear Power Plants
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- Underground Nuclear Power Plants in Abandoned Limestone Mines
  - The Resource
  - Siting Concepts
    - Underground Nuclear Power Plants + Data Centers
  - Licensability
    - Safety and Security Risks
    - Preliminary Siting Criteria
    - Layout Examples
  - **Room Height Issue**

Room Height Issue

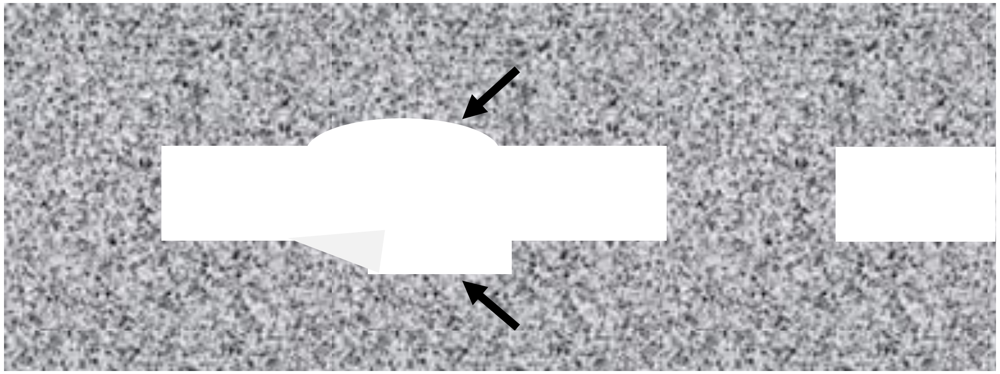
In some Mines, the room height might preclude the installation of vertically oriented large reactors and other large vertically oriented equipment

Photo of Brady's Bend Underground Storage Facility

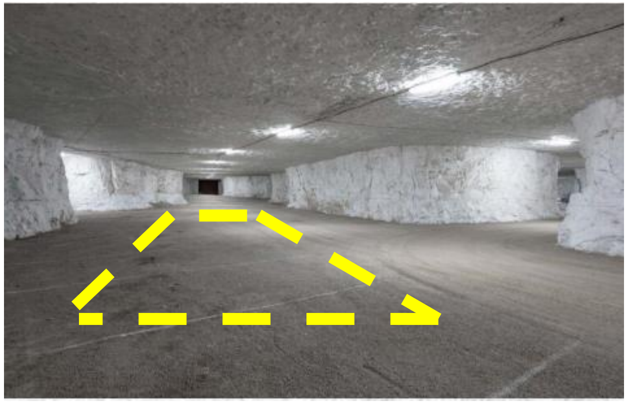
Possible Solutions

1. **Use small-diameter reactors that can be sited horizontally**
2. **Create added roof height by excavating below and/or above the room floor**

Excavate into the limestone below the room floor to create adequate roof height.



... probably with a road header



Road Header

Topics

- Underground Nuclear Power Plants
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    - Preliminary Siting Criteria
    - Layout Examples
  - Room Height Issue
  - **Benefits, Issues, and Needs**

Benefits

Reduced capital, operating, and decommissioning costs

...underground space for facility siting already exists
...no need for an expensive conventional containment structure
...reduced weather-related delays during construction and operations
...facilitates 3D layouts, e.g., Emergency Core Cooling System
...unit-cost reduction for the nth reactor
...lower utility cost
...lower building maintenance costs due to fewer buildings
...in-place decommissioning at much lower cost
...lower insurance cost?

Increased safety and physical security

...potential for greater containment safety
...natural radiation shielding provided by the rock mass
...easily controlled physical access to the underground
...greater protection against beyond-design-basis events
...a benign underground environment
...a predictable disposal path for spent fuel
...greater public acceptance

Reduced environmental impact

...underground siting conserves land surface area = reduced impact on ecosystems and landscape aesthetics

New approach to spent fuel management

...co-location of reactors and spent fuel storage and disposal facilities eliminates public resistance, cost, and safety issues associated with long-distance spent fuel transport.

Issues

Issues related to the area around the Mine
...proximity to key infrastructure
...proximity to populated areas

Issues related specifically to the Mine
...limestone strength, permeability, and mineralogy
...hydrology and geology below the Mine floors
...underground flooding risk
...water table depth, perched water (could perhaps be a benefit), heavy rains
...generic issues related to all underground operations (e.g., ventilation, emergency egress)
...increased maintenance and repair costs for facilities?
...psychological aversion to the "underground"

Needs

...NRC regulatory framework...
...Mine screening process: resource to possible and probable suitability
...Potential to excavate new space at Mine margins or inside carefully selected pillars

Need

Life-Cycle Cost Comparison Between an Above-Ground (AG) NPP *versus* a UNPP Sited in a Mine

Consider Two Situations

1st. AG-NPP is a single, conventional, large NPP with 1000MWe generating capacity. The Mine UNPPs consist of several SMRs with a total generating capacity of 1000MWe.

2nd. AG-NPP and Mine UNPPs each have 1000MWe generating capacity and consist of the same type and number of SMRs.

In Each Situation

--The facilities for long-term spent-fuel storage and permanent geologic disposal for AG-NPP spent fuel are sited elsewhere.

--The facilities for long-term spent fuel storage and permanent geologic disposal for the Mine UNPP spent fuel are co-located at the Mine as per the UNP concept

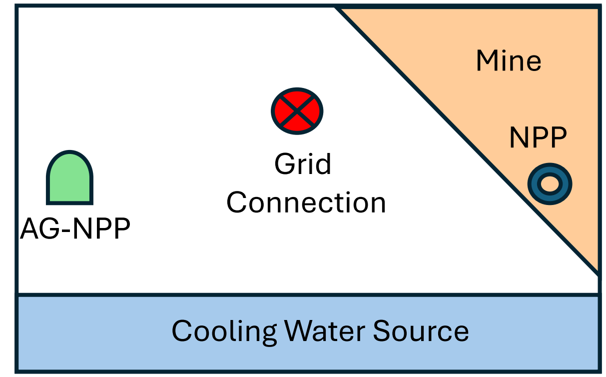
All Variables Held Constant, insofar as possible

Examples:

--equal distances to cooling water and grid connection

--equal seismic risk

--equal risk of attempted terrorist attack



For Each of the Two Situations:

Compare the life-cycle cost for the AG-NPP and Mine UNPPs based on the:

--Construction Cost

--Operations Cost

--Decommissioning Cost

--SF Storage and Disposal Cost

Topics

- Underground Nuclear Power Plants
  - Prior Studies and Experience
- Underground Nuclear Power Plants in Abandoned Limestone Mines
  - The Resource
  - Siting Concepts
    - Underground Nuclear Power Plants + Data Centers
    - Underground Nuclear Power Plants
  - Licensability
    - Safety and Security Risks
    - Preliminary Siting Criteria
    - Layout Examples
  - Room Height Issue
  - Benefits, Issues, and Needs
  - Conclusion

Abandoned Limestone Mines

Existing Underground Space

--Substantial resource

Some Suitable for Siting Nuclear Power Plants and Data Centers

--Several options for underground layout and reactor types

--Room dimensions can be modified

--Licensability is key

Several Probable Benefits Compared to Above-Ground Nuclear Power Plants

--Huge increase in physical security

--Moderate increase in safety

--Much reduced environmental impact

Life-Cycle Cost Will Be Reduced

--Why?

--Reduced cost for construction, operation, and decommissioning

--Co-located nuclear power plants and their spent fuel storage and disposal facilities

Two Advocates for Underground Nuclear Power Reactors

"Plainly, mankind cannot renounce nuclear power, so we must find technical means to guarantee its absolute safety and exclude the possibility of another Chernobyl. The solution I favor would be to build reactors underground, deep enough so that even a worst-case accident would not discharge radioactive substances into the atmosphere."

Andrei Sakharov, Memoirs,1990, p. 612

"My suggestion in regard to [the containment of nuclear material in case of an accident] is to place nuclear reactors 300 to 1000 feet underground..." ..."I think the public misapprehension of risk can be corrected only by such a clear-cut measure as underground siting."

Edward Teller, Memoirs, 2001, p. 565

Thank you for your attention

(Copy of presentation available upon request to myerswes@msn.com)

Supplementary Slides

Experience

Independent Geologist/Consultant (2005 - Present)

Los Alamos National Laboratory (1981 - 2005)

- Division Leader (Founding) Earth and Environmental Sciences Division
- Co-Leader of the Yucca Mountain Project
- Several Division/Group Leader positions

Rockwell Hanford Operations - Manager, Senior Geologist, Staff Geologist (1976 - 1981)

Appalachian State University - Assistant Professor (1974 – 1976)

Chevron Oil Company - Development Geologist (1968 – 1970)

Education

State University of New York at Stony Brook, Post-Doctoral Fellowship (1973 – 1974)

University of California, Santa Cruz, Ph.D. Earth Sciences (1970-1973)

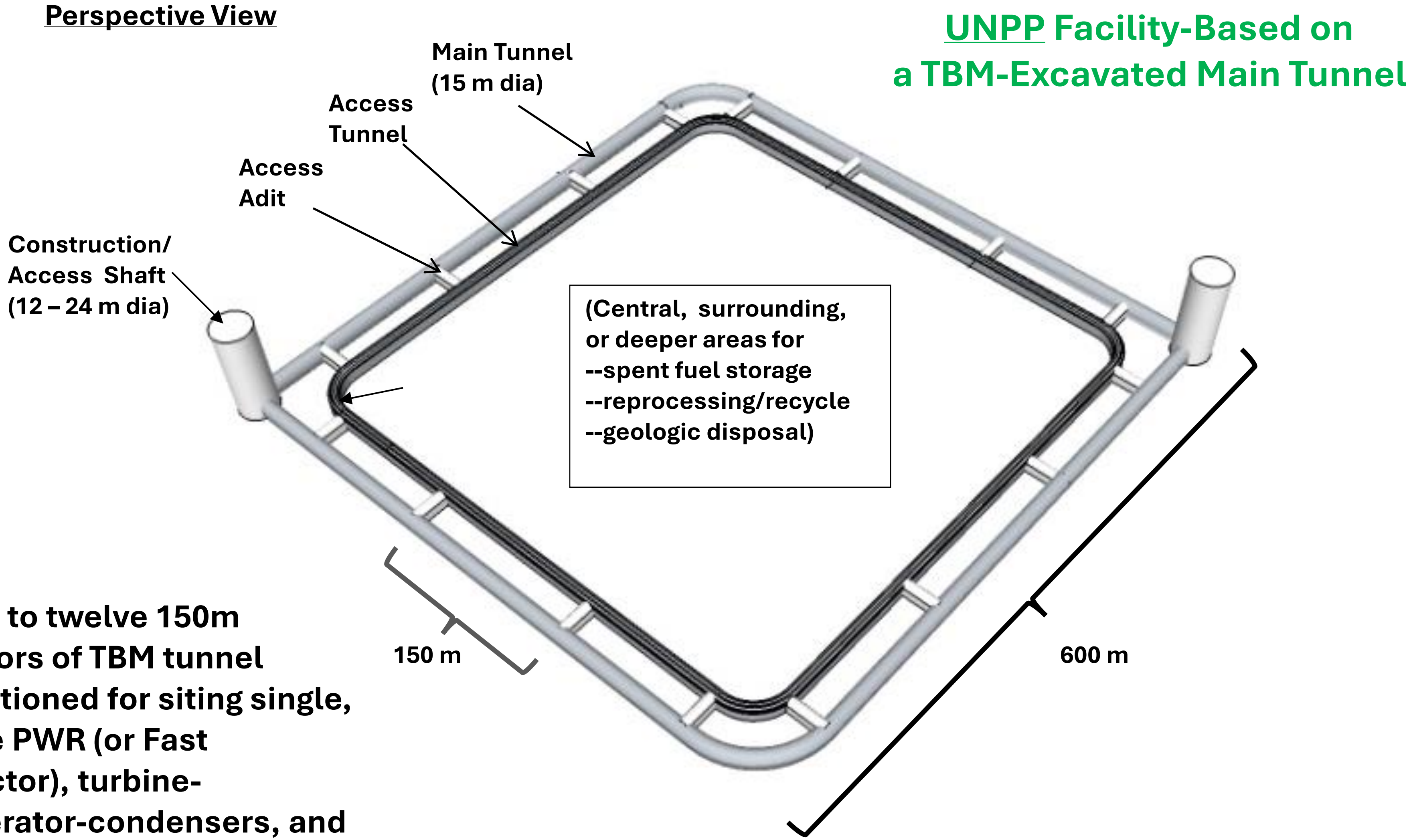
University of Georgia, BS (1966) Geology and MS (1968) Geology

Contact

myerswes@msn.com

UNP Concepts: 2. Granite, 1000MWe-Scale PWR, Closed Fuel Cycle

Selected Publications and Presentations : Giraud et. al., 2009; Giraud, 2009; Kunze, et. al., 2010, 2012, 2014; Mahar, et. al., 2007, 2008



Nine to twelve 150m sectors of TBM tunnel partitioned for siting single, large PWR (or Fast Reactor), turbine-generator-condensers, and spent fuel pool

Source: Modified after Giraud, et. al., 2009, Figure 1.

Superior Earthquake Protection

- **Subway Tunnel Experience***

Earthquake	Date	Magnitude	Impact on Subway
Mexico City	1985	8.1	No damage to tunnels.
Loma Prieta (SF)	1989	6.9	No damage to tunnels
Northridge	1994	6.7	No damage
Kobe	1995	7.2	No damage to tunnels
Taipei	2002	6.8	No damage
Chile	2010	8.8	Running next day.

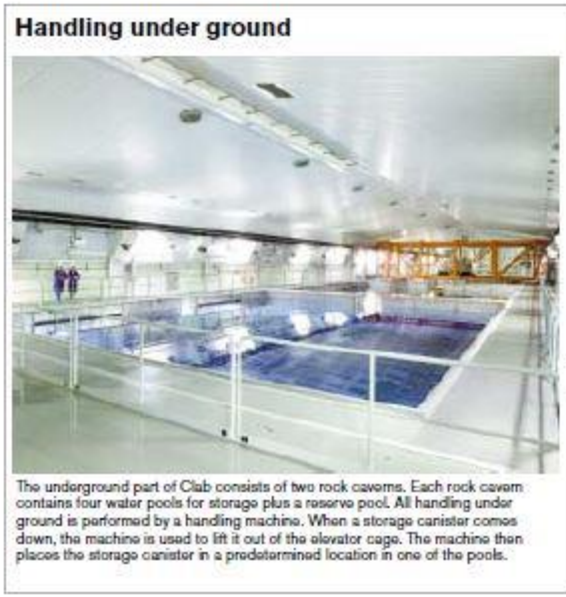
*https://about.ita-aites.org/publications/wg-publications/224-underground-solutions-for-urban-problems.

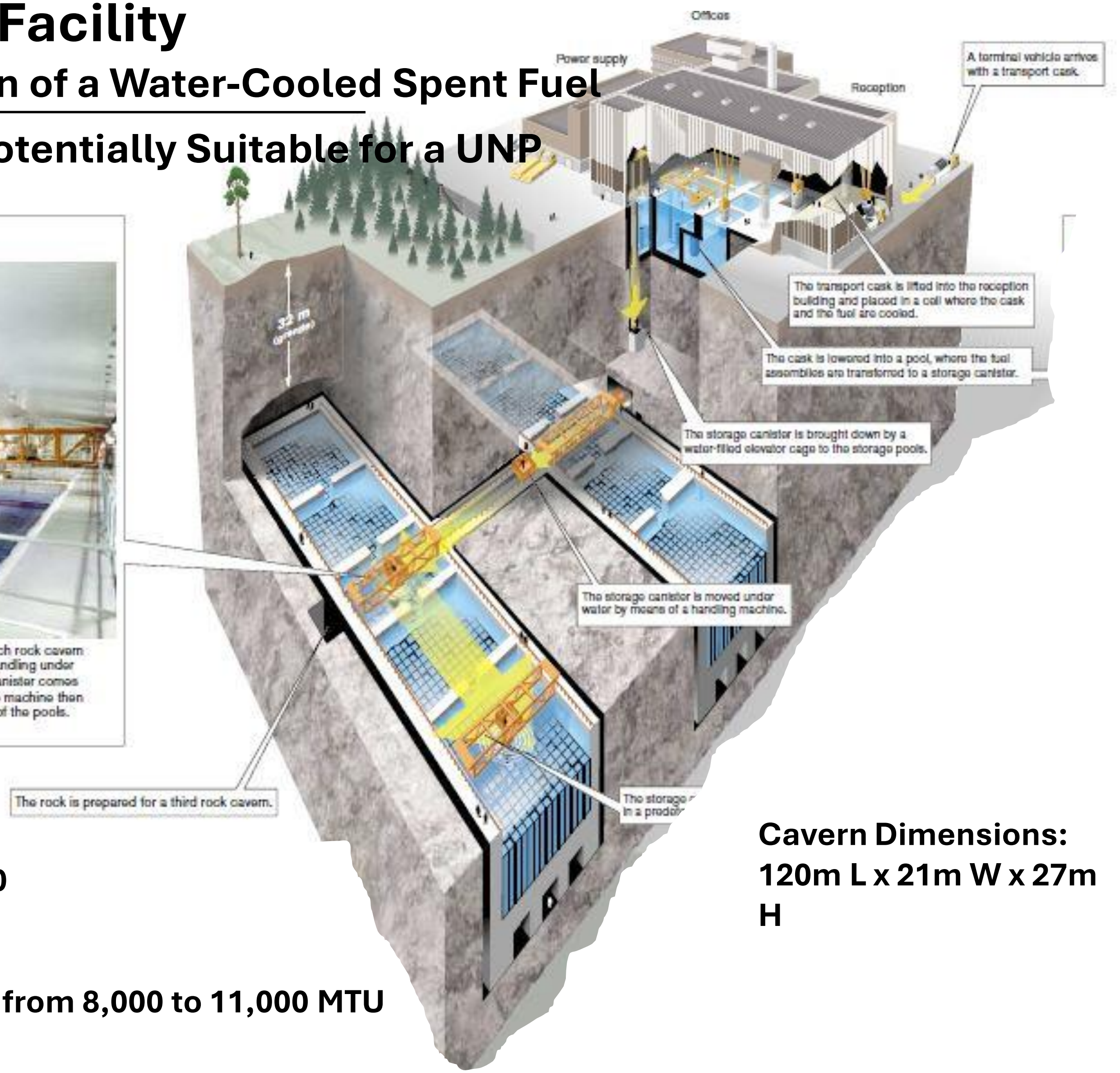
Superior Deterrence and Protection Against Enemy Attack

"The placement of a facility completely underground would be an example of an intrinsic PP [physical protection] feature." **(**The Proliferation Resistance and Physical Protection Evaluation Methodology Working Group of the Generation IV International Forum, 2011, "Evaluation Methodology…Physical Protection of Generation IV Nuclear Energy Systems". **)**

CLAB: Water-Cooled Spent Fuel Storage Facility

Full-Scale Demonstration of a Water-Cooled Spent Fuel Storage Facility That Is Potentially Suitable for a UNP





- Construction started 1980
- Operations started 1985
- 220MTU/year receipt rate
- Capacity being expanded from 8,000 to 11,000 MTU

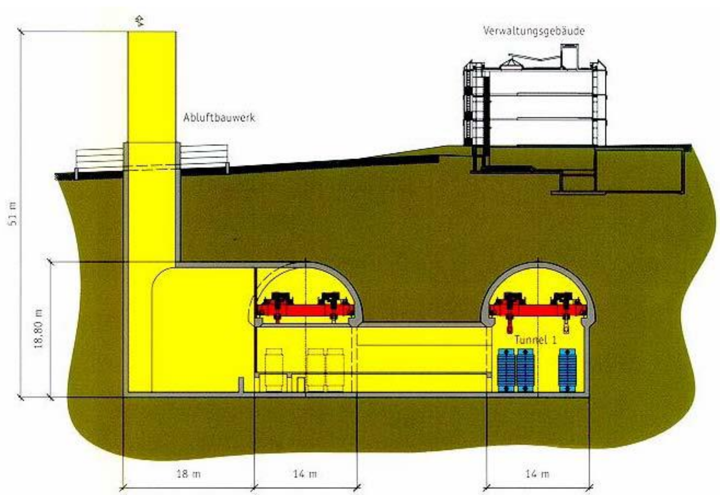
Cavern Dimensions: 120m L x 21m W x 27m H

https://www.skb.se/publikation/1109049/Clab.pdf
https: //www.sciencedirect.com/science/article/pii/B9781483284217501186)

Germany—Underground Storage is(was?) **Actually Underway**

"There are three technical concepts for on-site storage: storage buildings, a storage tunnel, and interim storage areas....storage buildings and the tunnel are envisaged for a license duration of 40 years..."

Neckarwestheim NPP



Two Tunnels*:

1) 112 m length x 12.8m wide x 17.3 m high = 24,801 m3

2) 82m length, 12.8m wide x 17.3m high = 18,158m3

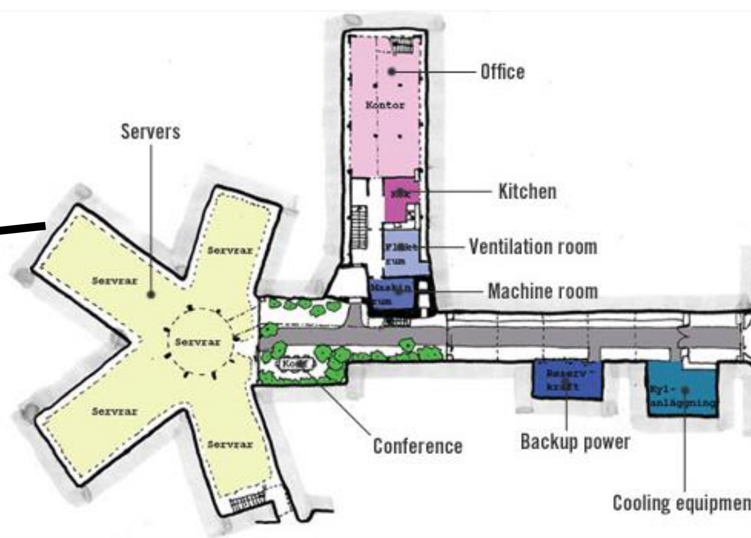
-- Number of canisters to be placed in tunnels = 151.

(= ~16 meters floor space per canister)

Facility Example: Ultra-Secure Data Centers

According to a Fortune report, the US saw $18.2 billion in investment for building or buying data centers in the first half of 2017. ...**Some of this growth is taking place underground**....**to save time, money and resources.**

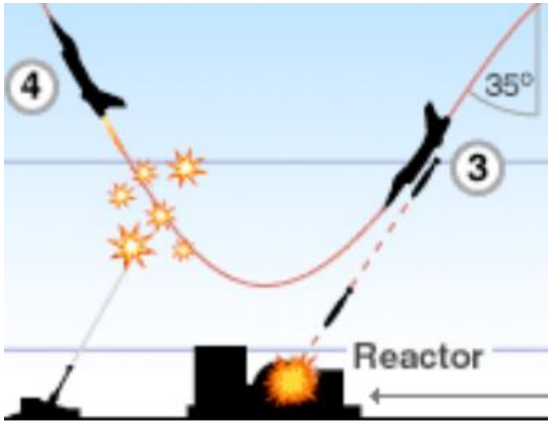
Bahnhof Pionen - Sweden



Demonstration of Human-Caused Risk to an Above-Ground Reactor

Result

Osirak reactor attack, 1981.



(http://news.bbc.co.uk/2/hi/middle_east/5020778.stm)

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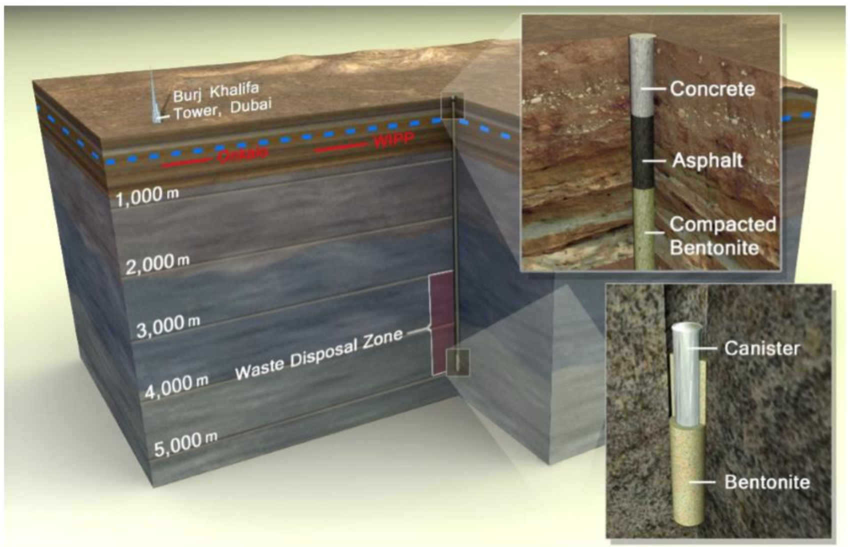
(https://fpif.org/israels_1981_osirak_attack_poor_precedent_for_attacking_iran/)

Geologic Disposal Facility: Borehole Disposal Option 1--Deep Vertical Borehole

Vertical Borehole Disposal of Spent Fuel *



- Deep Continental Basement
- Tectonically Stable Region
- Low Permeability Rock Mass
- Groundwater
  --High-Salinity,
  --Geochemically Reducing,
  --Long Residence Time

Estimated System Costs ($2011)*	Cost per Borehole
Drilling, Casing, and Borehole Completion	$27,296,587
Waste Canisters and Loading	$7,629,600
Waste Canister Emplacement	$2,775,000
Borehole Sealing	$2,450,146
Total	**$40,151,333**

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*Source: SAND2011-6749

For the 1200MWe UNP concept, assume

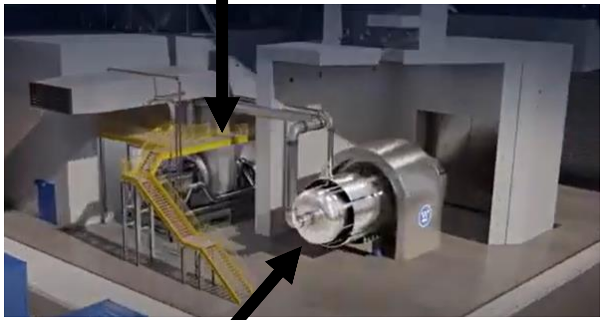
--60-year UNPP lifetime
--20 MTHM/1000MW/yr
--disposal capacity of 253 MTHM/borehole*...

...then, 6 boreholes would be required

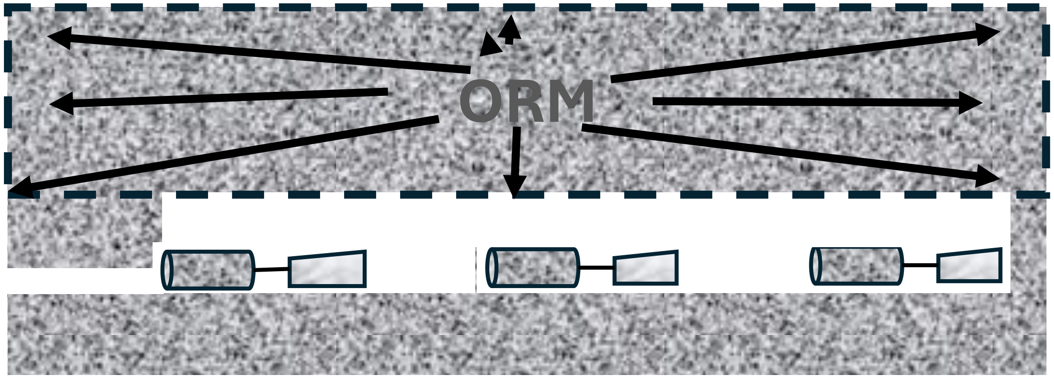
= **$240M** at $40m/borehole

Layout Example 3. Use Microreactors such as the eVinci
Containment Envelope = Reactor PV + ORM

eVinci Turbine-Generator



eVinci Reactor



- < 10 ft in length, est. ~3 ft, diameter
- Truck transportable
- Heat pipe technology
- TRISO fuel
- 8+ years operating life
- 15MWt, 5MWe

Possible Locations

eVinci diagram and information from Westinghouse

Lucens UNPP Reactor Accident*

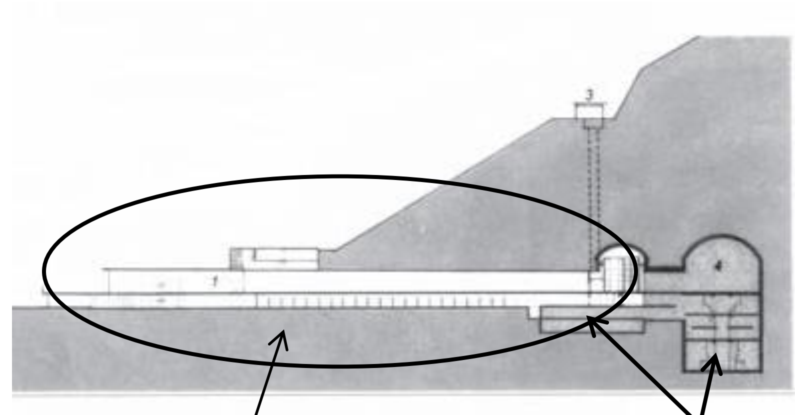
Demonstrated the containment effectiveness of a bedrock cavern

Reactor
CO2 cooled, HW moderated, 30MWt, 7MWe, 1962 construction begins, 1966 went critical

Accident (January 21, 1969)
Moisture in coolant → corrosion + fuel channel blockage→ cladding melted + pressure tubes ruptured→ explosion→2/3s core inventory released → Reactor vessel "damaged severely" → 5 tons contaminated HW flooded fuel handling room (4.44TBq primarily Cs137 and Sr90)

Consequences
"…no releases to the public…"
(IAEA Tech Report 439. p. 123)

D&D …included grouting of reactor chamber and fuel storage chamber. De-licensed 2003



~60m

Reuse

Grouted Chambers
(Reactor core and fuel pond)

Today: Lucens Cultural Centre
--Museum of Archaeology and History
--Storage for Cultural and Natural Artifacts

Source * https://en.wikipedia.org/wiki/Lucens_reactor and references therein