Underground Nuclear Parks and the Continental SuperGrid

SuperGrid 2 Conference

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Outline

- Nuclear Power Overview

- Concept of an Underground Nuclear Park
  - Advantages
  - Cost Issues
  - Specific Advantages of Thick, Massive Salt Units
- Potential for Capital and Operating Cost Reductions
- Reactors, Spent Fuel Storage and Repository
- Challenges and Issues
- Environmental Equity
- Energy and Hydrogen Storage
- Summary

Nuclear Power Overview

<u>Status</u>

- Commercial nuclear power reactor operations in the U.S.
  - Produce 20% of the electricity
  - Increased output by 1/3 from 1990 to 2003
  - Operated at 87% of capacity in ’03
  - “Clean, reliable, affordable”

- Excellent safety record continues
  - 2400 reactor years of operations
  - Three Mile Island might result in $\leq$ 5 cancer deaths over 30 years

- License extensions
  - Approved by NRC for 23 reactors, 19 under review, and more expected

- Nuclear power plants produce 18% of the global electricity supply
  - 27 reactors are under construction, 18 in Asia

(Information in part from Holt and Behrens, 2004, recent issues of *Nuclear News* and *Nucleonics Week*)

Nuclear Power Overview

Trends and Issues

- New Plant Construction
  - Interest stimulated by 2000-2001 electricity shortages and spike in natural gas prices
  - Nuclear Power 2010. DOE cost sharing to enable an industry decision by ’05 to deploy an advanced reactor by 2010
  - GEN IV Initiative

- Nuclear Hydrogen:
  - Growing interest in using high-temperature reactors to produce hydrogen

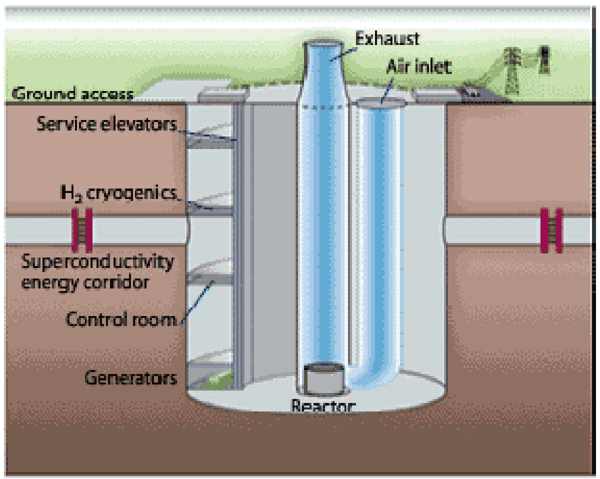
- Waste Management:
  - Continues to be controversial.
  - Direct geologic disposal is current policy. Yucca Mountain scheduled to open in 2010,
  - DOE’s Advanced Fuel Cycle Initiative is examining new approaches to reprocessing.

- Nuclear Plant Security:
  - Design basis threat increased by NRC in 2003.

- Proliferation
  - National and sub-national threats
  - Proliferation-resistant fuel cycle

Nuclear Energy and the SuperGrid

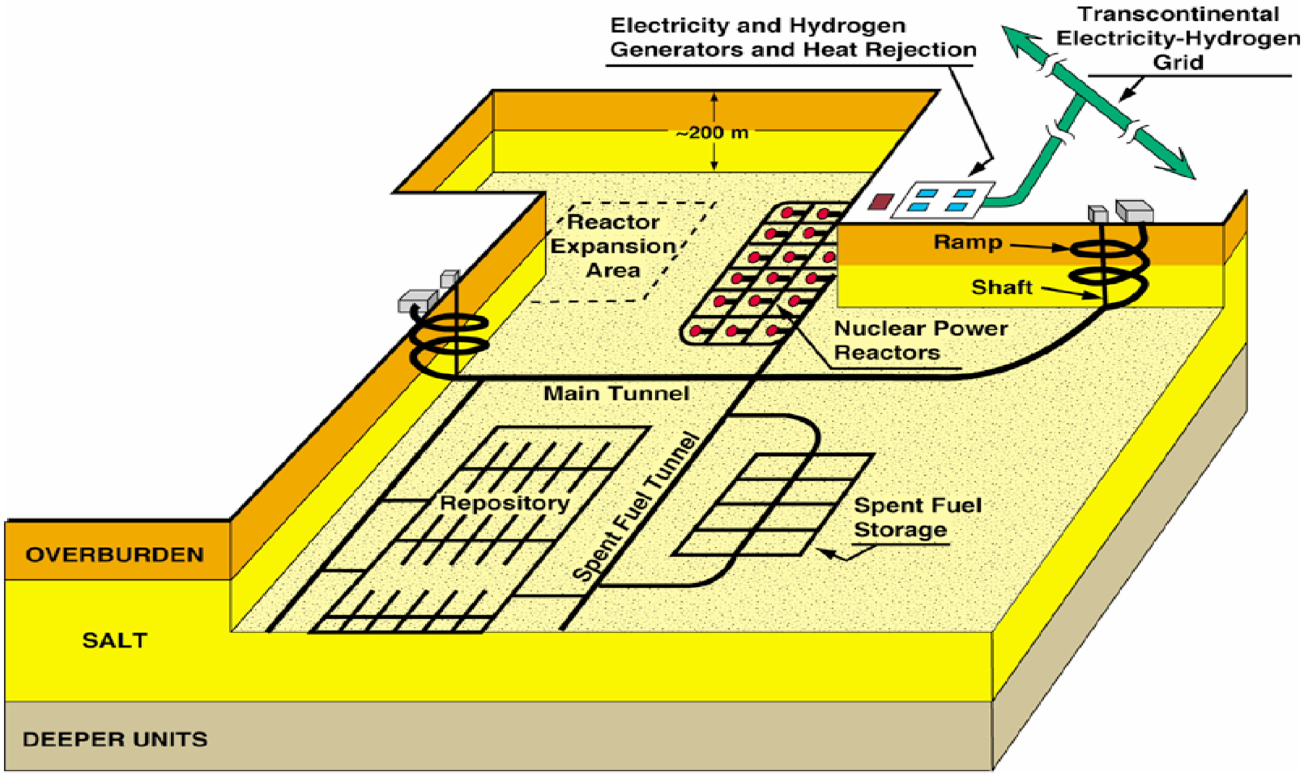
"We propose…an Energy SuperGrid, comprising a symbiosis of nuclear, hydrogen and superconducting technologies." (Grant, 2004)



SuperGrid section

- How will new nuclear power plants for the SuperGrid be deployed?
- Would deep underground siting provide advantages?
- Would co-locating several reactors to form an underground nuclear park be an advantage?

Concept for an Underground Nuclear Park to Supply Electricity and Hydrogen to the SuperGrid



- Superconducting materials for electrical transmission enables remote siting.
- Economies of scale are possible through co-locating numerous reactors
- Higher margins of security, safety, and proliferation resistance are possible through underground siting.

Why should the concept of siting nuclear power reactors underground be taken seriously?

1. Caliber of the Advocates

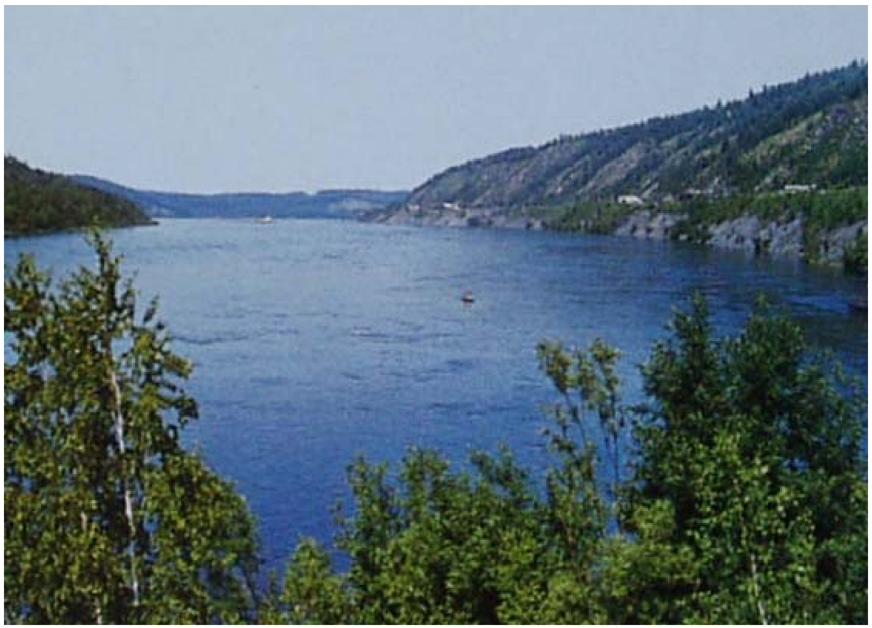
Plainly, mankind cannot renounce nuclear power, so we must find technical means to guarantee its absolute safety and exclude the possibility of another Chernobyl. The solution I favor would be to build reactors underground, deep enough so that even a worst case accident would not discharge radioactive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

Andrei Sakharov, *Memoirs, 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,* p. 565

2. Actual Experience: The world's first underground nuclear reactors were constructed and operated in central Siberia, Russia

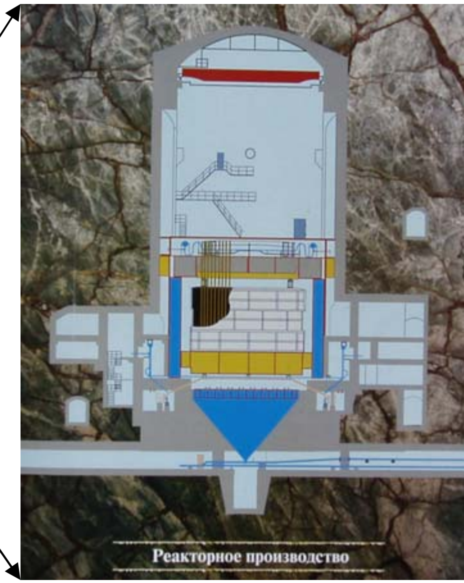


Yenisey River

Early construction operations

(Photographs from a brochure published by the Mining and Chemical Combine, Zheleznogorsk, Krasnoyarsk, Kray)

Russian reactors were commissioned in 1958, 1961, and 1964



Reactor
- *Uranium-graphite*
- *Water-Cooled*

The 1964 reactor produces electricity and provides hot water and heat for the city of Zheleznogorsk

Radiochemical Plant

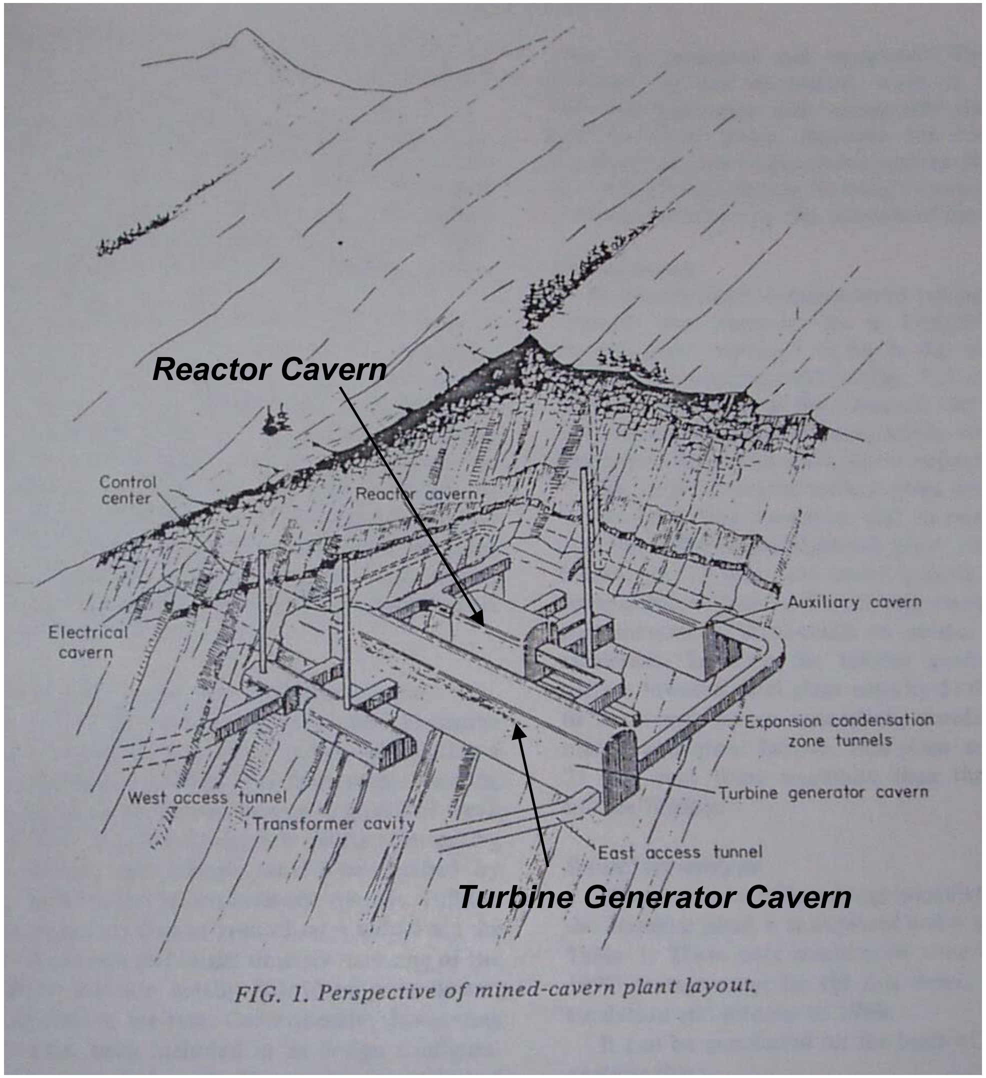
Turbine Room

(Photographs from a brochure published by the Mining and Chemical Combine, Zheleznogorsk, Krasnoyarsk, Kray)

3. Positive (mostly) Results from Studies in the 1970s in the U.S., Canada, Japan and Switzerland

- Scope of the studies included technical feasibility, safety, security, cost, advantages and disadvantages
- Siting concepts were based on existing designs of 1000 MWe light water reactors or 850 MWe CANDU reactors
- Components were positioned in interconnected caverns mined in bedrock.
- Technical and engineering conclusions
    - "…no insurmountable problems…"
    - "…proposed underground design concept is practically feasible
    - "…within the current state of the art…no technological restrictions"
    - "…feasible from the viewpoints of construction practice, schedule and cost penalty.

California Energy Commission Study



(after Finlayson, 1981)

- Produced a Conceptual Design Report
- Drew upon earlier design and operating experience for small underground reactors in France, Sweden and Switzerland
- Included PWR and BWR reactors
- Included underground and surface siting for the turbine/generators
- Generic tunnel and cavern complex
- Hillside location, 240 meters beyond portal, 100 meters deep

Ontario Hydro Study

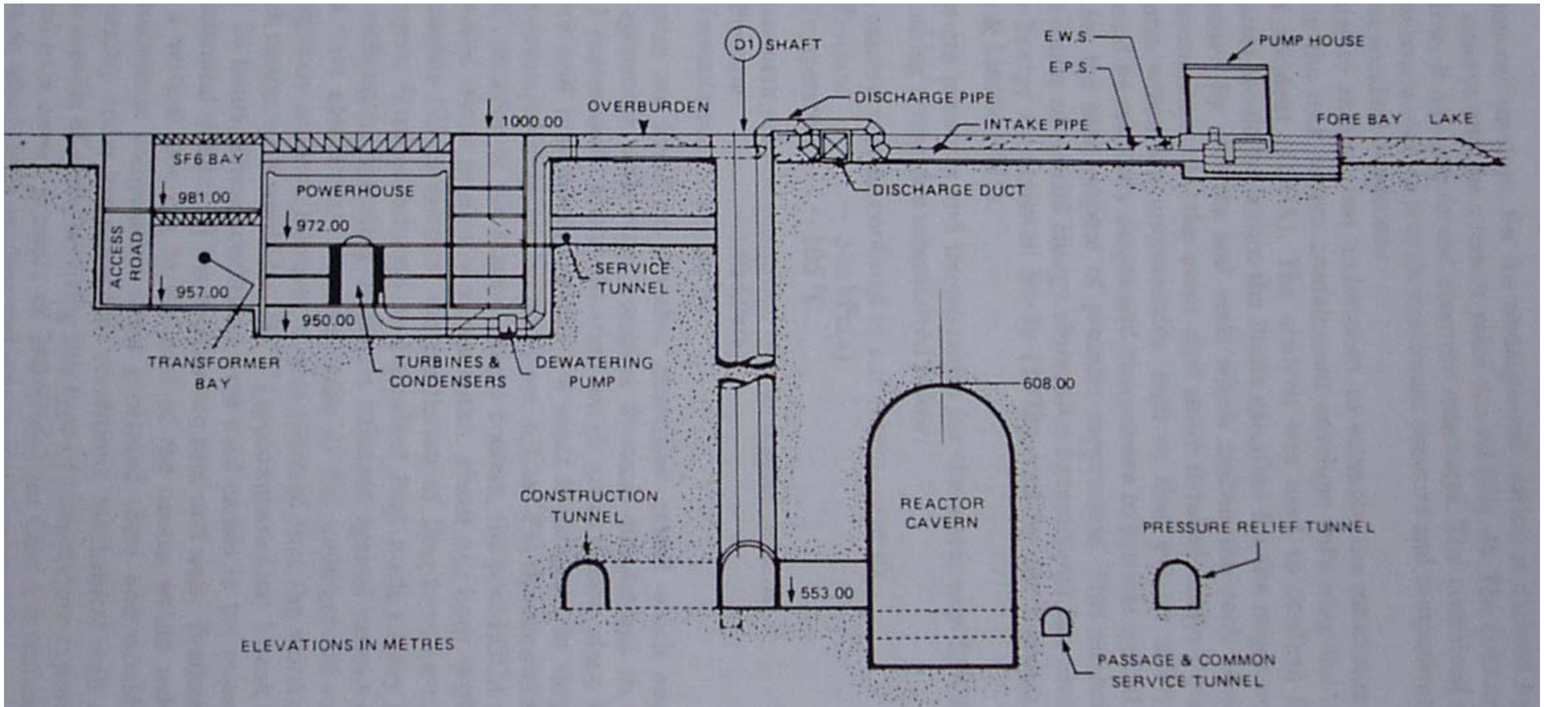


Fig. 5. Layout of rock caverns (plan and section).

- *CANDU Reactor*
- *Surface-Sited turbine/generators*
- *450 meters deep*

(after Oberth, 1981)

The 1970s studies revealed several probable <u>advantages</u> in underground siting

- Higher Resistance to…
  - Terrorist attack
  - Aircraft impacts
  - Proliferation
  - Sabotage and vandalism
  - Conventional warfare effects
- Higher Levels of…
  - Protection against severe weather effects
  - Landscape aesthetics
- Greater containment capability relative to a surface-sited plant…
  - Reduced public health impacts from extreme hypothetical accidents
- Less…
  - Seismic motion

BUT, the 1970s studies concluded there would be an almost certain schedule and cost increase caused by the construction of the underground facilities, and a possible cost increase during operations

Study Sponsor	Rock Type	Depth (meters)	Construction Cost Penalty
California Energy Commission	Granite	100	50-60%
Ontario Hydro	Granitic Gneiss	450	31-36%
Swiss Federal Institute for Reactor Research	Rock Types in the Swiss Alps	--	11-15%
Japanese Ministry of Trade and Industry	Sedimentary	150	20%

Result:

- Interest in underground siting waned in the West
- Three Mile Island
- Projected rates of demand growth in electricity did not materialize
- Surface sites appeared to be adequate

<u>However</u>, salt was apparently not considered in the 1970s studies as a potential rock type for underground siting

---Why Salt?---

- Thick, massive deposits of salt have attributes that could be significantly superior to granitic or sedimentary rocks.

- Salt has remarkable containment qualities, and well-known mechanical, chemical and thermal properties, as demonstrated through decades of successful…

  - Storage of crude oil, natural gas, and liquified petroleum gases in salt caverns
  - Worldwide salt and potash mining operations
  - Drilling through and into salt units during oil and gas exploration and production operations
  - Nuclear waste repository studies from the 1950's to present, especially in the U.S. and Germany
  - Waste Isolation Pilot Plant construction and operating experience

- Massive salt deposits are common in many of the world's sedimentary basins

- Thick massive salt beds can be 100s of meters thick and cover 1000s of square kilometers.

- These beds…
  - have relatively predictable lateral and vertical extent
  - are relatively dry, impermeable and lack fracturing
  - clearly low-cost to mine

Given these advantages, is the conclusion from the 1970s studies valid for salt, i.e., would underground siting of nuclear power reactors in salt deposits result in increased capital and operating costs?

- Possibly not…
- Why, because the positive attributes of salt for underground siting appear to have not been recognized, or, if recognized, not sufficiently appreciated. This is the case…

…especially for massive salt beds

…especially if several reactors, and spent fuel storage and repository facilities, are co-located to form an underground nuclear park.

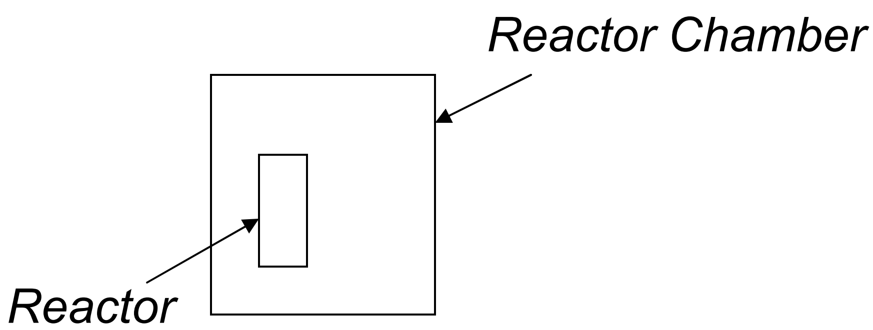
Moreover, we assert, capital and operating costs could actually be lower underground in salt--relative to surface siting--through the cumulative effects of a…

Reduction in …

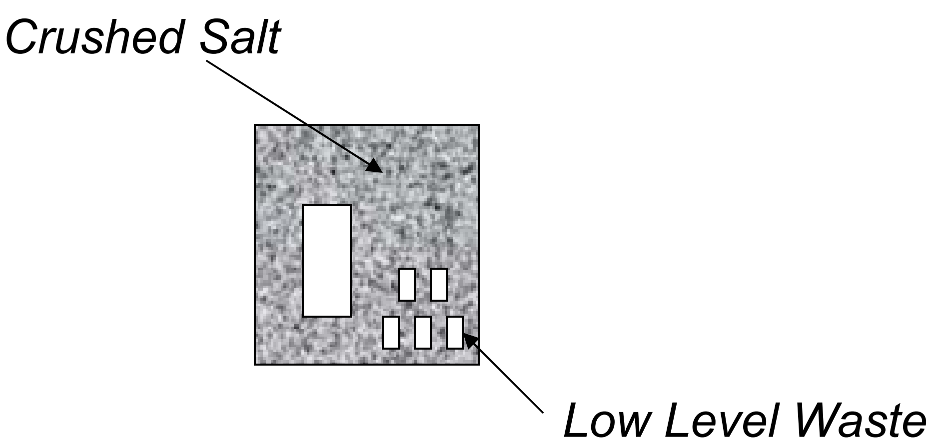
- Decommissioning costs, through in-situ decommissioning and disposal
- Transportation costs, through co-located storage/disposal facilities
- Excavation costs, which are ~$20/m^3 in salt *vs* ~$40 to $80/m^3 in granite
- Facility costs, through elimination of the containment structure
- Reactor costs, through the use of modular reactor
- Site costs for successive reactors, due to the lack of constraints on lateral expansion in the subsurface
- Security costs, because of the need for fewer guards and physical protection measures
- Insurance costs, through reduced health and property risks

Underground Siting Cost Reductions…

1. In-situ Decommissioning



• *Before Decommissioning*



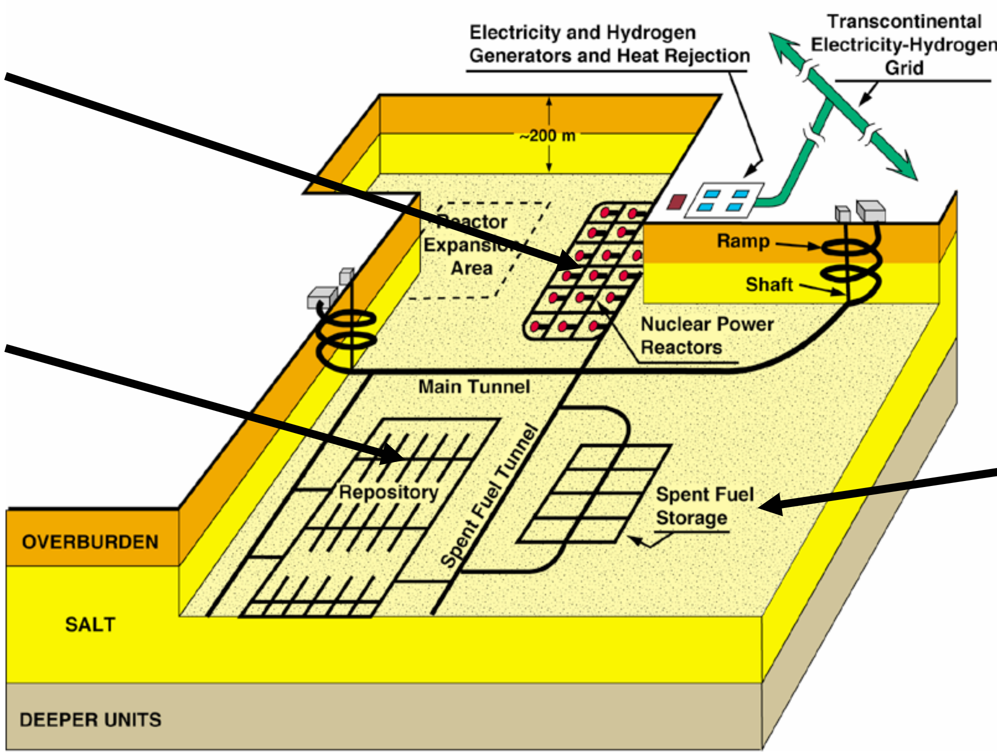
• *After Decommissioning*

"Underground nuclear power plants are also economical because they do not require expenditures…for disassembly, decontamination, and reburial. A spent underground nuclear power plant is simply buried where it is located with minimal work." Dolgov, 1994

2. <u>Spent fuel transportation costs and public concern associated with transportation will be reduced because of the close proximity, underground, of the reactors and the spent fuel storage facility and repository</u>

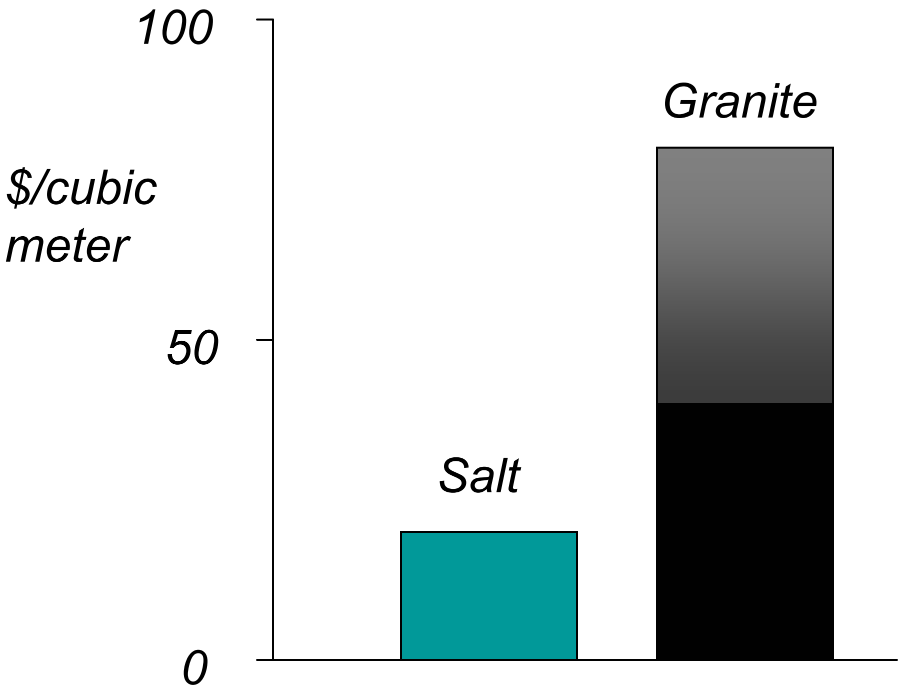
Reactors

Repository



Spent Fuel Storage

3. Lowered Underground Excavation Cost by 2x – 4x in Salt Relative to Granite



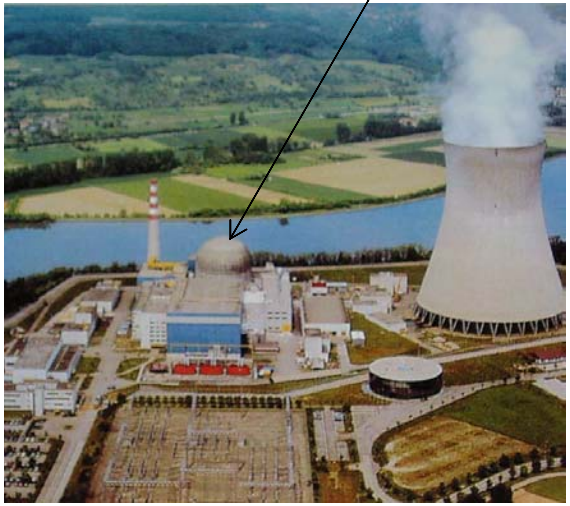
Alpine miner dressing out a tunnel mined by a drum road-header in the WIPP facility.

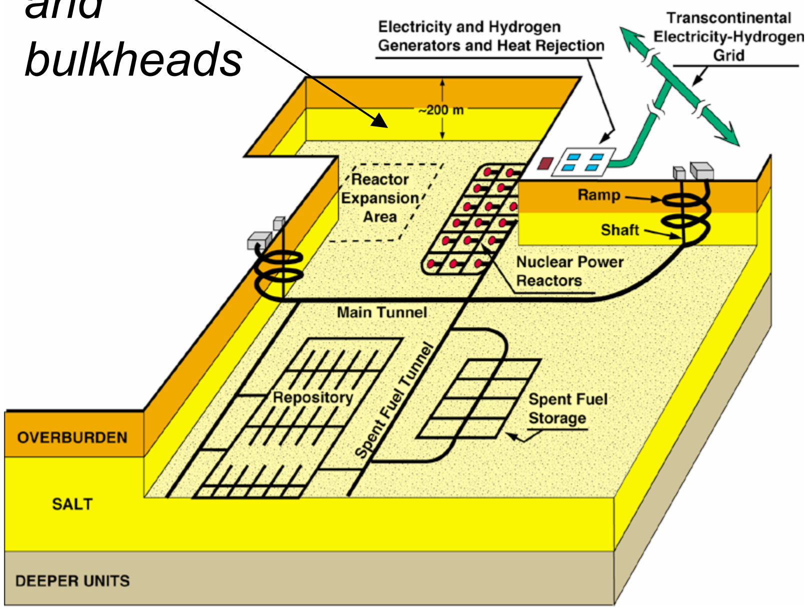
4. Elimination of Need for Conventional Containment Structure

Containment

concrete

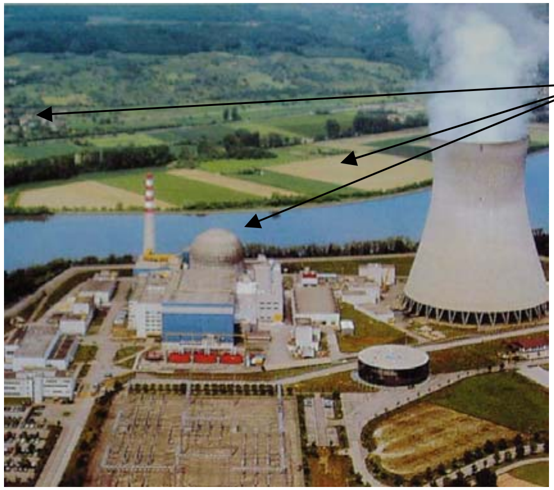
overburden and bulkheads



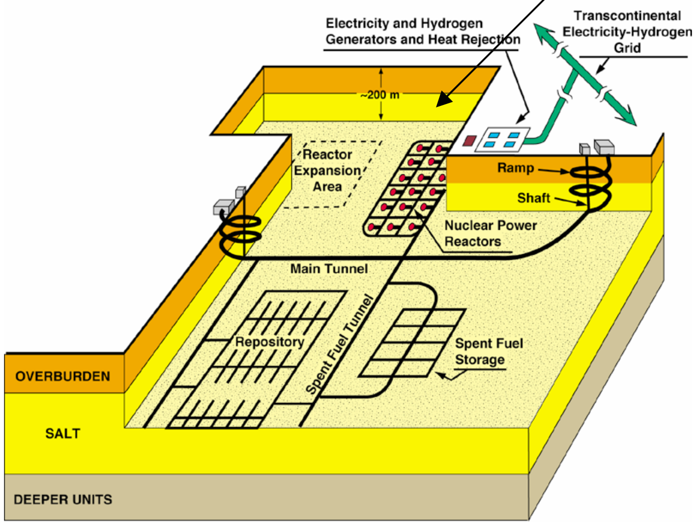


5. <u>Lack of constraints on lateral expansion will reduce siting costs relative to conventional surface sited reactors as successive reactors are deployed underground</u>

No constraints on lateral expansion



Conventional Siting



Underground Siting

6. Use of Modular Reactor Components

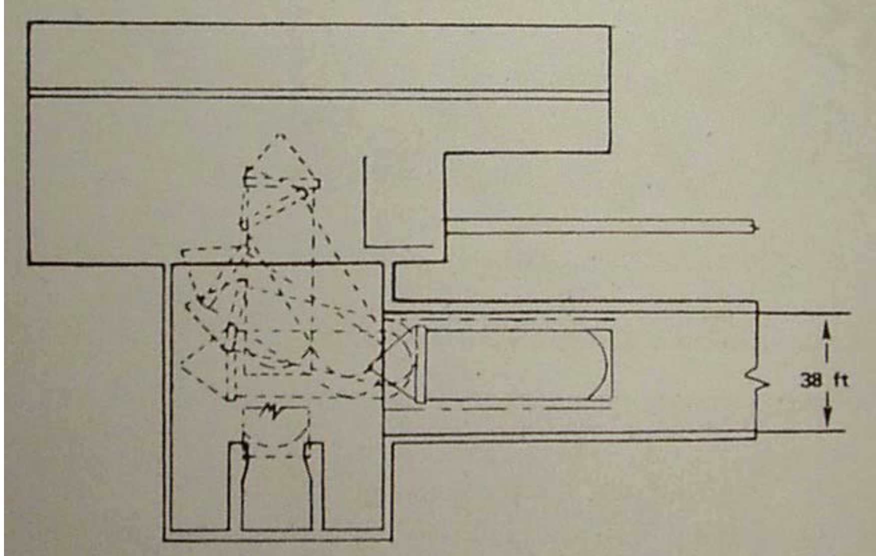


Fig. 7. BWR plant pressure vessel installation sequence diagram.

The preferred method of [reactor pressure vessel] transfer into the reactor chamber is down an inclined tunnel…[with] a diameter of 38-40 ft which is sufficient to provide both road and ceiling clearance …" (Kammer and Watson, 1975)

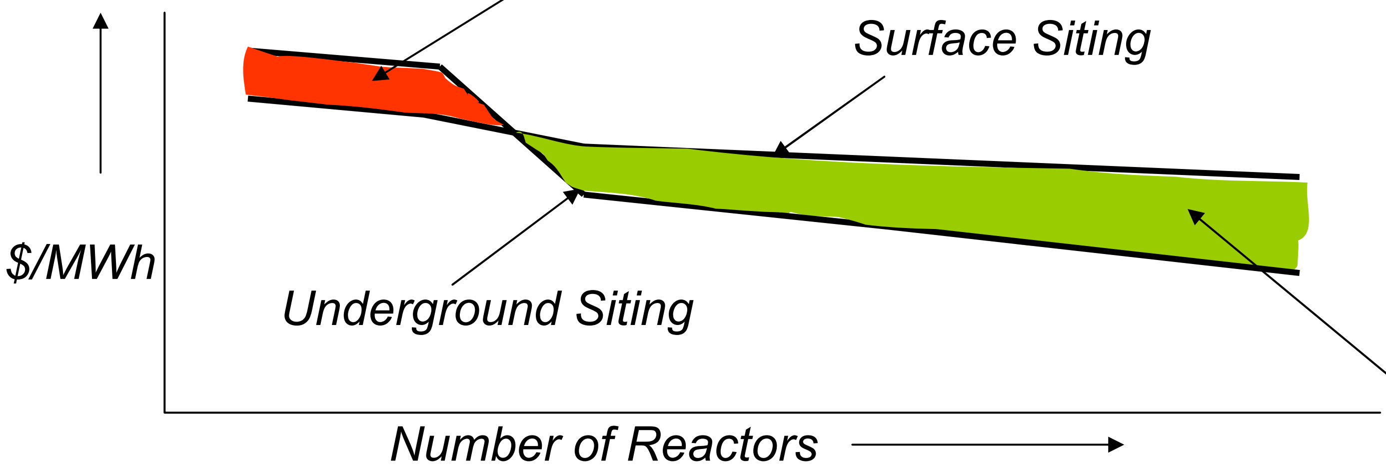
7. Reduced Requirements for Physical Protection

"The cost of security enhancements at Exelon's nuclear power plants alone is roughly $100 million. At Braidwood, for instance, the guard force has been doubled and where there used to be one – there are now seven guard towers – all of which will be manned 24/7." ABC7 Chicago, September 23, 2004.

Security measures to respond to the Design Basis Threat for an underground nuclear park should be less costly per reactor than for surface-sited reactors.

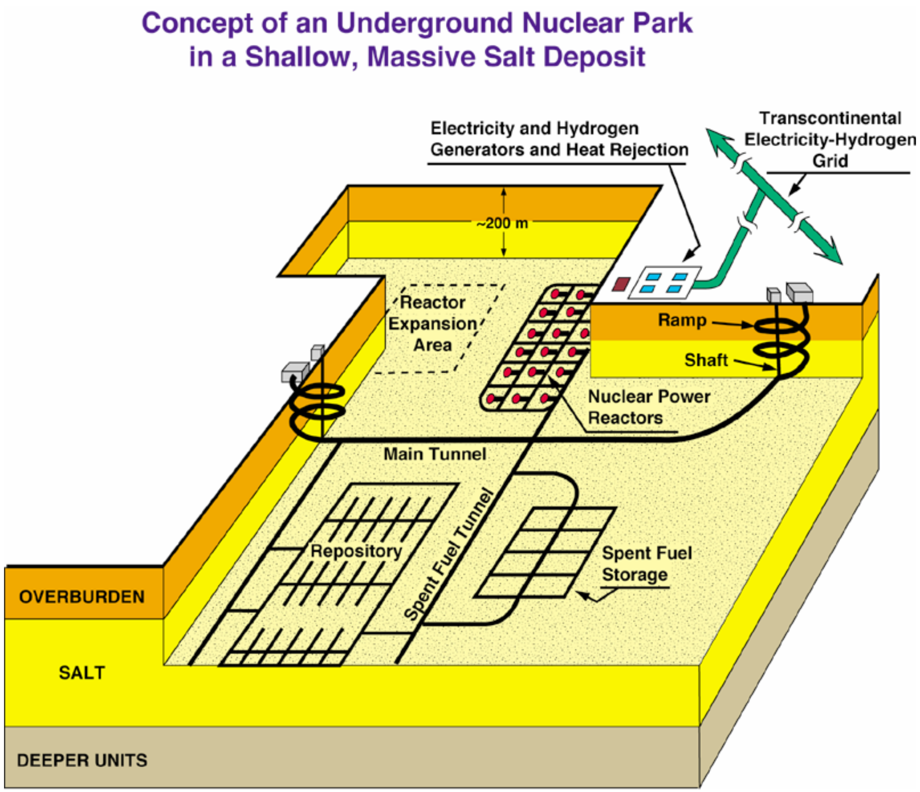
8. Reduced Premiums for Liability Insurance

First-of-a-kind engineering, procurement and construction (EPC) costs for the first reactors in an underground nuclear park would be high relative those for an equivalent surface sited plant.



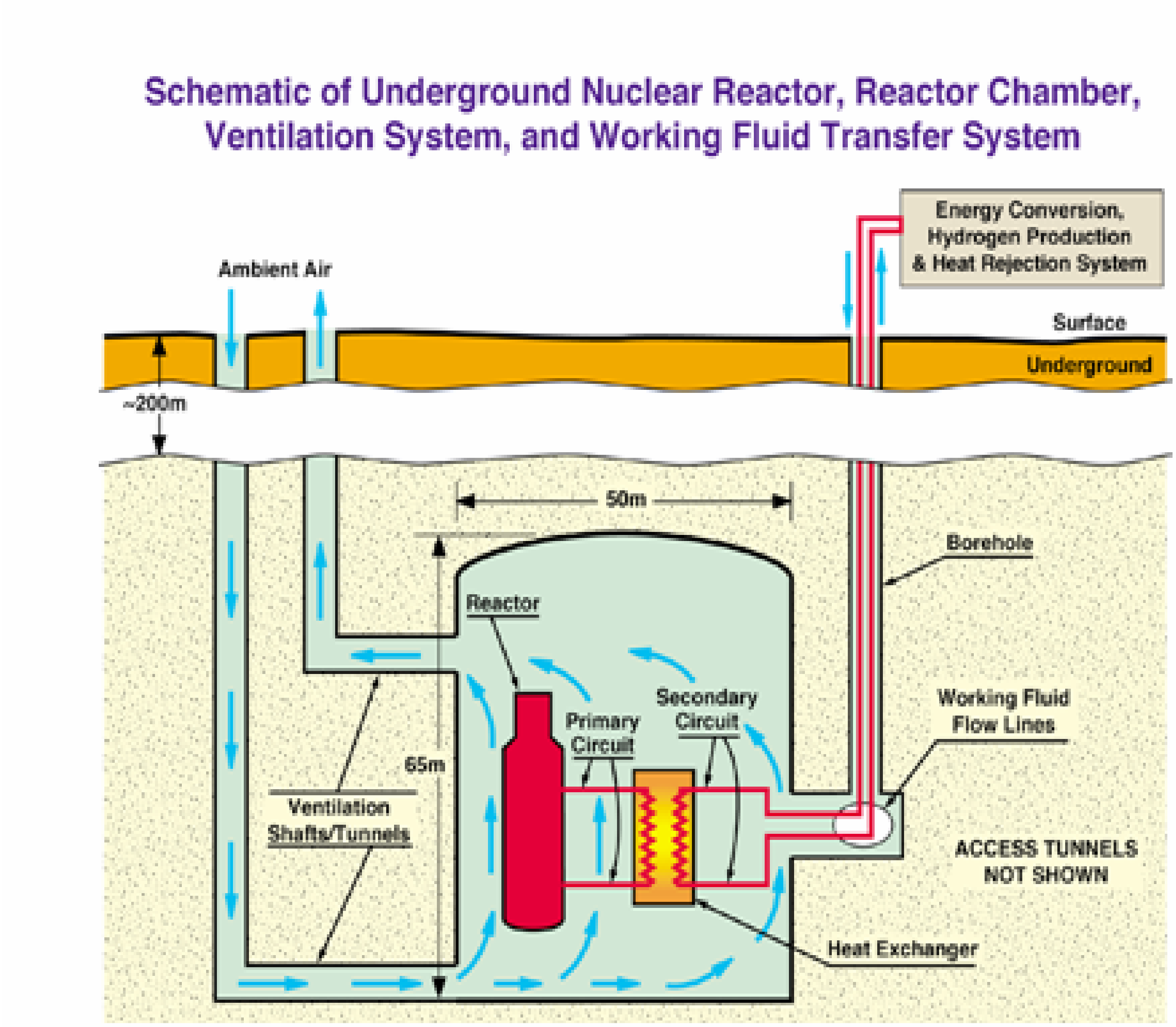
However, once the NRC approved specific reactor designs and specific underground layout and facility designs for combined construction and operating licenses, then the EPC process should be able to proceed with predictable and progressively lower costs for the nth reactor, relative to traditional surface-siting of equivalent reactors

Features of the Underground Nuclear Park Concept



- Array of high-temperature (>900^{0}C reactors suitable for electricity and/or hydrogen production
- Non-water cooled reactor designs
- Underground, passive air-cooling of spent fuel
- Use of ramps for entry of wheeled vehicles
- Use of seals and bulkheads to isolate individual reactors, sectors of the underground nuclear park, and the entire underground nuclear park from the surface

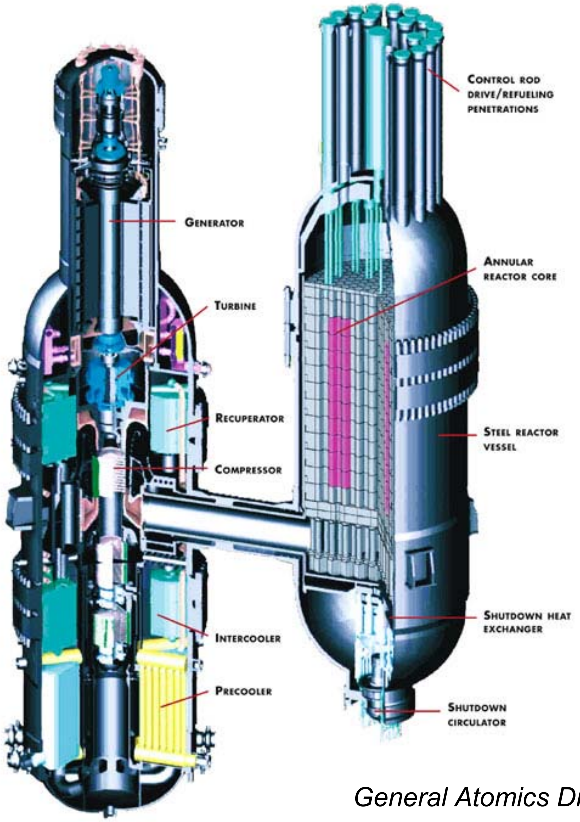
Reactor System Layout: One Possibility



Advanced Nuclear Reactor Designs Possibly Suitable for Underground Siting

Many possibilities, examples include

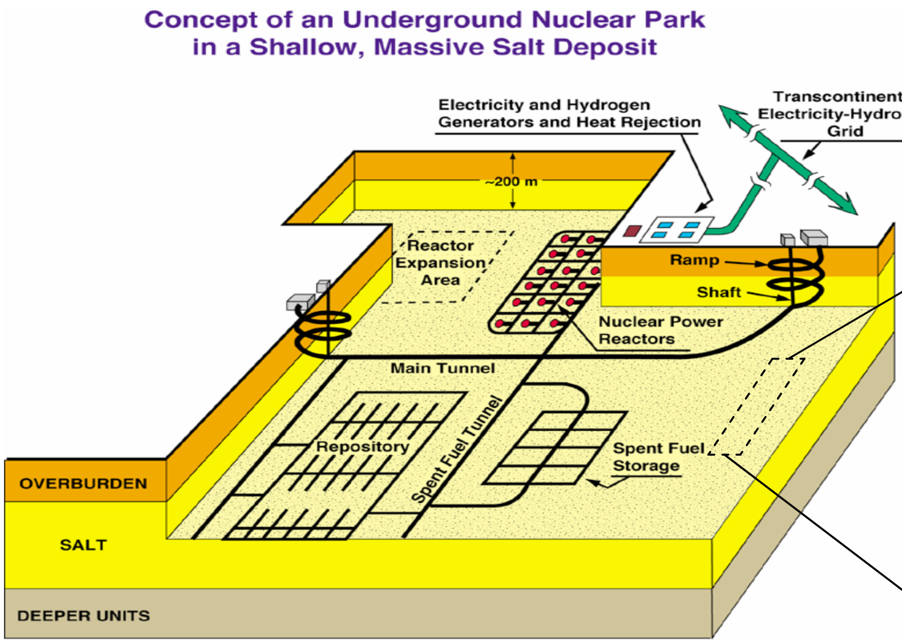
- Gas Turbine-Modular Helium Reactor (LeBar, Shenoy, Simon and Campbell,2003
- Advanced High Temperature Reactor (Forsberg, 2004)
- Pebble Bed Modular Reactor (Nicholls, 2001)



General Atomics Diagram

Gas Turbine-Modular Helium Reactor

Although Current U.S. Policy is for Direct Disposal of Spent Fuel, Underground Chemical Processing has been Demonstrated in Russia



…which raises the interesting prospect of whether reprocessing facilities could become part of an underground nuclear park, should U.S. policy change?

Challenges and Issues

Plastic Deformation (Creep)

- *Control by ground support and ventilation to remove heat*

Corrosion

- *WIPP and Salt Mining Experience demonstrates that salt is a desiccant—it removes water from the air*
- *Conclusion: Corrosion can be mitigated by control of water ingress and control of salt dust*

Abrasion

- *Salt is not an abrasive*

Optimum Reactor Type and Layout of System Components

- *3D layout is facilitated by the underground setting*

- *Safety Issues*
  - *Need for multiple access and egress points*
  - *Need for multiple fluid and ventilation circuits*

Regulatory Issue

- *USNRC does not have regulatory framework for underground reactors*

Psychological Issue

- *Dark, dirty, dripping, dangerous "mine" vs clean, dry, safe, modern underground industrial facility.*

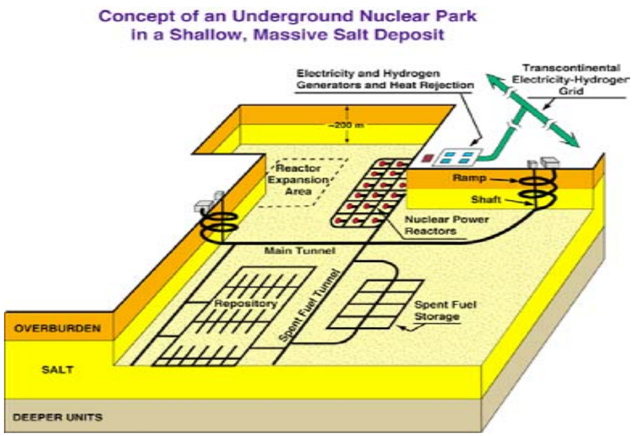
Environmental Equity and Underground Nuclear Parks

- Public opposition to siting nuclear waste facilities has been based on an equity argument:
  - If a community did not significantly benefit from the production of electricity from a nuclear power plant, then why should that community accept the nuclear waste from that nuclear power plant?
- Our concept of an underground nuclear park means that the community that benefits from the operation of the nuclear power plants is the same community that accepts the nuclear waste produced by those nuclear power plants---environmental equity is promoted.

Thick, massive salt deposits could be used to construct facilities for compressed air energy storage (CAES) and hydrogen storage

<u>CAES Plants in Salt</u>

- *Huntorf, Germany, 290 MWe plant, two 10 million cubic feet caverns*
- *McIntosh, Alabama, 110 MWe plant, one 20 million cubic feet cavern*



<u>Hydrogen Storage in Salt</u>

"For underground storage of hydrogen…options include abandoned natural gas wells, solution mined salt caverns, and manmade caverns."

(W.A. Amos, 1998, "Costs of Storing and Transporting Hydrogen, NREL/TP-570-2506)

Summary

Underground nuclear parks, especially in massive salt units, could possibly be a means to

- produce baseload quantities of electricity and hydrogen to supply to the SuperGrid, and provide
  - increased margins of security, safety and proliferation resistance
  - new approach to waste management
  - greater environmental equity
  - higher levels of public acceptance
  - lower capital and operating costs relative to equivalent surface-sited nuclear power plants