"Insights from worldwide experience for the design of underground workplaces"

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Focus on Design for People in Underground Rock Cavern Spaces

- Psychological and physiological effects in underground spaces
- Summary of design guidelines
- Exterior and Entrance design
- Layout and spatial configuration
- Interior design elements and systems
- Lighting
- Life safety

Psychological issues

- Perceptions of underground space
  - Typically negative
  - Occasionally positive (e.g. natural cave formations)
- Lack of stimulation
- Poor air quality and lighting
- Surveys
  - Unpleasant, dangerous, musty, dark, smothering, unfriendly, gloomy, isolating
- Analogous spaces aboveground

Summary of Psychological Problems Associated with Underground Space

- Lack of distinct image
- Finding entrance may be difficult
- Downward movement at entrance
- Lack of spatial orientation within facilities
- Loss of stimulation and connection to natural environment
- Sense of confinement and claustrophobia
- Darkness, coldness and dampness
- Connotation as less desirable/lower status space
- Associated with fear of collapse or entrapment

Summary of Potential Physiological Problems with Underground Space

- Lack of exposure to natural light and the sun
- Issues due to poor ventilation and air quality
- High levels of humidity and associated health issues, e.g. with molds and fungi

Mitigating Factors

- Building function
  - People oriented or non-person entry
  - Typically windowless due to function
- Occupancy patterns / freedom of movement
- Type of activity
- Social contact
- Size of space
- Degree to which space is fully underground
- Quality of interior spaces
- Individual variation

Entering the Underground Facility

- Hillside entrances
- Entrance pavilion

Entrances (2)

- Sunken courtyard
- Open-air covers

Vertical transport

- Elevator
  - Vertical
  - Inclined
- Escalator
- Mine Hoist

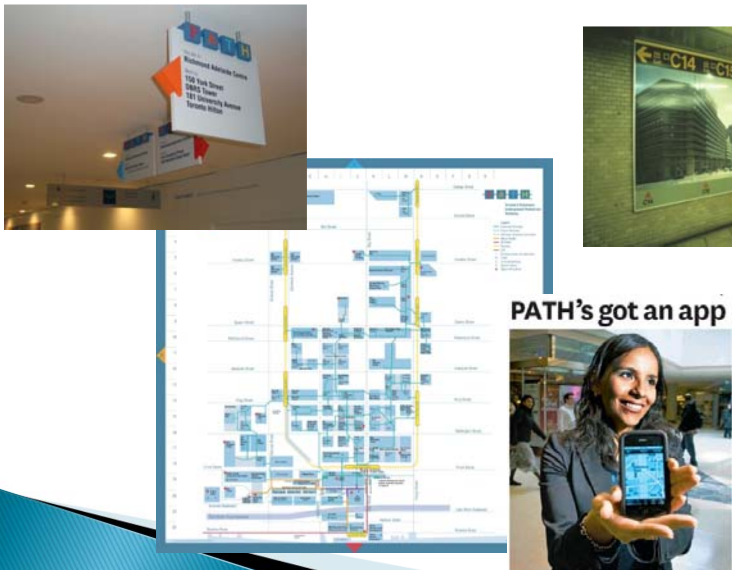



Layout and Spatial Configuration

- Enhance orientation and safety with a layout that is easy to understand
- Distinct image for interior spaces
- Stimulating and varied indoor environment
- Visual connection from interior to exterior
- Spaciousness through extended interior views
- Manipulate room size and shape to enhance spaciousness
- Arrange spaces to protect privacy

System of Paths, Landmarks, Activity Nodes and Zones

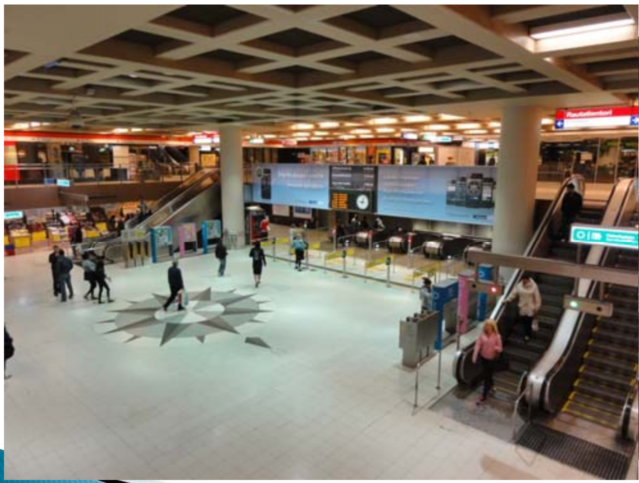
Clear System of Signs and Maps



Thoroughfares & Passageways

Interior Windows vs Privacy

Room Shapes, Heights and Interconnected Spaces



Interior Design Elements and Systems

- Interesting indoor environment to create a pleasant level of stimulation
- Connection to the natural world
- Feeling of spaciousness
- Feeling of warmth to offset perceptions
- Fresh air and thermal comfort
- High quality interior design elements and materials
- Clear and attractive system of signage

Colorful, warm and spacious

Line, Texture and Pattern

Natural Elements and Materials

Furnishings, Plants, Mirrors

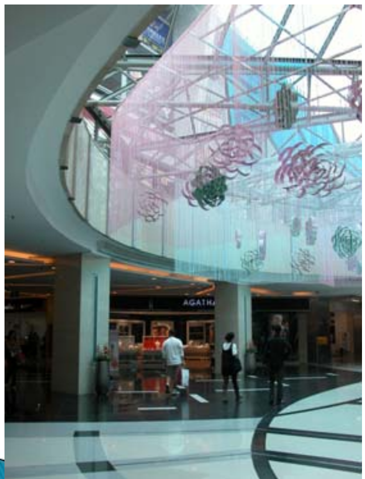
Alcoves and Paintings

Lighting

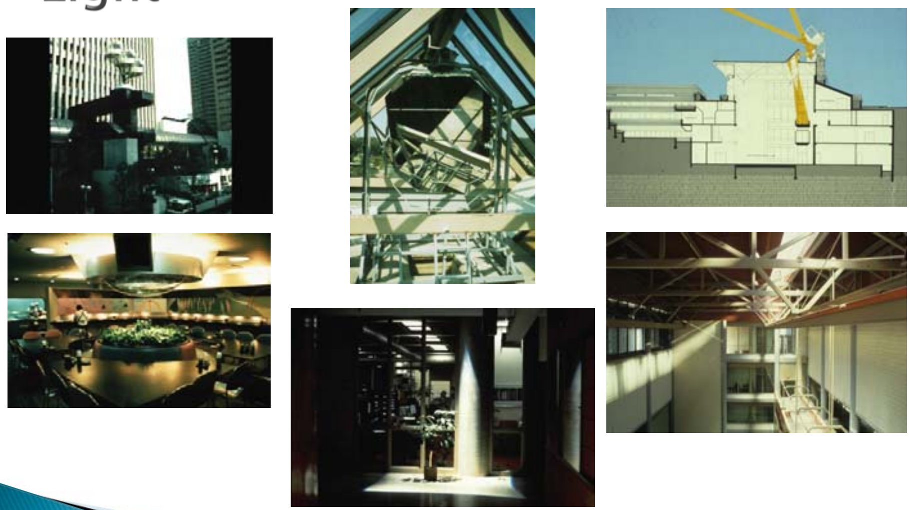
- Appropriate levels of illumination
  - Enhance visual clarity
  - Offset negative perceptions
- Provide natural light where possible
- Simulate the characteristics of natural light
- Use lighting to enhance feeling of spaciousness
- Create stimulating and varied environments
- Define and reinforce social spaces

Terraced building with hillside entrance

Natural Light through Windows and Skylights



Transmitted and Reflected Natural Light



Artificial Light with Natural Characteristics
Skylights and Wall Panels with Artificial Backlighting

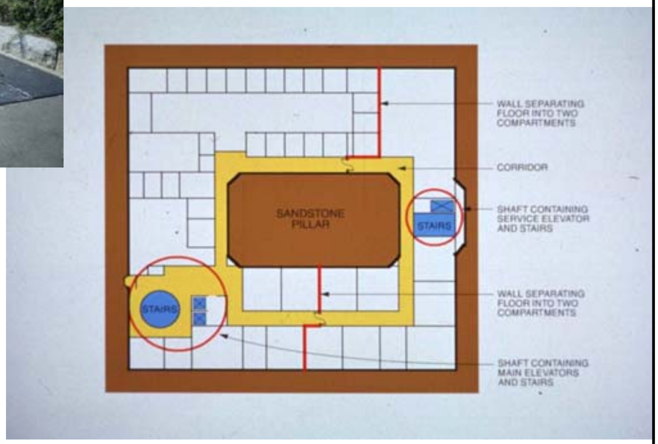
Life Safety

- Minimize hazardous/combustible materials or separate them from occupied areas
- Construct a fire-resistant building
- Construct a building resistant to appropriate natural disasters
- Early detection and warning systems
- Smoke removal and fire suppresion
- Efficient and timely evacuation of people to places of safety

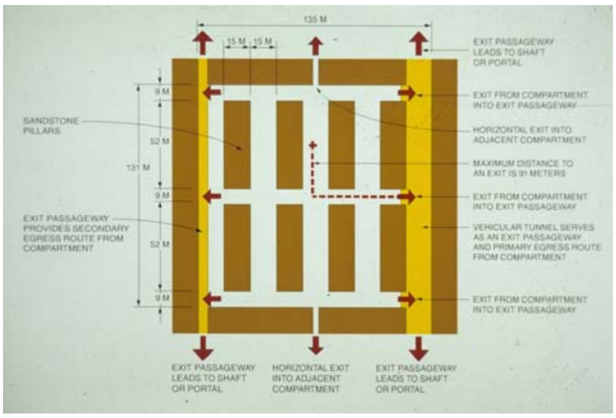
Clear Internal Organization and Egress System

- Emergency power
- Fluorescent strips
- Limit false alarms

Safe Vertical or Horizontal Egress



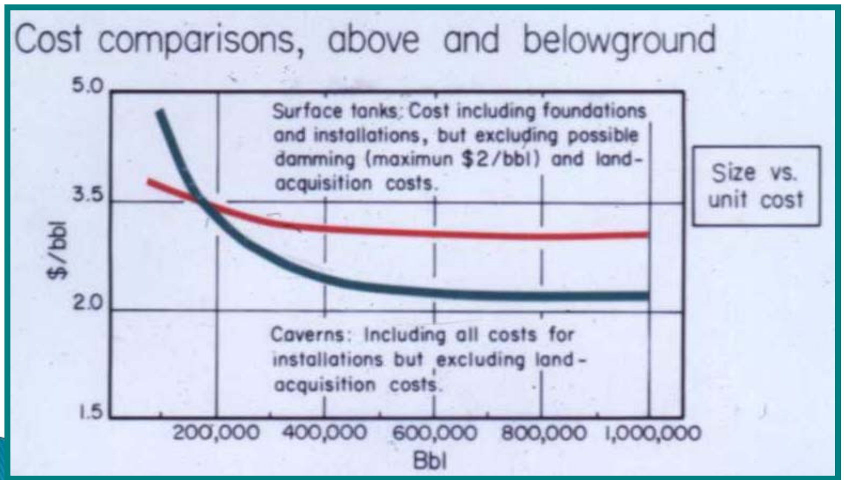
Compartmentalization and Places of Safe Refuge



Other Life Safety Components

- Clear Signage and Emergency Lighting
- Effective Detection, Alarm and Communication Systems
- Effective Smoke Removal and Air Handling
- Effective Fire Suppresion
- Fire-resistant Construction
- Restriction of Hazardous Materials

Cost versus Size for Oil Storage Caverns



Reuse of Mine Voids

Kansas City Area Facilities

- Many large facilities in limestone and salt
- One large mine (Hunt Midwest Subtropolis) Approx. Facts & Figures (2012)
  - 465,000 m2 mined out beginning in 1945
  - 46,500 m2 of leasable space
  - 50 companies; 1,500 employees
  - 4.9 m ceiling height; 10,000 limestone pillars
  - 10.7 km of paved roads; 3.38 km of railroad tracks
  - 394 truck dock locations

Public Use Facilities in Norway


Gjovik Swimming Pool

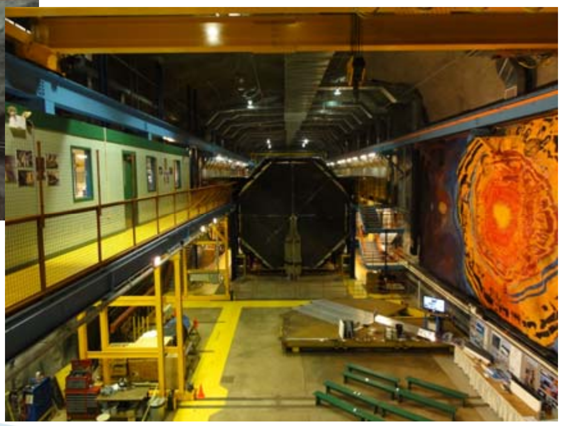

Gjovik Olympic Ice Hockey Arena

Military Facilities


NORAD Facility entrance

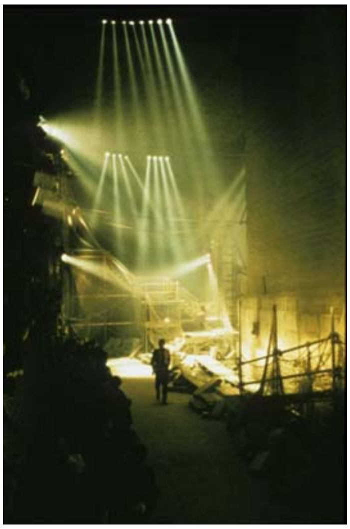

Sweden

Soudan Physics Research Facility



Ohya Stone Cavern, Japan

- Multiple uses
- Food storage
- Natural cold storage
  - Winter-summer convection differences
- Special events
  - Fashion show



Helsinki – Church in the Rock

A Healthy Mine: Wieliczka, Poland

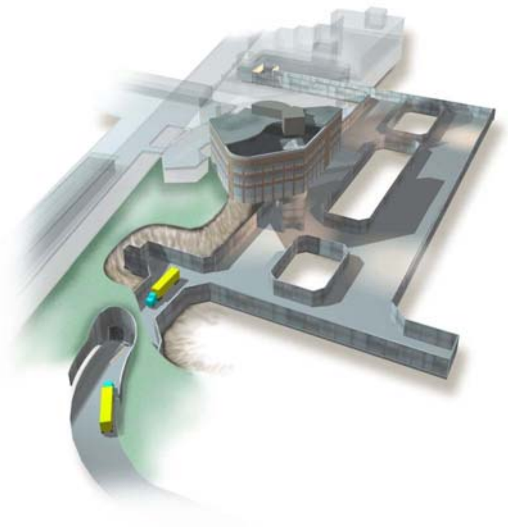
Station Caverns in Rock

- Washington D.C – consistent form in soil or rock

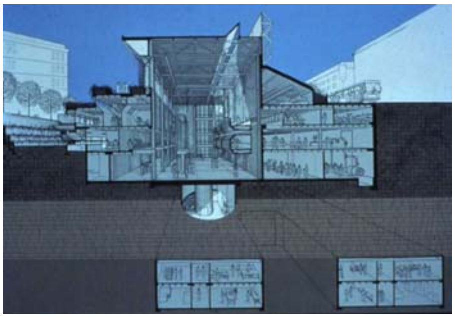
- Stockholm – individual artist decorated stations with natural rock contours

University of Minnesota Archives

- Public facility above
- Archives below in rock cavern



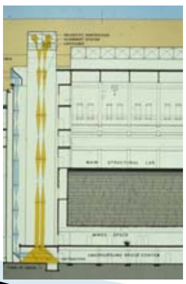
Civil Eng. Building, University of Minnesota



- Rationale: An energy-efficient demonstration building saving surface space on a crowded campus
- Key features: One third of building in mined space, sunken courtyards for entrance and faculty office area, variety of energy and lighting features
- Technical: Many technical issues
- Overall result: Opened in 1981 and recently renovated. Has served the Dept. well but has provided a range of difficulties and lessons learned

Lessons learned: Energy and lighting features

- Heliostat sun tracker difficult to maintain
- Lenses on passive view system too hard to clean
- Passive solar water wall too hard to control and developed algae issues
- Passive Fresnel lens sun tracker for walkway proved a nice feature



Lessons learned: Design features

- Sunken courtyard entrances present maintenance issues – snow, leaves, rain
- Hierarchy of office spaces worked well
- Graduate student spaces had mixed acceptance
- Most spaces functioned reasonably well
- Budget for building was the same as for a surface building of the same type

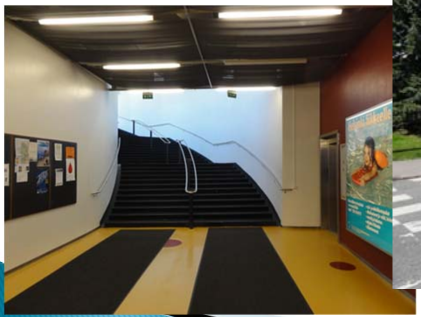
Lessons learned: Technical features

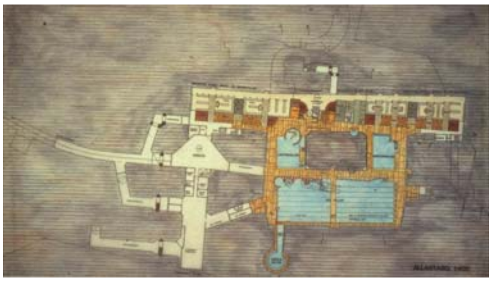
- Good energy performance despite large laboratories
- Environmental laboratories deep underground require long ductwork connections and high air exchange rates
- Drainage systems in mined space presented many problems
  - Rise in groundwater level required increased pumping
  - Suspended drainage system below rock roof suffered major corrosion and was hard to access
- Waterproofing of complex aboveground and shallow buried areas also presented many problems
- A/C units in mechanical room had poor condensate drainage system leading to leakage to the offices below

Williamson Hall, University of Minnesota

- Dual function building – offices and bookstore
- Similar design features to Civil Eng.
- Bookstore area OK
- Office area workers strongly against their working environment
  - Air intake too close to loading dock
  - Open plan office (overcrowding?)
  - Interior finishes
  - Access to light through solar planting scheme

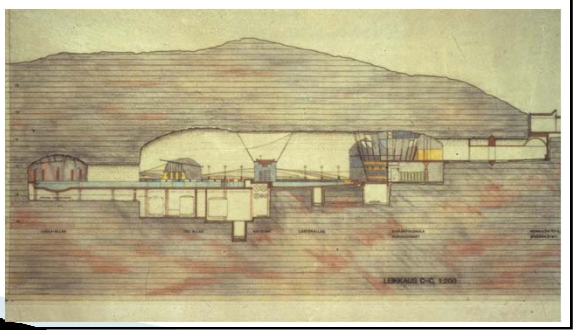
Itäkekus Underground Swimming Pool Helsinki, Finland





Itäkekus Experience

- Dual-use facility
- Well used by local community
- Attractive interior spaces using natural rock surfaces with shotcrete
- Still a well-liked showcase facility



Cavern Design

- Most economically viable when:
  - "Competent" rock with easy access
  - Rock useful as an aggregate or fill
- Depth and easy access is important
  - Deeper caverns require higher value uses
  - Favorable rock conditions may alter normal trend to higher costs with depth
  - Pedestrian access from surface probably within 100 m of surface
  - Utility tunnels in rock may be placed deeper to leave room for more critical uses near surface

Cavern Design (2)

- Integration of underground and aboveground developments to create synergy
- Features to address human psychological issues
- Match layout of facility to economical cavern shapes
- Back-up systems – especially for lighting and fire ventilation
- Planning for future flexibility in use
- Multi-use cavern developments
  - Ownership of common access shaft/tunnel?
  - Conflicting uses, e.g. boat manufacture with volatile materials

Cavern Construction

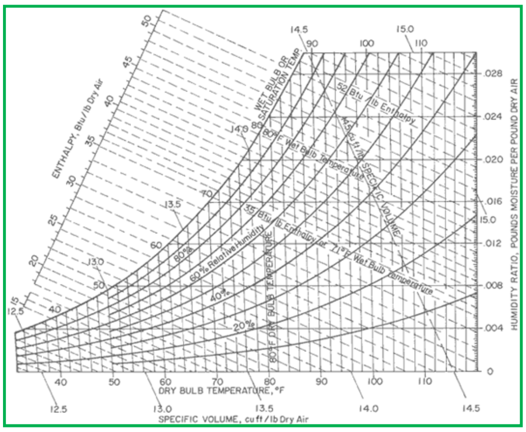
- Scale of excavation allows equipment use for high productivity
  - Mining costs vs civil construction costs
- Coordinating with surface uses and protecting the environment
  - Surface movement and groundwater monitoring
  - Vibration during construction and in operation
  - Utility and transportation access
- Mitigation methods, coordination issues
  - Control of excavation methods and timing
  - Integrated developments

Maintenance issues

- Business, operation and ownership models for existing cavern developments?
  - Generally single operator or owner, may sublease spaces.
- Mitigation measures to handle water/humidity within caverns
  - Waterproofing vs drainage
  - Plugging of drainage systems
  - Leak tracing
  - Level of water/humidity control

Moisture Control

- Cool rock surfaces
- Moist, warm outside air
- Without air-conditioning leads to condensation
- Re-heat systems
- Energy-efficient re-heat systems



Summary

- A wide variety of uses are possible and have been constructed in rock caverns
- Underground structures get special scrutiny for success/failure, have a long lifetime and they are difficult or impossible to remove
- Many long-term success stories but, some disappointments and failures
- Sustainable use of such facilities implies good design, longevity plus adaptability

Questions / Discussions

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