Safeguards for Geological Repositories: A Review and Considerations for Future Development

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Repository Safeguards

- Design information verification (DIV)
  - Undeclared structures, rooms, tunnels, etc.
- Nuclear materials safeguards
  - Timely detection of diversion
    - Nuclear material accountancy (NMA)
    - Continuity of knowledge (CoK)
    - Containment & Surveillance (C/S)
- Undeclared activities
  - Reprocessing
  - Tunneling/mining
  - Tampering with or removing casks

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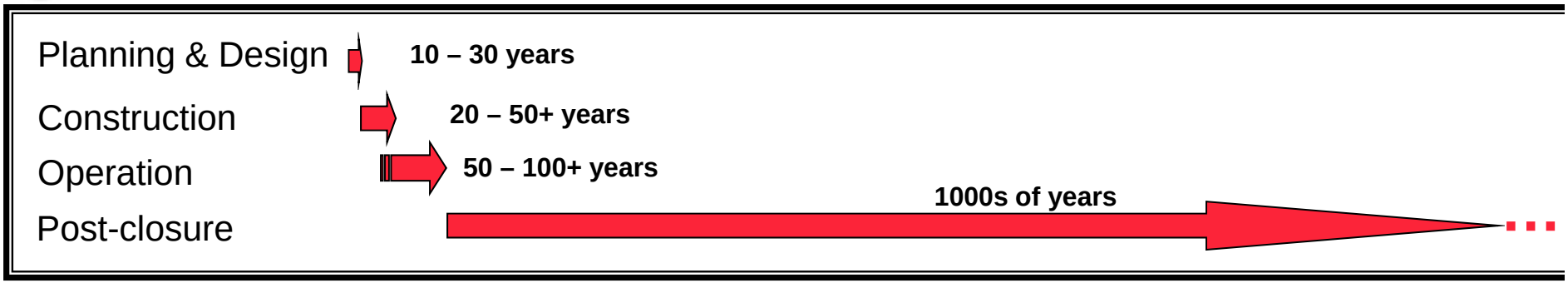
Major Repository Stages



- Planning and Design
  - Establish baseline: design information questionnaire (DIQ)
- Construction
  - Design Information Verification (DIV)
  - Potential design changes during construction
- Operation
  - Containment & Surveillance (C/S), Continuity of Knowledge (CoK)
  - Receiving, encapsulation, disposal/emplacement
- Post-closure
  - Monitor site activities
    - Inspections
    - Remote sensing
    - Passive monitoring systems

Concurrent Activities

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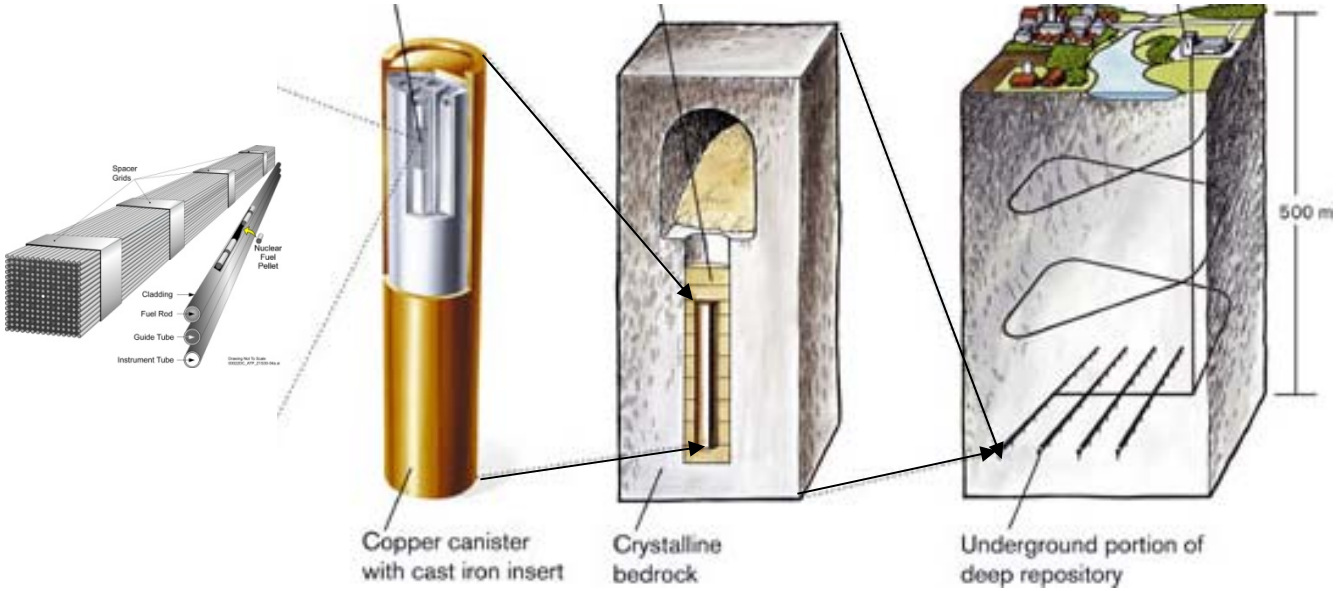
How to Maintain Continuity of Knowledge?
A Matter of Scale



METERS → TO → KILOMETERS

C/S: Containment is only effective if it can be <u>verified</u>

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Recognized Challenges

- Verify spent fuel
  - Fissile content
    - Technologies in development
- Continuity of knowledge after encapsulation
  - Effective Containment & Surveillance, Verification
    - Non-Destructive Assay (NDA) gross & partial defects
      - shielded cask or over-pack, unshielded canister, spent fuel assembly, can of consolidated spent fuel pins
- Time and spatial dimensions
  - Operation periods of *ca.* 100 years
    - Concurrent with construction
  - Repository area to be monitored (~tens km^2)
- Long-term safeguards post-closure
  - safeguards on spent fuel remain in force for as long as a safeguards agreement remains in force

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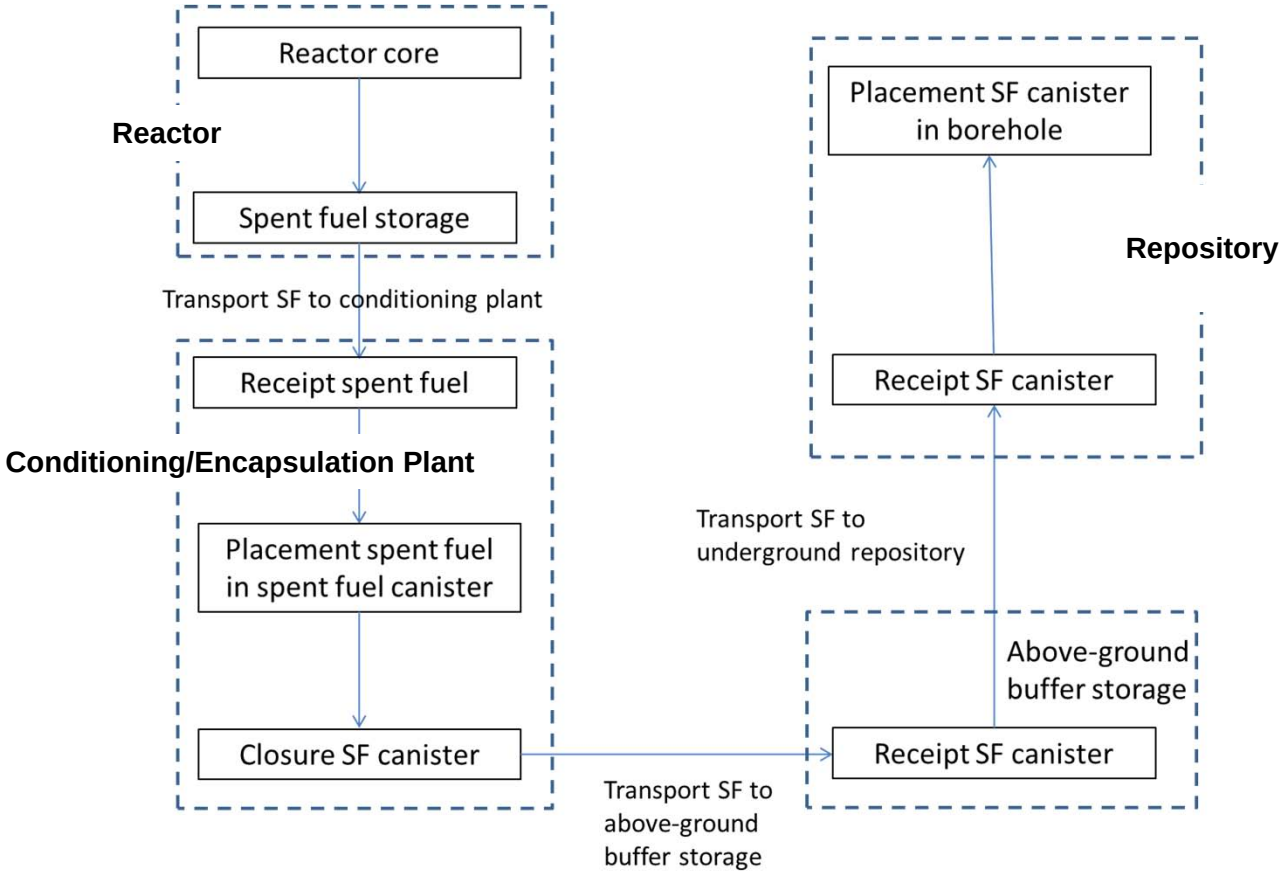
Material Flow

Fuel Assembles … from Reactor to Repository



Source: van der Meer & Turcanu, 33rd ESARDA Symposium, Budapest, May 2001.

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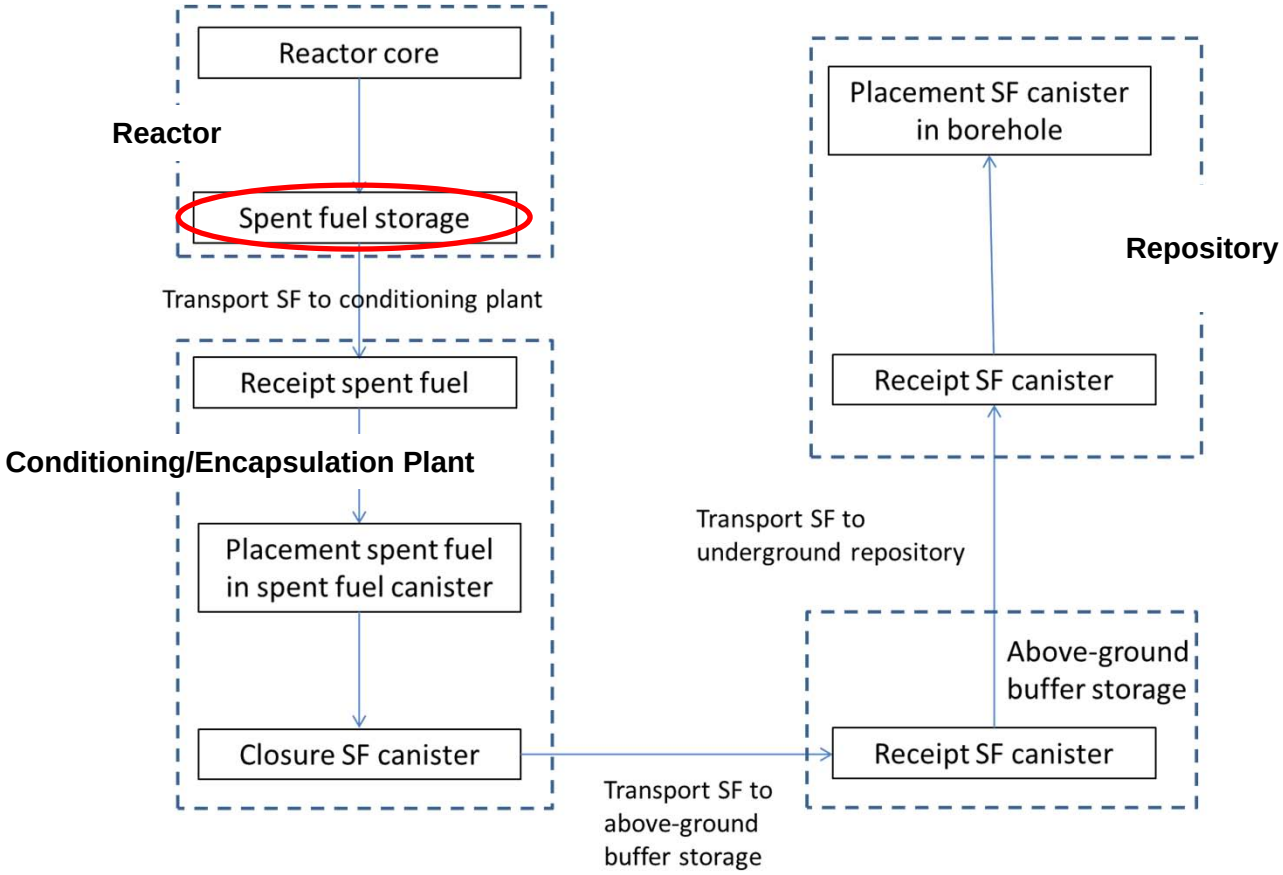
Potential Diversion Points
Reactor to Repository



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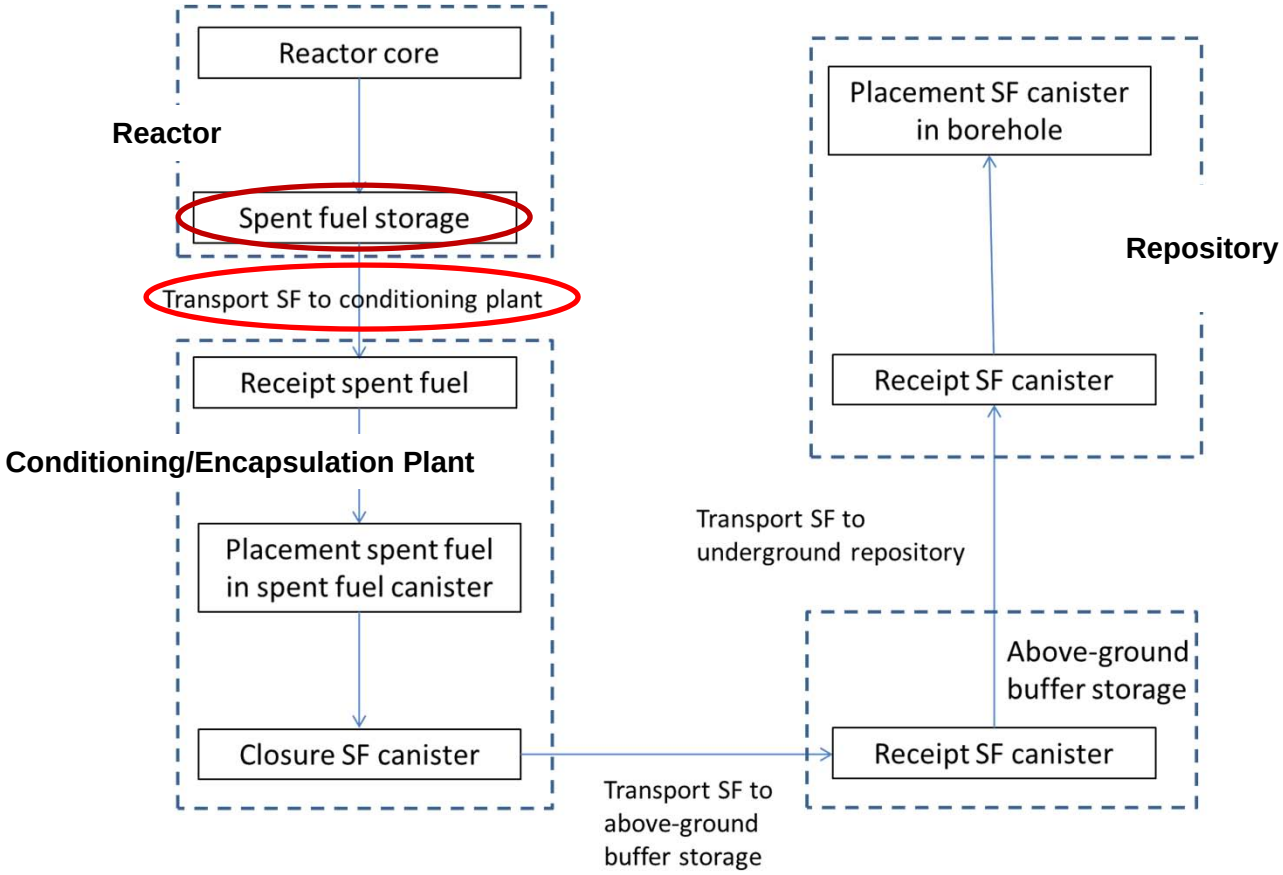
Potential Diversion Points
Reactor to Repository



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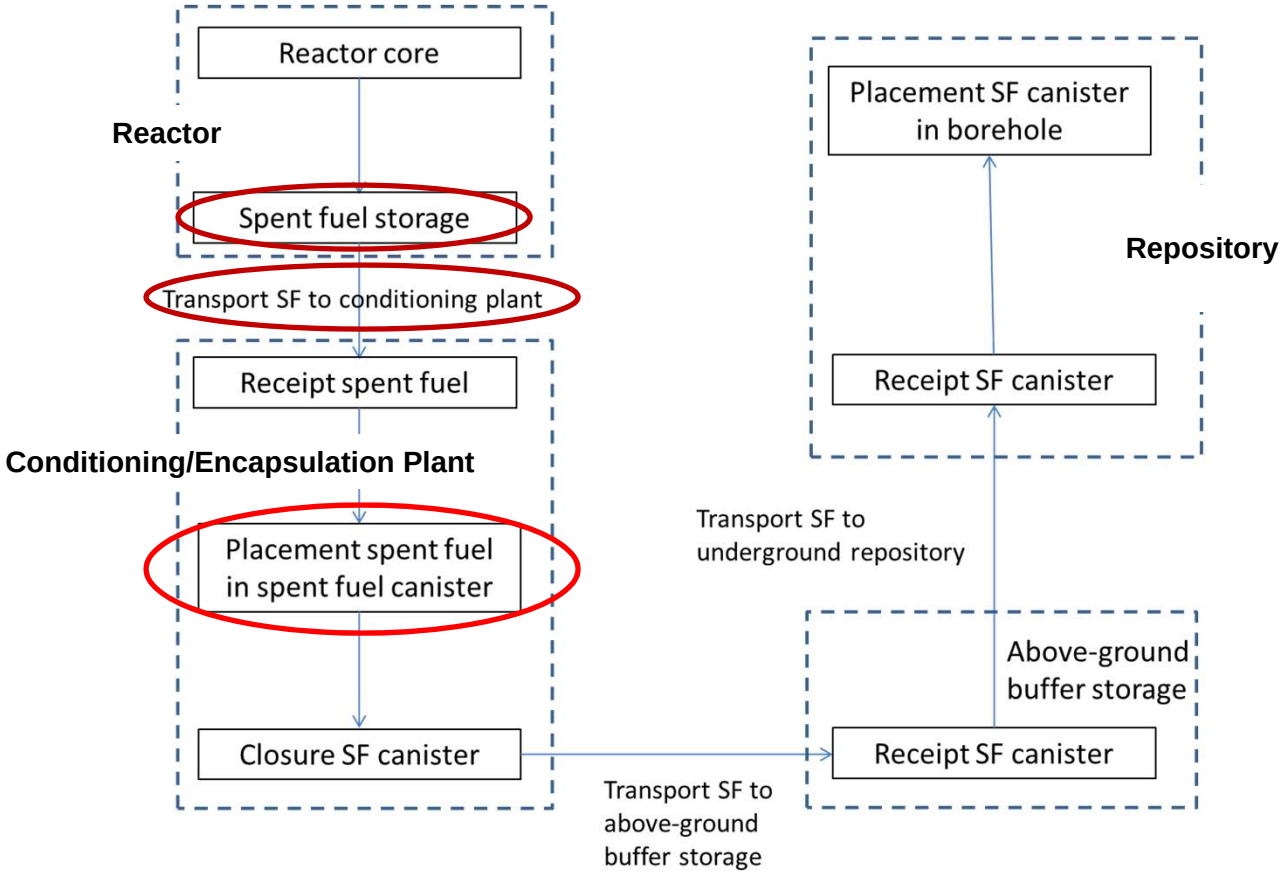

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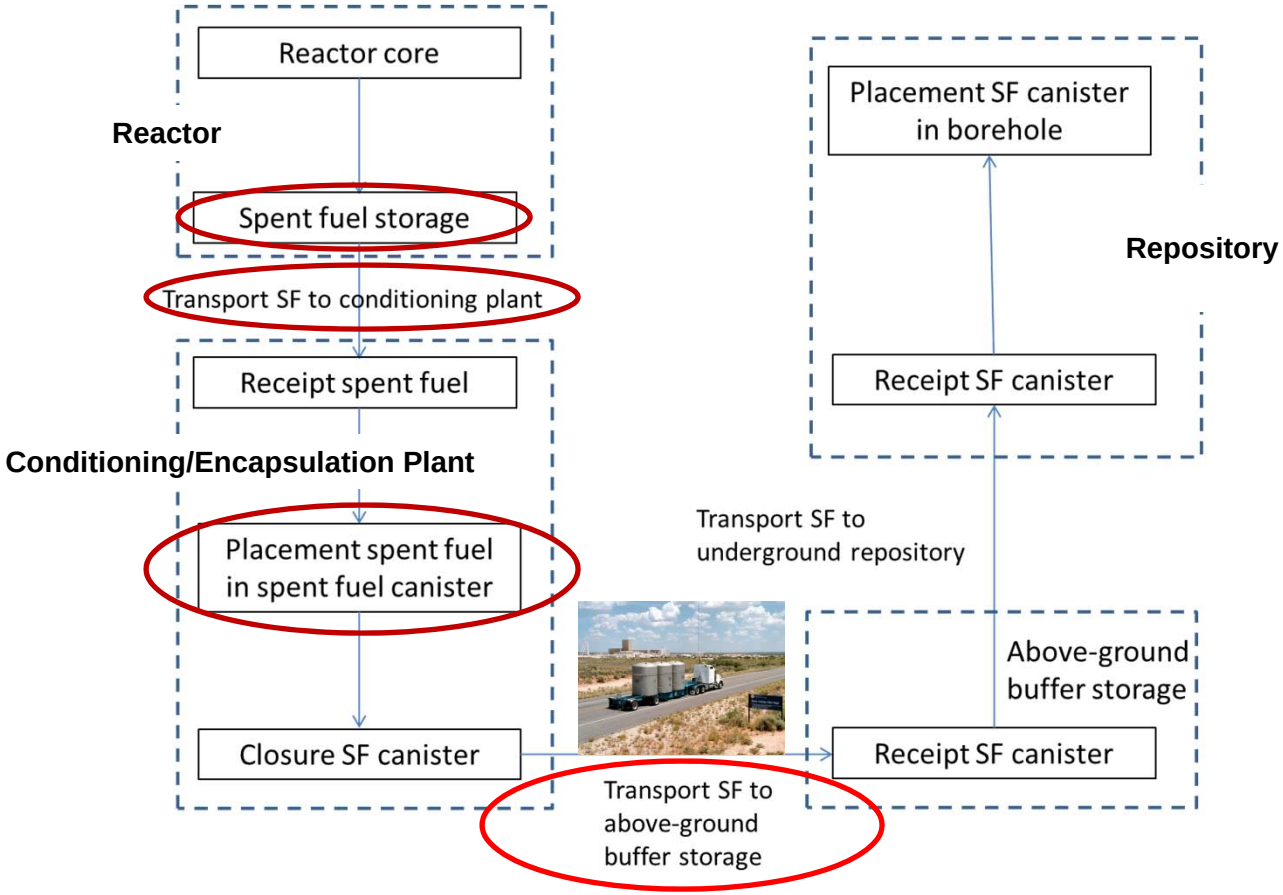
Reactor to Repository



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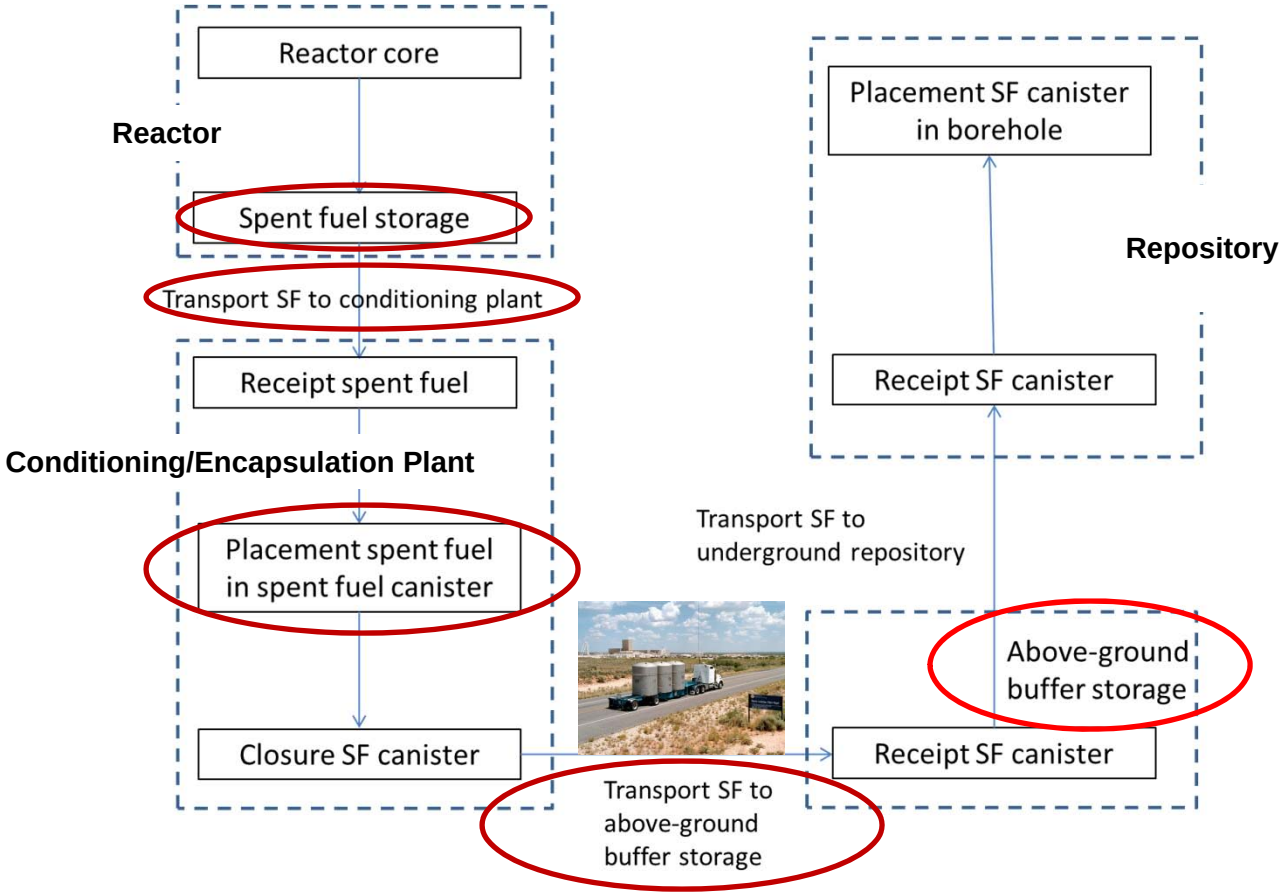
Potential Diversion Points
Reactor to Repository



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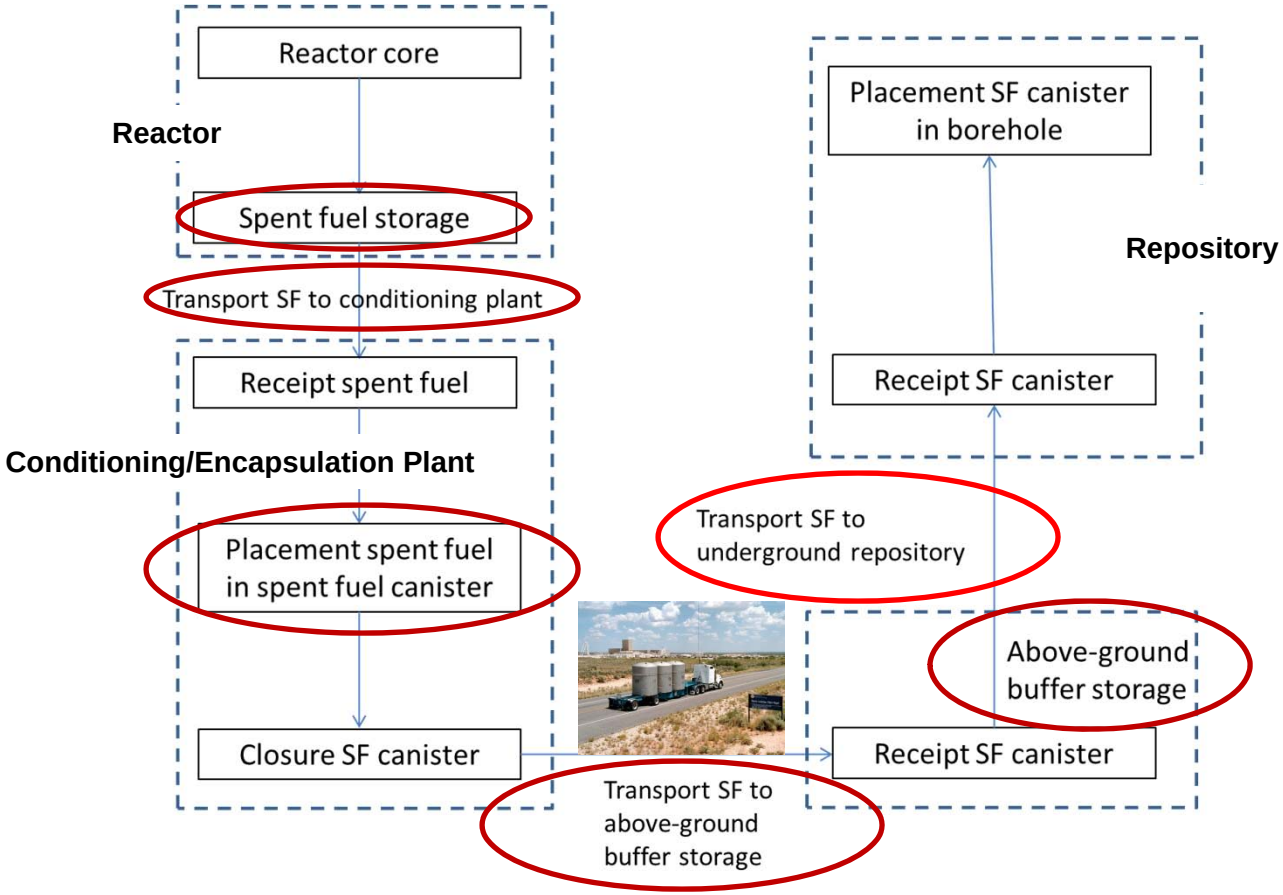

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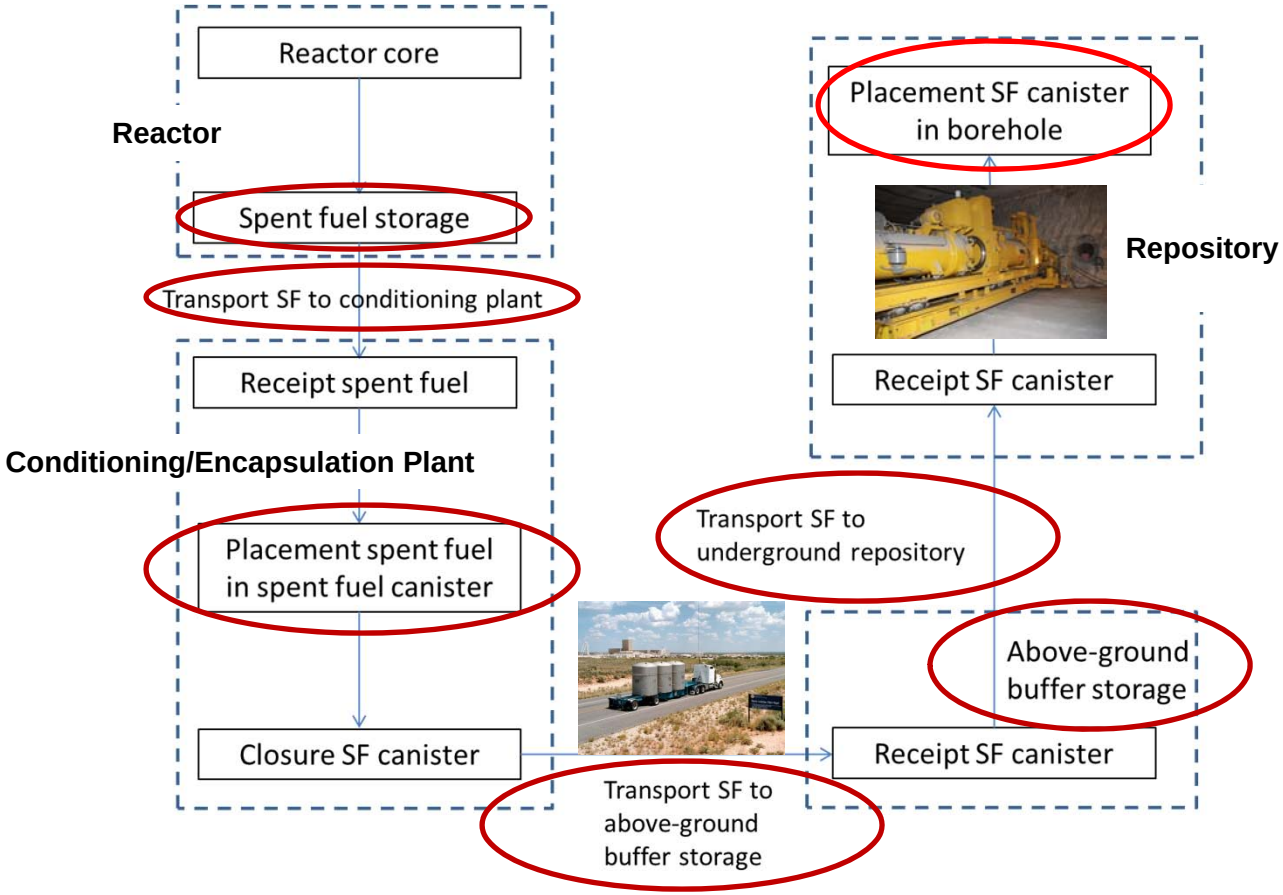
Potential Diversion Points
Reactor to Repository



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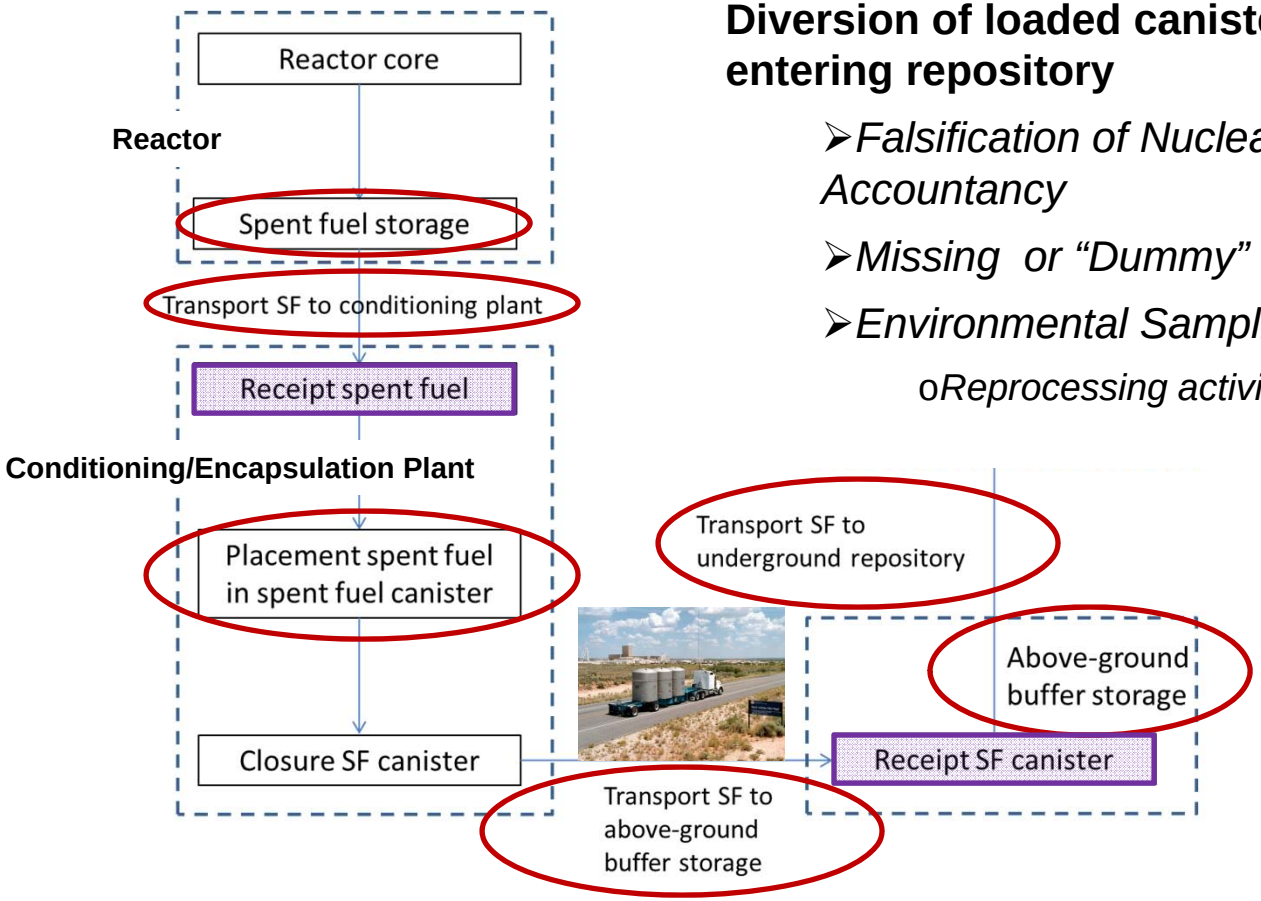
Potential Diversion Signatures
Reactor to Repository



Diversion of loaded canister <u>before</u> entering repository

- *Falsification of Nuclear Material Accountancy*
- *Missing or "Dummy" canister*
- *Environmental Sampling*
  - o*Reprocessing activities*

Source: van der Meer & Turcanu, 33rd ESARDA Symposium, Budapest, May 2011.

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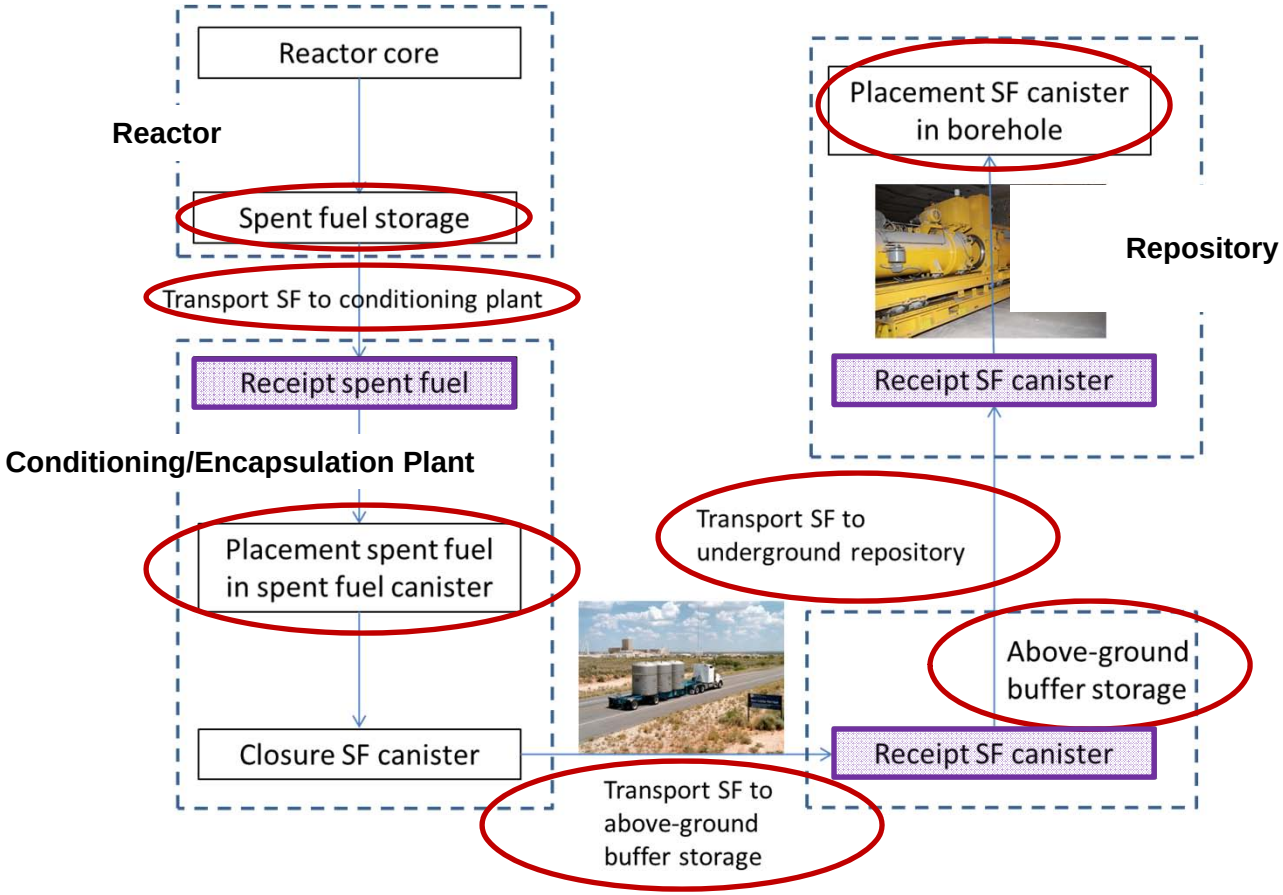
Potential Diversion Points
Reactor to Repository



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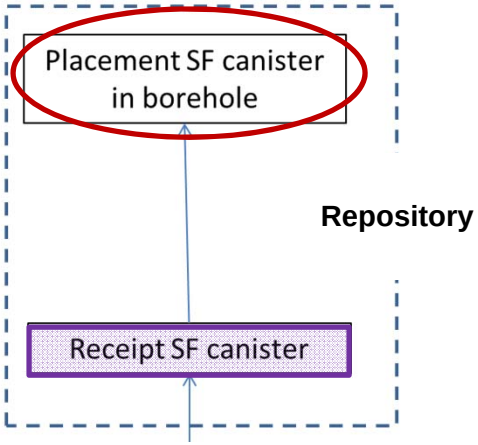
Potential Diversion Signatures
Emplacement in the Repository

Diversion of canister, assemblies or fuel pins <u>after</u> emplacement in repository

- Unreported transport of loaded canister to surface
  - o existing shafts or ramps
  - o unreported shafts or ramps
- Radiation signatures of casks coming from repository
- Unreported tunneling activities
- Hot cell facilities in repository
- Undeclared rooms
  - o Environmental Sampling (ES) signatures of reprocessing activities



Reprocessing <u>in</u> repository

- ES signatures for reprocessing activities
- Presence of rooms not according to Design Information
- Presence of reprocessing facility in repository
  - ohot cells with specific equipment

Diversion of canisters *via* undeclared tunneling

- Unreported tunneling activities
- ES signatures for reprocessing activities

Source: van der Meer & Turcanu, 33rd ESARDA Symposium, Budapest, May 2011.

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Encapsulation & Repository Operations

- Fissile content of waste packages must be confirmed before emplacement
  - NDA methodologies (in development)
    - Defect detection (gross & partial)
  - Multiple measurement points
  - Re-verification not an option
- Seals/Tags & cask ‘fingerprints’
  - IR & laser tags
  - Novel seals under development
  - Radiation & chemical signatures for waste packages & canisters
  - Welding signatures
    - chemistry & microstructure
- Portal monitors
  - Shielding containers must come out empty
- Video monitoring
- Material control & accountancy
- Site inspections & environmental sampling
- Verify emplacement

Source: ASTOR Expert Group, November 2010

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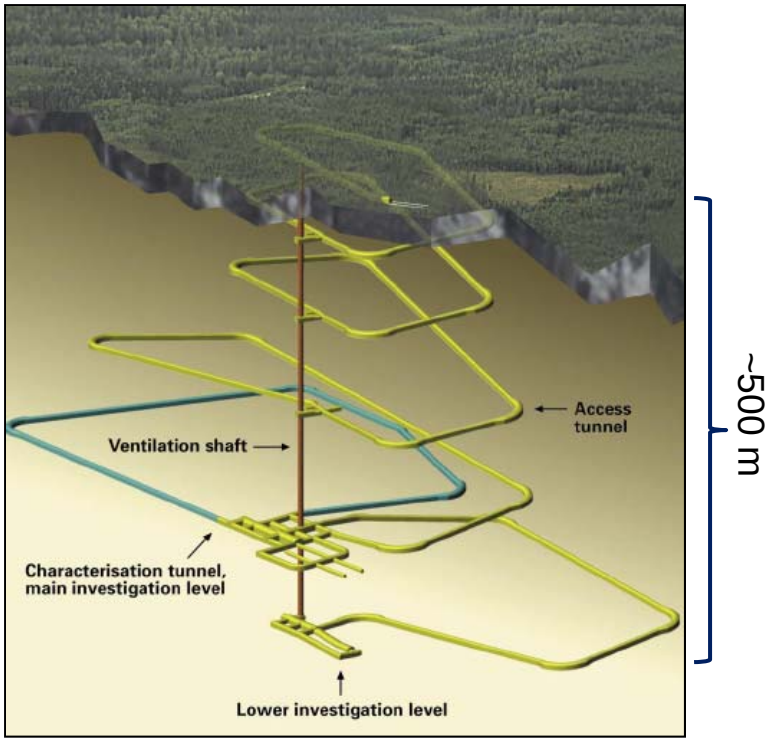
Repository Design Verification
Construction & Operation

- On-site inspections
  - Underground portable navigation system (UPNS) & tracking system
- 3-D laser scanning
  - DIV of underground facility
- Ground-penetrating radar (GPR)
  - limited penetration
- Near-field active seismic monitoring
  - acoustic sonar, thermal monitoring, electrical-resistance mapping, magnetic & gravity anomaly measurements
- Satellite imagery and analysis
  - Change Detection



Source: ASTOR Expert Group, November 2010

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Design Verification & Containment
Post Closure

- Site Visits/inspections
  - Environmental sampling
- Remote-sensing methods
  - Satellite imagery
    - Change detection
  - Seismic monitoring
    - Passive seismic emission tomography
      - Monitor mining activities
        - » Explosions, tunnel boring machines (TBMs)

Source: ASTOR Expert Group, November 2010

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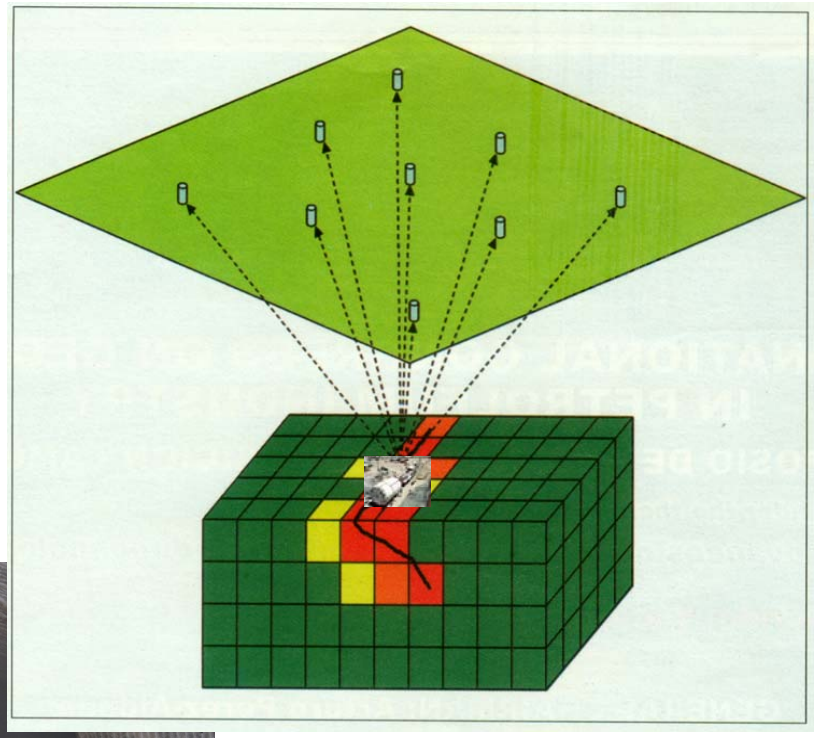
Monitoring with Passive Seismic Arrays

- Tunnel Boring Machines (TBM)



- Mining Activities

Identify activity source & location

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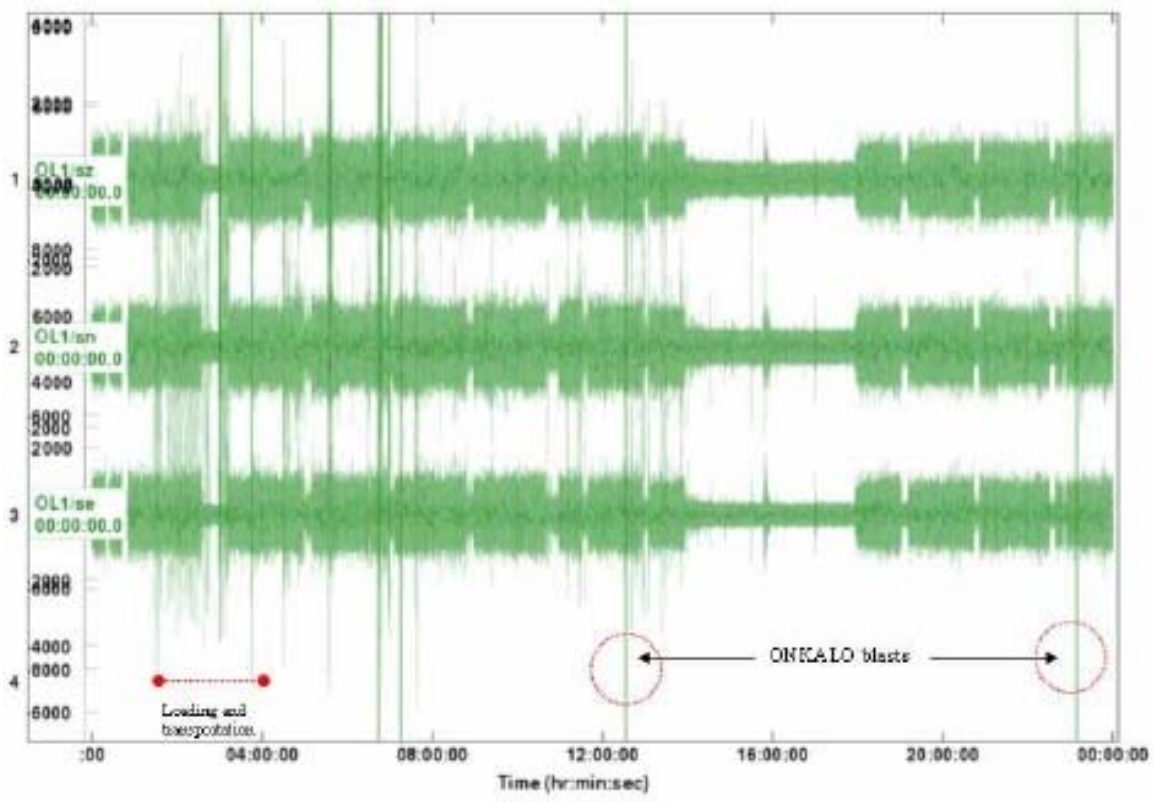
TBM Passive Seismic Monitoring



Signals from raised boring machine at ONKALO, Finland

Source: Saari & Lakio, POSIVA OY Working Report 2007-03, January 2007, p. 4

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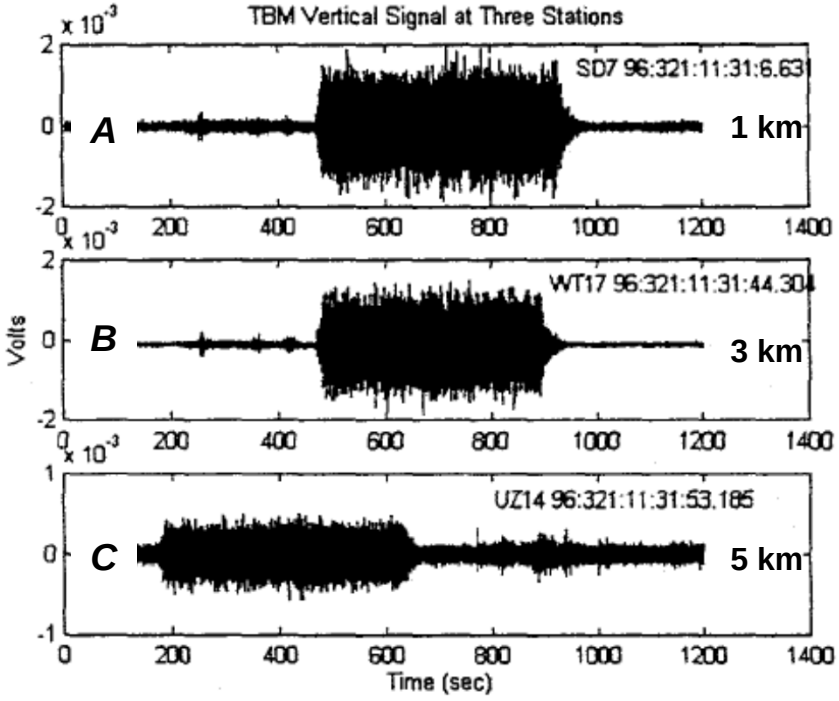
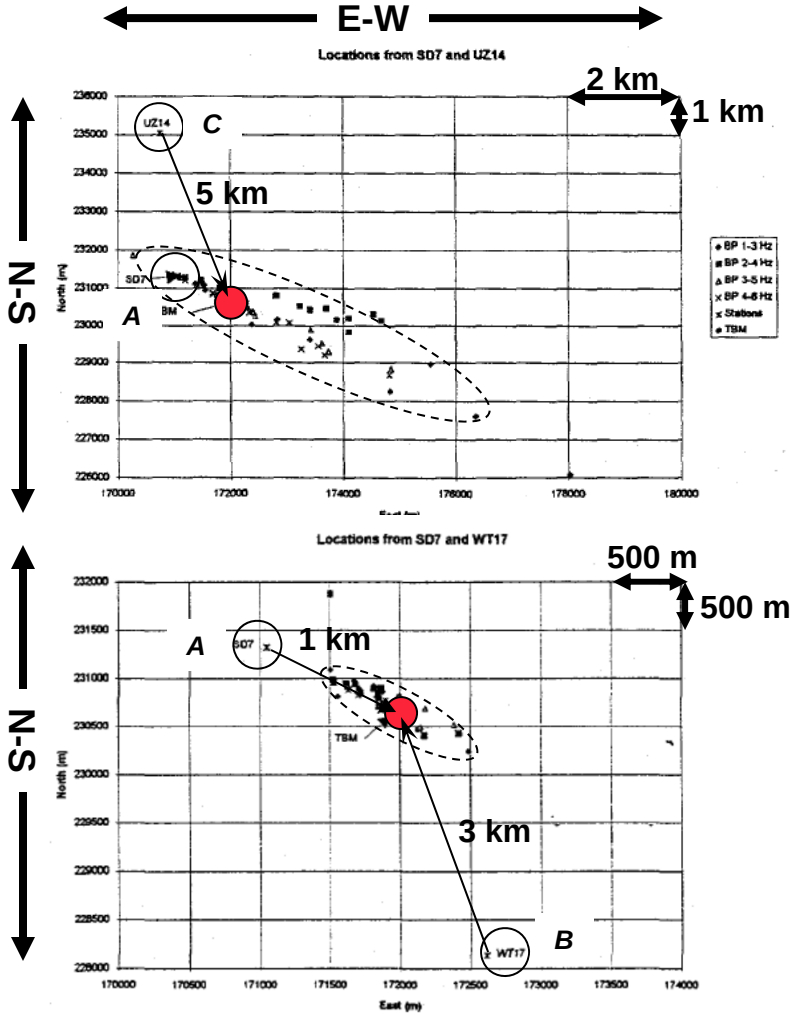
TBM Passive Seismic Monitoring

Yucca Mtn

Seismic signal



A,C: 3-element array of vertical sensors
B: Orthogonal 3-component system



Location Identification
(back azimuth)

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Source: Garbin et al. (1997) SAND97-1668c.

Some Novel Approaches

Encapsulation Plant and Repository Operations

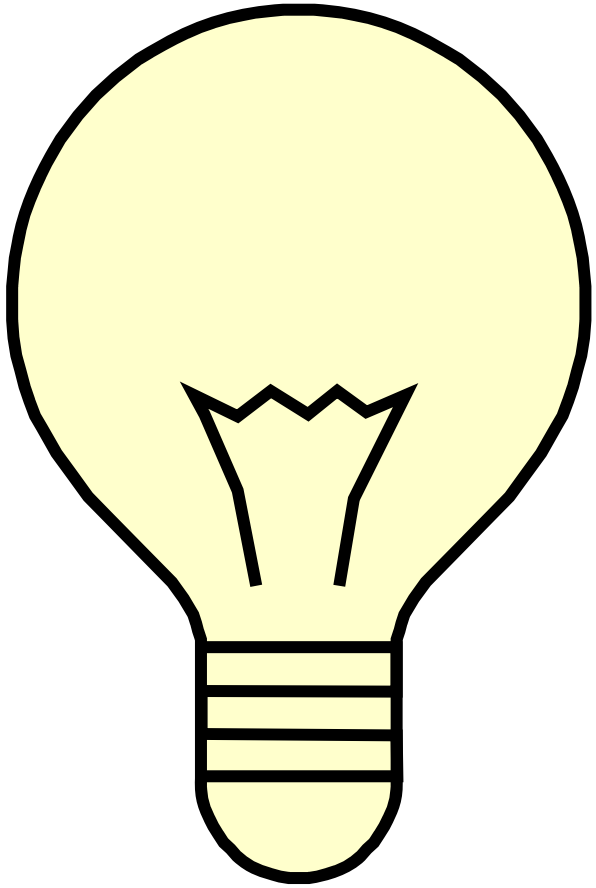
- Laser-Speckle Fingerprinting

Repository Post-closure Monitoring

- Passive Seismic Transmission Tomography (PSTT)

Alternative Disposal Concepts

- *Deep Borehole Disposal*



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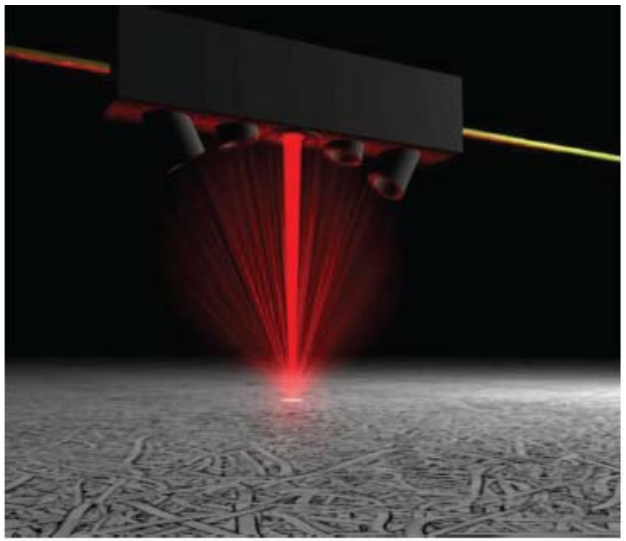
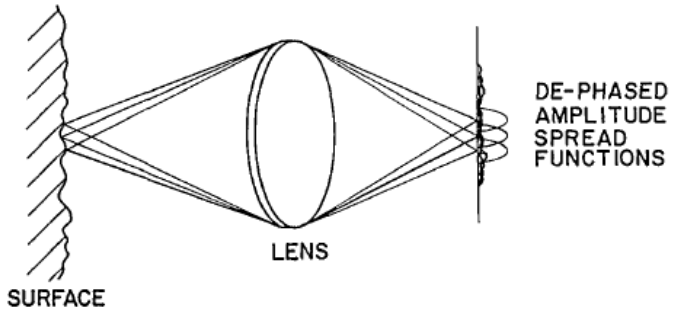
Fingerprinting with Laser Speckle

- Examine fine structure of a surfaces using diffuse scattering from a focused laser
  - Laser scans surface from multiple angles
  - Continuous recording of reflected intensity
  - Statistical analysis of fluctuations
- Fluctuations from mean intensity are digitized to give the fingerprint code
- Each package/container surface possesses a unique fingerprint
  - Fingerprint is intrinsic to each package, weld, and other surfaces
    - Potential for multiple fingerprints
  - Develop methodology for metallic surfaces
  - Testing and standardization required
    - Computer intensive requiring qualified interpretation





Sources: **R. Cowburn (2008) Contemporary Physics, 49(5) p. 331.**
J. W. Goodman (1976) J. Optical Society America, 66(11) p. 1145.

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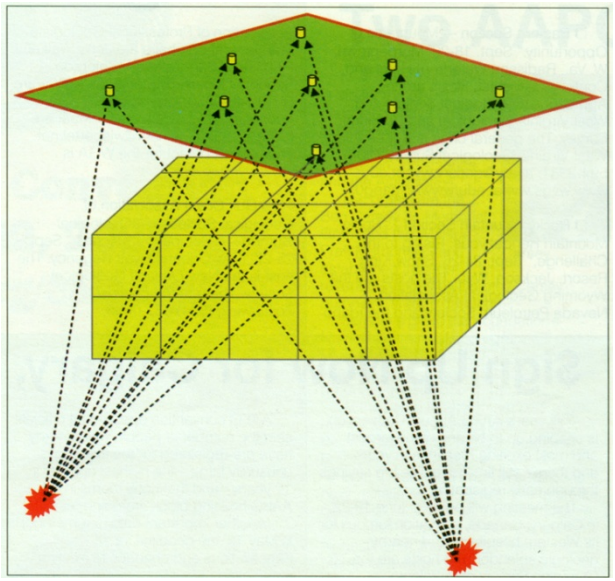
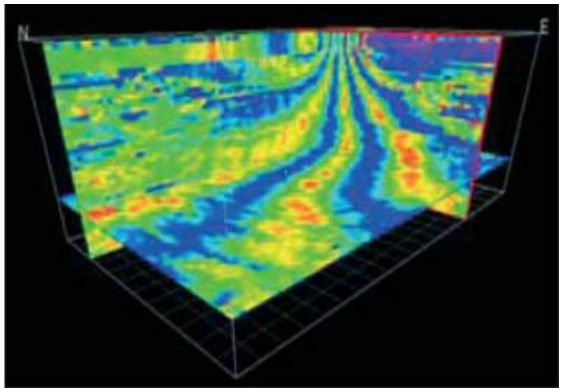
Passive Seismic Transmission Tomography (PSTT)





- Use naturally occurring seismicity to map the subsurface
  - 3-D multi-component velocity volumes provide 3-D subsurface map of desired resolution
  - Signals from micro-earthquakes & very-low-magnitude events
    - Tectonically 'quiescent' regions
  - New events are continuously incorporated into the model
  - Parallel data collection & processing
    - Continuous Quality Control of data
    - Real-time data correction
  - Full survey typically takes 9 – 12 months
  - Computationally intensive
    - Model dependent

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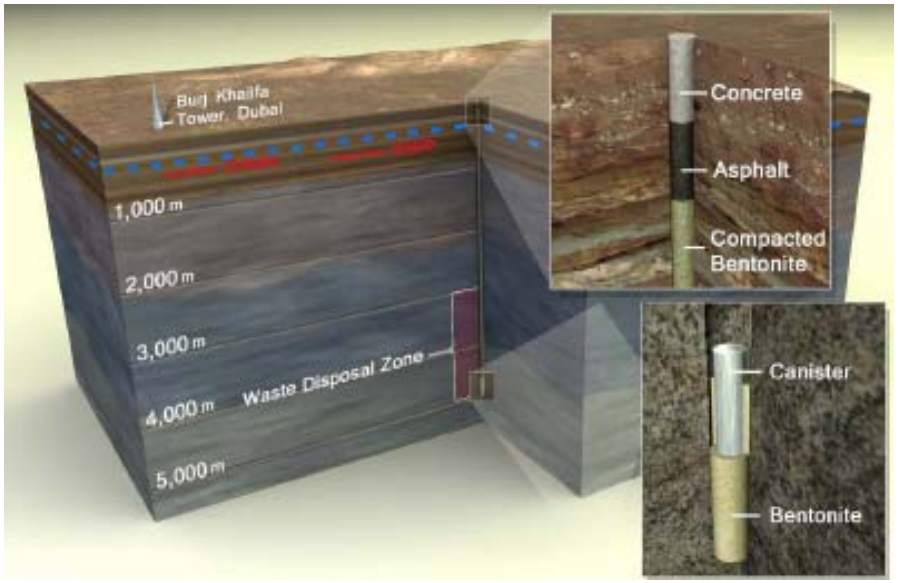
Source: P.M. Duncan (2005) *First Break*, vol. 23, June 2005, p. 111.

Alternative Disposal Concepts

- Reprocessing
  - Reduce Pu underground & recycle in advanced reactors
    - Adds other safeguards requirements
- Deep Borehole Disposal
  - ~10-times deeper than a mined repository



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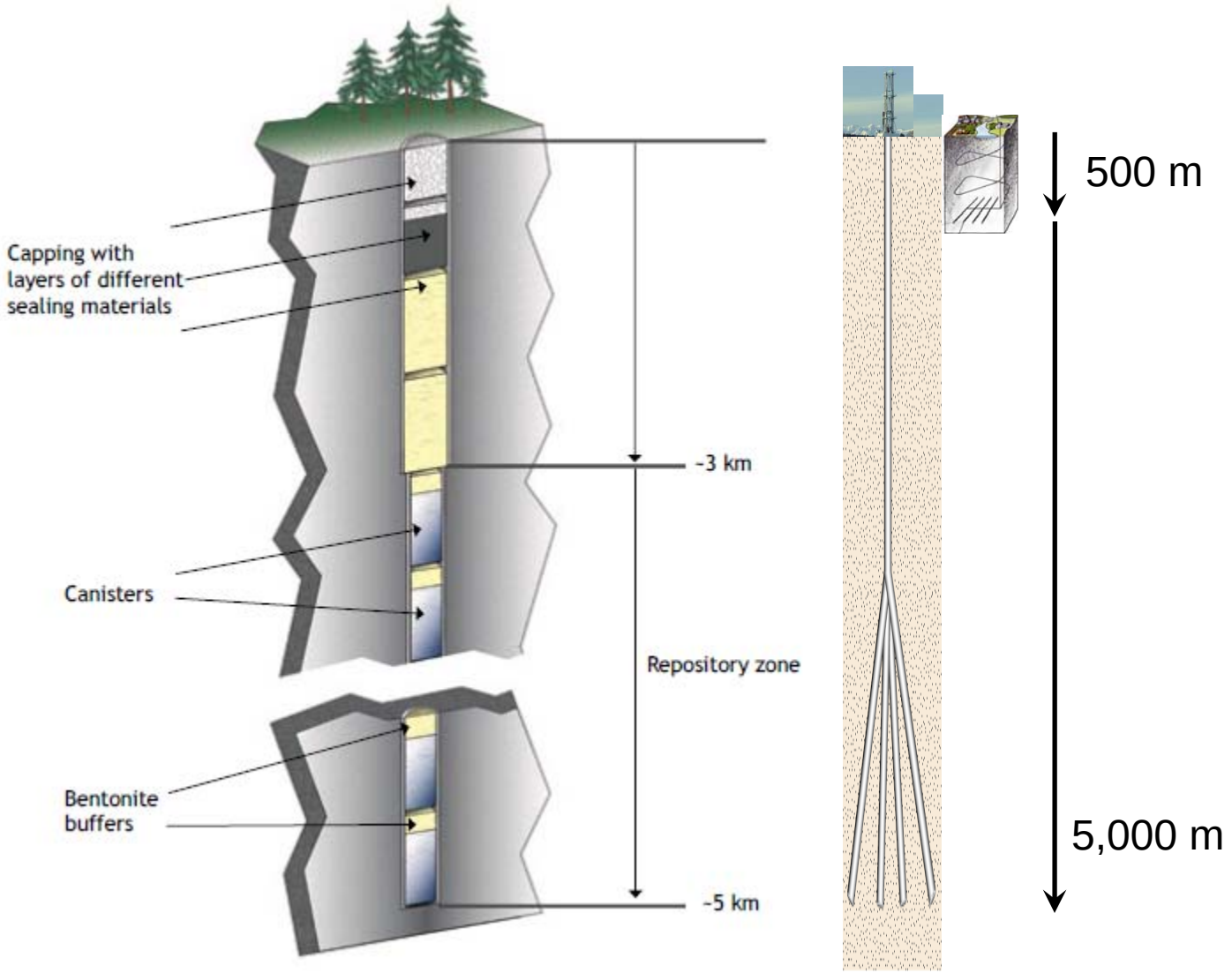
Source: Arnold et al. PSAM10, Seattle, Washington, June 2010 (SAND2010-1173C)

Deep Borehole Disposal



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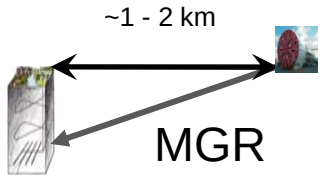
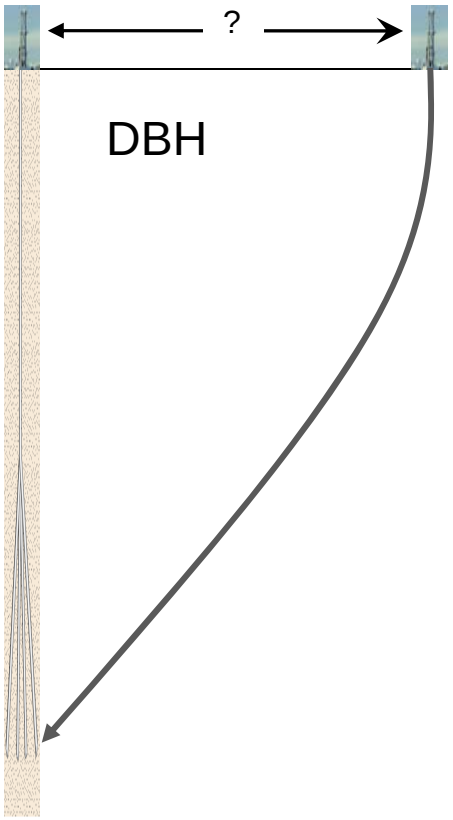
Source: **M. Kårelind, in K.-I. Åhäll (2006) MKG Report 2, December 2006, pp. 7,9.**

Deep Borehole Disposal (DBH)
vs.
Mined Geologic Repository (MGR)





- Monitored area
  - MGR: a few tens square km
    - Maximum TBM tunnel slope (15°- 30°) determines proximity to repository & *minimum* tunneling distance
  - DBH: Unknown
- Post-closure accessibility of nuclear materials
  - MGR: once mined ➔ always mineable
    - accessible by TBM & other mining methods
  - DBH: accessible by drilling (or re-drilling) only
- Seismic/acoustic detection of illicit activities
  - Uncertain comparisons
- Safeguards burden
  - MGR: considerable & under development
  - DBH: uncertain, but potentially much reduced

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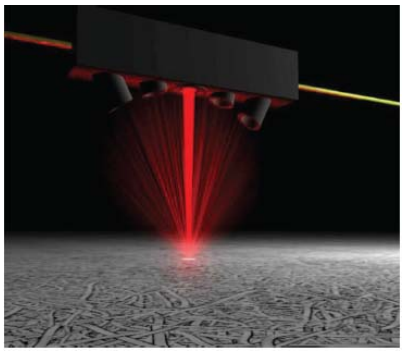
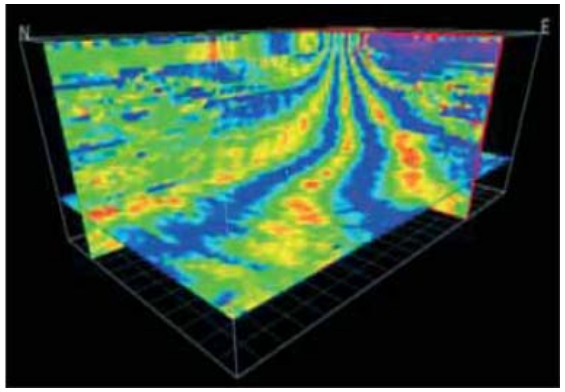
Some Novel Approaches



Encapsulation Plant and Repository Operations

- Laser-Speckle Fingerprinting
  - *Unique waste package/canister identification*

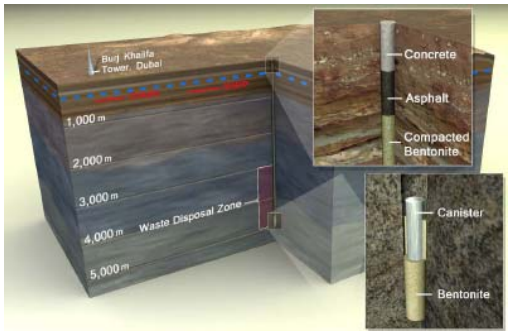


Repository Post-closure Monitoring

- Passive Seismic Transmission Tomography (PSTT)
  - *Underground 3-D mapping*
  - *Continuous Design Information & Monitoring*
- Seismic modeling of diverse host geologies
  - Granite, Shale/Clay, Salt
- Hydrological
  - Changes in water-table levels, flow paths
- Chemical
  - Changes in groundwater chemistry

Deep Borehole Disposal

- Renewed interest, but no plans
- Safeguards requirements not yet addressed



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Conclusions

1. Successful repository safeguards must encompass full range of time & length scales
   - Meter to kilometer & days to millennia
   - Maintain continuity of knowledge from encapsulation through emplacement, repository closure, and beyond …
2. Employ multiple approaches, including novel methodologies
   - Continuous research & development required
     - Potential diversion scenarios & capabilities will also expand
3. Consider safeguards requirements for alternative disposal concepts & multiple host geologies
4. Employ a systems approach for integrating a broad-spectrum of safeguards methodologies
5. Monitoring data may prove useful for performance confirmation
   - Benefit to state's safety case, as well as safeguards obligations

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Additional Slides

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Some TBM characteristics

- TBM performance
  - Utilization
    - fraction of time the TBM spends cutting
      - Reduced by maintenance & repair
  - Penetration rate
    - instantaneous penetration per unit time or per cutter-head revolution
  - Advance rate
    - Equals *utilization* times *penetration rate*
- Tunnel slope
  - TBM downward slopes usually less than 18°
    - up tp 30° slopes w/ improved muck removal, sensor modifications
      - Replace smooth conveyor w/ pleated
- Manpower requirements
  - 4 to 8 man crew
- TBM noise levels
  - vibrations are ½ to 100X lower than blasting
  - vibrations characterized as being similar to moderate-to-heavy street traffic
  - advanced tunneling technologies may have lower (and different) noise character
- Unforeseen adverse geologic conditions are the principal impediment to tunneling
  - excessive faulting/fracturing can reduce advance rates
  - potential repositories will likely be well characterized, better preparing potential tunnelers.

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Other Tunneling methods

- Drill-and-blast methods typically achieve advance rates of 2.5 m/day to 5.0 m/day
  - Numerous technological advances
- Water-jet cutting
  - Significantly reduced noise compared w/ TBMs & drill/blast
  - Application to salt repositories?
  - Muck & pump rates?
- Subterrene Penetrator
  - TBM that melts and displaces rock
    - electrically heated, refractory metal head
  - Significantly reduced noise w/r/t TBM
  - Energy intensive
    - Increased (monitor-able) electrical fields?

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