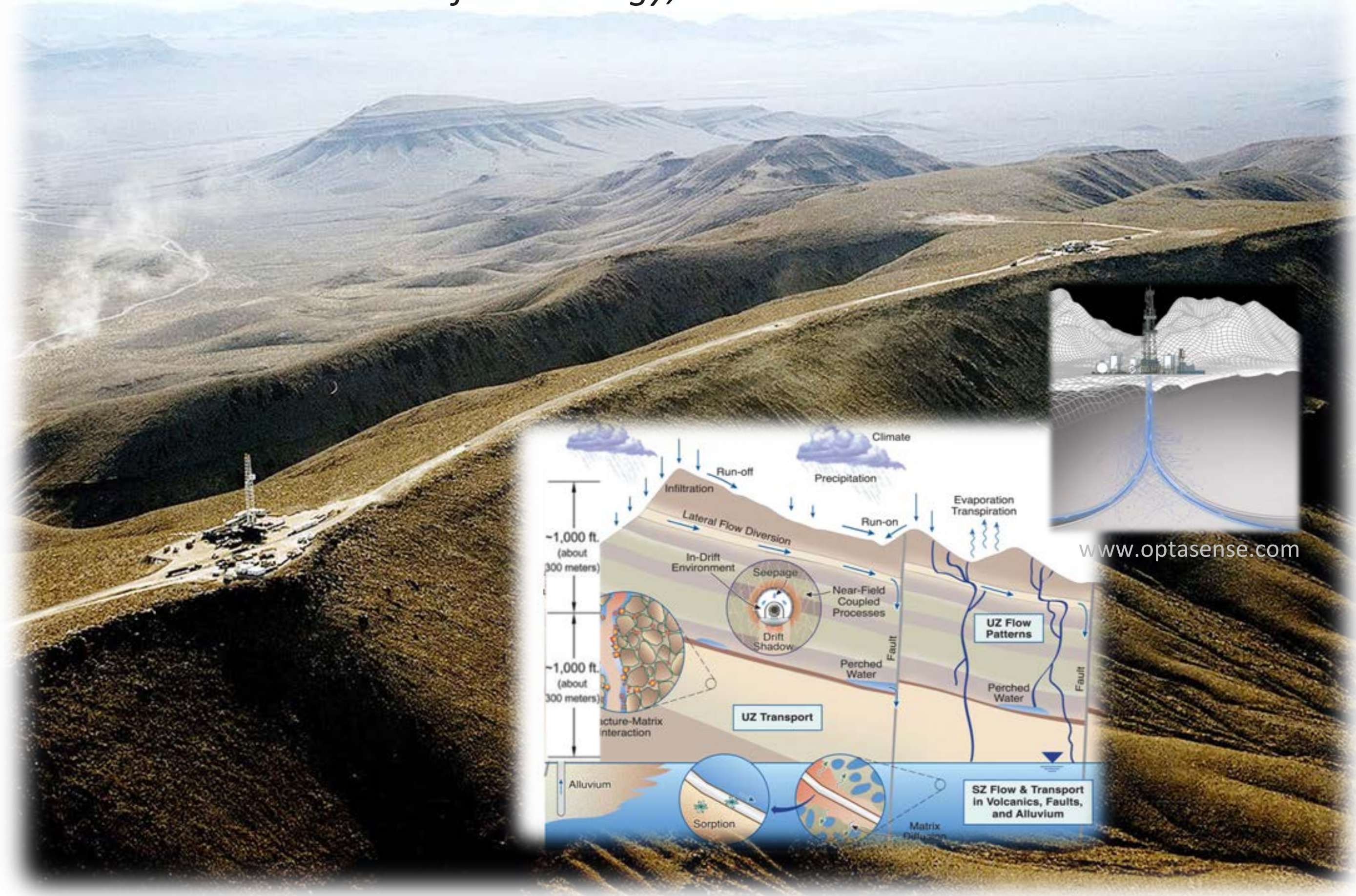
The challenge of long term monitoring in the deep vadose zone

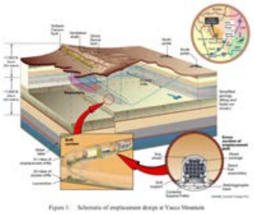
Dani Or - *Dept. Environmental Systems Science*
Swiss Federal Institute of Technology, ETH Zurich

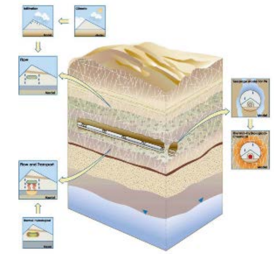


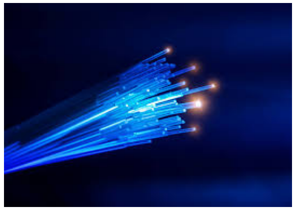
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

NWTRB – *Washington DC (March 27th 2018)*

Outline - *long term monitoring in the deep vadose zone*







- Common features of deep geologic HLW repositories *- YM, Onkalo, Cigeo*
- Monitoring and performance assessment challenges – *deep, long term, heterogeneity, low fluxes (YM)*
- Measurements in the VZ – *water content, potential, RH, temperature, pore water composition (radionuclides), mechanics*
- VZ long term monitoring limitations – *point measurements, placement and retrieval, poor sensor record limited longevity*
- The deep VZ is wet and stable – *unit gradients, mean flux, low sampling frequency, climatic adjustments*
- What's missing ? *robust sensors (temp-rad-hard), self-calibration, power, measurement protocols, monitoring targets, constraining deep fluxes*
- Technological partnerships for sensor development; fiber optical sensors: *borehole ready, versatile, rad-hard, long, spatially resolved*

Deep subsurface nuclear waste repositories

- **Objectives** - safe placement of spent nuclear waste with minimal human interactions, isolated from environmental fluxes and contained against leakage, inaccessible to “tomb raiders”, and resilient to climatic and geological perturbations

Yucca Mountain, USA

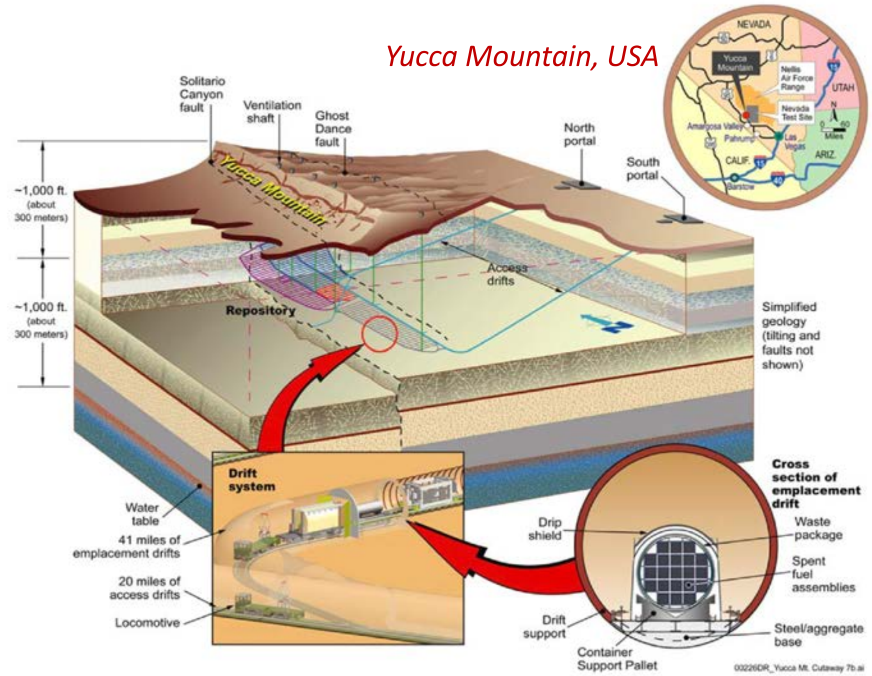
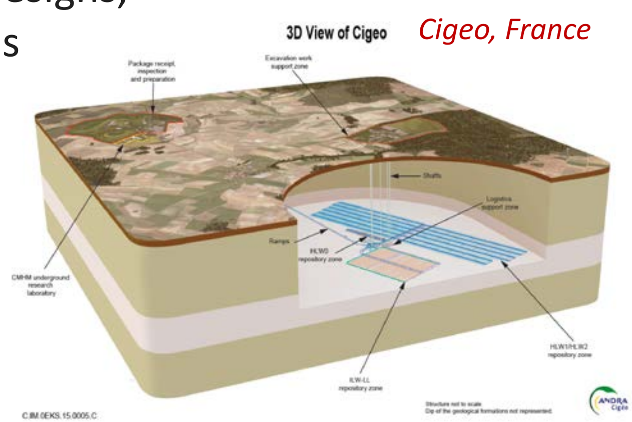
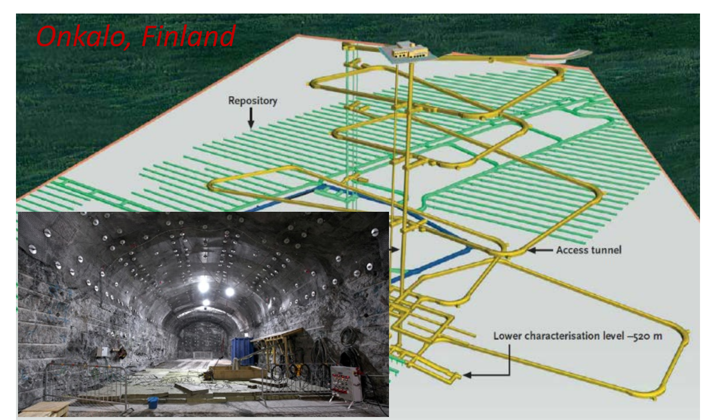


Figure 1: Schematic of emplacement design at Yucca Mountain

- **Different HLW repository solutions** – various host geologic formations (clays to granite), climates and biomes (desert, alpine to tundra), different containment plans, engineering designs, monitoring protocols and regulatory “landscapes”

Cigeo, France





Monitoring - *Performance assessment and site credibility*

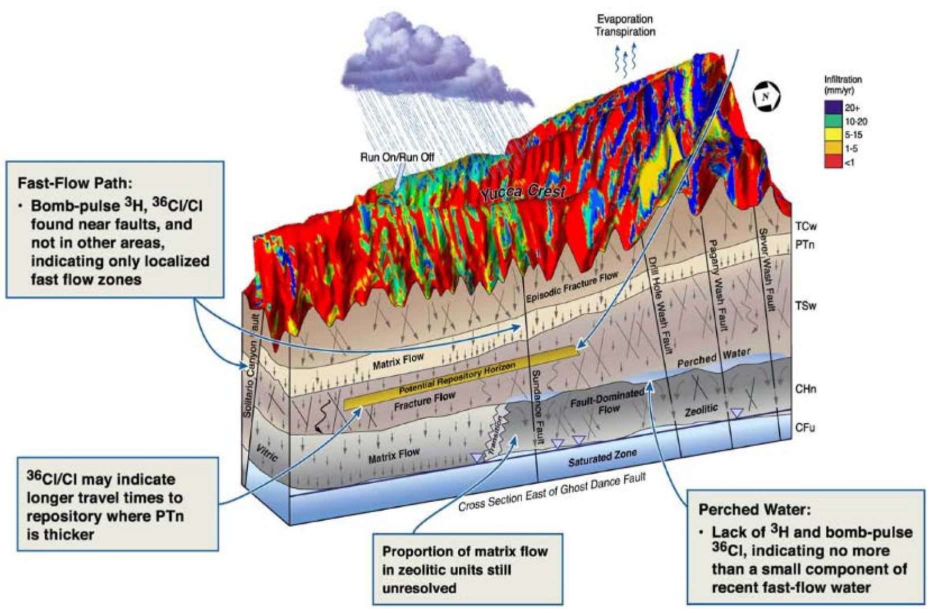
- Why continuous environmental monitoring? An integral part of site performance assessment; provides safety measures to alert for design deviations, variations in environmental conditions, leakage or other failures

➢ *"We regard continuous monitoring to be both a safety issue and a site-credibility issue"*

➢ *"We believe that a careful description of proposed monitoring strategy, and a detailed list of what is to be monitored—and why, where, how, and for how long— should be developed expeditiously"*

Yucca Mountain as a Radioactive-Waste Repository
Hanks TC et al. (1999) USGS circular 1184

- The vadose zone monitoring challenge – sensing in the deep subsurface (>500 m), long term observations and stewardship (>10k yrs), heterogeneous environment, slow response and relatively low fluxes (YM), *never been done before…*



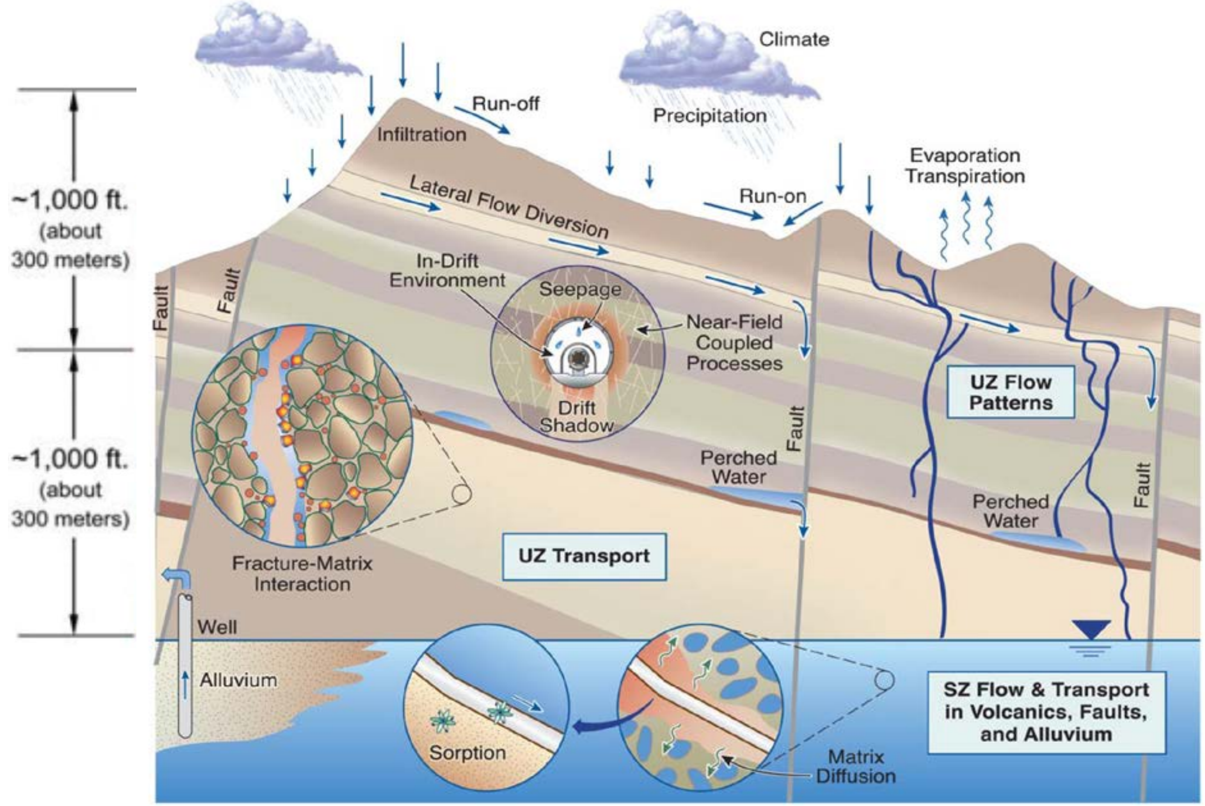
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

What should we monitor in the deep VZ?

- Hydrological state variables – water content and potential
- Estimate water fluxes
- Track pore water composition – detection of radionuclides transport
- Mechanical state

<u>Other technical challenges</u>

- Sensor placement, retrieval and power
- Self-calibration and diagnostics
- Sensors near drift – temperature and radiation hardening
- Measurement protocol, thresholds for action



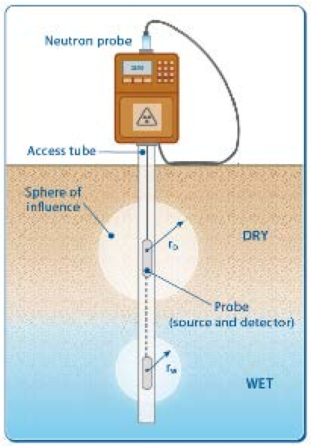
Karasaki et al. 2007, LBNL

OSTI, 2005

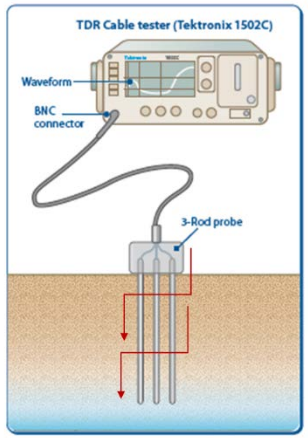
Overview - *water content and potential measurement methods*

- **Methods and sensors for measurement of *volumetric water content***

Neutron scattering

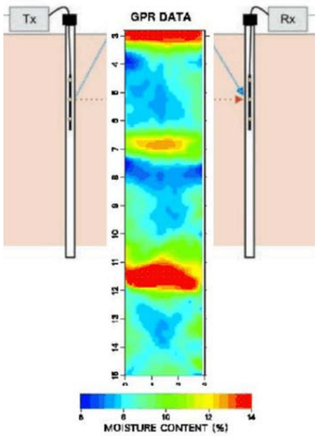


Time domain reflectometry (TDR)



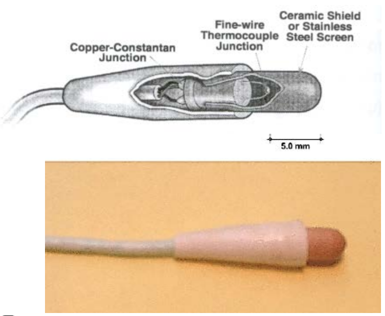
Capacitance/frequency domain

Geophysical (cross-borehole GPR)

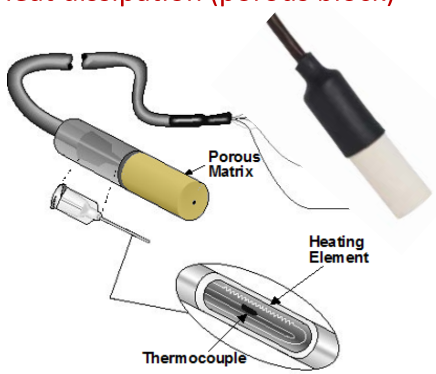


- **Sensors for *matric potential* measurement**

Thermocouple Psychrometer

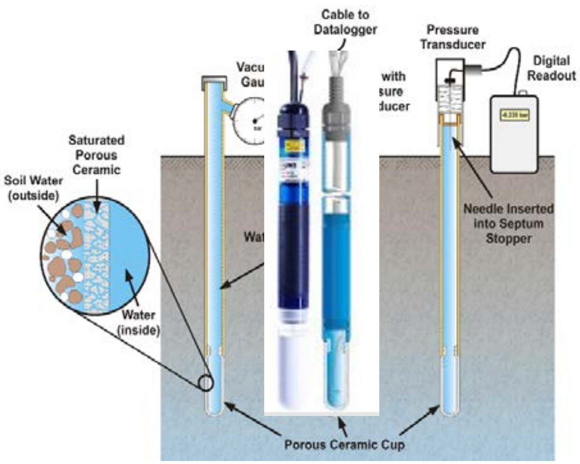


Heat dissipation (porous block)



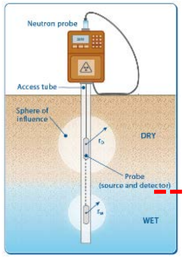
Dielectric porous disk

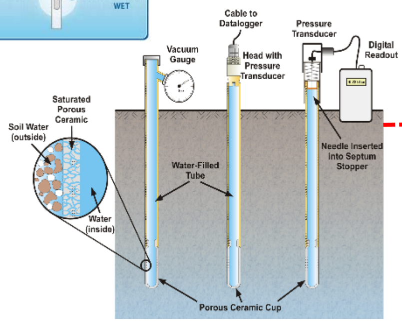
Tensiometers

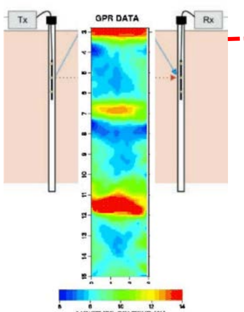


ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Overview - *water content and potential measurement methods*







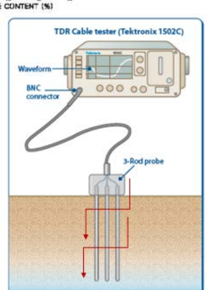
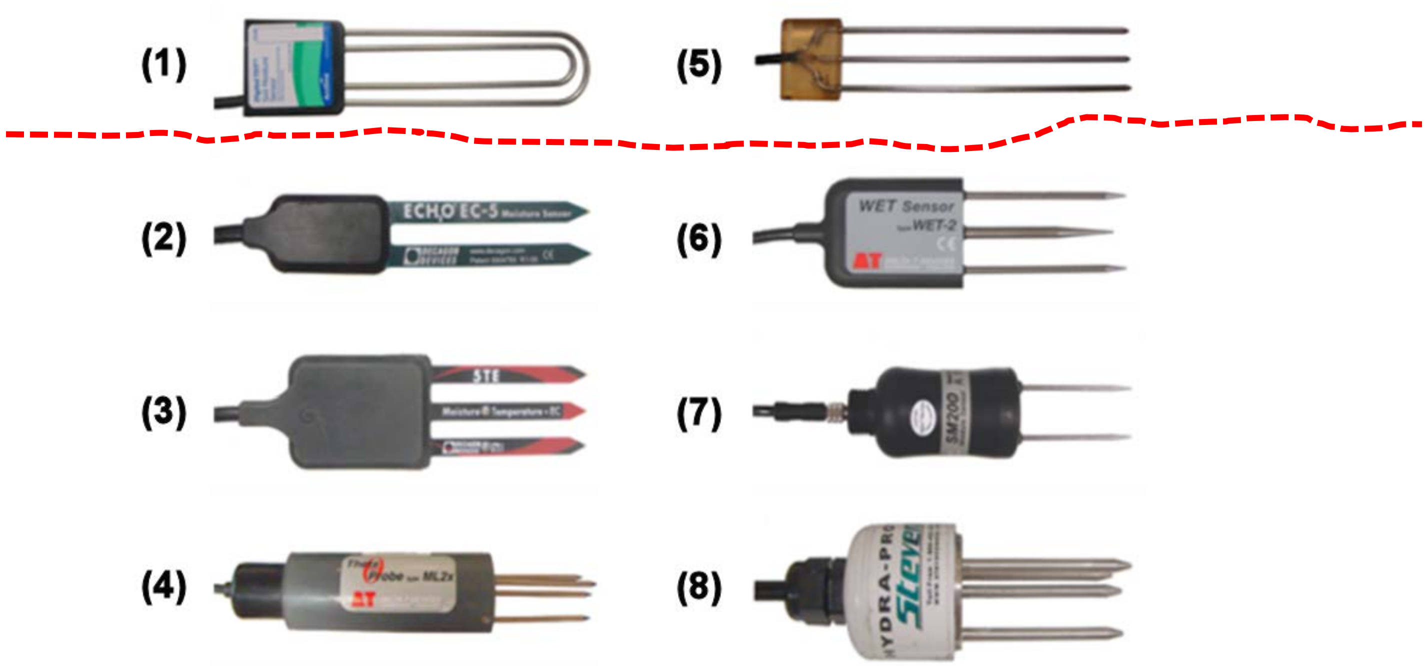


Table 5. Overview of moisture detection techniques

Technique	Property measured	Derived information	Resolution
Neutron probe	Hydrogen concentration	Moisture content, porosity, lithology	< 10 cm
Tensiometry/Lysimetry	Matric potential and chemical analysis	Matric potential, water content, hydraulic conductivity, water sample	Point
Electrical resistivity tomography	DC electrical resistivity	Bulk resistivity	>1 m
Crosshole radar	Dielectric permittivity	Moisture distribution, lithology, soil disturbances, buried materials	5-60 cm depending on frequency
Crosshole electromagnetic induction	Electrical conductivity and dielectric permittivity	Moisture distribution, shallow contaminant plumes, lithology	1.5 to > 4.5 m
High-resolution resistivity	DC electrical resistivity	Moisture, lithology, geologic structure, buried materials, shallow contaminant plumes	> 1 m
Time-domain reflectometry	Electrical conductivity and dielectric permittivity	Flow and transport, lithology	> 2 cm depending on probe length

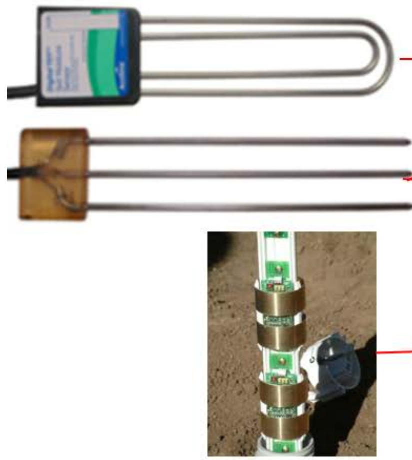
Sheen (2012) – Extended In-Situ and Real Time Monitoring (Argonne National Lab)

Available dielectric-based water content sensors



- **Many electromagnetic-based sensors based on different dielectric measurement techniques to determine soil water content are now available in the market**
- **(1)** *Acclima* time domain transmissometer (TDT), **(2)** *Decagon Devices* EC-5 sensor, **(3)** *Decagon Devices* 5TE sensor, **(4)** *Delta-T* ML2x sensor (Theta probe), **(5)** “home-made” 3-prong time domain reflectometry (TDR) probe, **(6)** *Delta-T* Devices WET sensor, **(7)** *Delta-T* Devices SM200 sensor, **(8)** *Stevens* Water Hydra Probe sensor
- **Measurement techniques include: *travel-time analysis* (1 and 5), *capacitance measurements* (2, 3, 4, 6 and 7) and *electrical impedance* measurements (8)**

Accuracy of water content measurements - *EM sensors*



Sensor	RMSE after offset adjustment	Offset error	Water content range	Soil type
	$m^3\ m^{-3}$			
Acclima	± 0.014	0.002	0.17–0.36	Silt loam
Theta	± 0.017	0.056	0.17–0.36	Silt loam
TDR100	± 0.022	0.081	0.17–0.36	Silt loam
Hydra	± 0.024	0.194	0.17–0.36	Silt loam
Tektronix TDR	± 0.025	0.060	0.17–0.36	Silt loam
CS-616	± 0.031	0.140	0.17–0.36	Silt loam
ECH_2O EC-20	± 0.041	0.136	0.17–0.36	Silt loam
Enviroscan	± 0.027	–	0–0.4	
Enviroscan	± 0.026	–	0–0.4	
Enviroscan (FC)†	± 0.05	–	~0.40	
DPHP	± 0.012	0.1	0.00–0.33	Broad range
DPHP	± 0.022	0.1	0.02–0.59	Broad range
GPR (WARR)†	± 0.030		0.02–0.39	Sands and loams
GPR (STA)†	± 0.037		0.02–0.39	Sands and loams

Robinson et al. (2008, *VZJ*)

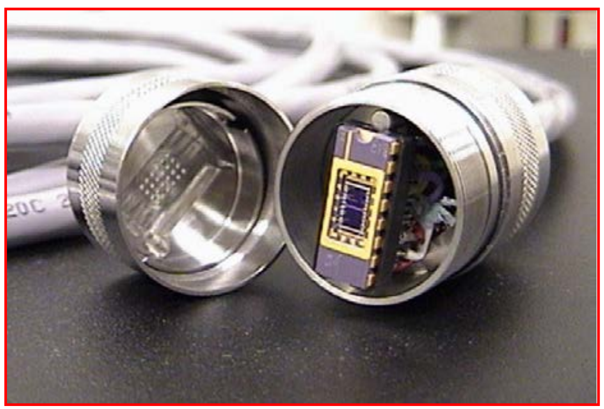
Matric-potential EM sensors

- **Water content** measurement errors ≈ 2-3 % volumetric (also for a well-calibrated down borehole *neutron probe* not on the list)
- **Matric potential** measurement error (porous dielectric blocks or heat dissipation) of the order of ≈ 25% of measured value! under wet conditions…

In-situ measurement of pore water composition

- Solution samplers operating under suction collect pore water from their neighborhood

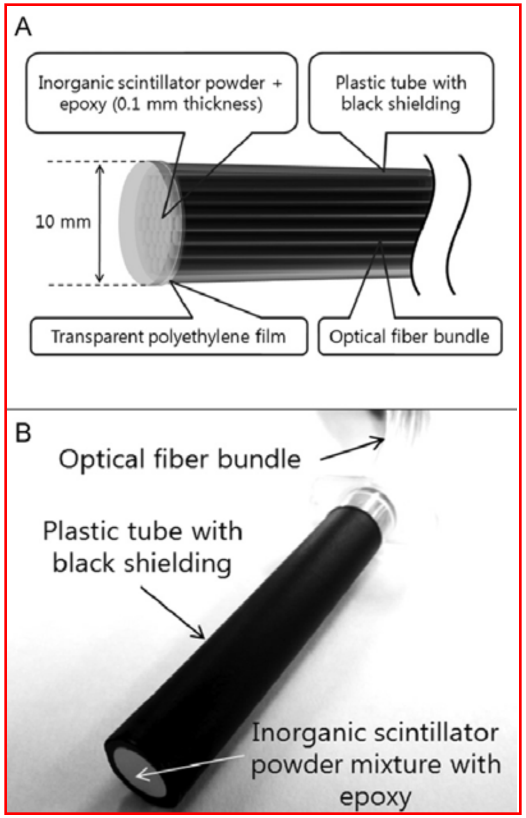
- Advanced in-situ sensors for detection of specific chemical compounds (or radionuclides)



Chemiresistor array for in-situ monitoring of volatile organic compounds (Ho et al. 2005, Sandia)

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

In-situ detection of radionuclides other compounds



Fiber optical sensor for Tritium detection (β radiation) in liquid potential for in-situ monitoring (Jang et al. 2011)

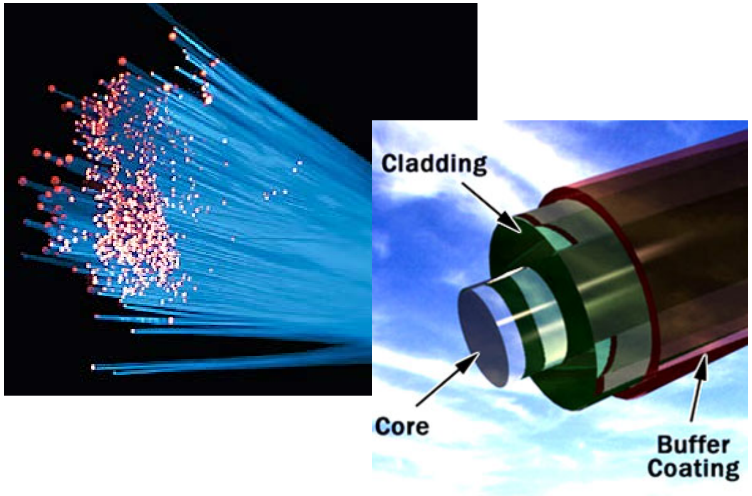
Table3. Common detectors for beta and gamma ray detection

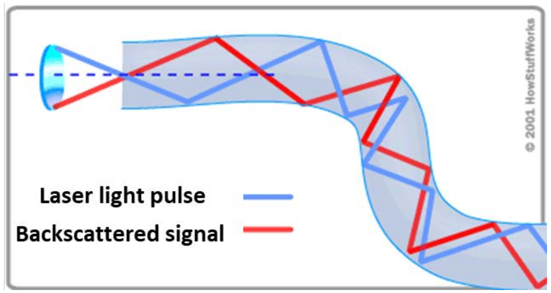
Detector Type	Detector Configuration	Applications		Sensitivity#	Remark
		Beta	Gamma		
Scintillation	NaI(Tl) up to 5cm x 5cm hand-held	--	Surface scanning	1 – 5 μR/hr or 200-1,000 cpm	Energy sensitive with the greatest response around 100-120 keV
	CsI or NaI(Tl) thin crystal	--	Scanning	--	Detection of low-energy radiation
	Plastic scintillator	Contamination measurement	Dose equivalent rate	--	Large area coverage
Solid state	Germanium semiconductor	--	Field γ spectrometry, multichannel analyzer	50keV with P-type, 10keV with N-type	Liquid nitrogen cooling, high voltage operation, long counting time (up to 1000 min)
Gas filled	Proportional	<0.1 mg/cm² window; probe area 50 to 1,000 cm²	Surface scanning and surface contamination measurements	Beta efficiency ranges from 5% to 35%, <1% for gamma	Require a supply of appropriate fill gas.
	Ionization	1-7 mg/cm² window	Handheld ionization chamber	0.05 mR/hr for γ. For beta, 10,000 Bq/m² @ 1 hr and 500 Bq/m² @ 24 hrs.	Exposure rate measurements.
	Geiger - Mueller	< 2 mg/cm² window; probe area 10 to 100 cm²	Pancake (<2 mg/cm² window) or side window (~ 30 mg/cm²)	Around 0.1 mR/hr in rate meter mode or 0.01 mR/hr for integrate mode for gamma detection. ~10% better for beta detection	Relatively poor sensitivity
Passive integrating	TLD	Secondary radiation detected	Left in the field for a period of a day and read in the laboratory on a calibrated reader.	Standard TLD sensitivity at 100 mrem/y, New Al_2O_3 TLD at 0.01 mrem/y.	Sensitive to visible light, direct sunlight, fluorescent light, excessive heat and humidity.
	EIC	7 mg/cm² window, or window-less, window area 50-180 cm², volume 50-1,000 ml	7 mg/cm² window, or window-less, window area 50-180 cm², volume 50-1,000 ml	In integrate mode, the sensitivity can be as low as 0.05 mR/hr.	Usable in high humidity and temperature.

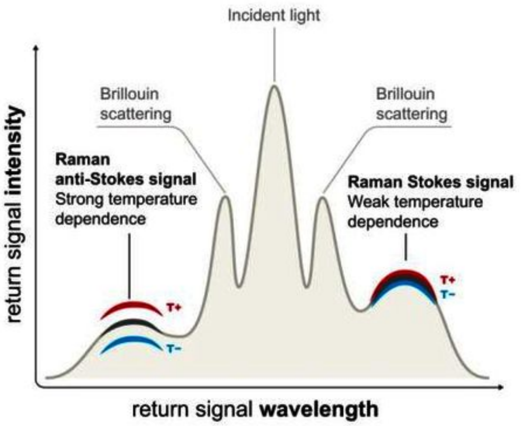
μR/hr = 10^{-6} rontgen per hour (1 röntgen = 2.58×10^{-4} Coulomb/kg); cpm = counts per minute; 1becquerel (Bq) = 27 pCi.

Sheen (2012) – Extended In-Situ and Real Time Monitoring (Argonne National Lab)

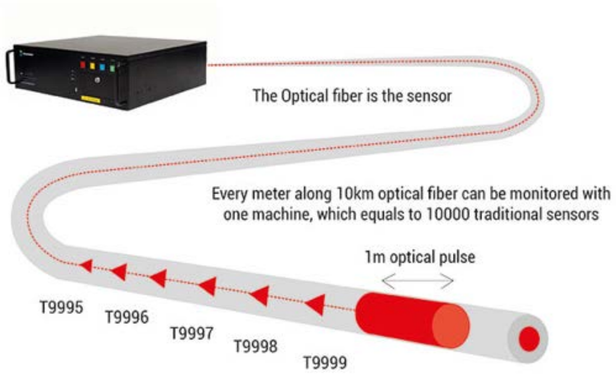
Fiber optical methods - *temperature and water content*







- A laser emits pulse (5 ns) into fiber optic cable and measuring the return signal scattering characteristics
- The return light signal is affected by temperature, mechanical stresses and more along its path
- 1 m resolution, cable length < 10 km (*each segment along the cable is a sensor*)
- DTS - temperature is measured at 30 s temporal resolution at 0.01 K with 30 min integration



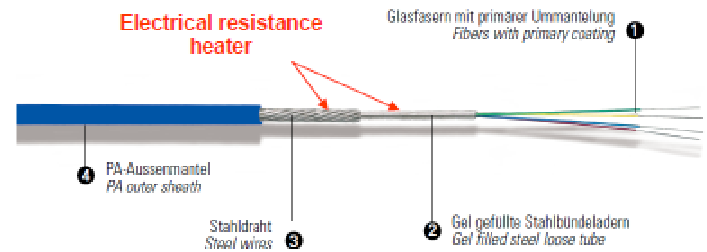
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

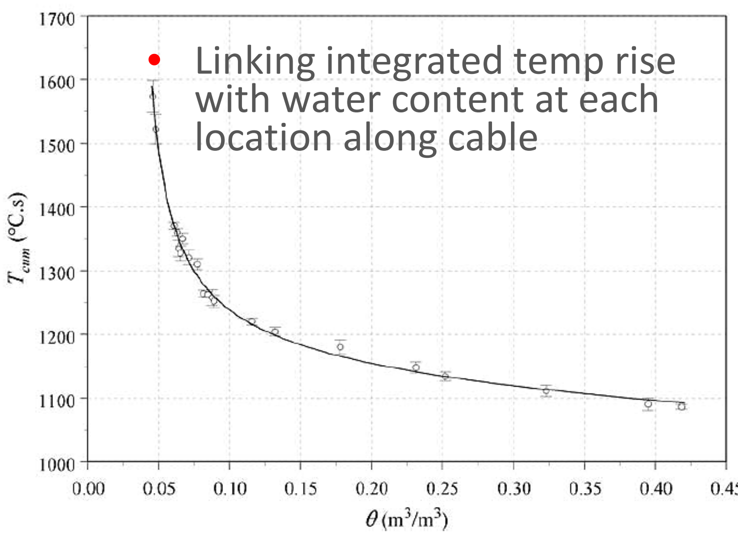
DTS measurement of water content – *active heating*

Feasibility of soil moisture monitoring with heated fiber optics

Chadi Sayde,[1] Christopher Gregory,[1] Maria Gil-Rodriguez,[2] Nick Tufillaro,[1] Scott Tyler,[3] Nick van de Giesen,[4] Marshall English,[1] Richard Cuenca,[5] and John S. Selker[1]

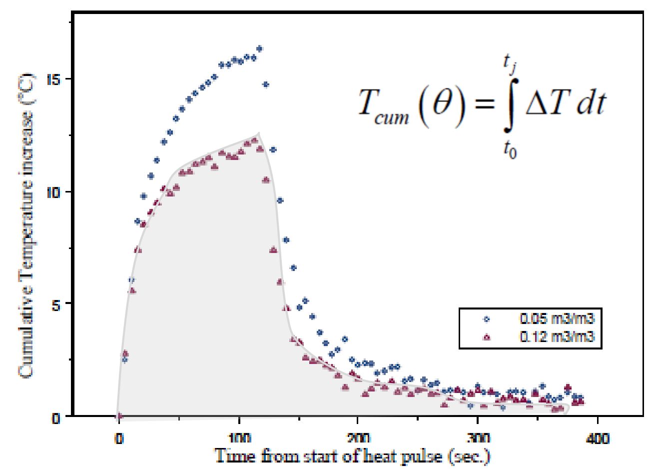
WATER RESOURCES RESEARCH, VOL. 46, W06201, doi:10.1029/2009WR007846, 2010





- Linking integrated temp rise with water content at each location along cable

- At each location along the cable temperature rise is integrated

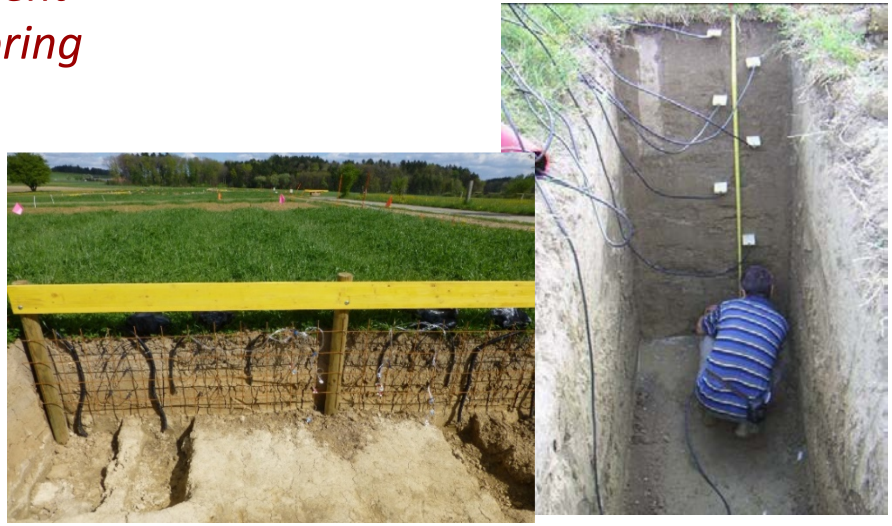


Technical challenges of monitoring the deep VZ

- Limited experience with long term measurements of water content, potential and related VZ variables (typically < 10 yrs)
- Most sensors are not designed for <u>decadal continuous</u> operation
- Sensors and measurement protocols designed for <u>near-surface</u> conditions (<10 m)
- Most are <u>point</u> measurements – limited information in heterogeneous systems
- Low measurement accuracy and limited measurement range

- *Despite advances in linking sensors to spatially distributed environmental networks, present hydro-environmental sensors and monitoring hardware are lacking; measurement protocols, sensor placement and retrieval, power and network (wireless) solutions for the <u>deep subsurface</u> lag behind*

Sensors and experiences limited to shallow subsurface



ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Technical challenges of VZ monitoring are not new…

- DOE-EM and Bechtel (NV) – proposed the *Advanced Monitoring Systems Initiative* (***AMSI***) for *"acceleration development and application of advanced monitoring systems"*
- AMSI was active (Ames lab) between *2001 and 2008*

Main Conclusions/Recommendations

1. Moisture (flux, content, and soil moisture potential) is a high priority for monitoring (and modeling) waste isolation facilities.
2. Monitoring surrogate parameters that indicate the condition of a facility or site is a priority.
   Changes at sentinel locations can be used to trigger conventional monitoring.
3. Most technologies for measuring surrogate parameters are well developed compared to chemical contaminant sensors.
   We should begin immediately to apply these existing methods.
4. Beware point measurements; seek lower uncertainty.

Near-Term Targets & Pathways

New sensors and sensor systems

- For wide range of GHBCT analytes, surrogates and indicators
- High accuracy [auto-calibrating]; sensitivity
- In situ; Non-invasive; Volume integrating
- High reliability; low maintenance; long life
- Miniature, easy emplacement, replacement
- Remotely operable; wireless

---- Technology Challenges ---- $22 M; 90 mo

Meeting the deep VZ (long term) monitoring challenge

- **Given the unsatisfactory state of VZ sensors for the long term (deep) VZ challenge** – a strategic investment in next generation VZ sensors is urgently needed: *rugged, redundant, self-diagnosing and calibrating, radiation and temperature hardened*

- **Developing a detailed monitoring plan** that considers *spatial representation (heterogeneity/ footprint), redundancy, replacement, power supply, sampling schedule/intervals*

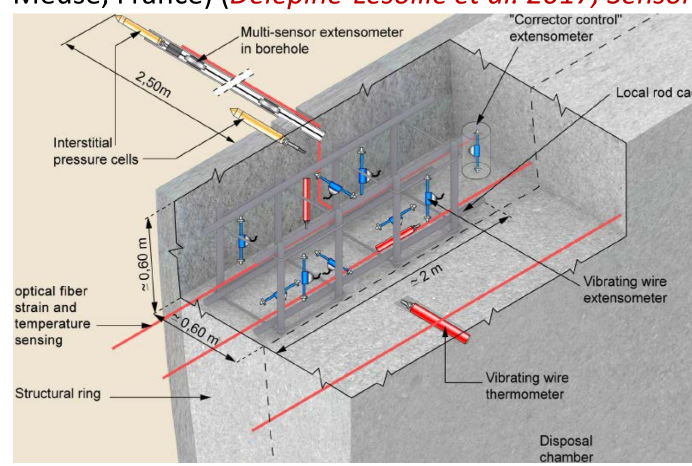
- **Monitoring information** – address information retrieval, processing and archiving; and formulation of (monitoring-based) actionable thresholds

- **Adaptive monitoring** – upgradable (space & technology), element replacement protocols

- **Subsurface monitoring begins at the surface** – measures to constrain flux estimates; periodic marking percolation fluxes with detectable and environmentally-friendly tracers

Subsurface wireless radio (*Grafe et al. 2012*)

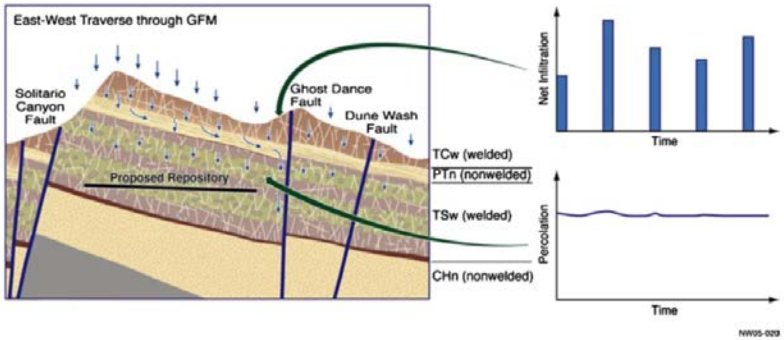
Monitoring design for ILLW disposal cells (Centre Meuse, France) (*Delepine-Lesoille et al. 2017, Sensors*)



FP7 *MoDeRn* Project "Monitoring Developments for Safe Repository Operation and Staged Closure"

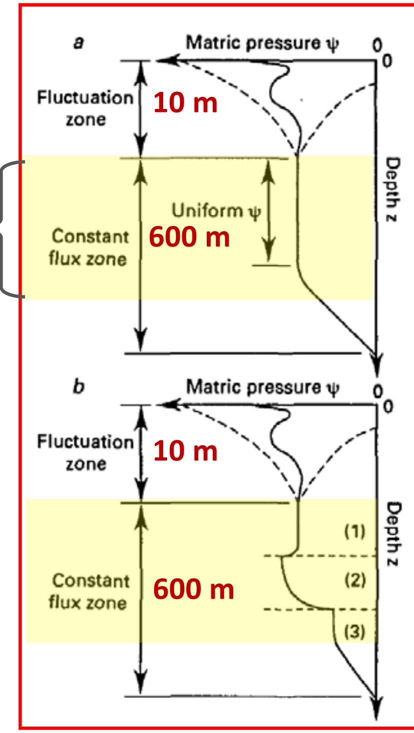
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

The deep VZ is "wet" and stable – *slow fluxes, unit gradient*



- Generally, conditions in the deep VZ are near steady state – slow dynamics (e.g., in YM) could relax monitoring intervals and permit observation of mean behavior (instead of gradients)
- States and fluxes averaged over longer times – *monthly, annually?*
- But…not necessarily uniform – beware of focused flow pathways

The deep vadose zone



Nimmo et al. 1994

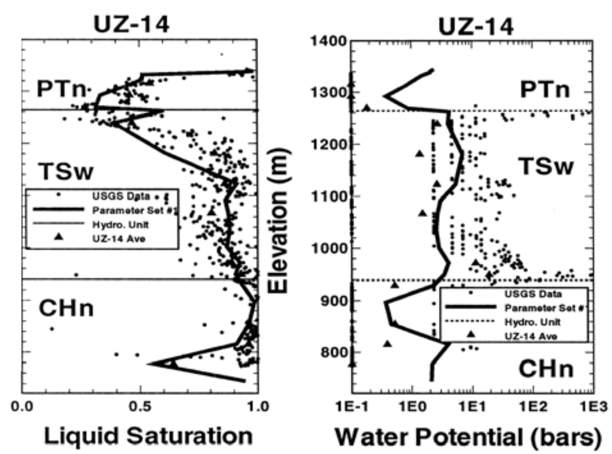


Fig. 4. Comparisons of the simulated and observed saturations and water potentials of borehole UZ-14.

Wu et al. 1999

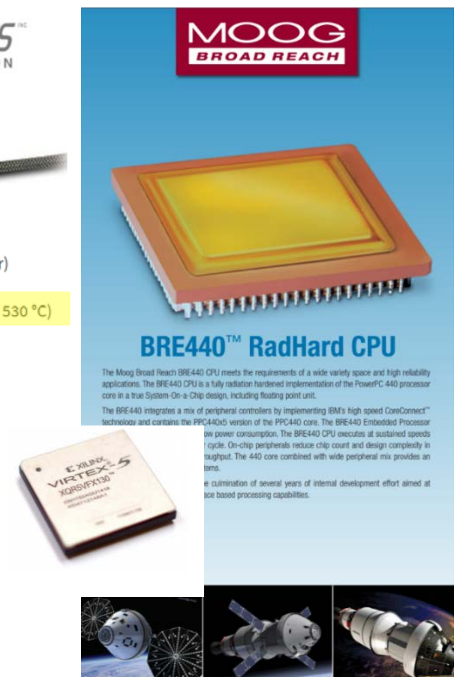
Rad/temp-hardened (next generation) sensors

- *Dinwiddie and Walter (2017)* highlighted the need for rad-hard and temp-hard sensors (especially for near drift monitoring)
- Need to promote technological partnerships for development of advanced and hardened sensors (>30 *Rad-Hard* companies in US)
- Identify other "*deep VZ*" potential partners (Oil-Gas, EPA, CZO's?)

PCB PIEZOTRONICS
MTS SYSTEMS CORPORATION

Model: 176M03

- Measurement Range: 20 psi (1.4 bar)
- Sensitivity: (±20%) 17 pC/psi (247 pC/bar)
- Sensing Element: UHT-12™
- Temperature Range: -94 to 986 °F (-70 to 530 °C)
- Electrical Connector: 7/16-27 2-Pin



XILINX
ALL PROGRAMMABLE.

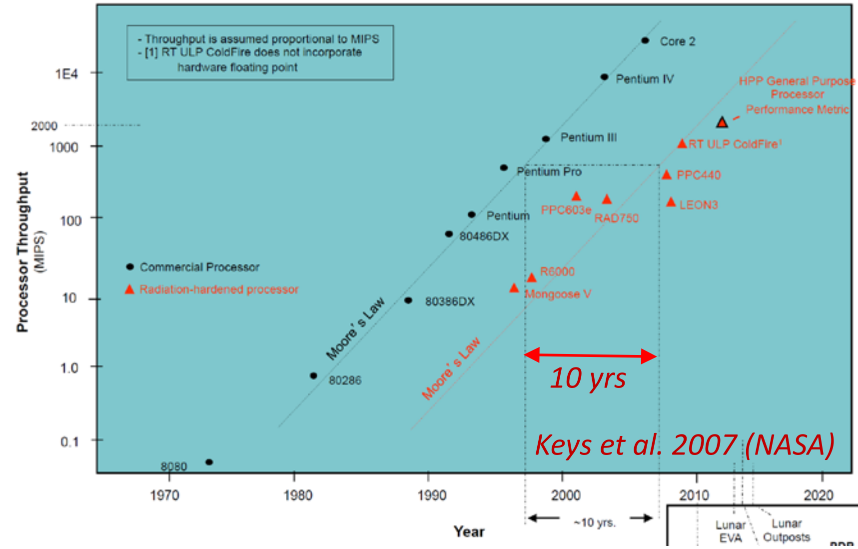
Table 4-1. List of Enabling Technologies that Would Support In-Drift Performance Confirmation Activities at Yucca Mountain [Based on Burgess et al. (2005) and Expanded per SNL (2008)].

Technology Candidates	Reclassified Priority	Research & Development	Benefits
Convert ambient gamma/neutron radiation to robot and or sensor power	High priority; high risk/ high reward	Define physics; conduct feasibility study of energy conversion process; calculate power that could be generated from radiation fields in loaded drifts; conduct experimental verification of physical prototypes	Extend operating life of robots, sensors, wireless sensor networks, and communication systems and reduce maintenance. Radiation cells would use ambient waste package radiation to supply long-term, in-drift power for monitoring
Radiation-hard, high-temperature electronics	High priority; high risk/ high reward	Develop a family of inherently tolerant electronics useful for a wide variety of applications, and guidelines for use given they may have radically different voltage ranges and levels of integration compared to COTS	Extend operating times and reduce maintenance costs and enable performance confirmation monitoring where rad levels are high and exposure times are long
Radiation-hard DC motors	Medium	Improve on existing technologies to undefined specifications	Extend operating life of in-drift robots and reduce maintenance
Non-contact, precision drift wall inspection system	High	Identify sensor technologies; sensor fusion; optimize scanning for in-drift conditions (i.e., lighting; resolution)	Enable fracture mapping and seepage monitoring (as in SNL, 2008, Section 3.3.1.2); decrease time to complete baseline drift inspection and periodic re-inspection activities to evaluate evolving structural integrity
In-drift moisture sensor and sampler	High	Develop radiation-hard {200 rad/hr [2 Gy/hr]}, high-temperature {203 °C [397.4 °F]} moisture sensors and samplers (direct/indirect)	Enable characterization and collection of thin films of moisture on in-drift surfaces for removal and water quality analysis
Robotic system to emplace/retrieve moisture samplers	High	Develop robotic system, including manipulators, to emplace/retrieve moisture samplers (e.g., water collectors/drip collection sheets/ drip cloths)	Enable collection of in-drift water and removal for chemical analysis
Radiation-hard, high-temperature radiation sensors to detect mobile radioactive gas and distinguish it from WP shine and radon	High	Develop radiation-hard {200 rad/hr [2 Gy/hr]}, high-temperature {203 °C [397.4 °F]} gas sensors to detect mobile radioactive gas and other gases important to performance confirmation	Ensure safety of subsurface operations staff and enable in-drift performance confirmation monitoring of gases

Dinwiddie and Walter (2017) - Methods and sensors for monitoring variably saturated fractured rock and thermal environments (CNWRA)

Environmentally hardened sensors - *point and linear sensors*

- Rad-hardened processors lag behind commercial ones by a decade



Point - temperature + radiation hard sensor

TMP461-SP (ACTIVE)

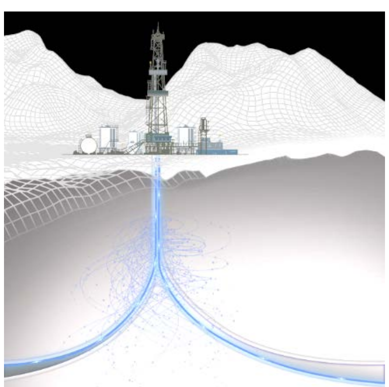
Radiation Hardness Assured (RHA) High-Accuracy Remote and Local Temperature Sensor

DATASHEET

TMP461-SP Radiation Hardened Remote and Local Digital Temperature Sensor datasheet (Rev. A)

View now Download

Linear - fiber optic-based

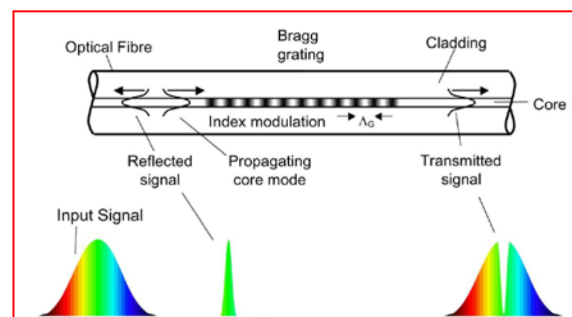


www.optasense.com

- In parallel to advancing *Rad-Hard* + *Temp-Hard* point sensors; promoting linear sensing technologies based on fiber optics appears most promising for addressing the deep VZ challenge *(passive, radiation hardened, borehole-ready, mechanical +temp +chemical +water content and possibly "backfilled boreholes" for matric potential)*

Fiber Bragg Grating Sensors for Harsh Environments

Stephen J. Mihailov *Sensors* **2012**, *12*, 1898-1918;



ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Optical fiber sensors (OFS) - *backbone of VZ monitoring ?*

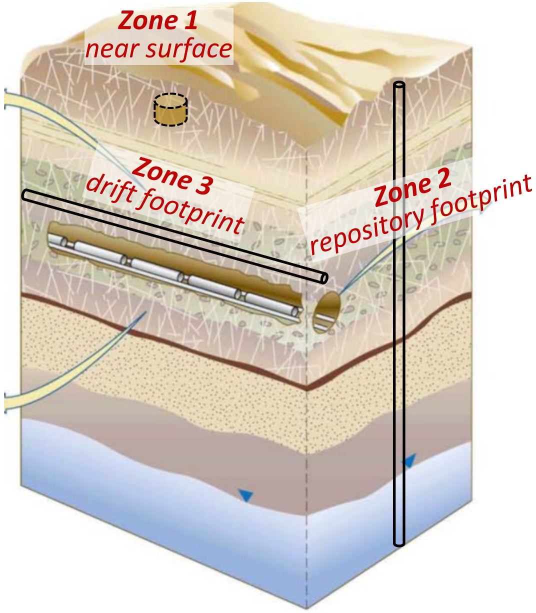
- In addition to the advantage of having a linear sensor extending hundreds of meters and providing >1 m resolution information, optical fiber sensors (*OFS*) offer rapidly expanding sensing capabilities including temperature, mechanical deformation, water content (heated), chemical and possibly matric potential

- OFS can be extended from the surface (safety provisions for leakage) down boreholes

- OFS are temperature and radiation hardened (*they feature prominently in the French Cigéo repository design - Delepine-Lesoille et al. 2017, Sensors*)

- An important flow feature difficult to constrain by point sensors is focused flow along fractures and faults – such important and performance sensitive (often unknown) regions might be better detected using horizontally installed OFS over individual drift footprints

- Recent advances in OFS technology warrant their consideration as important elements in the deep VZ monitoring network



ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Near surface monitoring - *fluxes, tracers, upgrades*

- Lysimeters over the repository footprint (where feasible) could provide robust and continuous estimate of deep percolation fluxes
- A prescribed release of a sequence of detectable and environmentally-friendly <u>tracers</u> to assess arrival times, test fidelity of pore water sensors, and refine flux estimates (decadal intervals?)
- Upgradable monitoring infrastructure - anticipating technology advances and benefiting from information gathered (e.g., *Freifeld and Tsang ,2006* for footprint); maintaining compatibility and record continuity/sensor legacy

Advanced lysimeters (UMS)

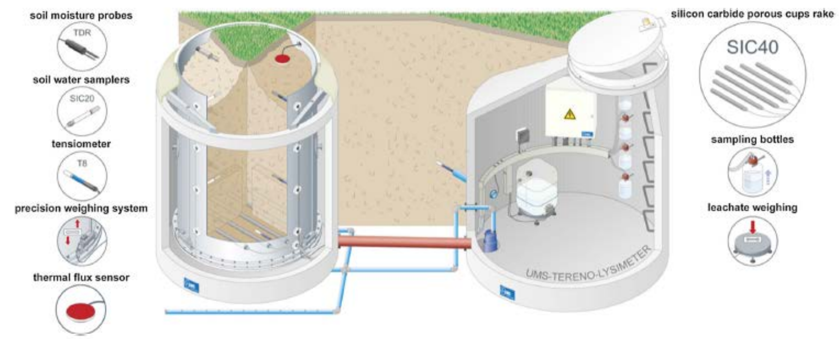
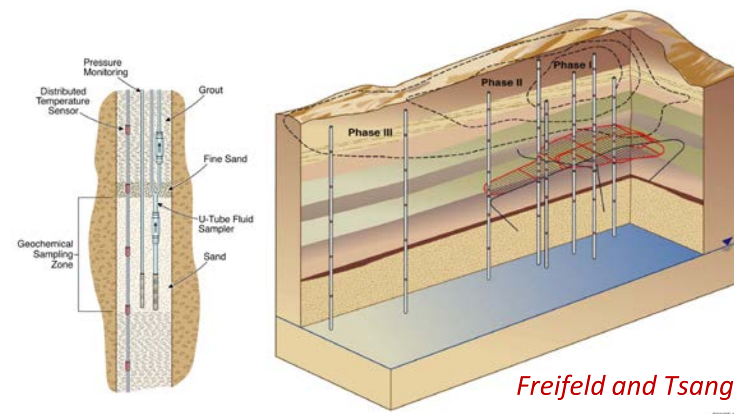
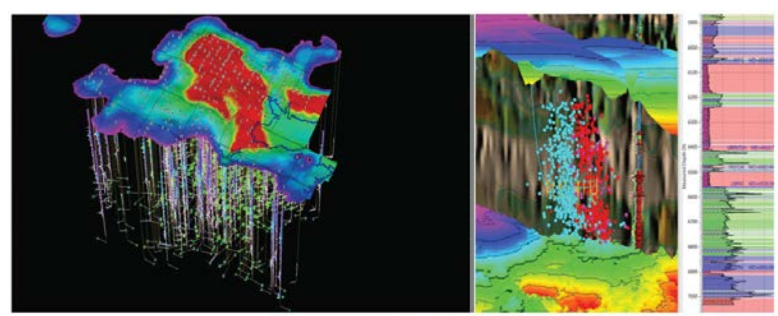


Fig. 3 Cross-section of a TERENO-SOILCan lysimeter (*left*) and the service well (*right*) (provided by UMS AG, München, Germany)



Freifeld and Tsang (2006)



www.aogr.com

Summary and recommendations

- Long term monitoring is part of performance assessment it is “both a safety issue and a site-credibility issue” – *ensures repository functioning and alerts for failure*

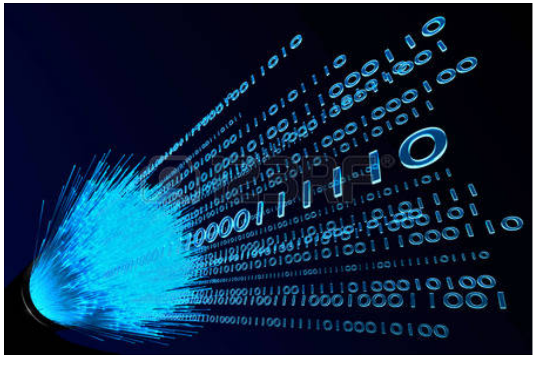
- Continuous monitoring of HLW in the deep VZ presents challenges of sensor placement, longevity, spatial heterogeneity, harsh conditions (near drift) – however, *the deep VZ is often hydrologically stable domain*

- Present methods for VZ monitoring conceived for shallow (and highly dynamic) subsurface and for hydrological time scales (a few years) – *a new generation of advanced and environmentally hardened VZ sensors is needed*

- Technological partnerships with space/defense industries and VZ partners could accelerate development of required sensors

- Advances in optical fiber sensors hold a promise overcoming point sensor limitations – rapidly expanding OFS capabilities

- Information management and monitoring infrastructure updates should be considered early in the process



Acknowledgments

- Special thanks to *Stu Stothoff* and *Cynthia Dinwiddie* and *Randy Fedors* (CNWRA), and *John Selker* (OSU) for many inspiring discussions

- I thank members and staff of the NWTRB for this invitation!

Thank you!

STEP Group at ETH 2016

Scope

The Board will hold a public meeting in the Washington, D.C. area on March 27, 2018. The meeting will consider the technical issues associated with preclosure operational and performance confirmation monitoring and the retrievability of emplaced high-level radioactive waste (HLW) and spent nuclear fuel (SNF). Technical specialists will discuss sensor/monitoring technologies for monitoring subsurface seepage, in-drift environmental conditions, and corrosion of waste packages for HLW and SNF. Representatives from several European countries will discuss national policies and approaches to monitoring and retrievability.

We are looking for a speaker that can talk about the state-of-the-technology in sensors and monitoring methods that potentially can be applied to subsurface seepage monitoring in a geologic repository for HLW and SNF. In a U.S. Department of Energy (DOE) Yucca Mountain Project Performance Confirmation Plan published in 2004, seepage monitoring was one of 20 activities DOE planned to conduct during the performance confirmation period. The purpose of seepage monitoring is to evaluate the spatial and temporal distribution of seepage flux for ambient and thermally perturbed conditions and to monitor seepage water chemistry. DOE planned to conduct seepage monitoring in unventilated alcoves or boreholes, in a thermally accelerated drift, and in drifts prior to emplacement. In several of the activities, DOE proposed methodologies or technologies for use in the unsaturated zone and thermal environment that did not yet exist. DOE stated that further development of specific monitoring devices or sensors would be needed, or that integration of specific technology not yet available would be needed to implement the measurements and inspections.

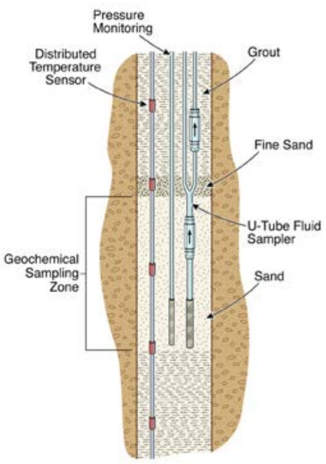
You were the lead author of two CNWRA reports published in 2006 and 2007 that reviewed the state-of-the-art in sensor technology for vadose zone measurements. The reports concluded that the technology available at that time is insufficiently developed to achieve the DOE monitoring goals, particularly due to the harsh temperature and radiation conditions anticipated within the repository near field. Given that technology has much advanced since the publication of the CNWRA reports, it would be useful to have a presentation on sensor/monitoring technologies that takes account of recent developments and that discusses the potential applications, as well as the limitations, of these technologies to seepage monitoring in a repository for SNF and HLW (i.e., high radiation and high temperature environment). There will be a similar presentation that will focus on waste package performance monitoring.

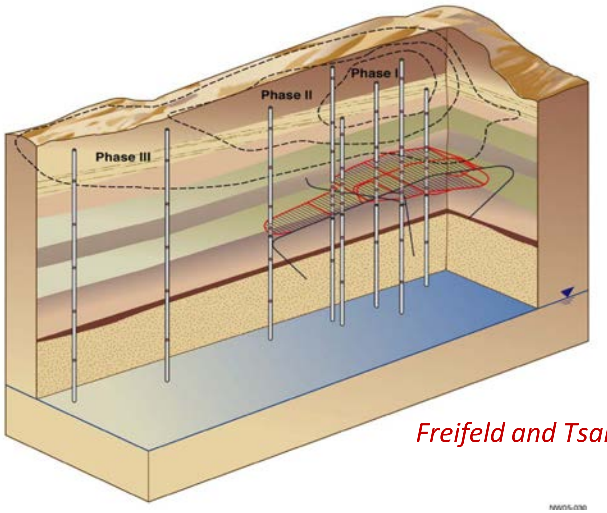
Some thoughts..

http://longnow.org/seminars/02006/jan/13/nuclear-power-climate-change-and-the-next-10000-years/

The problem of nuclear waste isn't a problem of storage for a thousand years or a million years. The issue is storing it long enough so we can put it in a form where we can reprocess it and recycle it, and that form is probably surface storage in very strong caskets in relatively few sites, i.e., not at every reactor, and also not at one single national repository, but at several sites throughout the world with it in mind that you are not putting waste in the ground forever where it could migrate and leak and raise all the concerns that people rightly have about nuclear waste storage. By redesigning the way in which you manage the waste, you'd change the nature of the challenge fundamentally.

https://www.theverge.com/2012/6/14/3038814/yucca-mountain-wipp-wasteland-battle-entomb-nuclear-waste





Freifeld and Tsang (2006)

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich