Enjeux socio-économiques et défis techniques du stockage souterrain aux Etats-Unis

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Stockage Souterrain pour l'Energie et l'Environnement
Ecole des Ponts Paris Tech, 25 novembre 2014

Enjeux socio-économiques et défis techniques du stockage souterrain aux Etats-Unis

1. Stockage de déchets
   - Déchets radioactifs
   - Capture et Séquestration du CO_2 (CCS)

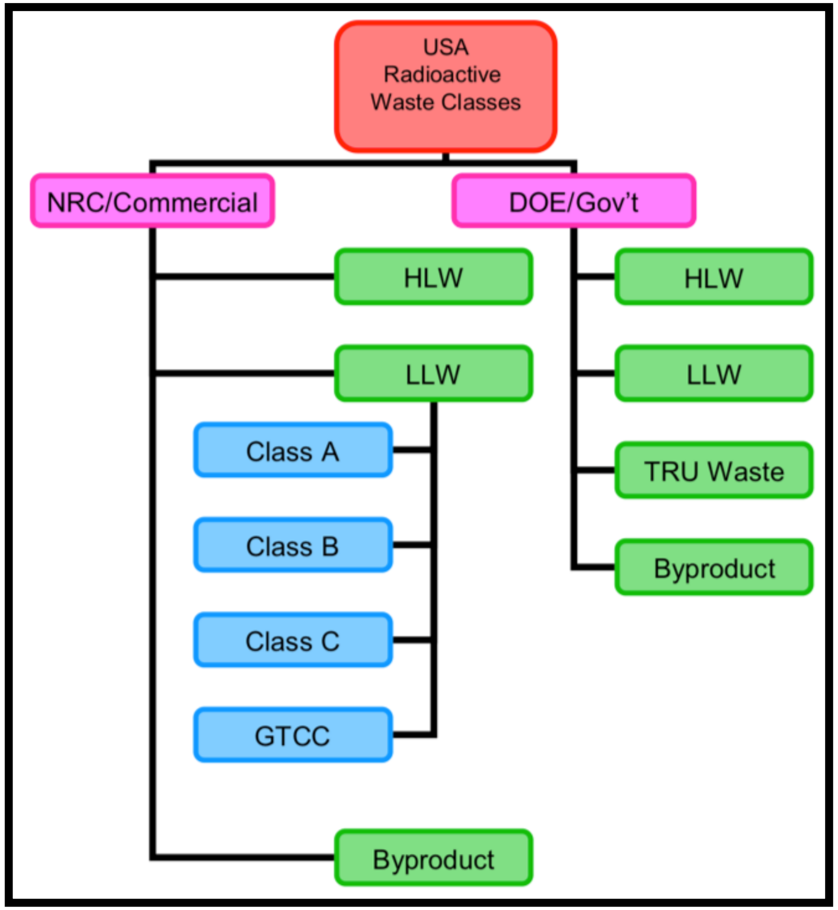
2. Stockage d'énergie
   - Gaz naturel
   - Stockage d'air comprimé (CAES)

3. Recherche sur le stockage géologique

Déchets radioactifs – Contrôle des sites

- 1954: ‘Atomic Energy Act’ – Le gouvernement américain du développement de l’énergie atomique à des fins commerciales.
- Les entités commerciales gèrent les exploitations privées et certaines exploitations qui sont propriété des Etats, pour les déchets à « faible » radioactivité (Low-Level Waste, LLW).
- Les sites de stockage seront administrés par les Etats ou par le gouvernement fédéral.
  33 des 50 Etats sont des ‘Agreement States’.
- Chaque site de traitement des déchets est assujetti à des lois fédérales et étatiques spécifiques.
  Ex: procédures de suivi des déchets: ‘Waste Inventory Records Keeping Systems’ (WIRKS)

Déchets radioactifs – Contrôle des déchets



HLW: High Level Waste
LLW: Low Level Waste
TRU Waste: Transuranic Waste
GTCC: 'Greater-Than-Class-C'

La 'Nuclear Regulatory Commission' (NRC) réglemente:

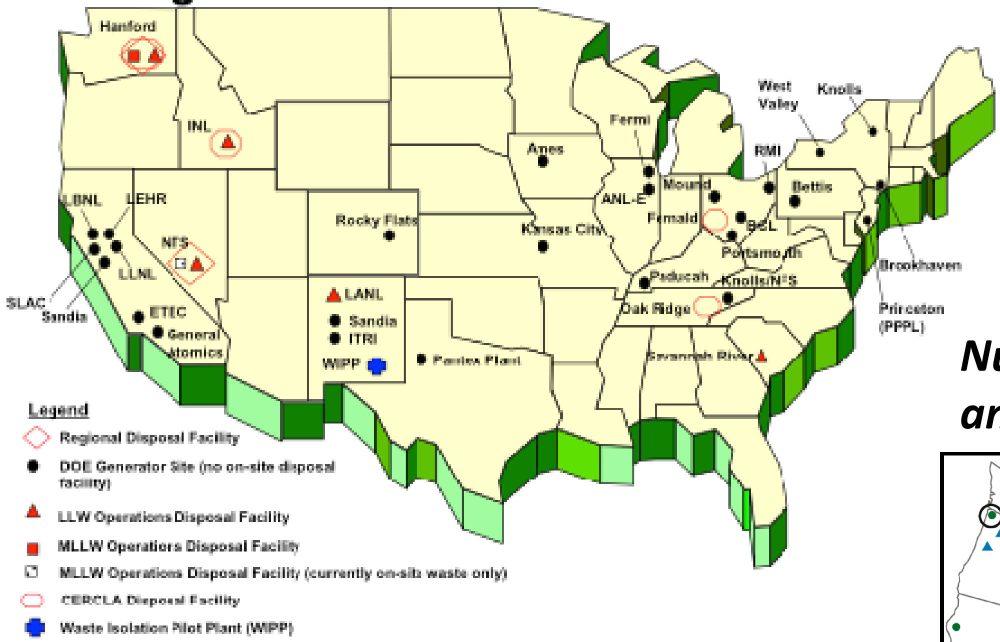
- Types de déchets: à faible radioactivité (LLW) et à forte radioactivité (HLW)
- Utilisation et stockage permanent des minerais (uranium, thorium)
- Techniques d'enrichissement
- Recyclage des déchets

Les Agreement States réglementent les sources de radioactivité (e.g., radium, radon).

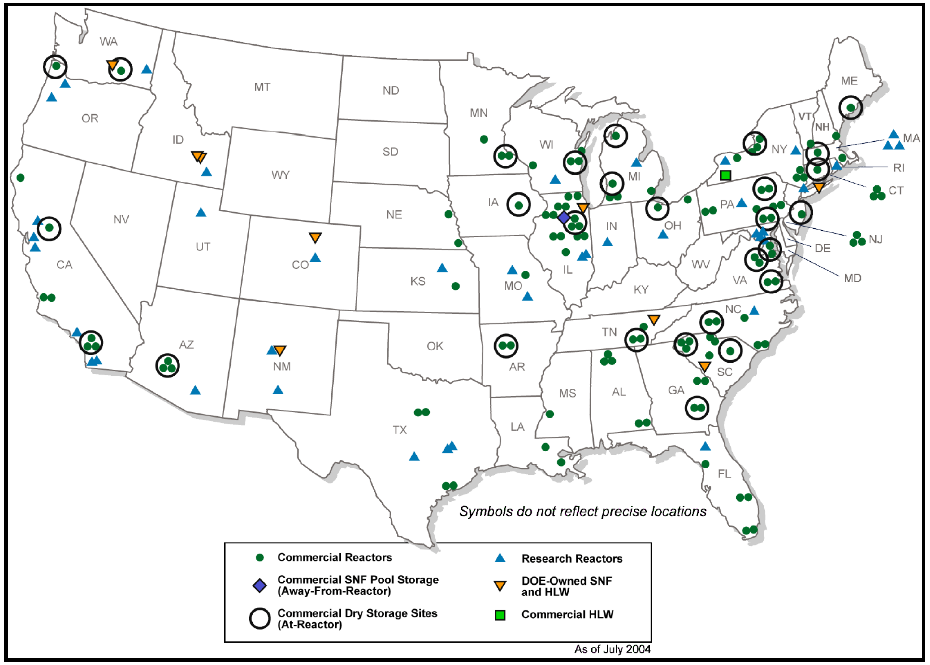
Le Ministère de l'Energie (Department of Energy, DoE) contrôle les activités des sites de stockage (e.g. recherche, développements technologiques, défense).

Déchets radioactifs – Cartographie

DOE's Waste Disposal Facility Configuration



Nuclear Power Plants, Research Reactors, and Spent Fuel Storage Facilities



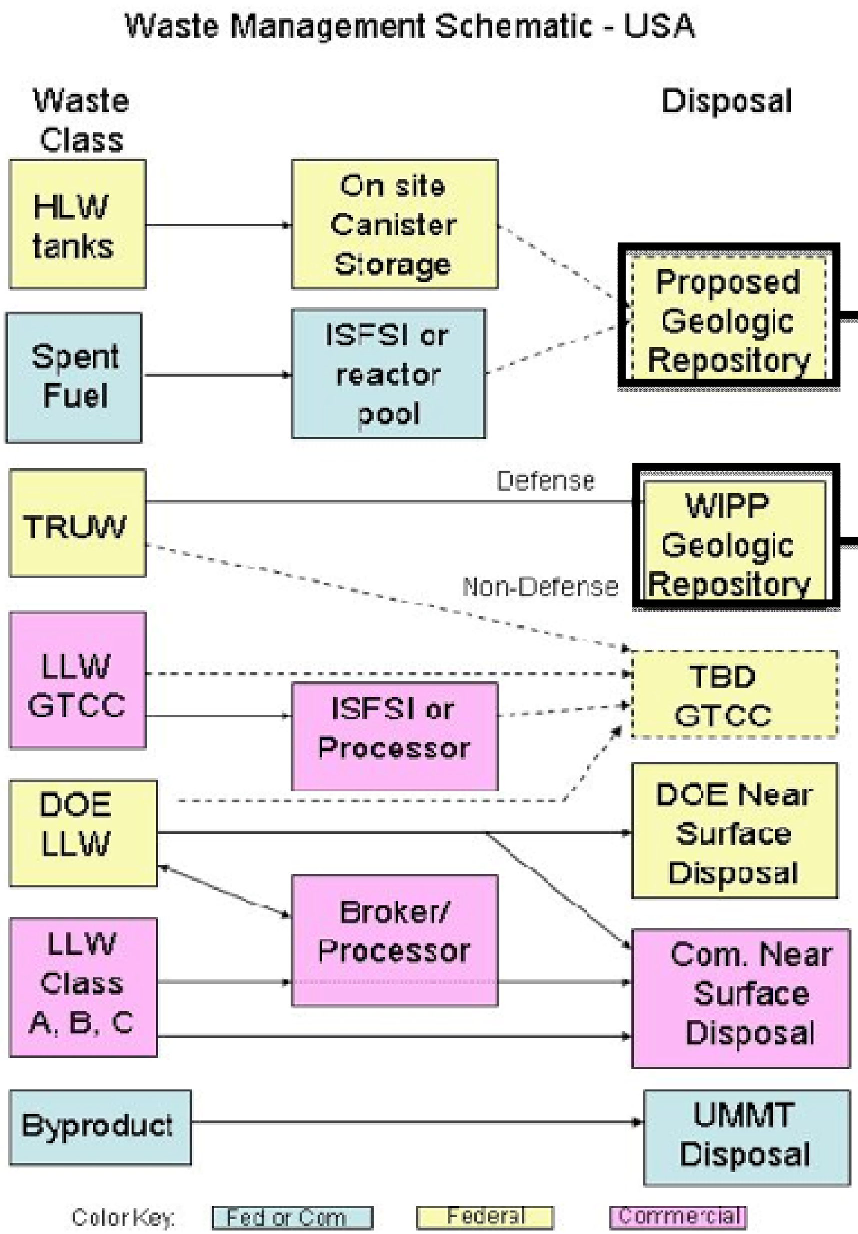
<u>Note</u>: 'Spent fuel' (carburant d'occasion)

•Matériau extrait des réacteurs après l'irradiation, et avant traitement pour recyclage

•Pas considéré comme un déchet

•Mais… matériau radioactif qui doit être stocké temporairement…

Déchets radioactifs – Gestion

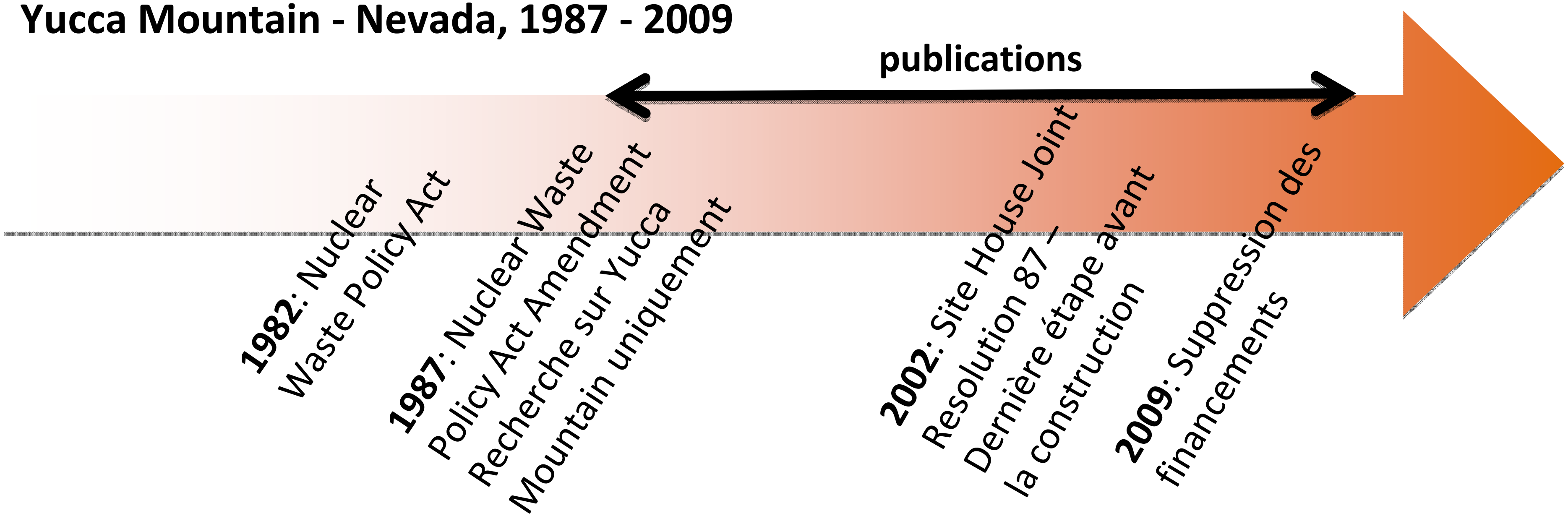


Yucca Mountain
Nevada, 1987-2009

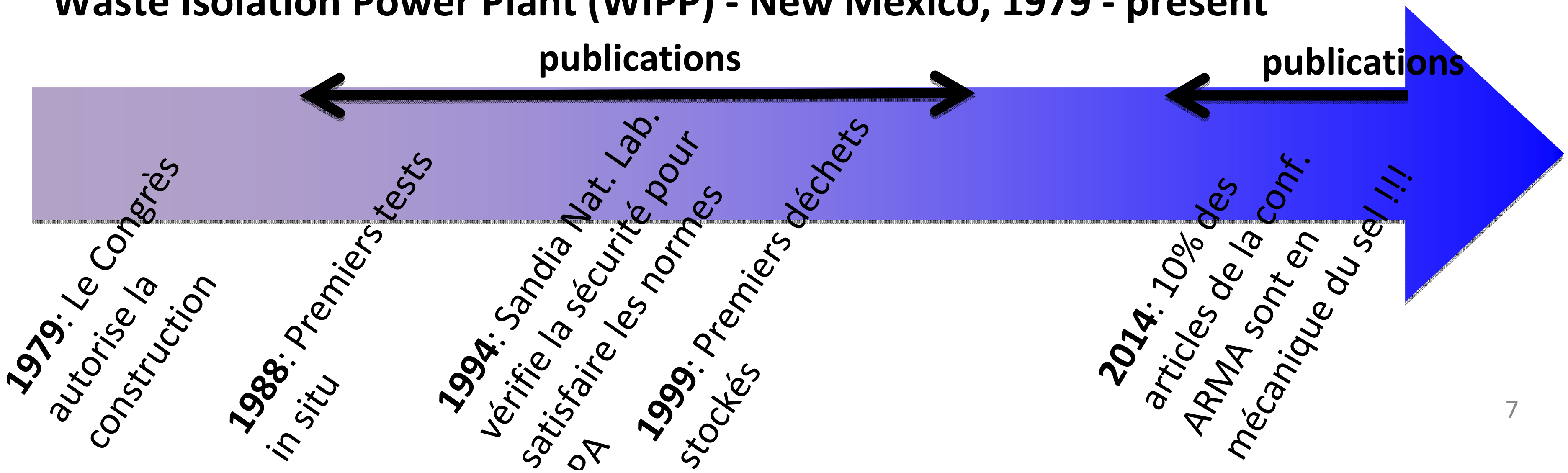
Waste Isolation Power Plant (WIPP)
New Mexico, 1979-present

Déchets radioactifs – Histoire des sites profonds

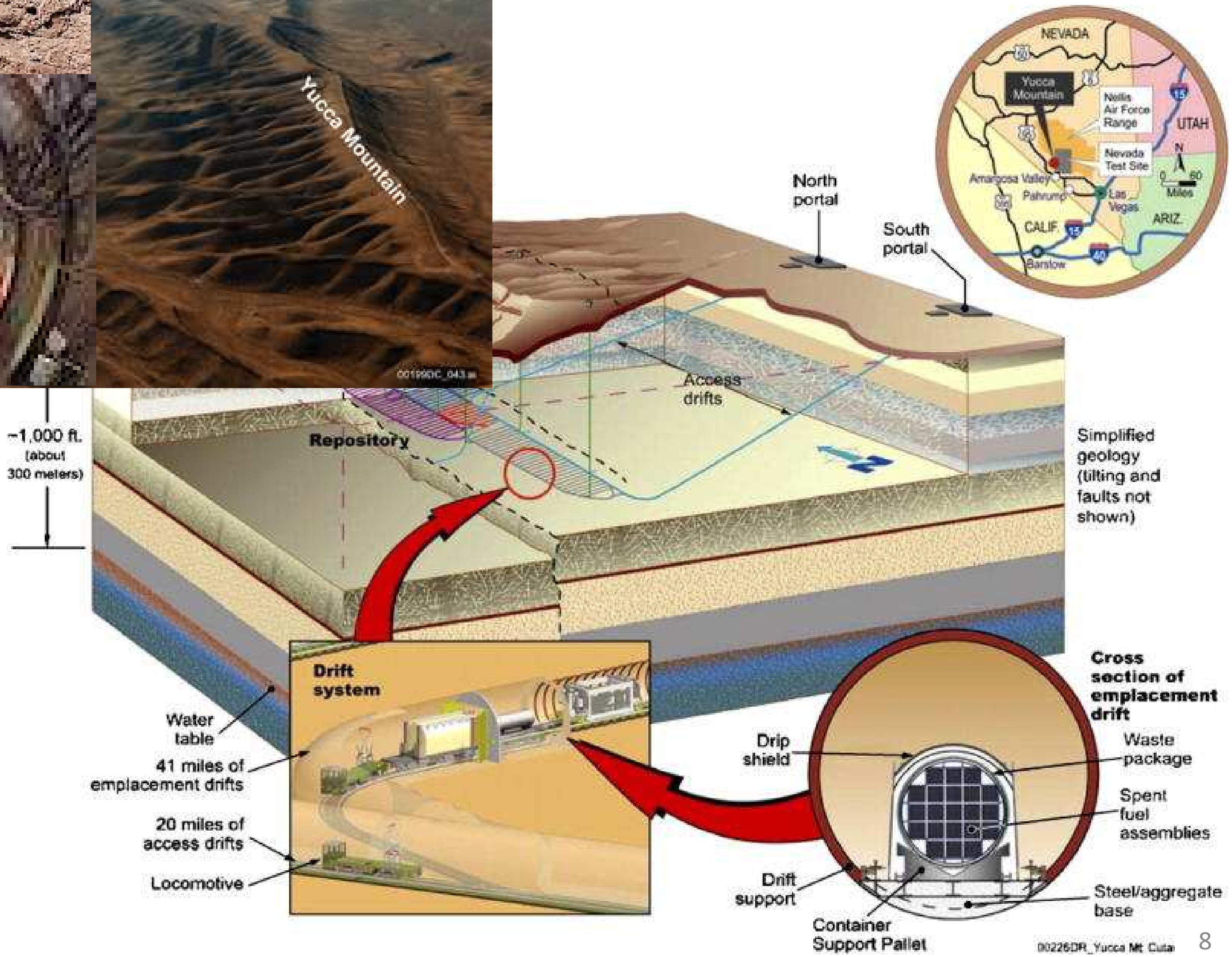
Yucca Mountain - Nevada, 1987 - 2009



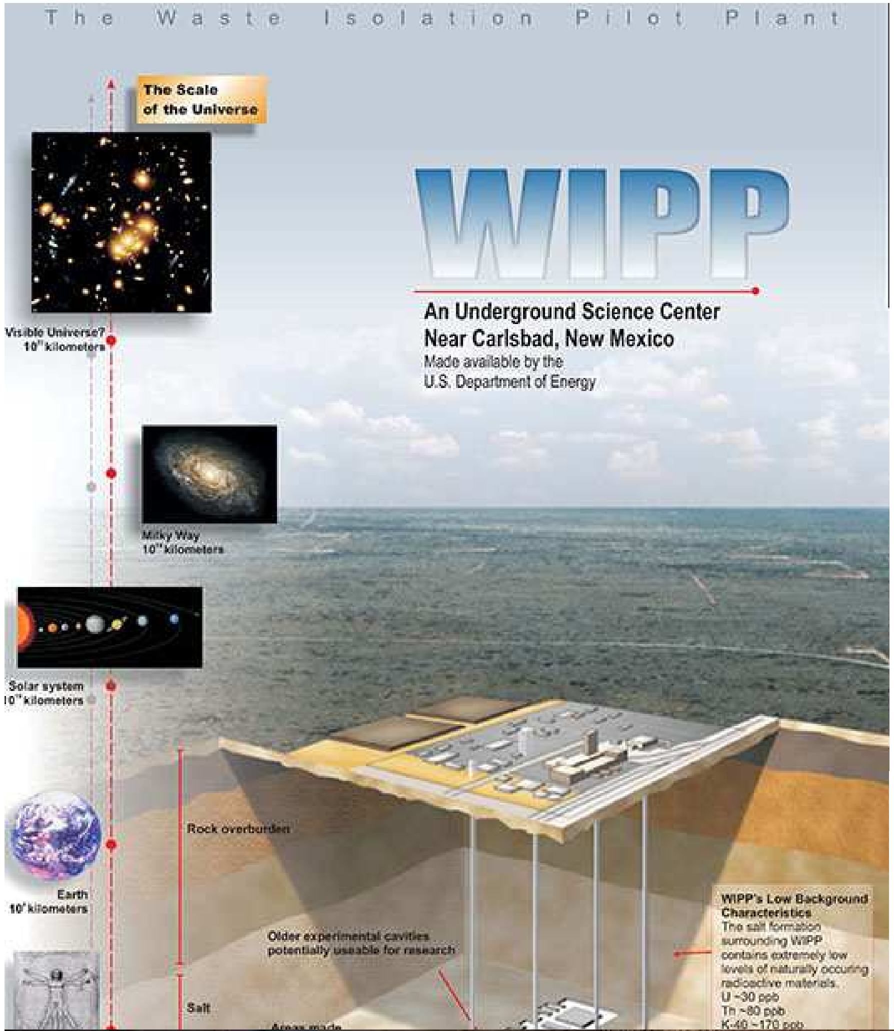
Waste Isolation Power Plant (WIPP) - New Mexico, 1979 - present



Déchets radioactifs
Yucca Mountain
Technologie



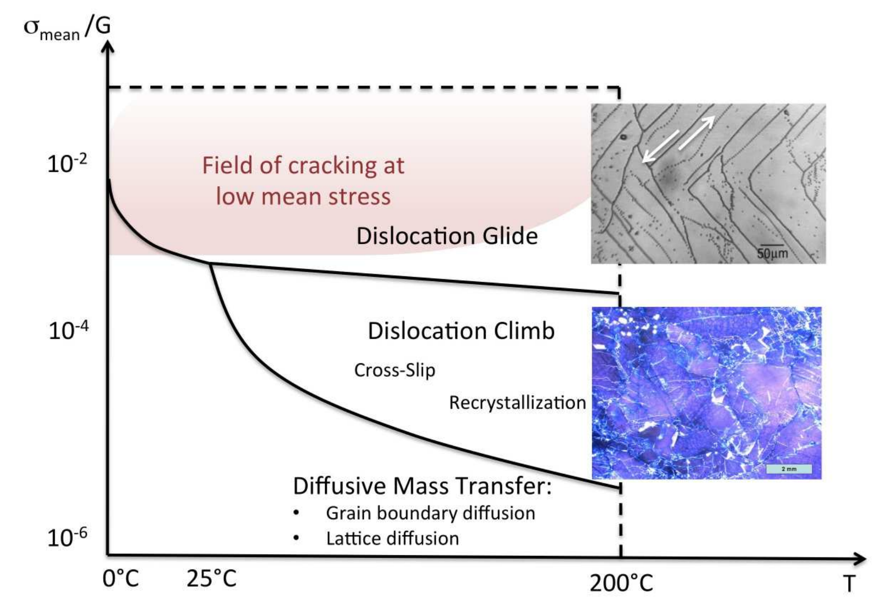
- **Tuff fracturé - roche volcanique**
- **Profondeur: 660m**
- **Capacité: 770,000 tonnes de déchets**
- **Recherche (ex): Berkeley Nat. Lab., USGS, Univ. Nevada Reno**



Déchets radioactifs – WIPP Technologie

- Sel gemme
- Profondeur: 600m
- Volume de déchets stockés jusqu'en décembre 2010: 72,422 m^3
- Recherche (ex): Sandia Nat. Lab., Los Alamos Nat. Lab., South Western Research Institute

Déchets radioactifs – WIPP
Recherche associée: mécanique du sel gemme

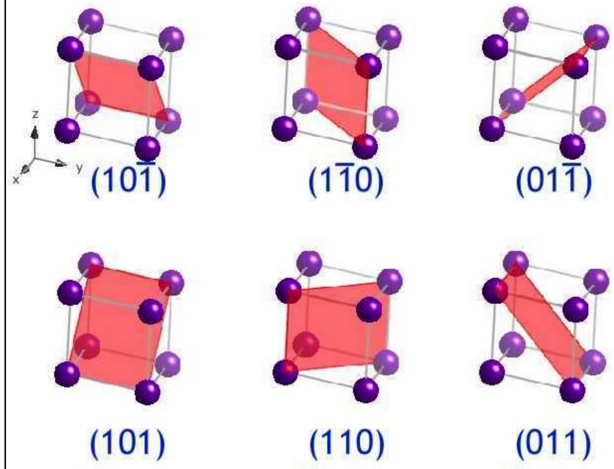


Dislocation Glide	$\dot{\varepsilon} = A\exp\left(-\frac{B\sigma_d}{RT}\right)\exp\left(-\frac{Q}{RT}\right)$
Dislocation Climb	$\dot{\varepsilon} = A\times\left(\frac{\sigma_d}{G}\right)^n\exp\left(-\frac{Q}{RT}\right)$
Diffusion	$\dot{\varepsilon} \propto K\times\left(\frac{D}{d^2}\right)\times\left(\frac{\Omega\sigma_d}{kT}\right)$

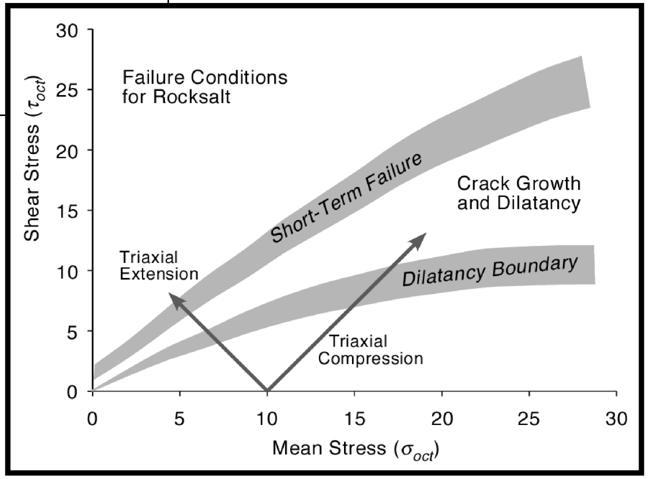
Figure 1: Micro-mechanism map for halite at repository conditions (dashed box).

Diagram and data from (Hunsche, 1981; Senseny et al., 1992; Fam et al., 1998). Photos from (Schleder & Urai, 2005; Barber et al., 2010).

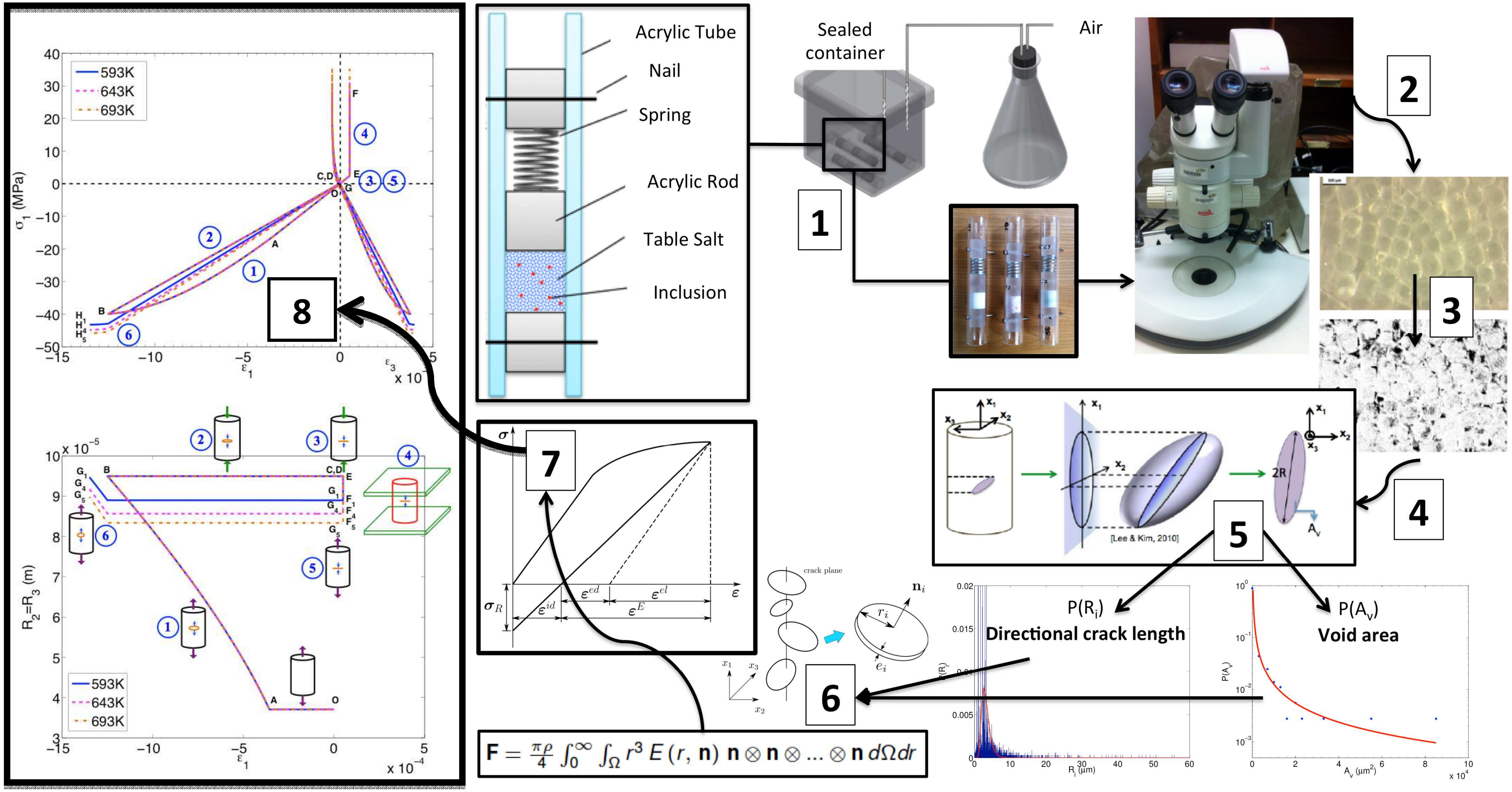
T temperature
σ_{mean} mean stress
σ_d deviatoric stress
G rock shear modulus
R=8.3142.10^{-3} kJ/K.mol
K Boltzman constant
Q activation energy
D diffusion coefficient
d grain diameter
Ω microstructure volume



- USA: Hansen, Chan, …
- Allemagne: Hou, Lux, Hunsche, Urai …
- France: Bérest, Pouya, …



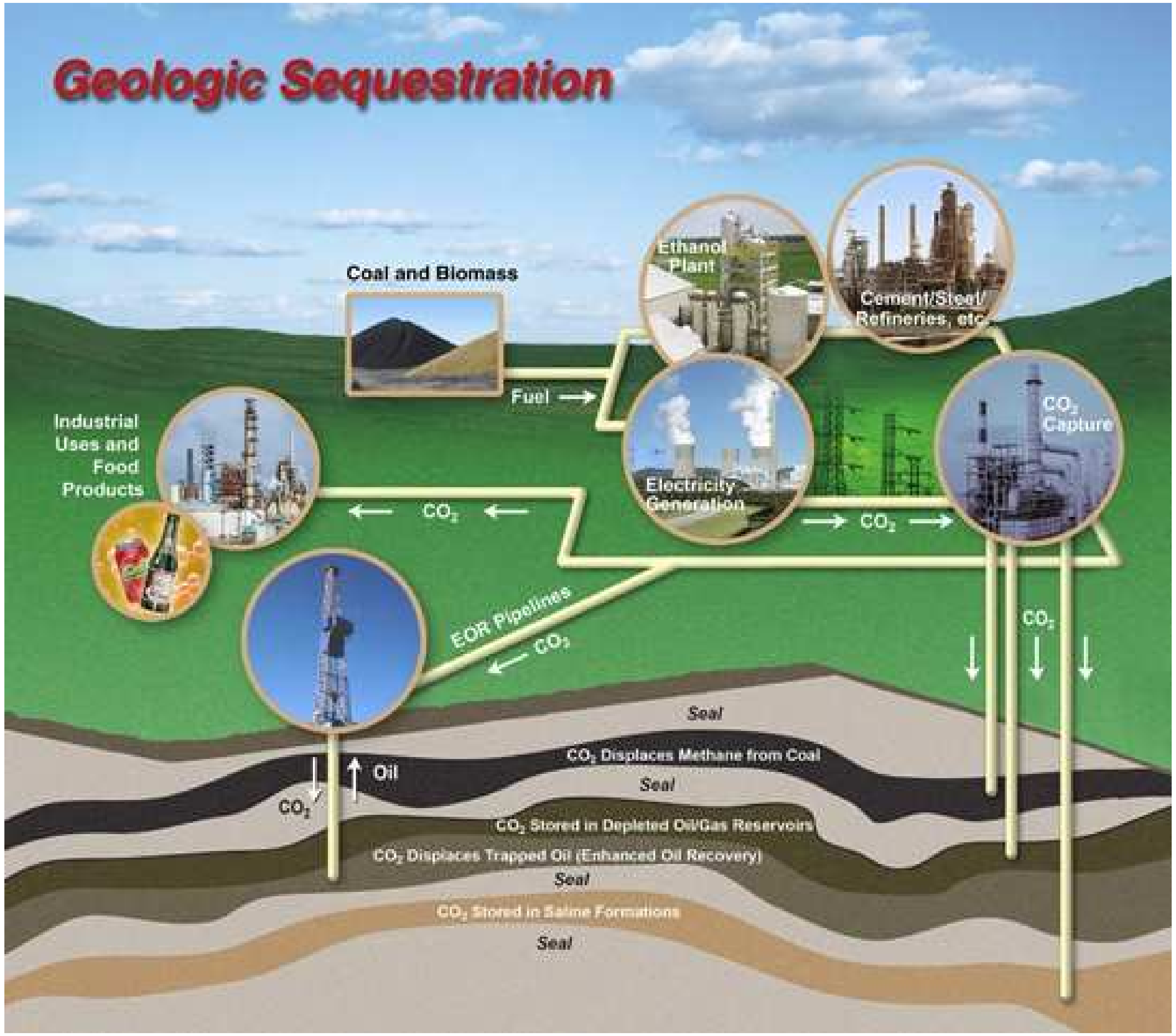
Déchets radioactifs – WIPP
Recherche – Endommagement et cicatrisation



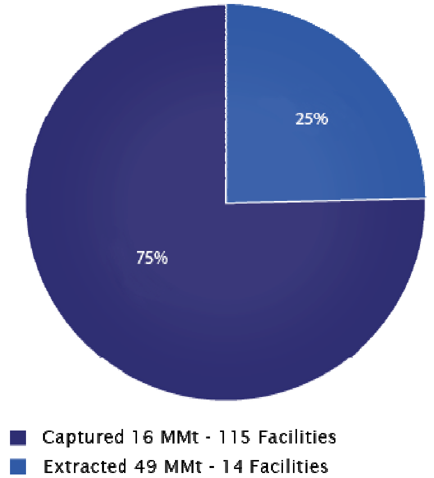
$$\mathbf{F} = \frac{\pi \rho}{4} \int_0^{\infty} \int_{\Omega} r^3 E(r, \mathbf{n})\, \mathbf{n} \otimes \mathbf{n} \otimes \ldots \otimes \mathbf{n}\, d\Omega dr$$

Fabric-Based Thermodynamic Models of Damage and Healing Mechanics (Arson et al.)

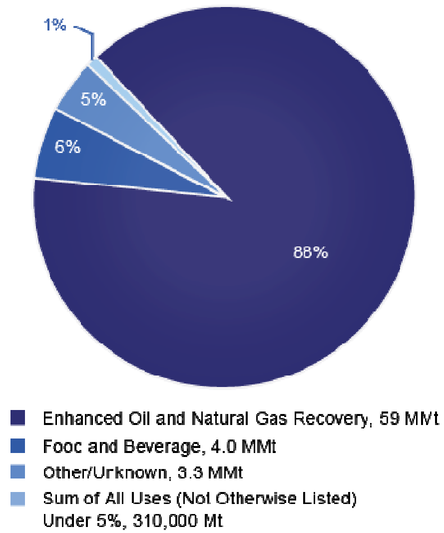
Capture et Séquestration du CO_2 – Principe et Applications
Carbon dioxide Capture and Sequestration (CCS)



* Source: EPA Greenhouse Gas Reporting Data - Subpart PP - Suppliers of Carbon Dioxide. Based on 2011 data. MMT = million metric tons

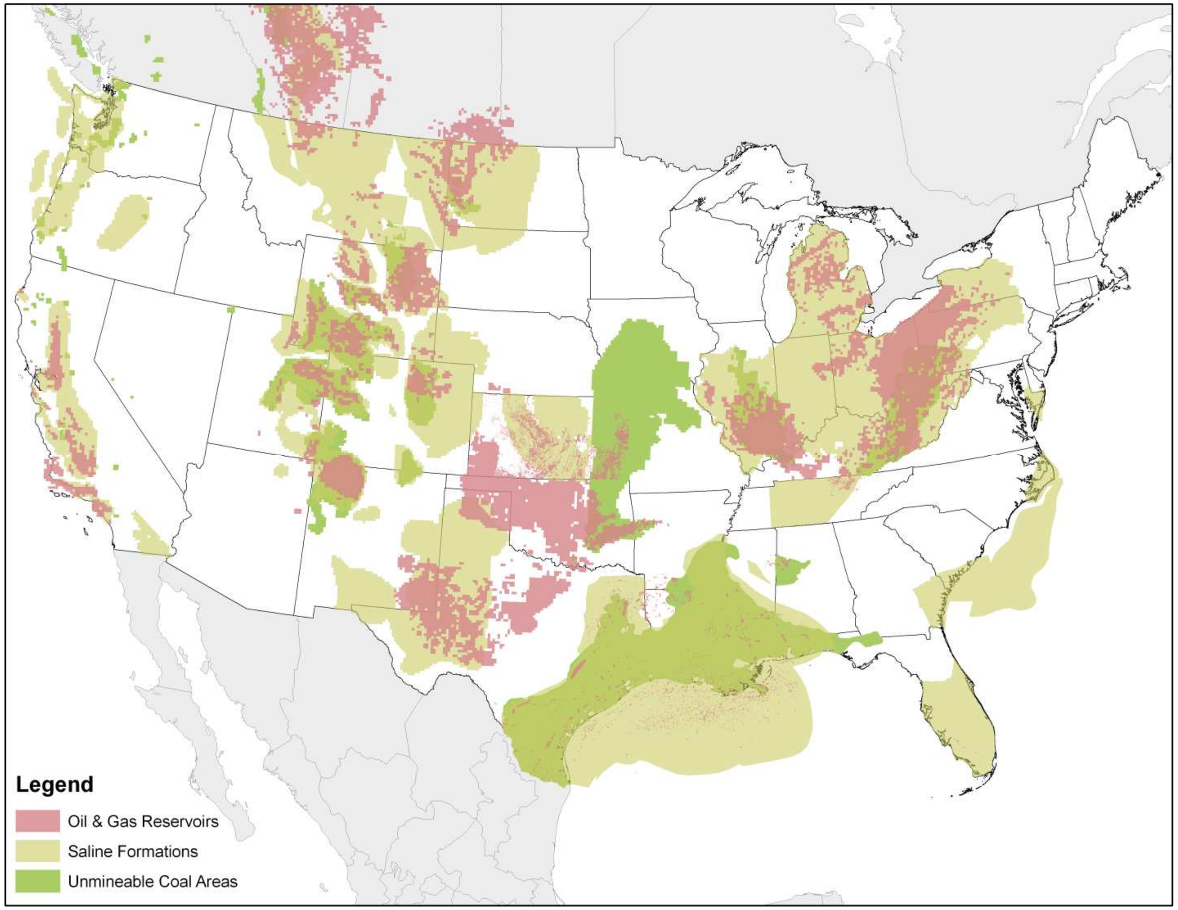


Capturé (2011)



Utilisé (2011)

Capture et Séquestration du CO_2 (CCS) – Potentiel aux USA

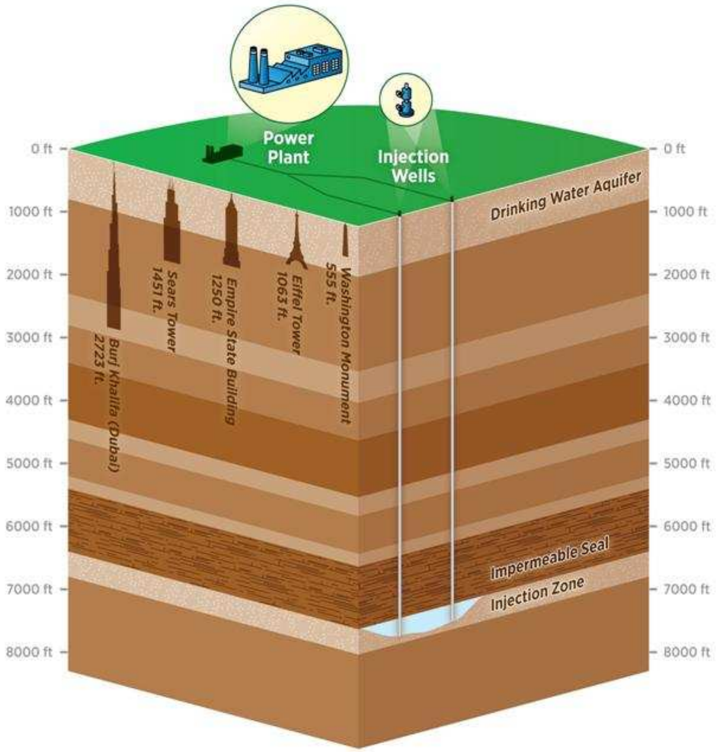


Le CO_2 comprimé est injecté dans une roche poreuse, e.g. grès, schiste, dolomite, basalt, veines de charbon.

Les formations géologiques doivent être situées sous des couches imperméable

Les sites de stockage de CO_2 comprimé sont régulés par l'Agence de Protection pour l'Environnement (*Environmental Protection Agency, EPA*)

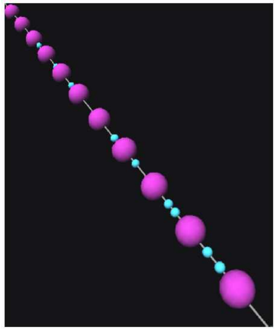
CCS et stimulation de réservoirs d'hydrocarbures (Enhanced Oil Recovery, EOR)

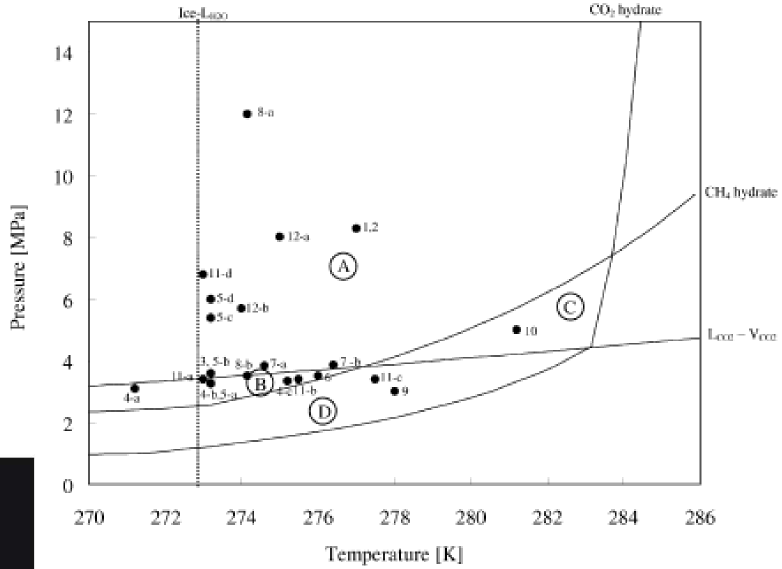


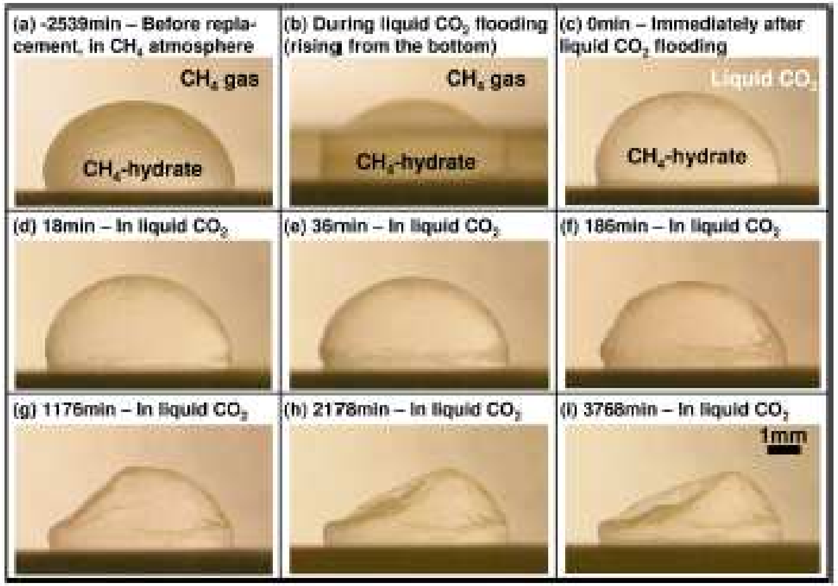
- Injection de CO_2 dans les réservoirs pour expulser les hydrocarbures *Extraction d'hydrocarbures + stockage de CO_2*
- Aux USA, 32 millions de tonnes de CO_2 sont utilisées pour l'EOR
- La pression du CO_2 doit être maintenue (basse) pour garantir l'intégrité du CO_2
- Applicabilité: lorsque le site de production du CO_2 est proche du site d'extraction d'hydrocarbures

CCS et extraction de méthane

- Injection de CO_2 dans des veines de charbon pour en extraire le méthane (CH_4)
- Le taux d'adsorption du CO_2 est deux fois supérieur à celui du CH_4
- Ressources en charbon aux USA: 6,000 milliards de tonnes; 90% impossible à exploiter par des techniques minières traditionnelles







Recherches en pormécanique: Vandamme, Brochard, Santamarina…

CCS – Projets associés aux USA (extraits de textes)

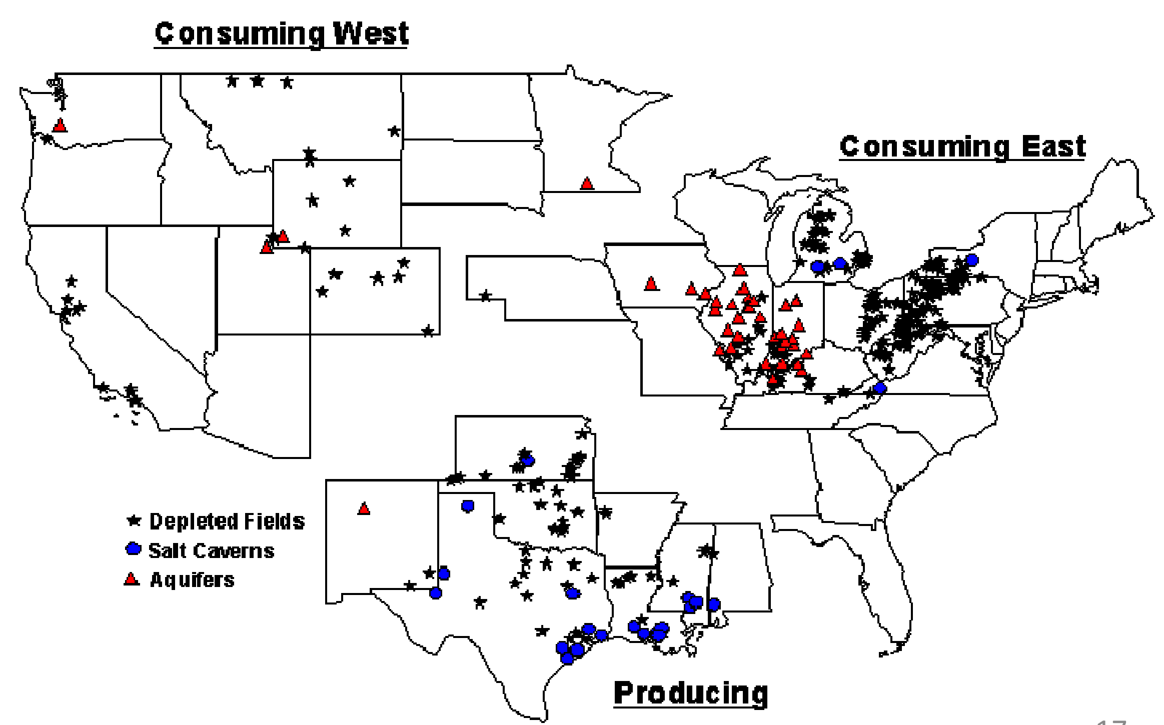
- **Methodology development and assessment of national CO_2 enhanced oil recovery and associated CO_2 storage potential**
  The objective of the CO_2-EOR research effort is to develop a geologic- and reservoir engineering-based, probabilistic assessment methodology that can be used to estimate the potential volumes of technically recoverable oil using CO_2-EOR and associated CO_2 sequestration in the onshore and state waters oil fields of the United States. After the methodology has been carefully reviewed by experts from industry, academia, and government, USGS plans to use the assessment methodology to conduct a national assessment of recoverable oil using CO_2. The resulting storage of CO_2 associated with enhanced oil recovery will also be assessed.
- **Geological studies of reservoirs and seals in selected basins with high potential for CO_2 storage**
  The objective of this research effort is to reevaluate selected regions of the country and selected SAUs to better define the distribution of the geologic storage resources for anthropogenic CO_2. Since reservoir pressure directly impacts CO_2 storage potential, regional models need to be developed to help understand the controls on over- and under-pressure development in basins. Geochemical models are needed to better understand the character of ground water and the subsurface geochemical environments in selected SAUs, which are important to assess the feasibility and potential environmental impacts of CO_2 storage projects. As the opportunities develop, task members, in coordination with the USGS Produced Waters project, may also work cooperatively with other organizations to better characterize the local and regional geologic and ground water controls on potential CO_2 storage.
- **Natural CO_2 reservoirs as analogues for CO_2 storage and resources for enhanced oil recovery**
  The primary aim of the research is to determine the origin of CO_2 that is in natural gas reservoirs by using geochemical and isotopic analyses of gas and reservoir rocks. Field and rock core investigations will help determine the degree and rate of CO_2 mineralization that has occurred in the reservoir rocks. Natural surface leaks associated with CO_2 reservoirs will be investigated to determine the potential leakage pathways and time of leakage development. help to determine the geochemical effects of CO_2 on reservoir fluids, and the rate of CO_2 dissolution into the reservoir formation waters. Another objective of this research is to build the geologic CO_2-system models needed to assess the nation for naturally occurring CO_2 gas resources.
- **Economics of CO_2 storage and enhanced oil recovery**
- **Storage of CO_2 in unconventional geologic reservoirs**
  The objectives of this research are to compile relevant information summarizing the state of knowledge concerning the use of coal beds, shale, and mafic/ultramafic rocks as potential reservoirs for the long-term storage of CO_2, and to use this information to prepare preliminary methodologies to assess the potential for CO_2 storage in these reservoirs. Initial products will be national maps showing the location and other available data (thickness for example) for deep (>3,000 ft; >914 m) coal beds and organic-rich shale that may be available for CO_2 storage.
- **Induced seismicity associated with CO_2 geologic storage**
  The primary objectives of this research are to develop a better understanding of the physical processes responsible for seismicity induced by deep CO_2 injection, develop procedures to quantify the resulting seismic hazards, and help design appropriate mitigation strategies.

Stockage de gaz naturel

Acteurs:
–Industries qui possèdent des pipelines
–Industries qui produisent de l'énergie
–Industries qui fournissent du stockage
Régulation:
–Lois de l'Etat (local)
–Federal Energy Regulatory Commission (FERC)

- Cavernes de sel
- Aquifères
- Mines abandonnées
- Anciens réservoirs de gaz naturel
- Cavités en roche dure

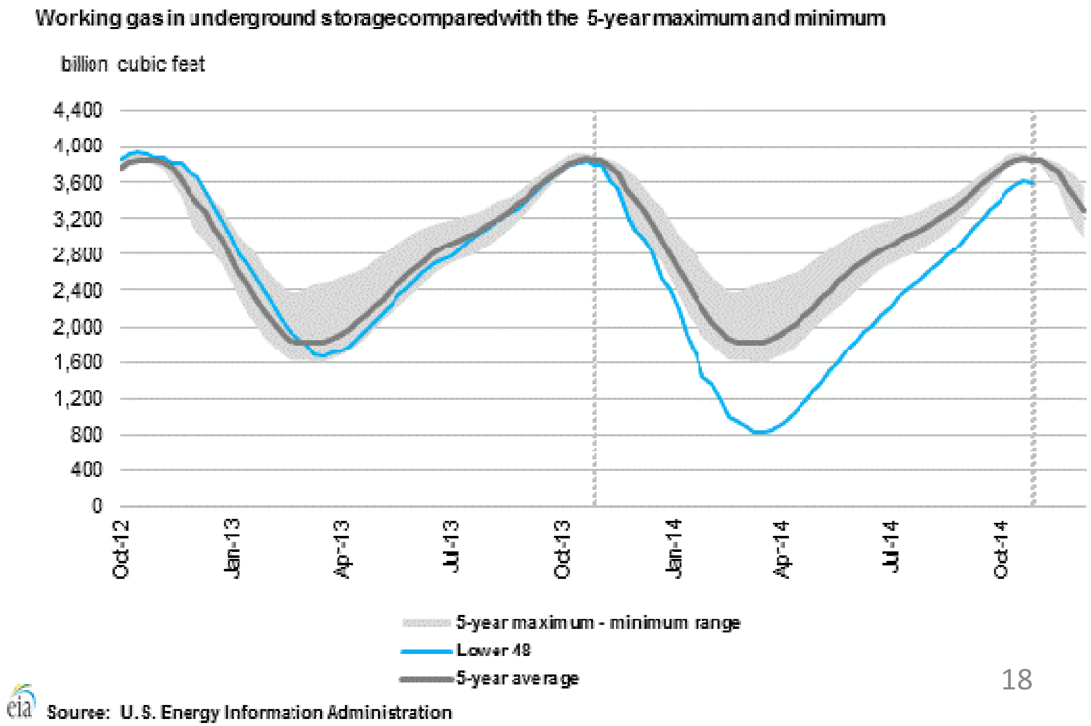
Figure 2. Underground Natural Gas Storage Facilities in the Lower 48 States



Source: Energy Information Administration (EIA), EIA GasTran Geographic Information System Underground Storage Data Base.

Stockage de gaz naturel - Technologies

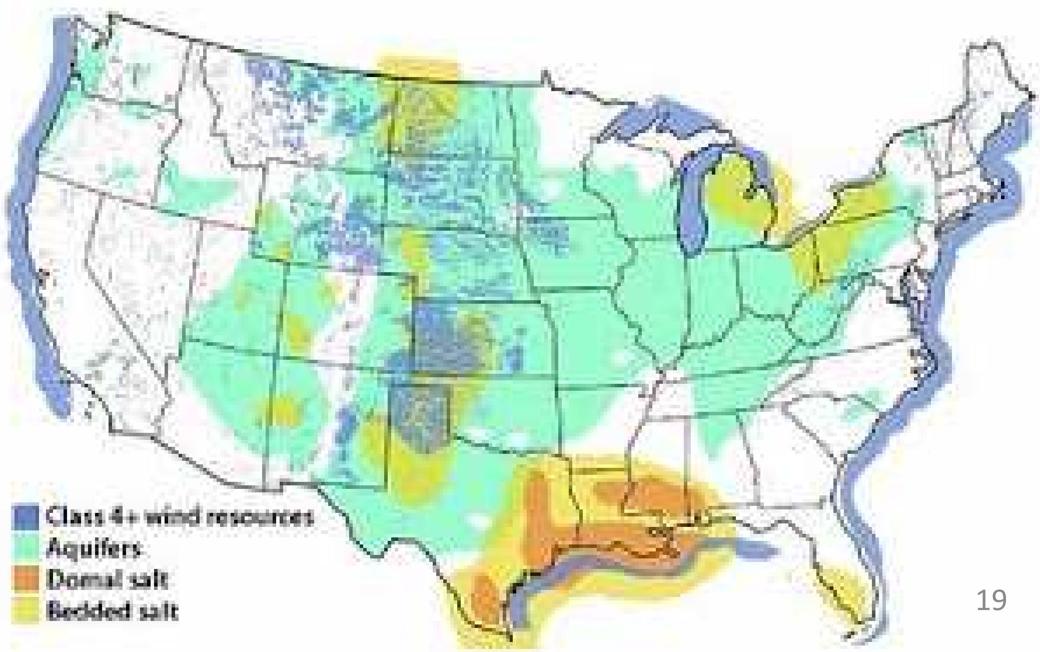
- "Base Load Requirements"
  - Besoins saisonniers
  - Cycles annuels: injection Avril-Oct, retrait Nov-Mars
  - Typiquement: anciens réservoirs d'hydrocarbures
- "Peak Load Requirements"
  - Besoins extrêmes, ponctuels, pour ajuster l'offre à la demande (imprévus)
  - Typiquement, dans des cavernes de sel ou dans des aquifères



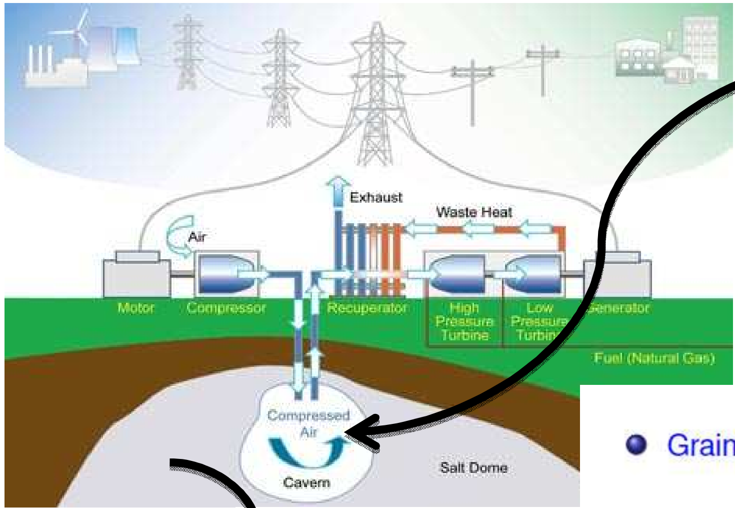
Stockage d'air comprimé

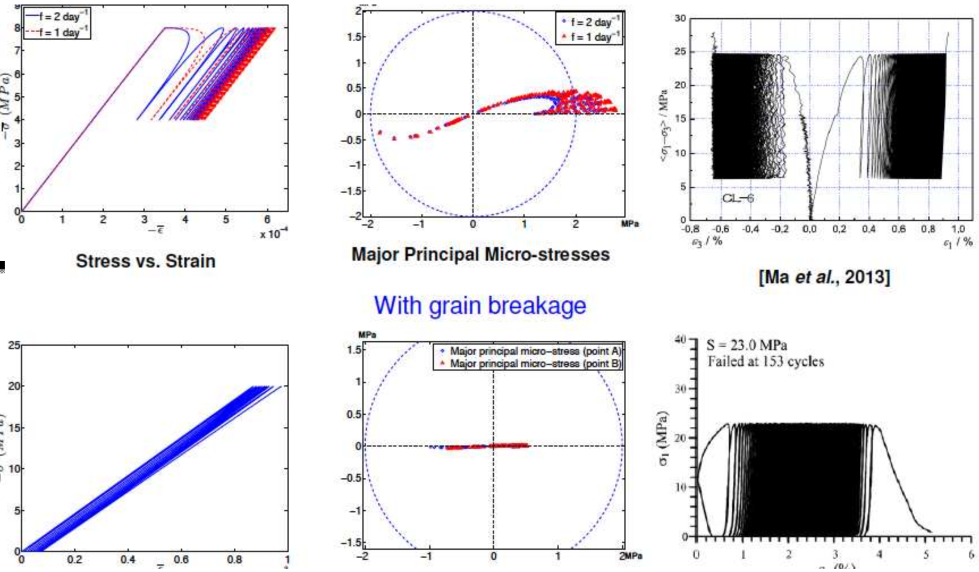
- Cavernes de sel
  Propriétés de cicatrisation, faible perméabilité
- Aquifères
  Majorité du potentiel de stockage aux USA, e.g. Iowa Stored Energy Park
- Mines abandonnées
  e.g. projet Norton (Ohio)
- Anciens réservoirs de gaz naturel

Sandia Nat. Lab. – research on domal salt



Stockage d'air comprimé
Cavernes de sel



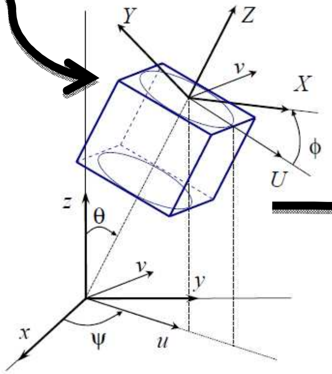


Stress vs. Strain

Major Principal Micro-stresses

[Ma *et al.*, 2013]

With grain breakage

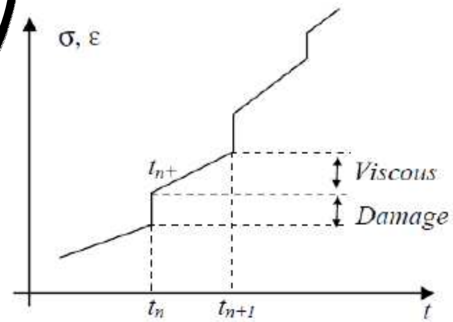


- Grain breakage (if $\sigma_n^{max} \geq 2$ MPa)

$$\sigma = \dot{\sigma} = \dot{\varepsilon}^{vp} = 0, \quad \dot{\varepsilon}^{el} \neq 0$$

- Grain viscoplastic deformation

$$\dot{\epsilon}_{ij}^{vp} = \sum_{l=1}^{L} \dot{\gamma}^l a_{ij}^l$$



Damage and Viscous Phases
[Pouya, Zhu & Arson, JMPS, under review]

For each time step :

1. Damage phase ($D = \frac{N_b}{N} = 1 - \frac{N_g}{N}$)

$$\sigma(t_n) \rightarrow \left\{ \begin{array}{c} < 2\text{MPa : grain is non-broken} \\ \geq 2\text{MPa : grain is breaking} \\ \text{broken grains remain broken} \end{array} \right\} \rightarrow \begin{array}{c} N_g(t_n) \\ N_b(t_n) \end{array} \rightarrow \tilde{\mu}(t_n) \xrightarrow{\sigma(t_n)} \delta\overline{\varepsilon}(t_n) \rightarrow \delta\varepsilon(t_n) \rightarrow \delta\sigma(t_n) \rightarrow \sigma(t_n^+)$$

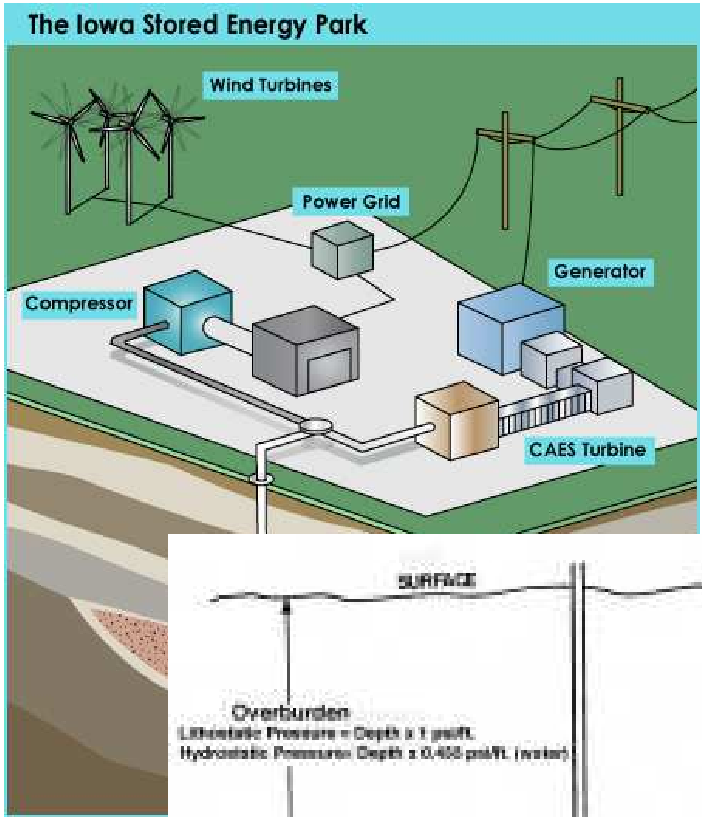
2. Viscous phase

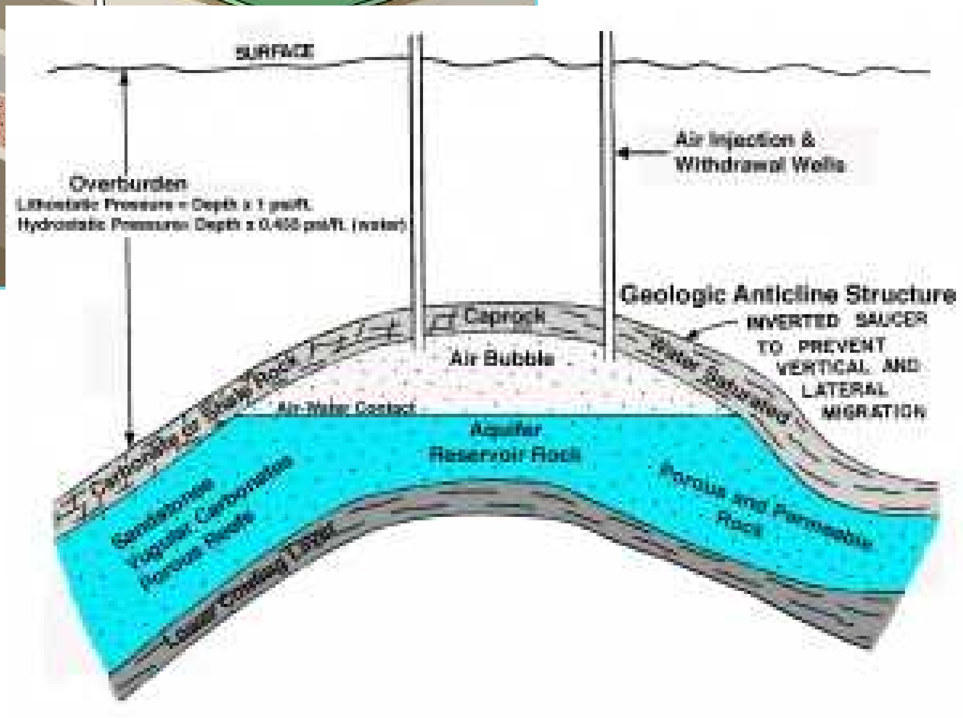
$$\begin{array}{c} \dot{\overline{\sigma}}(t_n^+) \\ \tilde{\mu}(t_n^+) = \tilde{\mu}(t_n) \end{array} \rightarrow \left\{ \begin{array}{c} \dot{\overline{\varepsilon}}^{vp}(t_n^+) \\ \dot{\gamma}^l(t_n^+) \rightarrow \dot{\varepsilon}^{vp}(t_n^+) \end{array} \right\} \rightarrow \dot{\sigma}(t_n^+) \xrightarrow{\sigma(t_n^+)} \sigma(t_{n+1})$$

Micro-macro modeling of damage induced by fatigue under cyclic loading

(Pouya et al.)

Stockage d'air comprimé – Aquifères





Principaux défis géomécaniques

•Synchronisation des cycles de pressurisation avec les cycles des turbines

•Résistance mécanique du massif rocheux

•Résistance aux séismes

- Circulation de l'eau
- Mobilité des bulles d'air
- Déplétion d'oxygène
- Oxydation

Recherche sur le stockage géologique – Qui?

Agences de Financement:

–National Science Foundation (NSF)
Géomécanique, comportement des materiaux
Pas de problèmes d'hydrocarbures!

–Department of Energy (DoE)

–U.S. Geological Survey (USGS)
Hydrologie

–Industrie

Organes de recherche:

–Universités

–Laboratoires Nationaux

–Entreprises de conseil (e.g., RESPEC)

–Département R&D dans l'industrie (e.g., Schlumberger)

Recherche sur le stockage géologique – Comment?

Opportunités de financement:

–Barrières géologiques (déchets radioactifs)
>> appels DoE pour les carburants, moins en géomécanique

–CCS >> très courtisé! (appels à propositions DoE, USGS)

–Stockage de gaz naturel
>> semble suffisamment maîtrisé au niveau technologique

–CAES >> financement industriel prometteur

Opportunités de collaborations Etats-Unis / Europe

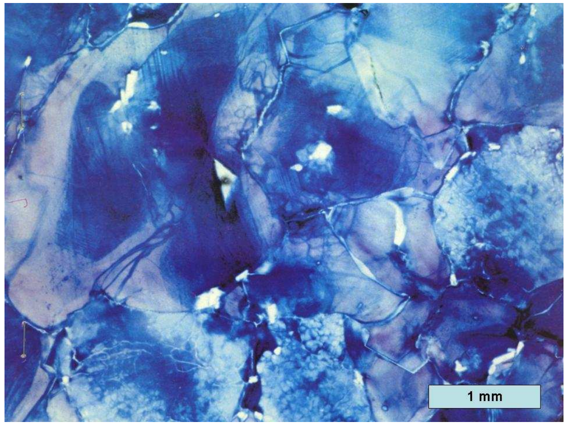
–Projets blancs NSF/ANR >> très ciblé, généralement en physique, chimie, science des matériaux; gros projets (lourd à préparer!)

–DoE >> collaborations très ciblées, e.g. USA/UK pour les déchets radioactifs

–USGS >> rien à ma connaissance

>>>> Suggestion: financement industriel avec le soutien financier et administratif de nos instituts de recherche

Merci….



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Références

Histoire et politique de gestion des déchets radioactifs

D. Tonkay (2005), 'Waste Inventory Record-Keeping Systems (WIRKS) in the United States of America ', report of the Office of Commercial Disposition Options United States Department of Energy

Yucca Mountain

http://en.wikipedia.org/wiki/Yucca_Mountain_nuclear_waste_repository

WIPP

www.wipp.energy.gov

http://en.wikipedia.org/wiki/Waste_Isolation_Pilot_Plant

Stockage de gaz dans les cavités salines et les réservoirs

http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/storagebasics/storagebasics.html

http://ir.eia.gov/ngs/ngs.html

http://naturalgas.org/naturalgas/storage/

CCS

http://www.epa.gov/climatechange/ccs/index.html

http://energy.gov/fe/science-innovation/carbon-capture-and-storage-research

http://energy.usgs.gov/EnvironmentalAspects/EnvironmentalAspectsofEnergyProductionandUse/GeologicCO2Sequestration.aspx#3776287-overview

CAES

R.H. Schulte, N. Critelli, Jr., K. Holst, G. Huff (2012). Lessons from Iowa: Development of a 270 Megawatt Compressed Air Energy Storage Project in Midwest Independent System Operator - A Study for the DOE Energy Storage Systems Program, Sandia report SAND2012-0388

http://www.neuralenergy.info/2009/06/caes.html

http://www.hydrodynamics-group.com/geological-consulting/compressed-air-energy-storage/overview/