Environmental Aspects of the Nuclear Fuel Cycle

Content

- Basics Radioactivity
- Uranium deposits and Mining
- Nuclear Energy
- Nuclear waste

Basics Radioactivity

- spontaneous transformation of unstable cores with emission of energy
  – Nuclear fission
  – Emission of nucleons and heavy particles
  – Emission of ionizing radiation
    - α-radiation
      – Helium cores (for U approx. 4.5 MeV), strongly absorbed → small range (in air <5 cm, in material <0.1 mm)
    - β-radiation
      – ~ electrons, middle range (depending upon energy in air cm to m, in material <1 cm)
    - γ-radiation
      – High-energy electromagnetic radiation, higher range (in air several meters, in material <10 cm)

Basics Radioactivity

- units
  – Activity [Becquerel]: 1 Bq = 1 disintegration/s = 2.7 x 10^{-11} Ci, 1 Curie = 3.7 x 10^{10} disintegration/s
  – half-life $T_{1/2}$:
    Time, in which half of the cores of a radionuclide disintegrates
    Activity decrease with increasing half-life
  – Absorbed (energy) dose *D* [Gray]: 1 Gy = 1 J/kg = 100 rad
    Ratio of the absorbed energy to the absorbing mass,
      1 J in 1 kg water: ΔT = 0.26 mK
      1 Gy in the human body causes: Damage bone marrow, gastrointestinal system, neuromuscular system, sickness
  – Absorbed dose rate: Gy/s = W/kg
    ~ exposition dose rate
  – Equivalent dose *H* [Sievert]: 1 Sv = 100 rem (X-ray equivalent)
    biologically effective absorbed dose, factors considering type of the radiation and irradiated organ (effective dose)
      → 2 Gy absorbed X-ray dose on skin = effective dose 0.02 Sv
      → 2 Gy absorbed alpha dose on lung = effective dose 4.82 Sv

Basics Radioactivity

- Natural Radioisotops:

^{14}C	$T_{1/2}$ = 5.7 x 10^{3} a
^{235}U	0.7 x 10^{6} a
^{40}K	1.2 x 10^{9} a
^{232}Th	14 x 10^{9} a
^{238}U	4.47 x 10^{9} a

Radioisotopes in the reactor

^{239}Pu	$T_{1/2}$ = 2.4 x 10^{4} a
^{131}I	8 d
^{90}Sr	29 a
^{137}Cs	30 a

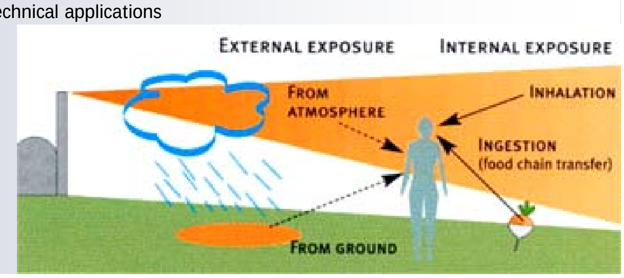
Basics Radioactivity Exposition

- Sources of exposition: $\sum$ approx. 4 mSv/y

  For comparison: U.S. regulation (1995): High-level nuclear waste 0.15 mSv/y

  – 84% naturally
    - 63% ^{222}Rn (alpha emission), U+Th, ^{40}K (beta and positron emission)
    - 12% internally (food, radioelements in human body)
    - 9% cosmic radiation (e.g. in 10 km 40 mSv/a, on 2 km 1 mSv/a)
      – http://www.gsf.de/epcard2/ (computation flight dose)

  – 16% technically
    - 15% medicine (e.g. X-ray diagnostics)
    - 0.6% other technical applications
    - 0.3% fall out



Basics Radioactivity
Impact of Radioactivity

- Effects:
  - Ionizing radiation → ionization and excitation of molecules → formation of free radicals (cellular poisons)
  - Radiobiological functional chain
    - Physical phase (ionization, excitation; 10^{-16} s)
    - Chemical phase (radical, peroxide formation; 10^{-6} s)
    - Biochemical phase (molecular changes; 10^{-2} s)
    - Biological phase (acute cellular changes in hours, late (e.g. cancer) in years, genetic damage in generations)

Basics Radioactivity
Impact of Radioactivity

- Limits for artificially caused effective dose
  - Occupationally exposed to radiation: 20 mSv/a
  - Population: 1 mSv/a
- Regulations:
  - Federal law from 22 March 1991: Radiation protection law StSG
  - regulation from 22 June 1994: Radiation protection regulation StSV

Uranium deposits and mining

- Uranium occurs in a number of different igneous, hydrothermal and sedimentary geological environments
  - Unconformity-related deposits in metasediments (approx. 33% of uranium ressources)
  - Granite Breccia complex deposits
  - Sedimentary precipitation deposits (approx. 18% of uranium ressources)
  - Volcanic deposits
  - Vein deposits (approx. 9% of uranium ressources)

Lambert et al. 1996

Uranium deposits and mining

- leading countries in cumulative uranium production from 1945-2003 were:
  - USSR (production only to 1991) – 378 kt U, or 17% of total production;
  - Canada – 375 kt U, 17%;
  - United States – 367 kt U, 12%;
  - Germany (mainly GDR until 1989) – 219 kt U, 10%;
  - South Africa – 158 kt U, 7%.
- Now over half of the world's production of uranium from mines is from Canada, Australia and Kazakhstan.
- Mining methods:
  - Approx. 40% underground
  - Approx. 30% open pit
  - Approx. 20% in situ leaching
- Investigated supply for about 50-200 y (~11 bn t, fast extendable to >23 bn t)

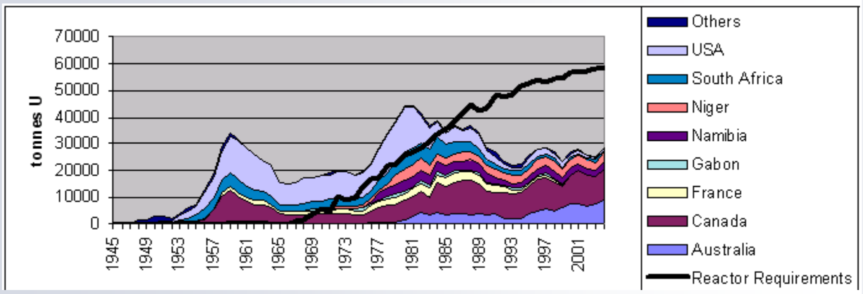
Production (tonnes U)

country	2006
Canada	9862
Australia	7593
Kazakhstan	5279
Niger	3534
Russia	3400
Namibia	3077
Uzbekistan	2270
USA	1692
...	
Total world	39655

Source: World Nuclear Association

Uranium deposits and mining

- The gap between primary supply and uranium requirements since 1991 has been filled by secondary supplies (e.g. military and commercial inventories, enriched uranium tails, reprocessed uranium and mixed oxide fuel=MOX).



Source: World Nuclear Association

Uranium deposits and mine tailings

- Worldwide nearly 940 Mio m³ tailings
  - Largest in Kazakhstan (209 Mio m³), Germany (161), Ukraine (130) and U.S. (120)
- After U extraction the mill tailings contain all the radionuclides of the U decay series → hazardous due to radioactive and toxic elements remain from ore processing
- Mobility of radionuclides and toxic metals is enhanced by acidification due to sulphide oxidation
- Adequate disposal of tailings to reduce the release of radionuclides and hazardous elements
- Longterm active remediation of contaminated ground water

Abdelouas 2006

Life Cycle Assessment

- B.J. Merkel, A. Hasche-Berger: “Uranium in the Environment.” Springer 2006
  – Suggesting a methodology for LCA of environmental protection measures and remedial actions using the remediation of mining sites as an example

- “Life-Cycle Energy Balance and Greenhouse Gas Emissions of Nuclear Energy in Australia.” Report of the Centre for Integrated Sustainability Analysis (ISA), University of Sydney, 2006

Nuclear Energy
Energy and CO_2

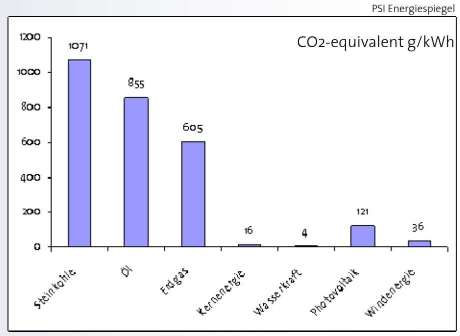
- U-ore (e.g. UO_2): 99.3% ^{238}U (92p+146n), +0.7% ^{235}U (92p+143n) = fissible
- Enrichment to 3-5% ^{235}U by gas diffusion or centrifugation (main CO_2 source)
- Producing 20 t of metallic U (typical for 1 GW power p.a.) requires the mining of 17 kt of 1 wt% U-ore
- Energy 1 kg ^{235}U equivalent to ~3000 t coal or 20 t nuclear fuel → 8 Mrd kWh power equivalent to 2 Mio t coal almost without CO_2, NO_x, SO_x)

Abdelouas 2006

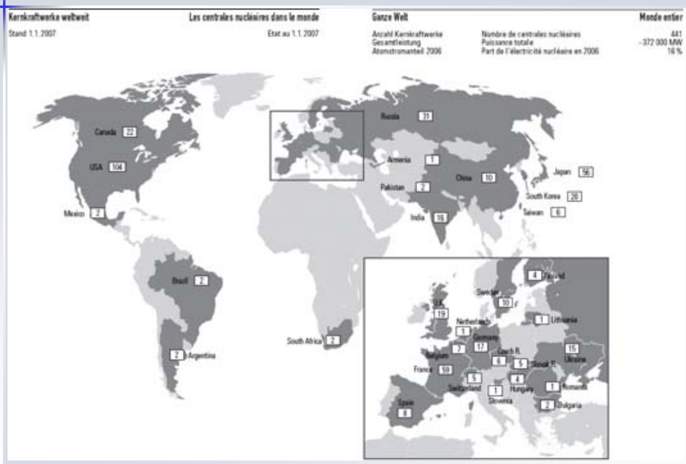
PSI Energiespiegel

- Energy input/output:
  – Nuclear <5%
  – Coal ~6%
  – Gas ~18%
  – Solar 10-20%
  – Wind 2-20%

- In Switzerland ~95% from water and NPP



Nuclear Energy - World



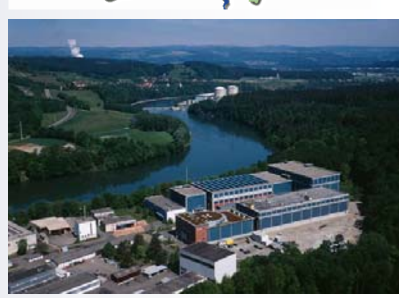
www.nuklearforum.ch

Today 441 nuclear power plants with 372 GW, 30 under construction

Nuclear energy production 16% (20-40% in western developed countries, France 78%)

Nuclear Energy- Switzerland

- ~42% of total ~58 Mrd kWh in 2006
- Beznau I+II (KKB) PWR
  - 365 MW each, 40 t, since 1969/1972
- Mühleberg (KKM) BWR
  - 355 MW, 40 t, since 1973
- Gösgen (KKG) PWR
  - 1 GW, 135 t, since 1979
- Leibstadt (KKL) BWR
  - 1.1 GW, 113 t, since 1984
- Interim storage facility ZWILAG Würenlingen
  - since 1996



Nuclear Energy

- Energy demand
  - 1 t CO_2 and 2000 W society:
    - Fossil fuels give 900-1100 W
    - more energy without CO_2 (electricity ~25% of energy)
    - Need for more electricity with almost no emission of greenhouse gases

    → „Renaissance“ of nuclear power!?

Nuclear Energy

„Renaissance“ of nuclear power!?

- Proven technology (produces already 16% of worlds electricity)
- Energy release by a factor of 1 Mio per unit mass higher as combustion
- Small and contained waste volume (~20 t per reactor/y)
- New reactor designs and advanced fuel cycles for elimination of important waste radionuclide (Pu, Np) or using as new fissile material
- Radioactivity and radiotoxicity drops by many orders of magnitude during the first 1000 years

→ Acceptance of nuclear power increased

Nuclear Energy

But!!!

- keep CO_2 level to twice pre-industrial level (550 ppm) needs fast and significant increase of nuclear power
- 10x increase of energy demand → appr. 3500 new 1 GW nuclear power plants necessary (producing >100 kt ! of spent nuclear fuel)
- optimistic future impact of nuclear power (10x more in 2050) CO_2 emission still 5 Gt C/a (today 7 Gt C/a (displacement of 0.5 Gt C/a by nuclear power only)
- 3x increase of nuclear power plant production would require the construction of about 2 GW capacity per months!

Ewing 2006

Compare: In Switzerland from project planning until operating approval about 18 a (SFOE/HSK)

Nuclear Energy

So:

- nuclear power will remain important but with increasing energy demand nuclear power seems to be not the solution
- Further reasons to hesitate:
  - Safety of nuclear power plants
  - Disposal of nuclear waste
  - Radioactive release from uranium mining and processing
  - Possible diversion of nuclear material for the production of nuclear weapons

Authorities

- World
  - Nuclear Energy Agency (NEA) within the Organization for Economic Co-operation and Development (OECD): www.nea.fr
  - International Atomic Energy Agency (IAEA) within the United Nations family ("Atoms for Peace") www.iaea.org

- Switzerland
  - Department of the Environment, Transport, Energy and Communications with the Swiss Federal Office of Energy (SFOE, BFE) as licensing authority
  - Swiss Federal Nuclear Safety Inspectorate (HSK, federal nuclear supervisory as regulatory authority for assessment and controlling security and radiation protection in Swiss nuclear installations): www.bfe.admin.ch, www.hsk.ch

  and as expert commissions advising the Federal Council
  - Federal interagency working group for nuclear waste management (AGNEB),
  - Commission for Nuclear Waste Management (KNE)
  - Commision for Nuclear Safety (KNS)

  www.ksa.admin.ch, www.ksr-cpr.admin.ch/

Nuclear Energy
The Federal Act on Nuclear Energy (March 2003)

- Radioactive substances must be handled in such a way as to **produce the least radioactive waste** possible
- Radioactive waste produced in Switzerland must in principle be **disposed of in Switzerland**
- Radioactive waste must be disposed of in such a way that the **lasting safety** of man and environment is ensured

Nuclear Energy
The Federal Act on Nuclear Energy (March 2003)

- Whoever operates or decommissions a nuclear installation shall be obliged to dispose of the radioactive waste produced by it, in a safe manner and at his expenses.
- The essential preparatory work, such as research and geological studies, as well as the preparation in good time of a deep geological repository, form an integral part of the radioactive waste disposal obligation
- Disposal = conditioning + interim storage + final storage
  - Conditioning includes all operations preparing radioactive waste for disposal
  - Conditioning procedures:
    - mixed with molten glass and encapsulated in standard steel containers, where it hardens to a solid glass matrix, afterwards placed in thick-walled safety canisters
    - Compaction and incineration are used to reduce volumes of low- and intermediate-level waste and the remaining material is mixed with cement or bitumen and poured into 200-litre drums for hardening.

Nuclear Energy
Financial situation

- NPP allowances (conditioning, interim storage, decommissioning, dismantling, disposal)
  - 40 years operating time 14 Mrd CHF
  - Today about 7 Mrd (federal disposal fond)
- Insurance:
  - In case of accident up to 1 Mrd CHF only (per NPP)
    - one reason for too cheap nuclear power?
    - Realistic estimation 4000 Mrd CHF damage
  - In next future increasing insurance to ~2 Mrd CHF

Disposal - Safety - Risk

- Radioactive waste exists since >40 yrs.
  - from nuclear power plants
  - from research, industrial and medical applications
- to date no long-term solution for the safe disposal

Disposal - Safety - Risk

- Current concept: Safe and effective disposal of this waste in final repositories with natural and engineered barriers in deep and stable geological formations
- Safety: a relative notion (absolute safety doesn‘t exist)
  - Acceptable levels
  - Connected risks to the environment (to quantify)
    - extent of undesirable consequences of an incident
    - Uncertainty of the incident (probability during a given time period)

Disposal - Safety - Risk

- Hazards in disposal of nuclear waste
  - Increased radiation dose
  - Released radionuclides
  - Unauthorized access
  - Awareness about even in centuries
  - Long time period

Nuclear waste inventory

Nuclear waste is any radioactively contaminated residual substances, from operation and dismantling of nuclear installations and from handling radioactive substances in medicine, industry and research (MIF), which can not decontaminated and reused.

Switzerland (50 a operation NPP and –2050 from other sources)

- Sources, Classification, Volumes
  - Spent fuel elements (SF, ~5 years working period in a reactor) and high-level waste (HLW) including dismantled reactor safety container
    - 7500 m^3
  - Intermediate-level long-lived waste (ILW) (from reprocessing SF until 2006)
    - 2600 m^3
  - Low- and intermediate-level waste (L/ILW)
    - 77‘000 m^3
  - Sum 90‘000 m^3 (assuming reprocessing 1/3 of SF (stopped 2006) and including waste from decommissioning of nuclear facilities)
- already today we have radioactive waste!!!

Nuclear waste regulation

- 1972 Nagra (National Cooperative for the Disposal of Radioactive Waste):
  - nuclear power plant operators (SNF)
  - Swiss Federal Government (waste arising from medicine, industry and research)
    - www.nagra.ch
  - Preparing inventories of all radioactive wastes in Switzerland (nuclear power plants, medicine, industry and research)
  - Planning geological repositories for safe disposal of all categories of radioactive waste
  - Carrying out geological investigations in potential siting regions
  - Preparing projects which demonstrate the safety of geological disposal
  - Promoting international collaboration on research and development projects

Disposal - Safety - Risk

- Protection Objective for the final disposal of radioactive waste:
  1. The release of radionuclides from sealed repository subsequent upon processes and due to reasonably expectable events shall at no time give rise to individual doses exceeding 0.1 mSv per year.
  2. The individual radiological risk of fatality from a sealed repository subsequent upon unlikely processes and events not taken into consideration in Protection Objective 1 shall, at no time, exceed one in a million per year.
  3. After a repository has been sealed, no further measures shall be necessary to ensure safety. A repository must be designed in such a way that it can be sealed within a few years.

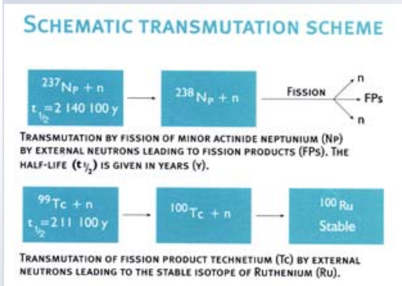
Nuclear waste disposal aspects

- concepts for different categories
  - Specific part. for HLW → low amount but safe disposal for >10‘000 a: Heat generation, high level of radiation, pot. release of toxic radionuclide (Pu)
- Temporal aspect in disposal
  - Safe handling until final storage
  - Disposal concept (technical, site)
  - construction, operation and closing of the final repository
- Site aspects
  - Technical questions/security
  - Economic aspects (costs, effects on regional economy)
  - traffic and environment
  - Emotional aspects, immaterial costs

Nuclear waste disposal concepts

- „marine disposal“, Since the London Convention 1975 (ratified 1994) prohibited internationally
  - e.g. Switzerland 1978-1982
- „long term surface disposal“
  - Netherlands: HLW, 100 a, HABOG (www.covra.nl)
  - Spain (www.enresa.es)
- „near surface disposal “
  - France: LLW, 300 a (www.andra.fr)
    - Centre de la Manche (1969-1994; 527´000 m^3)
    - Centre de l‘Aube (1992-...; 1 Mio m^3)
  - Spain
    - El Cabril (1992-...; 44´000 m^3)

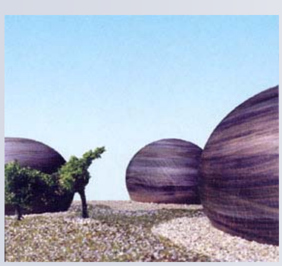
Nuclear waste disposal concepts



"Transmutation"

- further burning in the reactor as nuclear fuel through „a blowing on“ with neutrons from outside
  - Forming radionuclide with short half time
  - leads up to the stable ruthenium
- Still in research
- Still necessary are repositories to safely dispose of existing and future conditioned high level and medium level nuclear waste, which cannot be transmuted

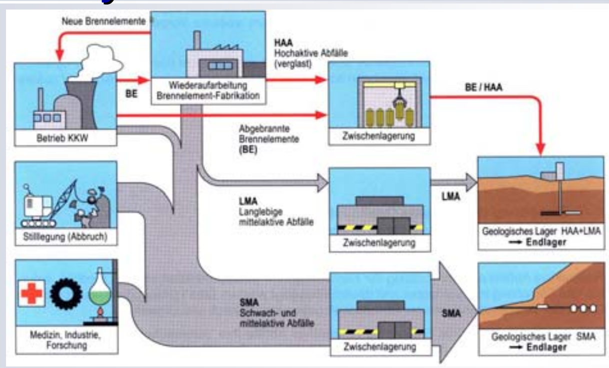
Nuclear waste disposal concepts - Surface disposal



15 m atom-eggs made from Steel and concrete
Project: Prof. Lehmden, Acad. Fine Arts Vienna

- Yes, for interim storage
  - Cooling
  - monitoring
  - access (future raw material, later disposal with the ultimate concept)
  - ZWILAG in Würenlingen and at the nuclear power plants
- but not as final
  - long term safety:
    - climate,
    - political situation
    - unauthorized access

Nuclear waste disposal concepts - Deep geological repository



- Two deep geological repositories are foreseen in Switzerland, one for spent fuel (SF), high-level waste (HLW) and long-lived intermediate-level waste (ILW) and one for low- and intermediate-level waste (L/ILW). The repositories will be constructed at a depth of several hundred metres in suitable rock formations.

Disposal of nuclear waste

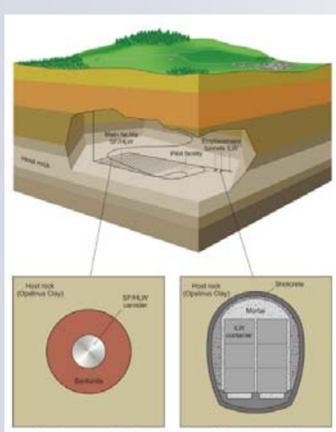
source	NPP	Medicine, Industry, research (MIF)
	↓	↓
Conditioning and interim storage	(**ZWIBEZ**) **ZWILAG**	**BZL** @ PSI
	↘	↙
Planning and realization of repository	**Nagra** National Co-operative for the Disposal of Radioactive Waste Nationalen Genossenschaft für die Lagerung radioaktiver Abfälle	
	↑	
Research	**PSI / LES** (Laboratory for Waste Management) ETHZ, Uni Bern, ...	

Nuclear waste

- State in CH:
  - Still sufficient interim storage place
  - Disposal LLW unsolved: disposal feasibility for L/ILW was determined by the Federal Government to have been brought successfully in 1988 (Wellenberg project)
    - however, 2002 politically rejected
  - Disposal HLW: disposal feasibility for HLW was determined by the Federal Government to have been brought successfully in 2006 (Opalinus Clay project NTB 02-0n)
  - until 2040-2050 construction and operation of HLW repository
    - The site decision is a matter for the future.
    - Involvement of the public in all decisions and licensing procedures is assured.

Nuclear waste

Possible layout for a deep geological repository

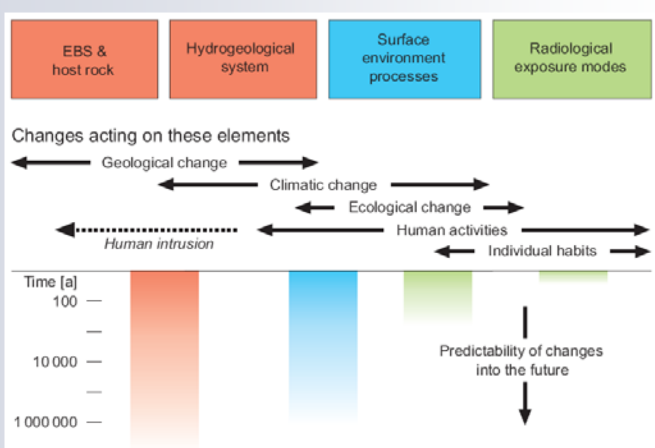


Nuclear waste
Disposal - Safety - Risk

- requirements on the geological environment:
  - Long-term geological stability
  - Favourable host rock properties (barrier function)
  - Sufficient extent of host rock body
  - Avoidance of, and insensitivity to, detrimental phenomena and perturbations
  - Explorability
  - Predictability

Nuclear waste

Limits of predictability of a geological disposal system



NEA 1999

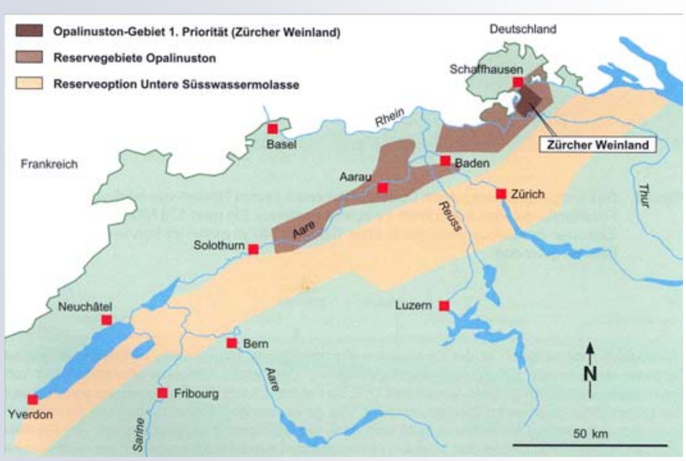
Nuclear waste
Geological risk factors

- Waste disposal in Northern Switzerland
  - Tectonically stable, depth of host rock
- Regional geological and neotectonic developments within the next 1 Mio years
- Scenario A:
  - Alpine orogenic cycle comes to an end, tectonic movements stop → no geological risk
- Scenario B:
  - Alpine orogenic cycle active for the next 10 Mio years
    - Continuation of tectonic movements
    - Basement uplift up to 400 m, shearing on faults about 50 cm
    - Erosion of about 200 m
    - Climatic changes, changes in the hydrogeological state will not affect the basement
- Plausible* future geological development will not affect the safety of a repository

  * plausible from the geological development until now and compared to other orogenic regions

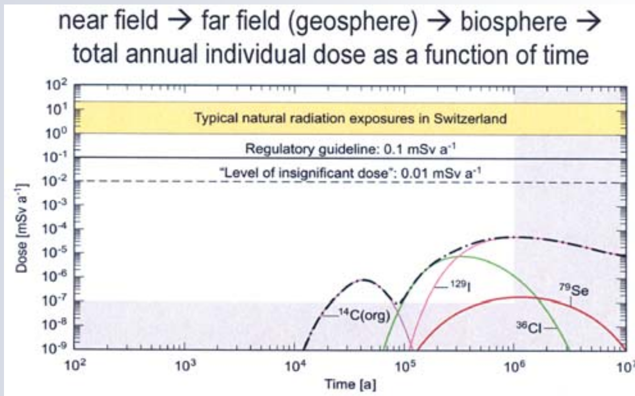
Diebold & Müller 1985: Szenarien der geologischen Langzeitsicherheit. NTB 84-26

Nuclear waste disposal



Disposal - Safety – Risk
Model chain calculation

- Safety assessment to demonstrate that the "Protection Objective" is fulfilled for a planned geological repository
  - geochemical and transport modelling.



Nuclear waste disposal

- Implementation steps
  - Technical realization strategy
    - Disposal concept, site selection, site investigation
    - construction and operation planning
  - Public confidence in this strategy
    - Comprehension of the public
  - Decision making process