Uranium Resources and Wastes

“I began more carefully to look around me. A serious study of the soil was necessary to negate or confirm my hypothesis.”

—Henry Lawson in “Journey to the Center of the Earth” by Jules Verne.
About Uranium (klaprothium?)

Uranium has an atomic number of 92, and was discovered by a German chemist named Martin Klaproth in 1789. He named it after the newly discovered plant Uranus.

There are currently 28 known isotopes of uranium yielding an atomic mass of 215 to 242.
About Uranium

Only three isotopes occur naturally:
Uranium-238 (99.284%)
Uranium-235 (0.72% and is fissile: capable of sustaining a nuclear chain reaction).
Uranium-234 (0.0055%)

Isotopes with masses 215 to 228 have short (≤ 9.1 minutes) and decay to thorium as

\[ ^{n}U \rightarrow ^{n-4}Th + \alpha \]
Although a typical as-mined sample of uranium is mostly $^{238}\text{U}$, and it radioactive because of alpha decay, the half-life of the reaction is comparable to the age of the Earth (circa 4.54 Ga).
Uranium ore versus waste

Uranium Concentrations in Rock

activity per nuclide of the U-238 series
Uranium Resources

About 64% of the world’s uranium comes from mines in Australia, Kazakhstan, Russia, and Canada.

In 2015, Canada mined 13,325 tonnes of (22% of the demand).

Australia: Mined 5,654 tonnes of U in 2015. Has largest reserves on earth. About 31% of the earth’s uranium (1,661,000 tonnes uranium)

Kazakhstan has 12% of the world’s resources. Now the largest exporter of U: 23,800 tonnes U in 2015 (39% of the demand).

Uranium Resources

Source: Uranium 2005: Resources, Production and Demand, OECD/IAEA. Based on Identified Resources which consist of Reasonably Assured Resources and Inferred Resources at costs less than $80 (US) per kilogram U as at January 1, 2005.
Reasonably Assured Resources of Uranium in 2009

*IAEA estimate

- Australia
- Canada
- Kazakhstan
- Niger
- USA
- Namibia
- Russia Fed.
- Brazil
- South Africa
- China
- Ukraine
- Uzbekistan

Legend:
- < USD 80/kgU
- USD 80-130/kgU
Background Levels

Ore-forming processes

Leaching of U(VI) then precipitation as U(IV)

Hydrothermal deposits

Geological processes that redistribute concentrated U

Sandstone with U

Erosion/transport

Stratigraphic unconformities (weathering that leaves breccia or conglomerates or precipitation of dissolved U)

U-enriched igneous rocks (granite)
Hydrothermal deposits

Metallic minerals formed by the precipitation from hot mineral-laden water (hydrothermal solution). The solutions arise in most cases from the deep groundwater heated by magma.
An unconformity is a buried erosional or non-depositional surface separating two rock masses or strata of different ages. Uranium-rich breccia may be present at the contact.
Why some areas have more uranium than others

Igneous rocks were/are close to the surface because of tectonic uplift (mountain building).
Areas of near-surface magma uplifts.
Once exposed at the surface, the igneous bedrock was eroded. Uranium concentrated.

Australia:
70% granitic breccia derived from uranium enriched granites and volcanic rocks.
19% unconformity-related deposits.
Saskatchewan Uranium

- Variety of Types:
  - Unconformity
  - Vein
  - Pegmatite
  - Shale
  - Sandstone/Lignite
Uranium Extraction

Underground mines 27%
Open pits 20%
In-situ leaching 46%
By-product 7%

(phosphate in Florida)

From http://world-nuclear.org/info/Nuclear-Fuel-Cycle/Mining-of-Uranium/World-Uranium-Mining-Production/
Uranium Resources

The largest mine in the world

McArthur River Mine in Saskatchewan, Canada.
Underground mine.
U as pitchblende/uraninite
Discovered in 1988
Ore quality: 17.5% $\text{U}_3\text{O}_8$,

Produced 105,500 tonnes of $\text{U}_3\text{O}_8$ from 2000 to 2011
(14% of the global production in 2011)
McArthur River
Located in northern Saskatchewan, the McArthur River mine has an annual uranium production capacity of 18.7 million pounds U₃O₈.
Uranium Resources

Ranger Mine in North Australia.
Open pit
Discovered in 1969
Ore quality: 0.2% U$_3$O$_8$
Produced 3,284 tonnes of U$_3$O$_8$ in 2011 (4 mines in Australia produced 7,701 tonnes in 2011)
Ranger Open Pit, Australia
2008 Australian uranium export sales (tonnes $U_3O_8$)

- EU = 3,308 t
- Japan = 2,464 t
- USA = 3,689 t
- China = 313 t
- South Korea = 214 t
- Canada = 249 t
- Taiwan = 447 t
- Other = 23 t

Total: 10,707 t delivered
## Active U.S. Mines

<table>
<thead>
<tr>
<th>State</th>
<th>mines</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colorado</td>
<td>One</td>
<td>Underground</td>
</tr>
<tr>
<td>Nebraska</td>
<td>One</td>
<td>In-situ leaching (ISL)</td>
</tr>
<tr>
<td>Utah</td>
<td>One</td>
<td>Underground, three on standby</td>
</tr>
<tr>
<td>Texas</td>
<td>3 mines</td>
<td>Open pit and ISL</td>
</tr>
</tbody>
</table>
### Wyoming
- **Smith Ranch-Highland mine**

ISL. Largest producer in US. Between 2002 and 2011 produced 7,500 tons of $\text{U}_3\text{O}_8$. Ore: 0.09%
Estimated resources: 207,400 tonnes. 4% of the Earth

Sources: Based on U.S. Department of Energy, Grand Junction Project Office (GJPO), National Uranium Resources Evaluation, Interim Report (June 1979) Figure 3.2; and GJPO data files.
Uranium Prices

2001 $7/pound (record low)
2007 $113/pound (almost record high)
Feb. 4, 2008 $75.00/pound
Feb. 12, 2010 $42.50/pound
Jan. 21, 2011 $69.00/pound as U₃O₈
Jan. 2, 2012 $52.00/pound as U₃O₈
Jan. 21, 2013 $42.50/pound as U₃O₈
Jan. 3, 2014 $34.50/pound as U₃O₈
Jan. 26, 2015 $36.75/pound as U₃O₈
Jan. 15, 2016 $34.74/pound as U₃O₈
Jan. 27, 2017 $24.50/pound as U₃O₈
Jan. 31, 2018 $23.75/pound as U₃O₈
Weekly U3O8 Spot Price Indicator

US$ per pound U₃O₈

© 2018 TradeTech
How long will the supply of uranium last?

Not an easy question. We are not sure how much is available, and the answer will depend on how we use it in the future.

Some previous assessments have been completely wrong!
How long will the supply of uranium last?

Terms to know first:

**Reserves**: known volume and concentration of uranium (ore); economical to mine.

**Resources**: suspected uranium deposits based on geology; undiscovered; uneconomical to mine.

**Secondary sources**: Reprocessed uranium, decommissioned nuclear weapons.

**Unconventional resources**: uranium-rich coal ash, oil shale, seawater.
### How long will the supply of uranium last?

<table>
<thead>
<tr>
<th>Source of estimate</th>
<th>Scenario</th>
<th>Year of depletion</th>
</tr>
</thead>
<tbody>
<tr>
<td>European Commission</td>
<td>Light-water reactors (LWR), all known resources</td>
<td>2043</td>
</tr>
<tr>
<td></td>
<td>Plus secondary sources</td>
<td>2073</td>
</tr>
<tr>
<td>Australian Uranium Association</td>
<td>“Present measured resources”</td>
<td>2079</td>
</tr>
<tr>
<td>Organ. for Economic Co-op Devel. (OECD)</td>
<td>All known sources plus undiscovered</td>
<td>2087</td>
</tr>
<tr>
<td></td>
<td>With breeder reactors</td>
<td>2273</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10503</td>
</tr>
<tr>
<td>International Atomic Energy Commission. (IAEA)</td>
<td>Known reserves, once-through. Plus secondary, undiscovered, unconventional sources</td>
<td>2107</td>
</tr>
<tr>
<td></td>
<td></td>
<td>49007</td>
</tr>
<tr>
<td>Cohen (1983)</td>
<td>Fast breeder reactors plus extracting uranium from sea water.</td>
<td>5 billion years</td>
</tr>
</tbody>
</table>
Uranium in Sea Water

The average concentration of uranium in sea water is about 3.3 μg/L.

However, it is estimated that there are 4.5 billion metric tonnes of uranium in all the oceans.

How to recover this uranium? Uranium-specific sorbents tested as fabric stacks and cages.

Dip, retrieve, then extract.

Not economical at present.
Marine equipment for uranium recovery

- Floating frame
  - Sea level
  - Rope 50 mm in diameter
  - 40 t Anchor
  - 50m
  - Mooring system of floating frame

- Adsorption bed
  - Up and down motion by wave motion
  - 14m

- Adsorption stacks
- Drawing up of adsorption bed packed with adsorbent stacks at northern sea in Japan (350 kg in three adsorbent beds)
Uranium Waste Rock

Most mines in the U.S. are in the west, and thus so are the wastes. Waste rock from mining. The non-ore rock that must be removed to access the ore.

In open pit mines, the ratio of waste-to-ore may be 40:1 or greater. That is, for each ton (0.91 tonne) of U ore, there’ll be 40 tons (36.3 tonnes) of waste rock.
Uranium Waste Rock

Example: an open pit at the Key Lake mine in Saskatchewan, Canada produced 3.67 tons of U ore (1.95% U) and 79.6 tons of waste rock. Now mined out.

The choice of pits or underground mines depends on depth of the ore. Underground mines are more expensive.
Historically

The waste rock was abandoned on-site as piles on the surface (not unique to U mining). Some waste rock contained sulfide minerals which oxidized to form sulfuric acid. These piles are sources of heavy metals and threaten surface and groundwater quality.
The waste rock "pyramids" in former East Germany
Uranium Waste Rock

Today there are on-going efforts to remediate old piles. The waste rock is graded on the surface, covered with soil, and re-vegetated.

Sometimes placed in flooded, mined-out excavations.
In-situ Leaching

http://www.youtube.com/watch?v=1tnvg6wx6

U8
Tailings from ore processing (milling)

Material left after removing the ore. The ore is crushed, then leached with sulfuric acid. The remaining solids are then washed with water, and the slurry is pumped to a retention pond in which the water evaporates, and the solids settle in the pond or are stored as a pile. Tailings are 70 to 80% sand-sized particles, mixed with waste sludge, and process fluids.
The basics about milling

Leaching/extraction:
Solid $\text{UO}_3 + \text{H}_2\text{SO}_4$ yields $\text{UO}_2(\text{SO}_4)_3^{4-}$

Extraction into the organic phase by reacting with $(\text{R}_3\text{NH})_2\text{SO}_4$.

Evaporate solvent then precipitate $(\text{NH}_4)_2\text{U}_2\text{O}_7$ by adding ammonia.

Heat to yield solid $\text{U}_3\text{O}_8$
Milling wastes may contain residual uranium because the extraction process is not 100% efficient, and decay products such as $^{230}\text{Th}$, $^{226}\text{Ra}$, and $^{222}\text{Rn}$ are present.
About radon

Radon-222 gas emanates from tailings piles and has a half life of 3.8 days. This may seem short, but because of the continuous production of radon from the decay of radium-226, which has a half life of 1,600 years, radon presents a long-term hazard. Further, because the parent product of radium-226, thorium-230 (with a half life of 80,000 years) is also present, there is continuous production of radium-226.
Atlas Co. uranium mill tailings, Moab, Utah,
Rio Algom Quirke Tailings, Canada
Ranger Uranium Mill
tailings pond, Australia
About the milling waste

At a grade of 0.1% uranium, 99.9% of the material is left over. Apart from the portion of the uranium removed, the sludge contains all the constituents of the ore.

Long-lived decay products such as thorium-230 and radium-226 are not removed; the sludge contains 85% of the initial radioactivity of the ore.
Longevity of activity
Summary of hazards

Uranium Mill Tailings Hazards

- radon-exhalation
- gamma-radiation
- dust blowing (radium, arsenic, ...)
- dam failure
- erosion
- flood
- earthquake
- heavy rain
- seepage (uranium, arsenic, ...)
- groundwater
The WISE Uranium Project

WISE Uranium Project - Slide Talk
Uranium Mining and Milling

http://www.wise-uranium.org/stk.html?src=stkd01e
Uranium Mill Tailings Radiation Control Act of 1978

The UMTRCA Title I program established a joint Federal/State-funded program for remedial action at abandoned mill tailings sites where tailings resulted largely from production of uranium for the weapons program. The Department of Energy (DOE) is responsible for cleaning up inactive milling sites.
LOCATIONS OF URANIUM MILL TAILINGS SITES

Most uranium mill tailings are located in the western United States—at the locations shown on the map.
Cover with compacted clays and rocks or vegetation on top of the clay: reduce gamma radiation, radon emissions, and blowing dust.

Groundwater monitoring: is there a plume of contaminated groundwater? Where is it spreading?

Groundwater remediation: Pump and treat (pump water to the surface, remove contaminants, then return the water to subsurface).
DOE term for tailings

According to 10 CFR 40.4, the term residual radioactive material means: “(1) Waste in the form of tailings resulting from the processing of ores for the extraction of uranium and other valuable constituents of the ores; and (2) other at a processing site which relates to such processing, including any residual stock of unprocessed ores or low-grade materials.”
UMTRA remediation examples

The Moab Uranium Mill Tailings Remedial Action Project.

Uranium milling operations from 1956 to 1984. Before 1970, for the defense program, after 1970 for commercial power plants. Waste slurry was discharged into an unlined pond. Tailings pile about 90 feet (27 m) tall; volume of tailings and contaminated soil: 9.2 million m³. Average activity: 665 pCi/g (24.6 Bq/g) of ²²⁶Ra.
The Moab Uranium Mill Tailings Remedial Action Project.

Site remediation began in 2009.
DOE (EnergySolutions) is hauling the tailings by rail to a disposal cell. One train/day, 4 days a week. Mid 2013, 6 million tons (5.4 tonnes) were moved (38% to the total). Completion planned for 2025.
Crescent Junction Disposal Cell

When completed, the cell will cover an area of 287 acres (116 ha), and will be 25 feet (7.6 m) tall/deep. It will be capped with a 9-foot (2.7 m) cover.
Groundwater contamination

The groundwater at the Moab site is contaminated with uranium and ammonia (and ammonium). Ten extraction wells are currently removing contaminated groundwater which is pumped into a lined evaporation pond. 32 injection wells are being used to pump diverted river water into the groundwater dilute and displace the plumes. The overall goal is to recover uranium and ammonia before they migrate to the Colorado River.
Disposal cells for six former mill tailings sites
# U.S. uranium recovery facilities that have a license from the NRC

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Licensee</th>
<th>Location</th>
<th>Type of Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crow Butte</td>
<td>Crow Butte Resources, Inc.</td>
<td>Chadron, Nebraska</td>
<td>ISR</td>
</tr>
<tr>
<td>Crownpoint</td>
<td>Hydro Resources, Inc.</td>
<td>Crownpoint, New Mexico</td>
<td>ISR</td>
</tr>
<tr>
<td>Dewey Burdock</td>
<td>Powertech Uranium Corporation</td>
<td>Fall River &amp; Custer Counties, South Dakota</td>
<td>ISR</td>
</tr>
<tr>
<td>Lost Creek</td>
<td>Lost Creek ISR, LLC</td>
<td>Sweetwater County, WY</td>
<td>ISR</td>
</tr>
<tr>
<td>Moore Ranch</td>
<td>Uranium One Americas, Inc.</td>
<td>Campbell County, Wyoming</td>
<td>ISR</td>
</tr>
<tr>
<td>Nichols Ranch</td>
<td>Uranerz Energy Corporation</td>
<td>Campbell and Johnson Counties, Wyoming</td>
<td>ISR</td>
</tr>
<tr>
<td>Ross</td>
<td>Strata Energy, Inc.</td>
<td>Crook County, WY</td>
<td>ISR</td>
</tr>
<tr>
<td>Smith Ranch</td>
<td>Power Resources, Inc.</td>
<td>Douglas, Wyoming (Converse County)</td>
<td>ISR</td>
</tr>
<tr>
<td>Sweetwater</td>
<td>Kennecott Uranium Co.</td>
<td>Sweetwater County, Wyoming</td>
<td>Conventional Uranium Mill</td>
</tr>
<tr>
<td>Willow Creek</td>
<td>Uranium One U.S.A.</td>
<td>Johnson &amp; Campbell Counties, Wyoming</td>
<td>ISR</td>
</tr>
</tbody>
</table>
## License applications submitted

<table>
<thead>
<tr>
<th>Proposed Expansion, New Facility, Restart, or Renewal</th>
<th>Type of Facility</th>
<th>Applicant/Licensee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crownpoint</td>
<td>ISR – Renewal</td>
<td>Hydro Resources, Inc.</td>
</tr>
<tr>
<td>Jane Dough</td>
<td>ISR – Expansion</td>
<td>Uranerz Energy Corporation</td>
</tr>
<tr>
<td>LC East/KM Horizon</td>
<td>ISR – Expansion</td>
<td>Lost Creek ISR LLC</td>
</tr>
<tr>
<td>Ludeman</td>
<td>ISR – Expansion</td>
<td>Uranium One</td>
</tr>
<tr>
<td>Kendrick</td>
<td>ISR – Expansion</td>
<td>Strata Energy, Inc.</td>
</tr>
<tr>
<td>Marsland</td>
<td>ISR – Expansion</td>
<td>Crow Butte Resources</td>
</tr>
<tr>
<td>North Trend</td>
<td>ISR – Expansion</td>
<td>Crow Butte Resources</td>
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<tr>
<td>Reno Creek</td>
<td>ISR – New</td>
<td>AUC, LLC.</td>
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<tr>
<td>Smith Ranch Highland</td>
<td>ISR – Renewal</td>
<td>Power Resources Inc.</td>
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<tr>
<td>Sweetwater Uranium Mill</td>
<td>Conventional Uranium Mill – Renewal</td>
<td>Kennecott Uranium Co.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site name</th>
<th>Location</th>
<th>Capacity (tons ore/day)</th>
<th>Status (Jan., 2018)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Mesa</td>
<td>Utah</td>
<td>2,000 (1,814 tonnes)</td>
<td>Operating</td>
</tr>
<tr>
<td>Piñon Ridge</td>
<td>Colorado</td>
<td>1,000 (907 tonnes)</td>
<td>In limbo</td>
</tr>
<tr>
<td>Shootaring Canyon</td>
<td>Utah</td>
<td>750 (680 tonnes)</td>
<td>Just bought by Uranium One (had been dormant)</td>
</tr>
</tbody>
</table>
First new uranium mill in the U.S. in decades! Well, Maybe.

Piñon Ridge site (Colorado)
Radioactive Materials License received Jan. 2011. Approved 2013

Review by the Colorado Department of Public Health and Environment [considered] . . . Radiological impacts to water, air, and wildlife as well as economic [and] social impacts.”

Sept. 2014. A Denver judge ruled against the license.

Sheep Mountain Alliance.
Piñon Ridge site
NRC requirements for new tailings sites

1. New sites must be appropriate for tailings disposal from the view of geology and hydrology.

2. The site should not be located on a geological fault.

3. It should not be threatened by the risk of earthquakes.

4. Natural impermeable layers should be present.

5. The site should not be located in the flood plain of rivers.
NRC requirements for new tailings sites.

6. The groundwater level should be relatively deep.

7. Leaching should not present a risk to groundwater quality.

8. Deposits of clay materials appropriate for lining and covering the deposit should be located nearby (i.e. use a clay liner as done with municipal landfills and coal ash ponds).

9. The site should be remote from residential areas.
Depleted Uranium (DU)

DU is a by-product of the process used to enrich natural U to make reactor fuel.

Depleted with respect to $^{235}\text{U}$

<table>
<thead>
<tr>
<th></th>
<th>Natural U (%)</th>
<th>DU (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{234}\text{U}$</td>
<td>0.006</td>
<td>0.001</td>
</tr>
<tr>
<td>$^{235}\text{U}$</td>
<td>0.72</td>
<td>0.2</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>99.28</td>
<td>99.80</td>
</tr>
</tbody>
</table>
Is DU a “waste?”

DU was listed a Class A waste in the draft Part 61 in 1981.
However, NRC does not currently classify DU as
Class A explicitly: only by default.

“When NRC regulations on low-level waste disposal
were developed, there were no commercial facilities
generating significant quantities of depleted
uranium waste. Therefore, the impacts of depleted
uranium disposal were not explicitly considered.”

http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/du-other-
waste-disposal.html
DU stored as UF$_6$ in Portsmouth, Ohio (25,000 cylinders) and Paducah, Kentucky (39,000)
New regulations for DU

“The NRC is in the early stages of amending its regulations to establish new requirements for the disposal of [DU]. The new regulation would require a site-specific analysis to determine if a proposed disposal site is appropriate and adequate for safely disposing of wastes that were not considered when current NRC regulations were developed.” (NRC Fact Sheet, 2009).
DU as a useful product

Because of its great density—\((19.1 \text{ g/cm}^3)\)—the main civilian uses of DU include counterweights in aircraft, radiation shields in medical radiation therapy machines and containers for the transport of radioactive materials.

The military uses DU for defensive armor plate.

DU is also used in armor-piercing military shells because of its high density, and also because DU can ignite on impact if the temperature exceeds 600° C.
DU ammunition
DU ammunition was first used in the Gulf War by U.S. forces, and then in the Bosnia and Kosovo conflict by NATO forces.

Like U, DU is an alpha source. Major route of exposure to DU is inhalation of small particles. DU residues were reported in battlefields in Iraq.
Depleted uranium on campus
Depleted uranium on campus
Depleted uranium on campus
Depleted uranium on campus
Depleted uranium on campus