Uranium in the Grants Mineral Belt – Ore Formation, Mining Techniques, Processing, Economics

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Outline

• Introduction
• Geologic setting of the Grants district
• Mining and processing
• Reasonable economic potential for development
Introduction
What are the important parameters that characterize uranium deposits?

- Location
- Shape
- Size and grade
- Depth
- Orientation
- Geotectonics
- Mineralogy
- Hydrology
- Boundary conditions

Uranium deposits, like all mineral deposits, are found in specific locations in the world, dictated by geologic conditions.
Major Uranium Minerals

- Autunite—\( \text{Ca(UO}_2\text{)(PO}_4\text{)}_2 \text{ 10-12(H}_2\text{O)} \)
- Carnotite—\( \text{K}_2\text{(UO}_2\text{)}_2\text{(VO)}_4 \text{ 3(H}_2\text{O)} \)
- Tyuyamunite—\( \text{Ca(UO}_2\text{)}_2\text{(VO}_4\text{)}_2 \text{ 5-8H}_2\text{O} \)
- Uraninite—\( \text{UO}_2 \)
- Uranophane—\( \text{Ca(UO}_2\text{)}_2\text{SiO}_3\text{(OH)}_2 \text{ 5(H}_2\text{O)} \)
Types of uranium deposits

- Unconformity-related deposits
- Sandstone deposits
- Quartz-pebble conglomerate deposits
- Vein deposits
- Hematite breccia complex deposits (IOCG deposits)
- Intrusive deposits
- Phosphorite deposits
- Collapse breccia pipe deposits
- Volcanic deposits
- Surficial deposits
- Metasomatite deposits
- Metamorphic deposits
- Lignite
- Black shale deposits
- Other types of deposits
  - Todilto limestone deposits
Grade verses tonnage for major types of uranium deposits

Potential critical minerals in Grants district uranium deposits

• Vanadium (produced in past from most deposits)
• Selenium
• Rare earth elements (REE)
Table 1. Estimated total production of major commodities in New Mexico, in order of estimated cumulative value (data from USGS, 1902-1927; USBM, 1927-1990; Kelley, 1949; Northrop, 1996; Hanner, 1965; USGS, 1965; Howard, 1967; Harben et al., 2008; Energy Information Administration, 2015; New Mexico Energy, Minerals and Natural Resources Department, 1986-2015). Figures are subject to change as more data are obtained.

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Years of production</th>
<th>Estimated quantity of production</th>
<th>Estimated cumulative value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas</td>
<td>1921-2014</td>
<td>&gt;73 trillion cubic feet</td>
<td>$160 billion</td>
</tr>
<tr>
<td>Oil</td>
<td>1922-2014</td>
<td>&gt;6.1 billion barrels</td>
<td>$115 billion</td>
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<tr>
<td>Coal</td>
<td>1882-2013</td>
<td>&gt;1.27 billion short tons</td>
<td>&gt;$21 billion</td>
</tr>
<tr>
<td>Copper</td>
<td>1804-2013</td>
<td>&gt;11.5 million tons</td>
<td>&gt;$20.6 billion</td>
</tr>
<tr>
<td>Potash</td>
<td>1951-2013</td>
<td>112,054,218 short tons</td>
<td>&gt;$15 billion</td>
</tr>
<tr>
<td>Uranium</td>
<td>1948-2002</td>
<td>&gt;347 million pounds</td>
<td>&gt;$4.7 billion</td>
</tr>
<tr>
<td>Industrial minerals**</td>
<td>1959-2013</td>
<td>40,276,083 short tons</td>
<td>&gt;$2.6 billion</td>
</tr>
<tr>
<td>Aggregates***</td>
<td>1997-2013</td>
<td>&gt;866 short tons</td>
<td>&gt;$2.5 billion</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>1951-2013</td>
<td>&gt;176 million pounds</td>
<td>&gt;$852 million</td>
</tr>
<tr>
<td>Gold</td>
<td>1931-2013</td>
<td>&gt;3.2 million troy ounces</td>
<td>&gt;$463 million</td>
</tr>
<tr>
<td>Zinc</td>
<td>1849-2013</td>
<td>&gt;1.51 million tons</td>
<td>&gt;$337 million</td>
</tr>
<tr>
<td>Silver</td>
<td>1903-1991</td>
<td>&gt;118.7 million troy ounces</td>
<td>&gt;$279 million</td>
</tr>
<tr>
<td>Lead</td>
<td>1848-2013</td>
<td>&gt;387,000 tons</td>
<td>&gt;$56.7 million</td>
</tr>
<tr>
<td>Iron</td>
<td>1883-1992</td>
<td>&gt;6.7 million long tons</td>
<td>&gt;$23 million</td>
</tr>
<tr>
<td>Fluorspar</td>
<td>1883-1962</td>
<td>&gt;721,000 tons</td>
<td>$12 million</td>
</tr>
<tr>
<td>Manganese</td>
<td>1909-1978</td>
<td>&gt;1.9 million tons</td>
<td>$5 million</td>
</tr>
<tr>
<td>Barite</td>
<td>1883-1963</td>
<td>&gt;37,500 tons</td>
<td>&gt;$400,000</td>
</tr>
<tr>
<td>Tungsten</td>
<td>1918-1965</td>
<td>113.8 tons (&gt;60% WO3)</td>
<td>na</td>
</tr>
<tr>
<td>Niobium-tantalum</td>
<td>1940-1958</td>
<td>34,000 pounds of concentrates</td>
<td>na</td>
</tr>
</tbody>
</table>

McLemore et al. (2017)
Table 1. Uranium production from 1947–2002 by type of deposit from New Mexico (McLemore and Chenoweth, 1989, 2003; production from 1988–2002 estimated by the authors). Type of deposits refers to Table 2. Total U.S. production from McLemore and Chenoweth (1989) and Energy Information Administration (2010).

<table>
<thead>
<tr>
<th>Type of deposit</th>
<th>Production (lbs U₃O₈)</th>
<th>Period of production (Years)</th>
<th>Production total in NM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary, redistributed, remnant sandstone uranium deposits (Morrison Formation, Grants district)</td>
<td>330,453,000¹</td>
<td>1951–1988</td>
<td>95.4</td>
</tr>
<tr>
<td>Mine water recovery (Morrison Formation, Grants district)</td>
<td>9,635,869</td>
<td>1963–2002</td>
<td>2.4</td>
</tr>
<tr>
<td>Tabular sandstone uranium deposits (Morrison Formation, Shiprock district)</td>
<td>493,510</td>
<td>1948–1982</td>
<td>0.1</td>
</tr>
<tr>
<td>Other Morrison Formation Sandstone uranium deposits (San Juan Basin)</td>
<td>991</td>
<td>1955–1959</td>
<td>—</td>
</tr>
<tr>
<td>Other sandstone uranium deposits (San Juan Basin)</td>
<td>503,279</td>
<td>1952–1970</td>
<td>0.1</td>
</tr>
<tr>
<td>Limestone uranium deposits (Todilto Formation², redominantly Grants district)</td>
<td>6,671,798</td>
<td>1950–1985</td>
<td>1.9</td>
</tr>
<tr>
<td>Other sedimentary rocks with uranium deposits (total NM)</td>
<td>34,889</td>
<td>1952–1970</td>
<td>—</td>
</tr>
<tr>
<td>Vein-type uranium deposits (total NM)</td>
<td>226,162</td>
<td>1953–1966</td>
<td>—</td>
</tr>
<tr>
<td>Igneous and metamorphic rocks with uranium deposits (total NM)</td>
<td>69</td>
<td>1954–1956</td>
<td>—</td>
</tr>
<tr>
<td><strong>Total in New Mexico</strong></td>
<td>348,019,000¹</td>
<td>1948–2002</td>
<td>100</td>
</tr>
<tr>
<td><strong>Total in United States</strong></td>
<td>927,917,000¹</td>
<td>1947–2002</td>
<td>NM is 37.5 of total U.S.</td>
</tr>
</tbody>
</table>

¹Production rounded to the nearest 1,000 pounds. There has been no uranium production in New Mexico since 2002. ²Todilto Formation (Cather et al., 2013).
Grants district

- ~340 million lbs of $\text{U}_3\text{O}_8$ have been produced 1948-2002
- ~409 million lbs of $\text{U}_3\text{O}_8$ historic resources have been reported by various companies
- Probably another ~200 million lbs of $\text{U}_3\text{O}_8$ remain to be discovered
- The district contained more than 900 million lbs $\text{U}_3\text{O}_8$
GEOLOGIC SETTING OF THE GRANTS DISTRICT
**FIGURE 3** Diagrammatic southwest-northeast cross section of San Juan Basin, from Craig, 2001 (p.12).
Description of the Grants uranium deposits
Tabular

- Less than 2.5 m thick
- Grades exceed 0.2% U₃O₈
- Sharp boundaries
- Locally offset by Laramide (Late Cretaceous)-Tertiary faults
- Black to dark gray because of the associated humate
- Also called primary, trend, prefault, black banded, channel, blanket ore
Redistributed

- 3-46 m thick
- Grades less than 0.2% U₃O₈
- Commonly localized by faults
- Form roll front geometries locally
- Diffuse ore to waste boundaries
- Dark, brownish gray to light gray
- Also called postfault, stack, secondary, roll front ore
Redistributed or roll-type uranium deposits

Open pit mine in Wyoming, Power Resources, Inc.

http://www.wma-minelife.com/uranium/mining/rllfrnt1.html
Remnant-primary sandstone uranium deposits

- Surrounded by oxidized sandstone
- Where the sandstone host surrounding the primary deposits was impermeable and the oxidizing waters could not dissolve the deposit, remnant-primary sandstone uranium deposits remain
- Also called ghost ore bodies
Ambrosia Lake area
Mt. Taylor area
HOW DID THE DEPOSITS FORM?
The primary uranium deposits are associated with humates. Therefore we need to understand the origin of the humates as well as the uranium.
Origin of humates

• Organic matter, not petroleum derived
  – Plant debris incorporated into the alluvial fans at the time of deposition
  – Plant material associated with the overlying lacustrine units
  – Dakota and pre-Dakota swamps
• Locally it is detrital (L-Bar deposits)
• At most places, were deposited just after the sandstones were emplaced but before the uranium
There is no consensus on details of the origin of the Morrison primary sandstone uranium deposits

- Alteration of volcanic detritus and shales within the Morrison Formation (Lacustrine-humate model)
- Ground water derived from a volcanic highland to the southwest
- Combination of the above
Possible episodes of uranium mineralization

- During and soon after deposition of the host sandstones (i.e. Jurassic)
- During pre-Dakota erosional interval (Late Jurassic to early Cretaceous)
- During the present erosional cycle (which started in late Miocene or early Pliocene)
Lacustrine-humate model

• Ground water was expelled by compaction from lacustrine muds formed by a large playa lake

• Humate or secondary organic material precipitated as a result of flocculation into tabular bodies

• During or after precipitation of the humate bodies, uranium was precipitated from ground water
From Turner-Peterson and Fishman (1986)
Brine-interface model

- Uranium and humate were deposited during diagenesis by reduction at the interface of meteoric fresh water and basinal brines.
- Uranium precipitated in the presence of humates at a gravitationally stable interface between relatively dilute, shallow meteoric water and saline brines that migrated up dip from deeper in the basin.
- Ground-water flow was impeded by upthrown blocks of Precambrian crust and forced upwards.
- These zones of upwelling are closely associated with uranium-vanadium deposits.
Jurassic plutons
(Kowallis et al., 1999; du Bray, 2007)

Jurassic caldera (Lawton and McMillan, 1999)

approximate direction of sedimentation

Jurassic arc (Kowallis et al., 2001)

subduction zone

approximate limit of Morrison Basin
(Turner and Peterson, 2004)

Paradox Basin
Ancestral Rocky Mountains
Denver Basin
San Juan Basin

Jurassic Mexican Borderland rift (Lawton and McMillan, 1999)

POTENTIAL SOURCE
from McLemore (2011)
Redistributed uranium deposits

• After formation of the primary sandstone uranium deposits, oxidizing ground waters migrated through the uranium deposits and remobilized some of the primary sandstone uranium deposits.

• Uranium was reprecipitated ahead of the oxidizing waters forming redistributed or roll front sandstone uranium deposits.

• Evidence suggests that more than one oxidation front occurred in places (Cretaceous and a Tertiary oxidation front).
Ground water movement in permeable sandstone

Secondary roll-front ore

Diagenetic U ore lenses (not essential to form roll-front deposit)

Molybenite, pyrite, calcite

Hematite, limonite (magnetite) core

Sidereite, goethite, S

Uraninite, pyrite, Se

Oxidized rocks (diagenetic hematite and limonite)

Reduced sandstone (diagenetic pyrite, marcasite, calcite, organic material)

20 to 100 m

Semipermeable sandstone or shale

From Nash et al. (1981) and Devoto (1978)
FIGURE 4. Map showing distribution of Tertiary-Quaternary oxidation in sandstone of Westwater Canyon Member, Morrison Formation. See Saucier (11), from which this figure is taken, for full discussion of details shown on map.
MINING

• Open pit
• Underground
• Heap leaching
• In situ leaching or recovery
OPEN PIT MINES

Sweetwater mine, Wy
Underground Mining
Methods of uranium processing

- Conventional mining and milling
  - Higher grade deposits
  - Mineralogy and lithology determine if it is acid or alkaline leach
  - No mills in NM, although there are plans underway for at least 1 mill in the Grants district

- In situ recovery
  - Typically roll front deposits
  - Mineralogy and chemistry important
  - Mo and V interferes with recovery of U

- Heap leaching
Conventional Uranium Mill Unit Processes
Rock Crushing, Sampling, Stockpiling

- Trucks are weighed
- Ore is sampled
- Ore is crushed to $< \frac{1}{4}''$ size in series of crushers
- Crushed ore is stockpiled
Grinding

- Rod Mills
- Ball Mills
- Semi-Autogenous Grinding (SAG) Mills
- Water is added to make pulp

- Grinders in Operating Mill
- Ball Mill in foreground
- SAG Mills in background
Leaching Process

- Acid Leaching System
- Sulfuric Acid Leach
- Acid, Heat and Oxidant (sodium chlorate) applied

- 50% solids/ 50% water is mixed w/ Acid to ~22% solids
- Uranium is “leached” into solution
Classifiers/Settling Tanks

- Solids are washed of the Uranium
- Solids advance to thickeners to separate “tailings”
- < 1% of Soluble Uranium remains in tailings
- 99% of Uranium is now in the “pregnant” liquor
Solvent Extraction

- Dissolved Uranium is chemically extracted from “pregnant” liquor
- Selective removal of Uranium from solution
- Uranium is concentrated 4x

- Mixer-Settler mixes Ur-acid solution w/ kerosene
- U transferred to Solvent phase
- Raffinate – barren aqueous solution, free of Uranium
- Stripping concentrates U 40x
Precipitation and Drying

- U “falls out” of solution
- Settles to bottom of Precipitation Tanks
- U is now a solid
- Dewatering via Centrifuge or Filter Press
- Final Drying step produces Yellow Cake
- Drying Temp ~1200 degrees F
Tailings Ponds

- Solids and liquid wastes are disposed in lined ponds
- Water is recycled
- Solids allowed to dry

- Dried solid “tails” are Capped w/ ~13’ of clay, rock and topsoil
- Capped pond is re-vegetated
- Extensive environmental monitoring
- Heavily regulated, financially bonded
  - ensures protection of environment
Mill Process Summary

1. Coarse Ore
2. Crushing
3. Fine Ore Storage
4. Tailings
5. Liquid Solid Separation
6. Leaching
7. Grinding
8. SX
9. Precipitation
10. Dry & Package
A Conventional Mill

White Mesa Uranium Mill, Blanding Utah
ORE

Grinding

H2SO4 Oxidants

Acid Leaching

Water or Barren Recycle Sol’ns

Liquid-Solid Separation

Concentration and Purification

NH3

Precipitation and Purification

Barren Sol’ns

Dewatering and Drying

Product

ACID CIRCUIT

Ore Preparation

Recycle Sol’n

Density Control

Carbonate Leaching

Liquid-Solid Separation

Recarbonation

Precipitation and Purification

Dewatering and Drying

Product

ALKALINE CIRCUIT

NA2CO3

FIG. 4. Mill processing flowsheet.
Heap Leaching

FIG. 5. Heap leaching pad construction.
Past ISR in New Mexico

- Mobil at Crownpoint
- UNC-Teton at Section 23
- Grace Nuclear at Hook’s Ranch
- Section 13 north of Seboyeta and Church Rock
- Anaconda at Windwhip, part of the Jackpile Paguate mine
- Mine water recovery from Ambrosia Lake and other mines
FIG. 23. Process flow diagram for a typical uranium in situ leaching mining facility.

In situ recovery
In situ Recovery

http://www.wise-uranium.org/uisl.html
South Texas
South Texas
Uranium Potential in New Mexico
Historical Production from the Morrison Formation

- 340 million lbs of $\text{U}_3\text{O}_8$ from 1948-2001
- Accounting for 97% of the total uranium production in New Mexico
- More than 30% of the total uranium production in the United States
- 7th largest district in total uranium production in the world
New Mexico is 2nd in uranium reserves 15 million tons ore at 0.277% U₃O₈ (84 million lbs U₃O₈) at $30/lb
## U.S. Forward-Cost Uranium Reserves by State, December 31, 2003

<table>
<thead>
<tr>
<th>State(s)</th>
<th>$30 per pound</th>
<th></th>
<th>$50 per pound</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ore (million tons)</td>
<td>Grade(^a) (percent U(_{3})O(_8))</td>
<td>U(_3)O(_8) (million pounds)</td>
<td>Ore (million tons)</td>
</tr>
<tr>
<td>Wyoming</td>
<td>41</td>
<td>0.129</td>
<td>106</td>
<td>238</td>
</tr>
<tr>
<td>New Mexico</td>
<td>15</td>
<td>0.280</td>
<td>84</td>
<td>102</td>
</tr>
<tr>
<td>Arizona, Colorado, Utah</td>
<td>8</td>
<td>0.281</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Texas</td>
<td>4</td>
<td>0.077</td>
<td>6</td>
<td>18</td>
</tr>
<tr>
<td>Other(^b)</td>
<td>6</td>
<td>0.199</td>
<td>24</td>
<td>21</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>74</strong></td>
<td><strong>0.178</strong></td>
<td><strong>265</strong></td>
<td><strong>424</strong></td>
</tr>
</tbody>
</table>

\(^a\)Weighted average percent U\(_{3}\)O\(_8\) per ton of ore.

\(^b\)Includes California, Idaho, Nebraska, Nevada, North Dakota, Oregon, South Dakota, and Washington.

**Notes:** Uranium reserves that could be recovered as a byproduct of phosphate and copper mining are not included in this table. Reserves values in forward-cost categories are cumulative: that is, the quantity at each level of forward-cost includes all reserves at the lower costs. Totals may not equal sum of components because of independent rounding.

Why did uranium production cease in New Mexico?

- Three Mile Island produced a public perception in the U.S. that nuclear power was dangerous.
- At the same time, NM uranium deposits in production were decreasing in grade by nearly half.
- Significant changes were beginning to occur that would increase the cost of mine and mill reclamation as well as future permitting in the U.S.
- More attractive, larger, higher grade uranium deposits in Canada and Australia were discovered.
- Large coal deposits were found throughout the U.S. that could meet the nation’s energy needs.
There is sufficient uranium reserves to meet the current reactor demand.

In order for NM deposits to once again be economic—Must build new reactors to increase demand.

Wait for reserves at other localities to be depleted by production.

Decrease cost of production/increase price.

Mine closure plans must be approved before mining can begin.
Importance of sandstone uranium deposits in the Grants district

• Major mining companies abandoned the districts after the last cycle leaving advanced uranium projects.

• Inexpensive property acquisition costs includes $$ millions of exploration and development expenditures.

• Availability of data and technical expertise.

• Recent advances in in situ leaching makes sandstone uranium deposits attractive economically.
Comments

• None of the uranium mills remain in the Grants region.
• Current plans by some companies are to mine uranium by in situ recovery.
• Any conventional mining of uranium will require shipping to an existing mill in Utah or licensing and building a new mill in New Mexico.
• The Navajo Nation has declared that no uranium production will occur in Indian Country.
Reasonable economic potential for development
NUCLEAR POWER PLANTS

https://www.theguardian.com/environment/interactive/2012/mar/08/nuclear-power-plants-world-map
Uranium Production in The United States

USA Cum. Production = 353,877 Tonnes U
Grants Uranium Region Cum. Production = 133,590 Tonnes U
USA Cum. Reactor-Related Demand = 404,500 Tonnes U

Tonnes U / GWe Capacity = 178.5


Pelizza and McCarn (2002)
• Production to 2017
• Canada 524,437 tU
• USA 376,396 tU
• Kazakhstan 316,473 tU

http://www.wise-uranium.org/umaps.html
Uranium Resources (RAR - $40/kg U)

[t U] Reasonably Assured Resources (recoverable), 1/1/2015, Cost range < US$40/kg U (OECD 2016)

World Total = 478500 t

http://www.wise-uranium.org/umaps.html
USA is 10th

http://www.wise-uranium.org/umaps.html

http://www.world-nuclear.org/opinion/opinion6.html
Some analysts suggest uranium prices could exceed $40/lb U₃O₈ by 2020.
Uranium Price History
Events & Macroeconomic Factors (1968 – 2016)

1976: Uranium Price Hits $176/lb. (Inflation Adjusted)

Late-60’s to Early-70’s: Major Global Reactor Construction

1974: Three Mile Island

2007: Ranger Mine Damaged by Cyclone

2011: Fukushima

2008: Global Financial Crisis

2006: Cigar Lake Mine Floods

2005: China’s 11th 5-Year Plan Promotes Nuclear

1988: Chernobyl

2003: McArthur River Mine Floods


1985: NUEXCO Bankruptcy

2015: Kazakh U3O8
Production = ~60M lbs.

Global Reactor Growth Expected to Increase

Global Reactor Growth Expected to Decrease

Reactor Growth Expected to Increase
Future of Nuclear Power

- Renewable energy is becoming more important throughout the world and is competitive with nuclear energy, because of the subsidies
- But must have a sustainable baseload that does not create CO2 emissions
- Small nuclear reactors could be a game changer
- Thorium reactors could be a game changer
- Assumption that U.S. Navy will continue to operate nuclear power
- Plenty of uranium resources in world
Future of uranium mining in Grants district

• Higher cost reserves than elsewhere in world
• Most Grants deposits must be mined by conventional methods, not in situ recovery, unless the technology changes—requires a mill
• Heap leaching is a possibility, if it could be permitted
• A lot of public opposition to mining in the Grants district
Summary

• Sandstone uranium deposits have played a major role in historical uranium production.
• Although other types of uranium deposits are higher in grade and larger in tonnage, sandstone uranium deposits will in the future become a significant player:
  – As in-situ leaching technologies improve cutting production costs.
  – As demand for uranium increases world-wide increasing the price of uranium.
  – Probably in the long-term >10 yrs in NM.
FUTURE WORK

• Refine our estimates of uranium resources/reserves potential in the state
• Continue detailed mineralogy studies (XRD and electron microprobe)
• Define the origin of distribution of primary verses redistributed deposits in the San Juan Basin
• Geochemical characteristics of naturally-occurring groundwater that oxidized, remobilized, and redeposited primary tabular uranium deposits in the Grants district
• Study of clay species in the mineralized zones, and their impacts on porosity and permeability characteristics during uranium extraction and mobility