# The End of Cheap Uranium

**Science of the total environment 461-462 (2013) 792-798**

**Michael Dittmar (ETH-Zürich) 6.2.2014**

- **Uranium demand and supply:**
  The scale of the problem
- **Uranium Resources (Claims and Realities):**
  Lessons from past uranium mining
- **How mining depletes uranium deposits:**
  A hypothesis about present and future uranium mining
- **The future demand/supply situation**
- **Conclusions**

Sources (most important only): **IAEA**( Red Book 09/11, the Red Book Retrospective and the World Distribution of Uranium Deposits Database (UDEPO) (http://www-nfcis.iaea.org/UDEPO/UDEPOMain.asp) and **World Nuclear Association (WNA**) at http://www.world-nuclear.org/info/default.aspx

# Uranium demand and supply (I)

**from the NEA/IAEA Press declaration (July 26, 2012) about the new Red Book 2011**

- ``By the year 2035, ..,**world nuclear electricity generating capacity is projected to grow** from 375 GWe net (at the end of 2010) to between 540 GWe net in the low demand case and 746 GWe net in the high demand case..”
- ``Accordingly, world annual reactor-related uranium requirements are projected to rise from 63 875 tonnes of uranium metal (tU) at the end of 2010 to between 98 000 tU and 136 000 tU by 2035.”
- ``Although ample resources are available, **meeting projected demand will require timely investments in uranium production facilities**. **This is because of the long lead times (typically in the order of ten years or more in most producing countries) required to develop production facilities…**”

# Uranium demand and supply (II)

## Questions to be addressed in the next 10 minutes:

**1) The ``Identified Uranium Resources":**

**How (un)reliable are they?**

**2) Existing mines and deposit depletion profiles:**

**How to estimate extraction limits during the next decades?**

**3) The predictable end of ``cheap uranium":**

**What are the consequences for the future of nuclear energy?**

# Uranium demand and supply (III)

## 2011 (pre Fukushima) demand situation:

**World Demand = 68 000 tons (2011);**

**Western-Europe (21 000 tons), USA (19 000 tons) and Japan+Korea (10000 tons)**

**The largest uranium users are without significant mines!**

## Today's primary (mining) supply situation:

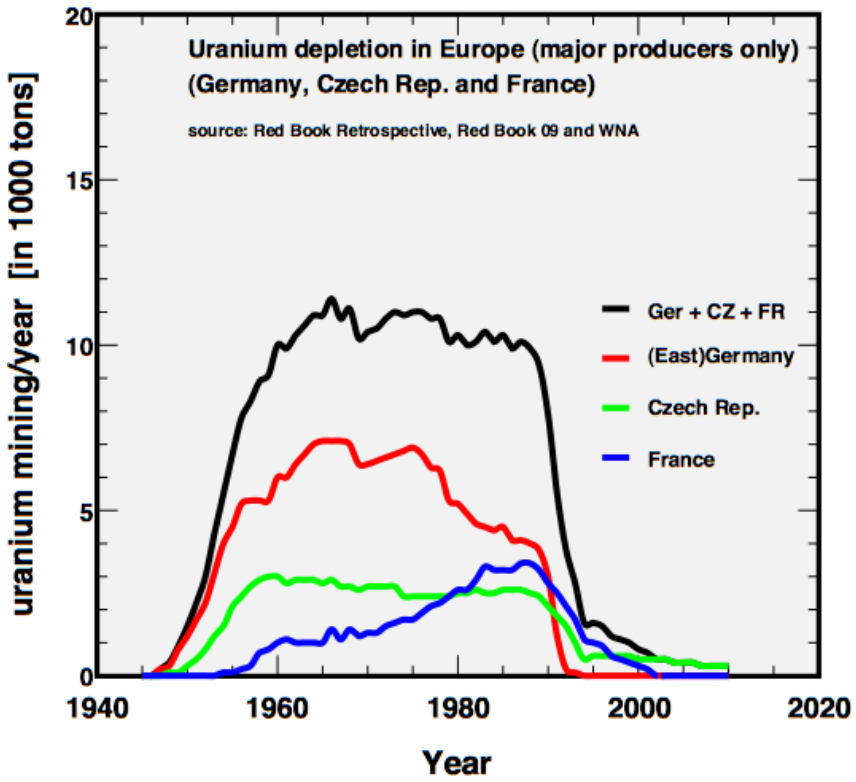
**total mining 2010 = 53 700 tons (rest from secondary supplies)**

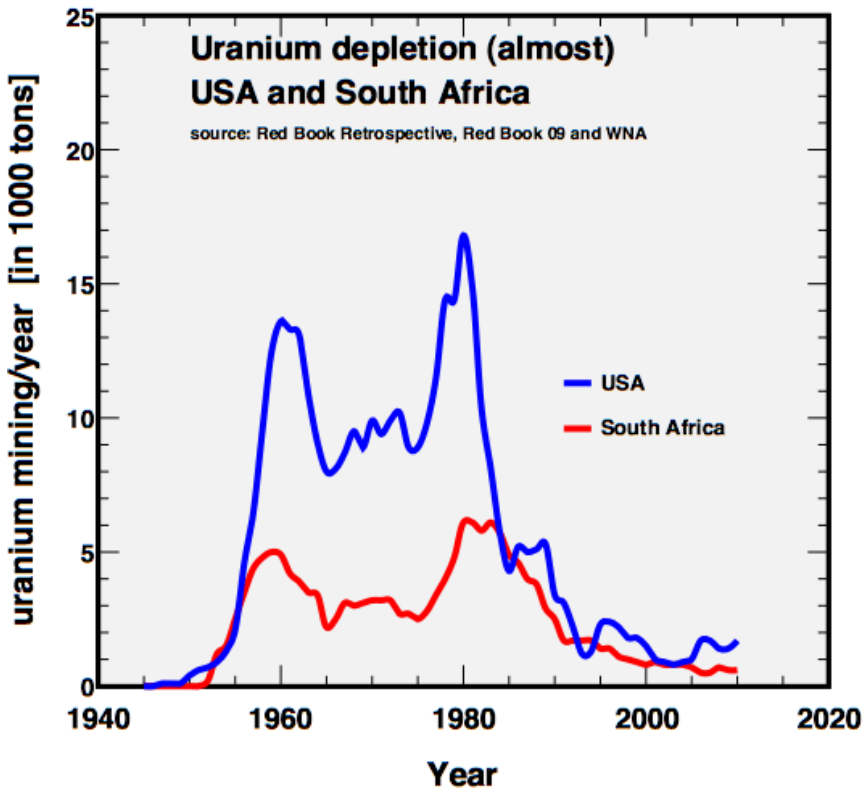
**85% from only 6 countries, 75% from 20 large mines**

**72% of mining controlled by only 6 huge companies!**

# Lessons from past uranium mining (I)

## Mining history in countries where extraction ended (or almost)



# Lessons from past uranium mining (II)

- **Uranium mining in Western-Europe stopped (despite large demand)**
  **only 58% of original resource estimate could be extracted!**
  (Similar for many other countries and regions on the planet)

| Country | Demand 2010 [ktons] | Peak production [ktons] (year) | Initial resource estimate [ktons] | Extracted total [ktons] | Fraction extracted |
|---|---|---|---|---|---|
| Germany | 3.45 | 7.1 (1967) | 334.5 | 219.5 | 66% |
| Czech Rep. | 0.68 | 3.0 (1960) | 233.4 | 109.4 | 47% |
| **France** | **9.22** | **3.4 (1988)** | **110.8** | **76.0** | **69%** |
| Bulgaria | 0.28 | 0.7 (1985-88) | 49.1 | 16.4 | 33% |
| Hungary | 0.30 | 0.6 (1960-83) | 32.8 | 21.1 | 64% |
| Romania | 0.18 | 2.0 (1956-58) | 37.1 | 18.4 | 49% |
| Spain | 1.46 | 0.3 (1994-00) | 26.4 | 5.0 | 19% |
| **Western Europe** | **21** | **12.3(1976)** | **≈ 810** | **≈ 460** | **58%** |

# Lessons from past uranium mining (III)

## Past uranium mining activities show:

- **Many formerly uranium rich areas and countries now depleted:**
  **Ontario Elliot Lake (Canada), New Mexico, Utah…(USA),**
  **Germany, Czech Republic, France… (Western-Europe),**
  **D.R. Congo, Gabon…(Africa)**

- **Terminated uranium mining in Europe demonstrates:**
  **1) Interesting uranium deposits are limited ➔ a finite resource (like fossil fuels),**
  **mining of individual deposits and of uranium rich regions and countries must eventually stop.**

  **2) Mining techniques: Only 50-70% of original resource estimates extractable.**

  **3) Remains from mines: a heavy environmental burden for future generations.**

# A hypothesis about the mining of uranium deposits (I)

**Data from (recently) depleted mines (nearby deposits) in Canada (and Australia):**

**Real extraction ``allways" on low side of initial resource estimate!**

| Name (deposit) | Initial estimate [ktons] | Total extracted [ktons] (operating period) | Plateau value [ktons] | 10 year hypothesis total [ktons] |
|---|---|---|---|---|
| Rabbit Lake (main) | 10-25 | 15.8 (1974-84) | 1.4* | 14 ± 3 |
| Collins B | 10-25 | 11.3 (1985-91) | 1.9* | 19 ± 4 |
| Collins A+D | 7.5-15 | 8.6 (1994-97) | 2.7* | 26 ± 6 |
| Eagle Point | 25-50 | 24.9 (1992-98+2003-10) | 2.5-3* | 27.5 ± 6 |
| **Rabbit Lake (all)** | **52.5-115** | **60.6 (1974-10)** | | **86.5 ± 10** |
| Cluff Lake (5) | 14.5-30 | 10/14.4 (1980-92/92-03) | 1/1.4* | 10/14 ± 2 |
| Key Lake (1) | 25-50 | 32 (1983-87) | 6.4* | 64 ± 13 |
| Key Lake (2) | 25-50 | 42 (1989-01) | 5.4 | 54 ± 11 |
| Mc Clean (1) | 10-25 | 19.2 (1999-10) | 2.35 | 23.5 ± 5 |

***plateau estimated as the annual average**

# A hypothesis about the mining of uranium deposits (II)

- **To minimize the cost of the entire mining infrastructure:**
  **deposit exploitation planned for ``constant" annual extraction (plateau value)!**

- **Total exploitable resource (tons) = plateau value (tons)× 10 ± 2 (years)**
  **(20% uncertainty from slow startup and phase out periods)**

- **Testing the hypothesis with the 10 (normal*) deposits combined:**
  **real extraction = 310 ktons and hypothesis result = 319 ± 24 ktons!**

*** three ``abnormal" deposits/mines**

**Rabbit Lake Collins A+D and Key Lake (1) (Canada):**
**total extraction largely overestimated by our model (very short mining period!),**
**Olympic Dam (Australia):**
**Good agreement, but uranium is a byproduct (more detailed data needed)**

# A hypothesis about the mining of uranium deposits (III)

**A forecast for the upper production limit up to 2030 and combining large existing and well defined future mines:**

- **Extraction from all deposits declines rapidly after 10 ± 2 year,**
- **only few new projects with large deposits and interesting grades exist:**

**➔ planned mines can not compensate for declines at operating mines!**
**➔ The resulting maximum world annual uranium extraction:**

**peaking at around 58 ± 4 ktons (2015)**
**followed by a decline to 56 ± 5 ktons (2020),**
**54 ± 5 ktons (2025) and 41 ± 5 ktons(2030).**

# A hypothesis about the mining of uranium deposits (IV)

**Forecast for maximum extraction in different countries:**

**Kazakhstan: Production Maximum 20-22 ktons, decline begins after 2015.**

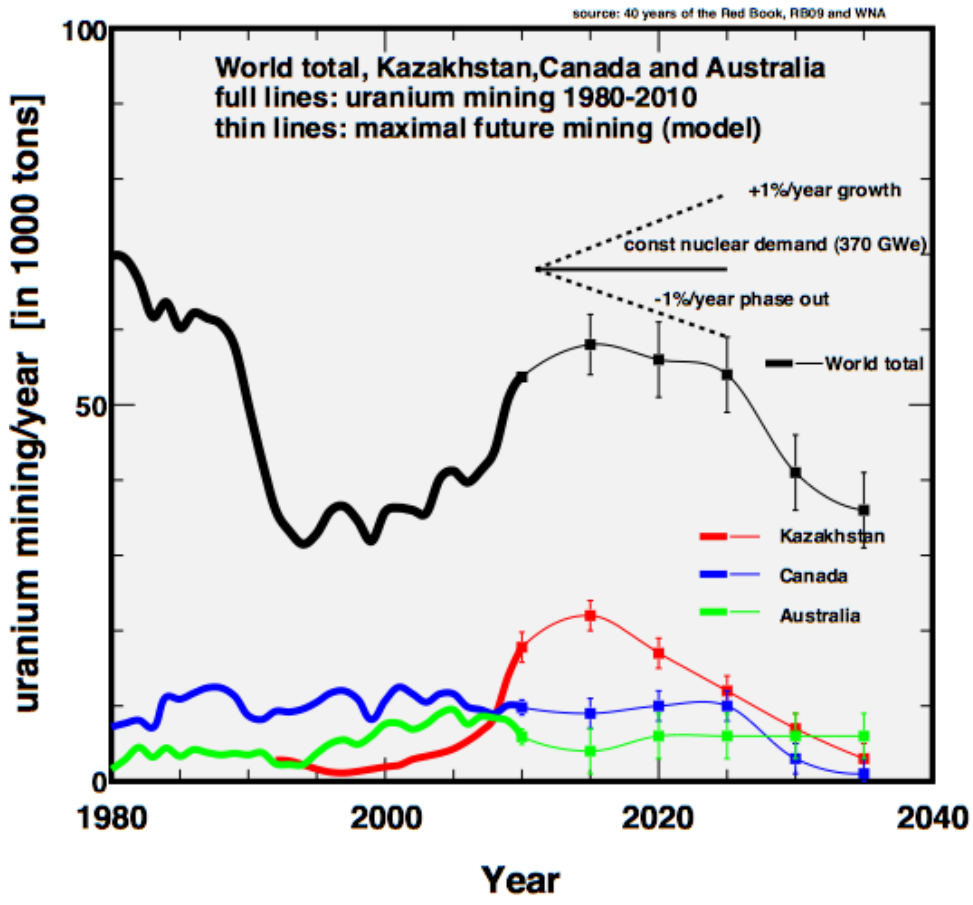
**Canada: announced decline of McArthur mine (after 2016),**

**Cigar Lake (7 kt/y from 2017-2027?) needed to "keep on going"**

| Country | Production 2010 [ktons] | Forecast 2015 [ktons] | Forecast 2020 [ktons] | Forecast 2025 [ktons] | Forecast 2030 [ktons] |
|---|---|---|---|---|---|
| Kazakhstan | 17.8 | 22 ± 2 | 17 ± 2 | 12 ± 2 | 7 ± 2 |
| Canada. | 9.8 | 9 ± 1 | 10 ± 2 | 10 ± 2 | 3 ± 2 |
| Australia | 5.9 | 4 ± 1 | 6 ± 3 | 6 ± 3 | 6 ± 3 |
| Russia | 3.6 | 6 ± 2 | 6 ± 2 | 9 ± 3 | 9 ± 3 |
| All others | 16.6 | 17 ± 2 | 17 ± 2 | 17 ± 2 | 17 ± 2 |
| World (max) | 53.7 | 58 ± 4 | 56 ± 5 | 54 ± 5 | 41 ± 5 |

# A hypothesis about the mining of uranium deposits (V)

**Model forecast for different countries: Even a constant nuclear capacity leads to ``the end of cheap uranium"**



# Summary

- **Regions and countries with terminated uranium mines demonstrate:**
  **1) uranium is a finite resource (like fossil fuels)**
  **2) on average only about 50-70% of the original resource can be extracted.**

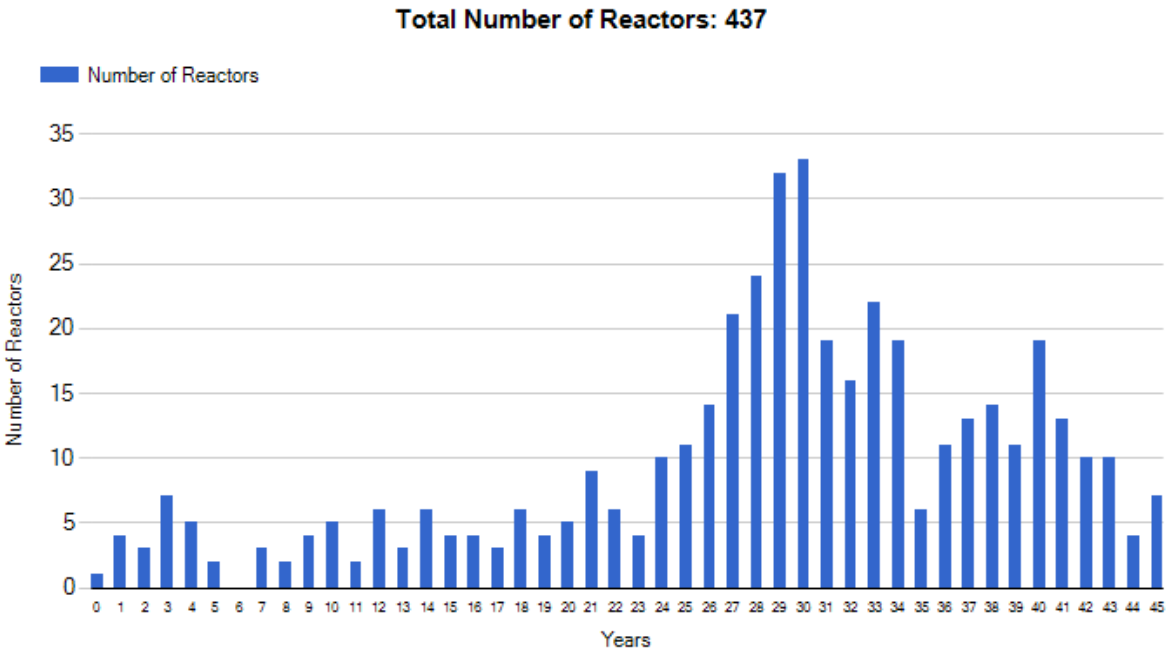
- **Depletions of uranium deposits in Canada and Australia leads to a simple and accurate mining model:**
  **A ``constant" annual production value is determined such that the best resource estimate allows a mine lifetime of 10 ± 2 year.**

- **Model prediction of ``maximal annual uranium extraction" up to 2030":**
  **58 ± 4 ktons around 2015, 56 ± 5 ktons (2020), 54 ± 5 ktons (2025) and 41 ± 5 ktons (2030)**

- **Supply gaps will develop within a few years and lead to ``The End of Cheap Uranium!"**
  **(even under a constant world nuclear capacity scenario of 370 GWe)**
  **A supply crunch can only be avoided under -1%/year (or more) worldwide nuclear power phase out scenario.**

# Appendix (I): Uranium needs and Nuclear Fission Energy today

**374 GWe Nuclear Power (2014) = 12% of worlds electric energy**
**natural uranium fuel requirement (170 tons/GWe/year)**
**2014 Uranium demand: 65 900 tons/year (mining 2012 = 58 000 tons)**
**Future demand = Existing - Termination + New build**
**Typical reactor lifetimes = 40-50(?) years:**



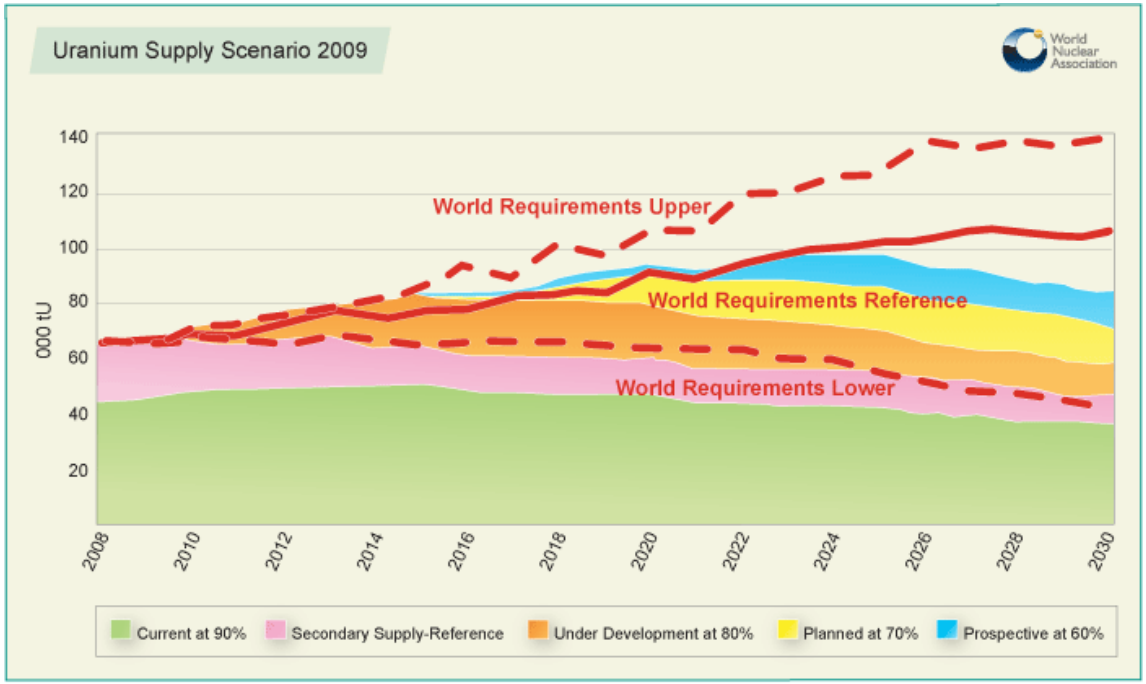

**≈100 reactors (in OECD countries) reach critical age during next 10-20 years.**

Source: IAEA PRIS data base

# Appendix (II):
# WNA (2009) uranium supply scenario:

➔ **Slower decline (longer lifetime) model for operating mines**
**(in contrast our 10 year model is based on data!)**

➔ **Still inconsistent with a 2% growth/year (50% increase by 2030)**
**the (hypothetical pre Fukushima) Nuclear Renaissance Scenario,**
**and consistent with -1%/decrease/year (50% decrease by 2030)**
**the slow (the post-Fukushima) phase out scenario**




Source: World Nuclear Association (WNA)

# Appendix (III): Lessons from past uranium mining (0)

Uranium mining (four periods)

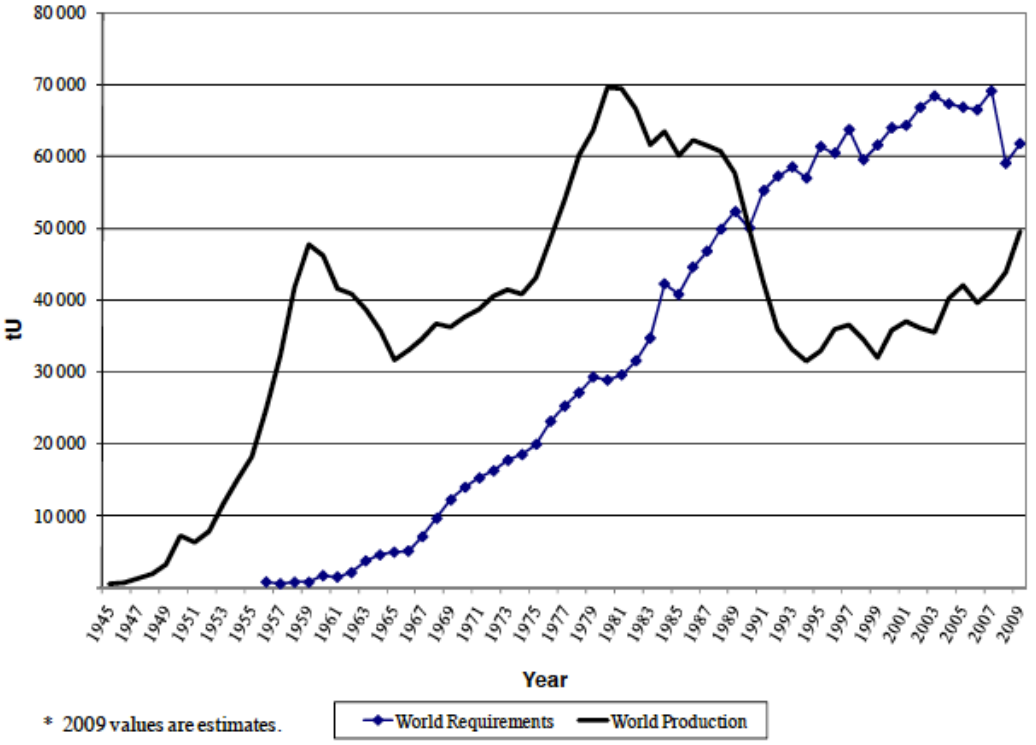
1. Nuclear Arms Race (1945-75)
large US/Russia military reserves

2. Nuclear power booms (1975-90).
   20-30 new reactors/year
3. End of nuclear boom (1991-05)
   annual demand >> supply

4. Nuclear Renaissance(?) (2005-?)

   uranium mining increases again
   from 40 ktons/year to
   54 ktons in 2010
   but:
   • essentially only in Kazakhstan
   • annual demand > supply

**Figure 13. Annual uranium production and requirements***
(1945-2009)

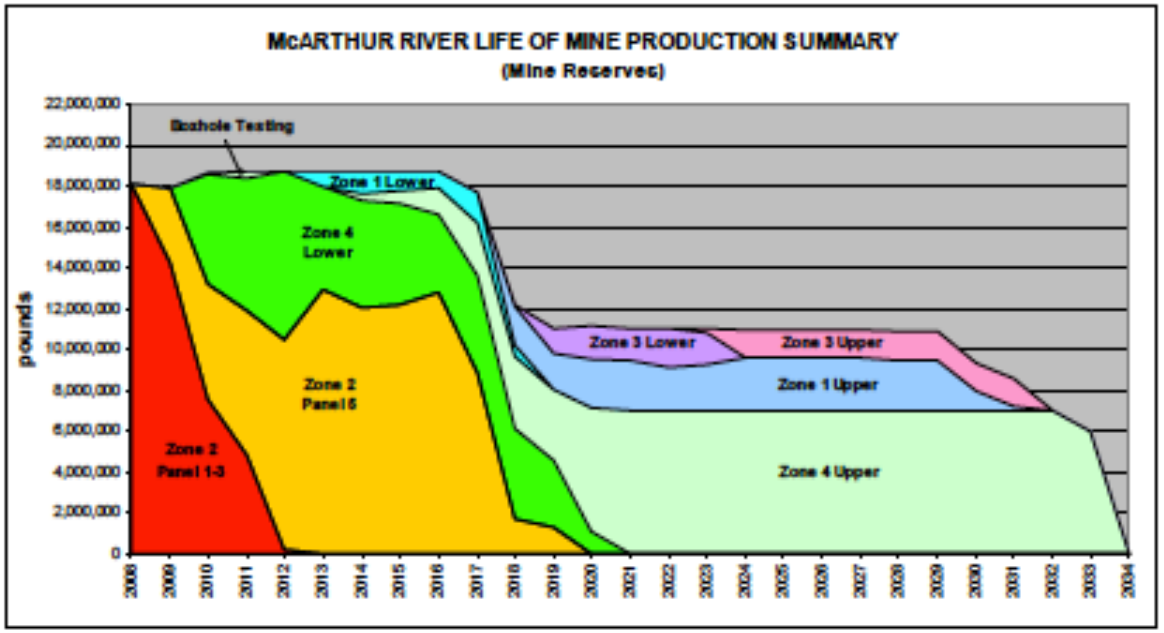


# Appendix (IV):The future of the McArthur Deposits

**the McArthur Mine, an announced decline?**

**(importance roughly like ``Saudi Arabien" for oil)**

Figure 27 – Life of Mine Production Summary - Mineral Reserves only




**Total Produktion**

**Zone 2 (red ``depleted")**

**2000-2010 = 73 ktons**

**(7.2 kt/year grade=14.7%)**

**``Proven" (2011-2016)?**

**Zone 2 (yellow) and 4 (green)**

**44 kt (grade 14%)**

**+20 kt (grade 31%)**

**``Probable" (2017-2030)??**

**Zone 4 (lightgreen) and 1+3**

**42 kt (grade 31%)+20 kt (grade 22%)**

Source: Cameco McArthur Technical Report 31.12.2008

## Appendix (V): Uranium mining in Australia and Kazakhstan and other future projects

- **Australia: Peak Production 9500 t (2005)**

  **2009 = 8000 tons from 3 larger mines inen (Ranger, Olympic Dam und Beverly)**

  **2010 = only 5900 t (significant decline in all three mines!)**

  **Status of future projects: ``unclear”!**

- **Kazakhstan: almost ``unbelievable” growth:**

  **from 4300 tons (2005) to 14000 tons (2009) and about 22000 tons (2013)**

  **according to the 2009 Red**

  **production will peak around the year 2015 with 28000 Tons**

  **and decline to 24kt (2020), 14 kt (2025) , 12 kt (2030) 6k (2035)**

- **Other larger projects in Russia, Niger and Namibia:**

  **Data and many details not yet public, schedule unclear!**

# More details and references

**``The end of cheap uranium" (long version of this paper)**

**M.Dittmar, http://arxiv.org/pdf/1106.3617v2**

**and ``The future of nuclear energy, facts and fiction an update"**

**January 2011,** http://arxiv.org/pdf/1101.4189v1

**further references at:**

- **Red Book 2009 Uranium Ressources IAEA/NEA(OECD) (updated every 2 years)**
- **IAEA (Vienna) PRIS-Reaktor Data Basis: http://www.iaea.org/programmes/a2/**
- **World Nuclear Association (WNA): http://www.worldnuclear.org/info/default.aspx**
- **Uranium Miner: http://www.uraniumminer.net/index.htm**
- **UxC Consulting Company: http://www.uxc.com/**

# Appendix VI: Uranium Resources

- **Uranium is not a rare element but:**

**definitions (IAEA/NEA Red Book 2009)**

(extraction costs up to 260 $/kg uranium)

**RAR (reasonable assured resources) "safe" 4 004 500 tons (?)**

**IR (inferred resources) "not yet found but one seriously believes in them" 2 301 800 tons (??)**

## In addition:

**UR** (undiscovered resources) "perhaps we believe in them" and

**UPR** (undiscovered prognosticated) and

**USR** (undiscovered speculative) "we would like to believe in them"

all combined perhaps another 10 400 500 tons

# countries with contradictions between real production and claimed RAR amounts

| Country | RAR (2009) [tons] | production 2010 [tons] | total production [tons] | peak production [tons] (year) |
|---|---|---|---|---|
| USA | 472 100 | 1 660 | 366 800 | 16 811 (1981) |
| South Africa | 195 200 | 583 | 157 400 | 6 100 (1981) |
| Canada | 387 400 | 9 783 | 446 600 | 12 522 (2001/02) |

# Uranium and mining in Australia and Africa

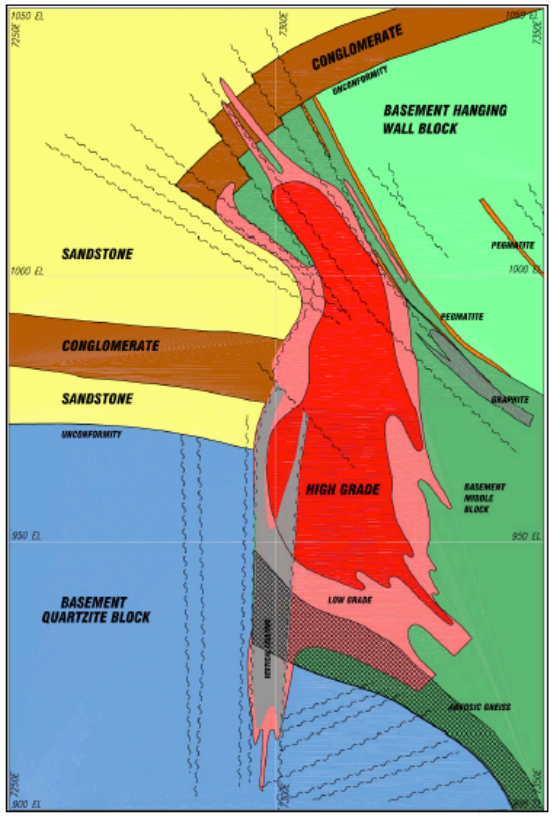
(**Australia and Africa:** (demand 2010: 300 tons)

| **Country** | **RAR (2009) [tons]** | **production 2009 [tons]** | **total production [tons]** | **peak production [tons] (year)** |
|---|---|---|---|---|
| Australia | 1 179 000 | 8500 | 156428 | 9512 (2004/05) |
| Namibia+ South-Afrika | 157000 195200 | | 156312 | 10188 (1980/81) |
| Niger | 244600 | 3208 | 110312 | 4363 |
| Congo+ Gabun | 1400 4800 | 0 | 51000 | ? |

# Plots (McArthur)



Figure 10 – Typical Zone 2 Geological Section Looking North

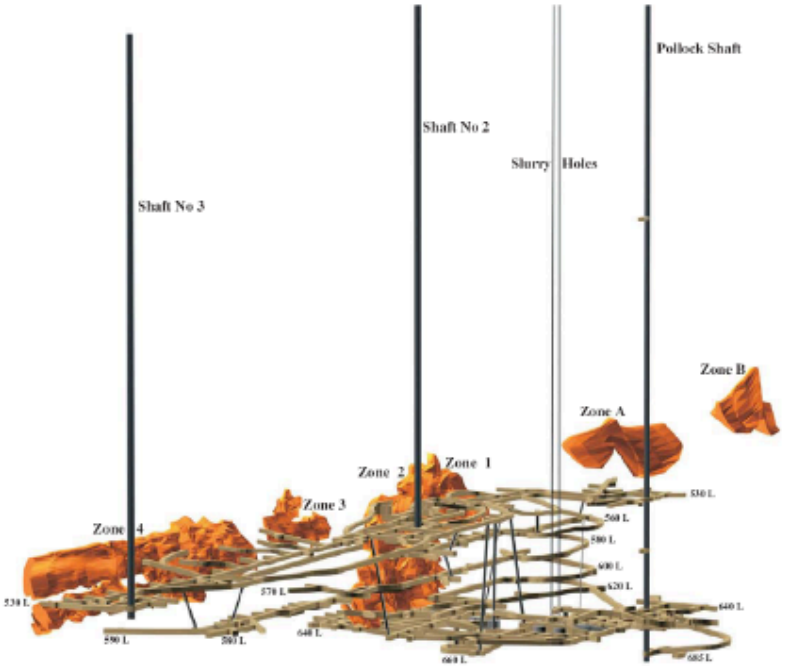





Cameco

## McArthur River Operation

Underground Development
and Mineralized Zones from Drilling



# Zahlen (McArthur)

**Table 17-1: Production Reconciliation with Reserves**

| | Mine Production | | | Reserves Model | | | Percent Difference Production vs Reserves | | |
|---|---|---|---|---|---|---|---|---|---|
| Year | Tonnes (x1000) | Grade $\%U_3O_8$ | Lbs $U_3O_8$ (millions) | Tonnes (x1000) | Grade $\%U_3O_8$ | Lbs $U_3O_8$ (millions) | Tonnes | Grade | Lbs $U_3O_8$ |
| 2000 | 43.7 | 11.6 | 11.174 | 34.2 | 9.8 | 7.354 | 28% | 18% | 52% |
| 2001 | 48.0 | 16.2 | 17.166 | 48.3 | 14.2 | 15.117 | -1% | 14% | 14% |
| 2002 | 52.5 | 16.0 | 18.524 | 47.6 | 16.5 | 17.281 | 10% | -3% | 7% |
| 2003 | 45.4 | 15.2 | 15.243 | 40.9 | 12.4 | 11.227 | 11% | 23% | 36% |
| 2004 | 55.9 | 15.2 | 18.699 | 60.4 | 13.1 | 17.345 | -7% | 16% | 8% |
| 2005 | 60.4 | 13.9 | 18.512 | 63.9 | 14.8 | 17.950 | -6% | -6% | 3% |
| 2006 | 57.6 | 14.7 | 18.698 | 61.5 | 13.0 | 17.660 | -6% | 13% | 6% |
| 2007 | 59.6 | 14.2 | 18.718 | 67.0 | 12.1 | 17.851 | -11% | 17% | 5% |
| 2008 | 53.2 | 14.9 | 17.502 | 58.5 | 13.4 | 17.277 | -9% | 11% | 1% |
| **Total** | **476.3** | **14.7** | **154.236** | **482.2** | **13.1** | **139.062** | **-1%** | **12%** | **11%** |
| 2004 to 2008 | 286.7 | 14.6 | 92.129 | 311.2 | 12.8 | 88.083 | -8% | 14% | 5% |

Since the start of ore mining, production tonnes are within 1% of the model, uranium grade higher by 12% and pounds $U_3O_8$ higher by 11%. At the end of 2003, based on the production results from previous years, the uranium grade of the zone 2 model was increased by 6%. Since then, for the years 2004 to 2008, the reconciliation of mine production with the model is within 5% on the estimated pounds $U_3O_8$, which is considered excellent. Comparing the tonnage mined with

# Zahlen (McArthur)

**Table 17-4: Mineral Reserves and Resources by Zones – December 31, 2008**

| Category | Area | Tonnes (x1000) | Grade % $U_3O_8$ | Contained Lbs $U_3O_8$ (millions) | Cameco's Share Lbs $U_3O_8$ (millions) |
|---|---|---|---|---|---|
| **Reserves** | | | | | |
| Proven | MCA Stockpile | 3.5 | 23.39 | 1.8 | 1.3 |
| | KEY Stockpile | 0.6 | 16.71 | 0.2 | 0.2 |
| | Total Stockpile | 4.1 | 22.23 | 2.0 | 1.4 |
| | Zone 2 | 368.6 | 14.22 | 115.6 | 80.7 |
| | Zone 4 | 7.7 | 31.15 | 52.5 | 36.7 |
| | Total In-Situ | 445.1 | 17.13 | 168.1 | 117.3 |
| | Total Proven | 449.2 | 17.18 | 170.1 | 118.8 |
| Probable | Zone 1 | 60.0 | 26.62 | 35.2 | 24.6 |
| | Zone 3 | 59.9 | 14.46 | 19.1 | 13.3 |
| | Zone 4 | 160.0 | 30.66 | 108.2 | 75.5 |
| | Total Probable | 280.0 | 26.33 | 162.5 | 113.4 |
| **Total Reserves** | | **729.2** | **20.69** | **332.6** | **232.2** |
| **Resources** | | | | | |
| Measured | Zone 1 | 22.0 | 10.22 | 5.0 | 3.5 |
| | Zone 2 | 34.1 | 6.48 | 4.9 | 3.4 |
| | Zone 4 | 18.9 | 10.20 | 4.2 | 3.0 |
| | Zone 4South | 134.0 | 9.58 | 28.3 | 19.8 |
| | Total Measured | 209.0 | 9.20 | 42.4 | 29.6 |
| Indicated | Zone 1 | 21.2 | 9.82 | 4.6 | 3.2 |
| | Zone 2 | 16.8 | 6.13 | 2.3 | 1.6 |
| | Zone 3 | 1.8 | 12.52 | 0.5 | 0.3 |
| | Total Indicated | 39.8 | 8.37 | 7.4 | 5.1 |
| **Total Measured & Indicated** | | **248.8** | **9.07** | **49.7** | **34.7** |
| Inferred | Zone 4South | 98.1 | 4.26 | 9.2 | 6.4 |
| | McA South | 82.3 | 16.66 | 30.2 | 21.1 |
| | Zone A | 255.6 | 8.19 | 46.2 | 32.2 |
| | Zone B | 151.3 | 14.90 | 49.7 | 34.7 |
| | McA North | 55.3 | 3.06 | 3.7 | 2.6 |
| **Total Inferred** | | **642.6** | **9.81** | **139.0** | **97.0** |

The footnotes under Tables 17-2 and 17-3 apply equally to Table 17-4.

**Table 17-4: Mineral Reserves and Resources by Zones – December 31, 2008**

| Category | Area | Tonnes (x1000) | Grade % $U_3O_8$ | Contained Lbs $U_3O_8$ (millions) | Cameco's Share Lbs $U_3O_8$ (millions) |
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| **Reserves** | | | | | |
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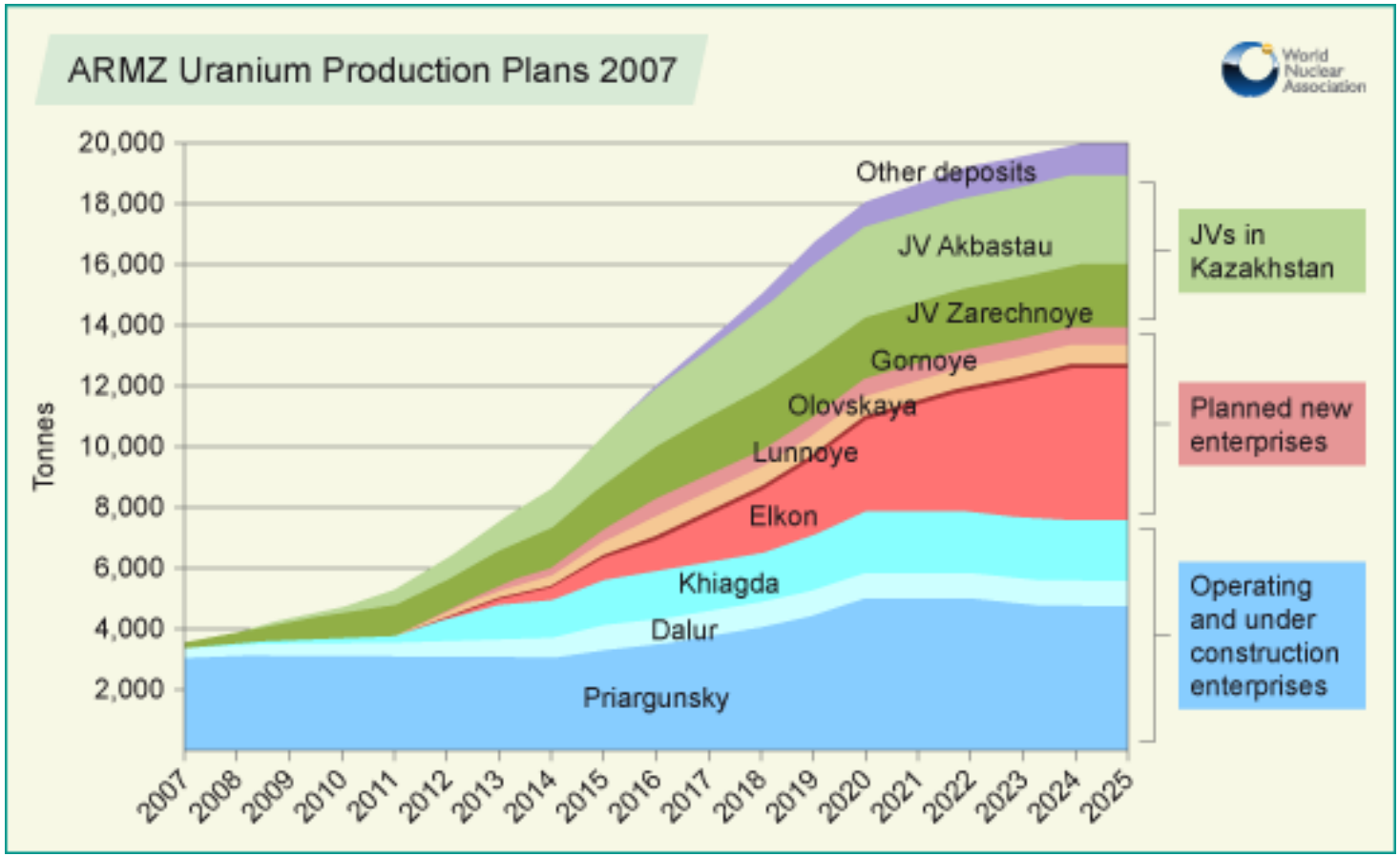
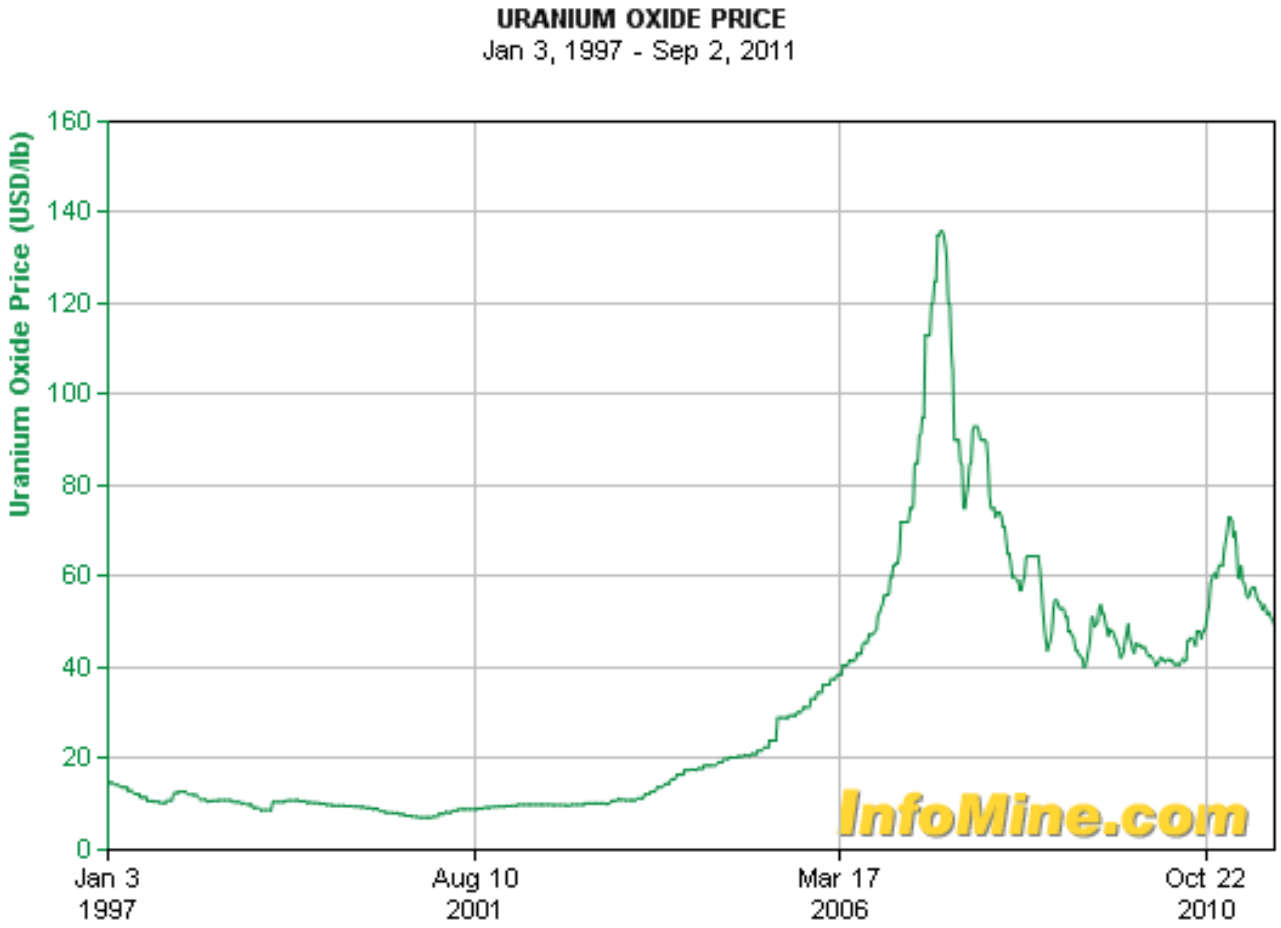
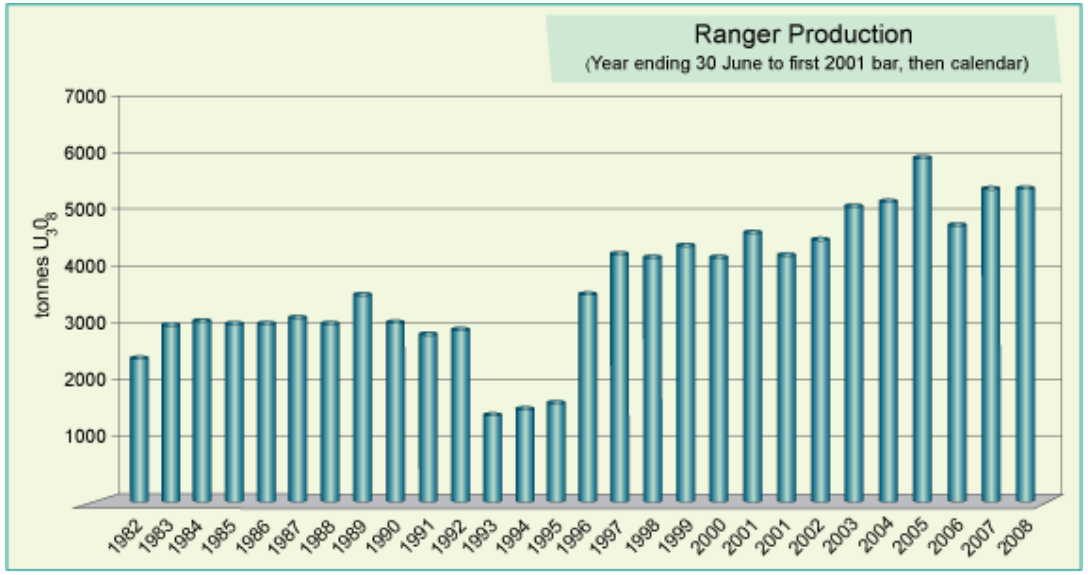
# Plots (Russia and ..)

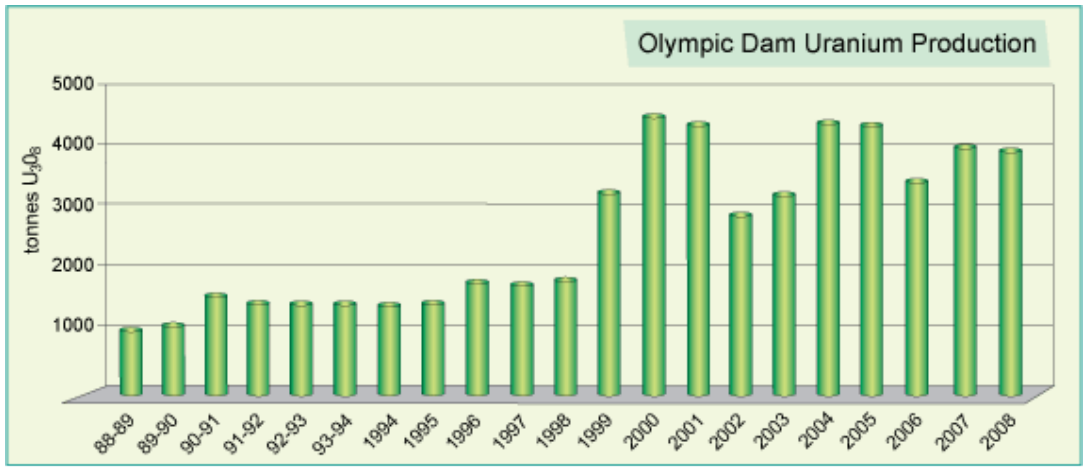


# Plots (Uranium price)



# Plots (Ranger)



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