Clean Nuclear Power for the 21st Century

Part 1 of 2: The Fuel Cycle

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Safety and Logistics

• Please familiarize yourselves with the nearest exits

• In case of emergency, WALK, DO NOT RUN!
About the Speaker: Ara Barsamian

- BS, MS (Engineering)
- Member AIChE, ASTM, ISA, IBIA

Exxon Research & Engineering:
- Mainly responsible for computerized fuels production world-wide:
  - Gasoline, Diesel, Bunker Fuel
  - Consultant to Jersey Nuclear on AVLIS; and patent memos on nuclear explosives for stimulation of depleted oil & gas fields

- 3X Corporation: President
- ABB Simcon: VP, Refinery Automation
- RAI: blending consultant
Why Nuclear Power?

High Standards of Living Require MORE ENERGY
Why Nuclear Power?

• Pro’s
  – No GHG, SOX, NOX, VOC
  – Very cheap, predictable cost
  – Inexhaustible (for millenia)

• Con’s
  – Politics, high construction costs (US, EU), disposition of waste
Basis of Nuclear Energy

- Splitting Atoms = Unbalanced Binding Energy = Mass Defect = Energy = $mc^2$

Fissionable Nucleus

Kinetic Energy = Heat

Unstable

Fission products

+200 MeV of energy

Neutrons

Triggers Splitting

Neutron

U-235
Basis of Nuclear Energy

- Fission results in 2 or more neutrons, which in turn cause more fissions, making possible an exponential (divergent) chain reaction, releasing more and more (kinetic) energy

\[ N(t) \sim N_0 e^{(k/\lambda)t} \]
Chain Reaction Needs a Critical Mass

A self-sustaining sequence of fissions needs a minimum mass for the initial neutrons to create new fissions: depends on speed of neutrons, shape of mass, type of fissile material

\[ N(t) = N_0 e^{(k/\Lambda)t} \]

\( \Lambda \) = mean n-gen time

k > 1: supercritical
k = 0: critical
k < 0: subcritical

Figure 1.48. Effect of increased mass of fissionable material in reducing the proportion of neutrons lost by escape.
Nuclear Fission Basics

- Fission process (by neutrons) needs fissionable materials
  - Typically ACTINIDES (U, Th, Pu)

- Classes of Actinides
  - Fissionable (only by hi speed neutrons)
  - Fissile (by neutrons of all energies)
Nuclear Fission Basics

• Best Material has high fission cross-section (ease of splitting)
  – Typically U235, and Pu239
  – U238 (common isotope) needs high energy (fast) neutrons; hence not good for power reactors

• U235 is only 0.7% of natural Uranium (U238), hence need for enrichment in isotope 235
Nuclear Fission Basics

• Can we use natural Uranium (99% U238, 0.7% U235), for power reactors?
  – Yes, if we use “moderators” to slow down fission neutrons so they can fission the tiny amount of U235 (0.7%) in the natural Uranium
  – Original reactors (Fermi’s Pile) and Hanford Plutonium reactors did just that
    • Used graphite as moderators
  – Disadvantage: they are huge, and have poor efficiency
Nuclear Fission Basics

• Light Water Reactor (LWR) more efficient than moderated reactors
  – Do not use moderator like Graphite or Heavy Water to slow down neutrons
  – Fuel is natural Uranium (U238), enriched to ~5% U235
  – Advantage:
    • they are smaller, and have good efficiency
    • Produce less Plutonium for weapons
Fig. 1. The nuclear fuel cycle.
Ore to Yellowcake to UF6 Gas

Ore: Pitchblende  Yellowcake: U3O8  UF6 Gas
### Enrichment Methods for U235

<table>
<thead>
<tr>
<th>Based on</th>
<th>Examples</th>
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<tbody>
<tr>
<td>Diffusion in a pressure gradient</td>
<td>Gas centrifuge&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>Separation nozzle</td>
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<td>Vortex tube</td>
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<td>Diffusion principles</td>
<td>Gaseous diffusion&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>Mass diffusion</td>
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<td>Thermal diffusion</td>
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<td>Phase equilibrium principles</td>
<td>Distillation</td>
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<td>Chemical equilibrium principles</td>
<td>Chemical exchange</td>
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<td>Ion exchange</td>
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<td>Photo excitation principles</td>
<td>Atomic vapor laser isotope separation (AVLIS)</td>
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<td>Molecular laser isotope separation (MLIS)</td>
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<td>Electromagnetic principles</td>
<td>Plasma separation process (PSP)</td>
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<td>Electromagnetic isotope separation (EMIS)</td>
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<tr>
<td></td>
<td>Plasma centrifuge</td>
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1. Enrichment by Gaseous Diffusion
2. Gas Ultra Centrifuge

Iranian/Pakistani Copies of Urenco
## Gas Ultra Centrifuges

<table>
<thead>
<tr>
<th>Rotor</th>
<th>Diameter cm</th>
<th>Height m</th>
<th>SWU kg/yr</th>
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<tbody>
<tr>
<td>P-1</td>
<td>aluminum</td>
<td>10</td>
<td>&gt; 2</td>
</tr>
<tr>
<td>P-2</td>
<td>maraging steel</td>
<td>15</td>
<td>&gt; 5</td>
</tr>
<tr>
<td>TC10</td>
<td>maraging steel</td>
<td>15</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>TC12</td>
<td>carbon fiber</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>AC-100</td>
<td>carbon fiber</td>
<td>60</td>
<td>330</td>
</tr>
<tr>
<td>Enrichment process</td>
<td>Separation factor</td>
<td>Throughput</td>
<td>Specific inventory (kg/U/SWU/year)</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>-------------------</td>
<td>------------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>Gaseous diffusion</td>
<td>1.004</td>
<td>High</td>
<td>0.1–0.3</td>
</tr>
<tr>
<td>Gas centrifuge</td>
<td>&gt;1.3</td>
<td>Low</td>
<td>–0.0005</td>
</tr>
<tr>
<td>Aerodynamic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>—Vortex tube</td>
<td>1.03</td>
<td>High</td>
<td>0.003</td>
</tr>
<tr>
<td>—Separation nozzle</td>
<td>1.015</td>
<td>High</td>
<td>0.002</td>
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<tr>
<td>Chemical exchange</td>
<td>1.0026</td>
<td>High</td>
<td>1.1</td>
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<td>Ion exchange</td>
<td>1.001</td>
<td>High</td>
<td>0.1–0.4</td>
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<tr>
<td>Laser</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>—Molecular</td>
<td>2–6</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>—Atomic vapor</td>
<td>2–6</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>Electromagnetic isotope separation (EMIS)</td>
<td>~30</td>
<td>Very low</td>
<td>N/A</td>
</tr>
</tbody>
</table>
3.1 AVLIS
(atomic vapor laser isotope separation)

In the laser system used for the LIS uranium enrichment process (right), electrons from the $^{235}$U atoms are separated (left), leaving positively charged $^{235}$U ions that can be easily collected for use.
3.1 Laser – AVLIS

Atomic Vapor Laser Isotope Separation

Diagram labels:
- Laser Beam
- Mirror
- Uranium Vapour
- Crucible
- Tails Collector
- Product Collector
- Electron Beam Gun
3.2 SILEX/Molecular Isotope Separation
Reactor Fuel Fabrication

Steps

1) Convert Enriched U235 to UO2 (pellets)
2) Encase pellets in a sheath of Zirconium Alloy (old reactors had Aluminum sheathing)
Reactor Fuel Fabrication

Steps

1) Convert Enriched U235 to UO2 (pellets)
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(a) Fuel Rod Inspection, no shielding
Burning Fuel in a Power Reactor

Pressurized Water Reactor (PWR)

- Steam generator
- Pressure vessel
- Control rods
- Reactor core
- Containment structure
- Steam
- Turbine
- Generator
- Pump
Spent Fuel Reprocessing

• Most reactors fuel burn-up limited
  – Poison build-up (e.g. Xe) slows/stops fission reaction (absorbs neutrons!!!)
• Most U235 still intact and can be re-used
• U238 in fuel absorbs neutrons and becomes Plutonium 239, also fissile
  – supports chain reaction and produces power
• Need to Recover $$$ U235 and Pu239
Spent Fuel Reprocessing

Uranium Reprocessing

Fuel Slugs

NaOH → Disassembly and Deloading

HNO₃ → Dissolver

Gases

Coating Removal Waste

Evaporator

Waste Discharge

TBP + Kerosene

HNO₃ → Fission Product Removal

HLW

Tank

Dilute HLW

Pu Precipitation and Recovery

Waste Discharge

Pu Reduction Agent

Pu Removal

U and Pu Solutions

U Solutions

UO₂ Recovery

Waste Discharge

HNO₃

U Removal

Source: U.S. Department of Energy
Figure 1: Schematic description of standard PUREX flowsheet

- Fuel input data
- Off-gas treatment
- Dissolution: Nitric Acid
  - Undissolved fuel, insoluble residues and fuel assembly hardware
- Solvent extraction: TriButyl Phosphate + Kerosene
  - Fission products and minor actinide waste
  - Uranium product
  - Plutonium product
- Nitric Acid
- Ferrous Sulphamate
Megatons to Megawatts!!!

• End of Cold War = Tens of Thousands of Nuclear Weapons Cores of HEU235 and Pu239 became SURPLUS!!!
• Surplus Cores of HEU235 and Pu239
  – HEU235 cores converted to UO2 Oxide, downblended from 94% enrichment with U238 to make ~5% U235, and then pressed into fuel pellets for LWR
  – Pu239 cores of ~94% enrichment converted to PuO2 Oxide, and them mixed with UO2
    • Result: MOX (mixed Oxide of U235~93% and Pu239~7%), pressed into ceramic pellets
    • About 30 reactors in EU use MOX
  – Concerns about proliferation (recover Pu239!)
Spent Fuel Waste Handling

• Issue: Spent Fuel Waste Radioactivity
  – Short lived fission products: Cs, Sr, La, Xe, etc.
    • Intensely radioactive, decays to half every 7 hrs
    • Decay Heat - cooling ponds before reprocessing or long terms storage; no imagination how to harvest “free heat”
  – Long lived fuel: low level radioactivity
    • Pu239 - 24,000 yrs, Natural U- millions of years

• No US national strategy what to do
Spent Fuel Waste Handling

- Currently stored in pools or dry storage at the 60+ nuclear reactor sites in the U.S.
- Generated at approximate rate of 2100 MTHM/yr
- Slated for direct disposal into Yucca Mountain geologic repository
  - Yucca Mountain is not licensed or open at this time, spent fuel inventory will exceed legislated capacity before it is opened
Summary

• Plentiful Nuclear Fuel Available for Millenia
  – Natural U for (Heavy Water or Graphite) HWR
  – U enriched to ~5% U235 for LWR
  – MOX of Pu239 and HEU235 for fast reactors

• New
  – Ultra-Safe Reactor Technology, e.g. pebble-bed reactor
  – Modular nuclear reactor for predictable cost and performance

• Politics and ignorant public
  – still fearful of nuclear power (75+% France’s Electricity=66GW, zero accidents in 56 years)
Nuclear Fuel Cycle

Q & A
Credits & References

- Slide 1 – Forbes magazine
- Slide 3 – A. Barsamian-Personal Photo Collection
- Slide 4 -ExxonMobil; Energy Outlook to 2040
- Slide 6, 26 - Garwin, RL; Nuclear Power in World’s Energy Future
- Slide 7, 8 – Glasstone & Dolan; The Effects of Nuclear Weapons
- Slide 13 – ORNL/TM2005/43-Uranium Plant Enrichment Characteristic
- Slide 14 – Wikipedia
- Slide 7, 16, 30 – NNSA/DOE
- Slide 9, 10, 15, 18, 20 – O. Heinonen-Laser and Centrifuge Enrichment
- Slide 21, 22, 23, 24 – Krass, SIPRI 83-Ch.6-Enrichment
- Slide 28, 29, 33 – Todd, T.; Spent Fuel Reprocessing; Idaho Nat Lab