Comments on ARIES-ACT Strawman

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DOE

ARIES Project Meeting
Bethesda, MD

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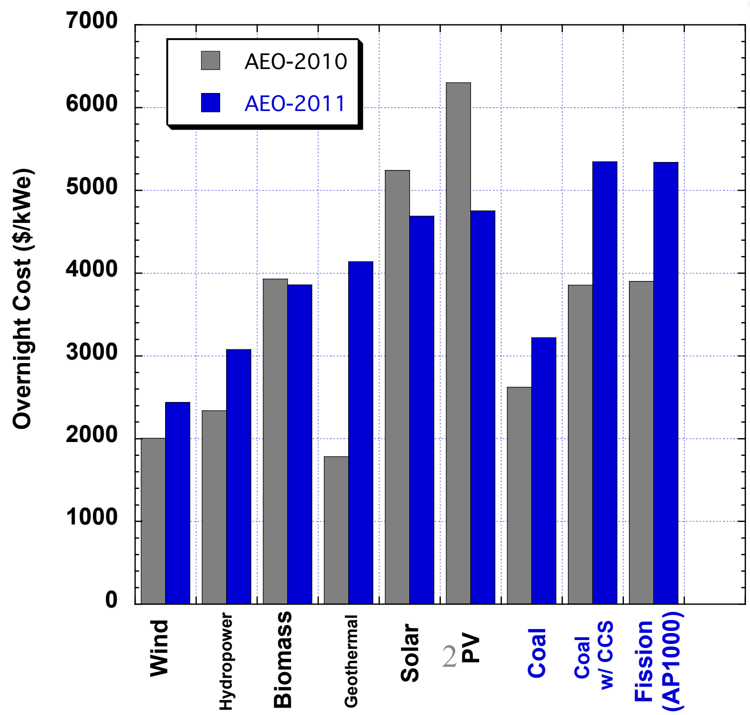
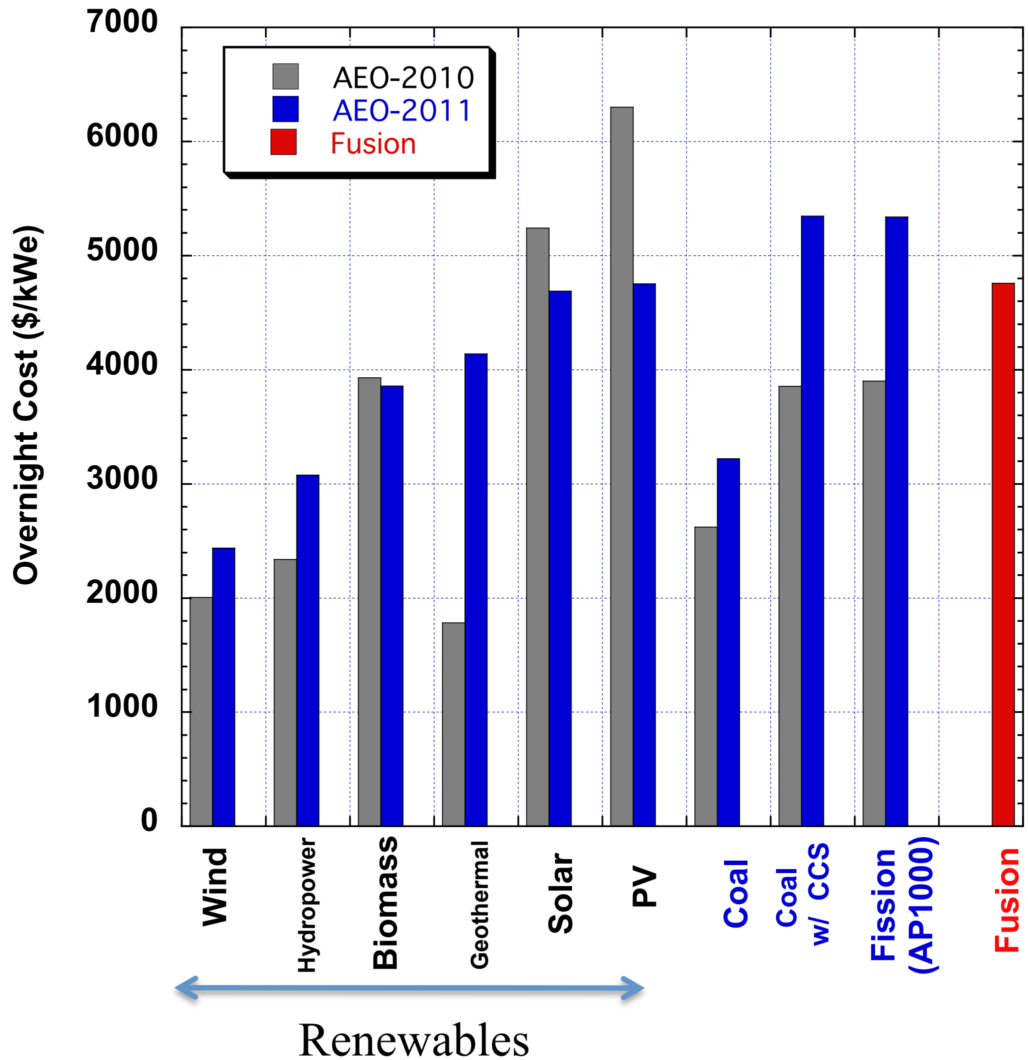
11/2010 DOE Annual Energy Outlook for 2011

- http//:www.eia.gov/oiaf/beck_plantcosts/pdf/updatedplantcosts.pdf
- Report provides critical input into development of energy projections and analyses.
- It outlines current (2010) and projected (2011) **Overnight Cost** for fission, coal, natural gas, and renewables
- For nuclear and coal, projected cost increased by 37% due to:
  - Higher global commodity prices
  - Rising costs of capital intensive technology
  - Scarcity of construction firms experienced in complex engineering projects.

Do these attributes apply to fusion?



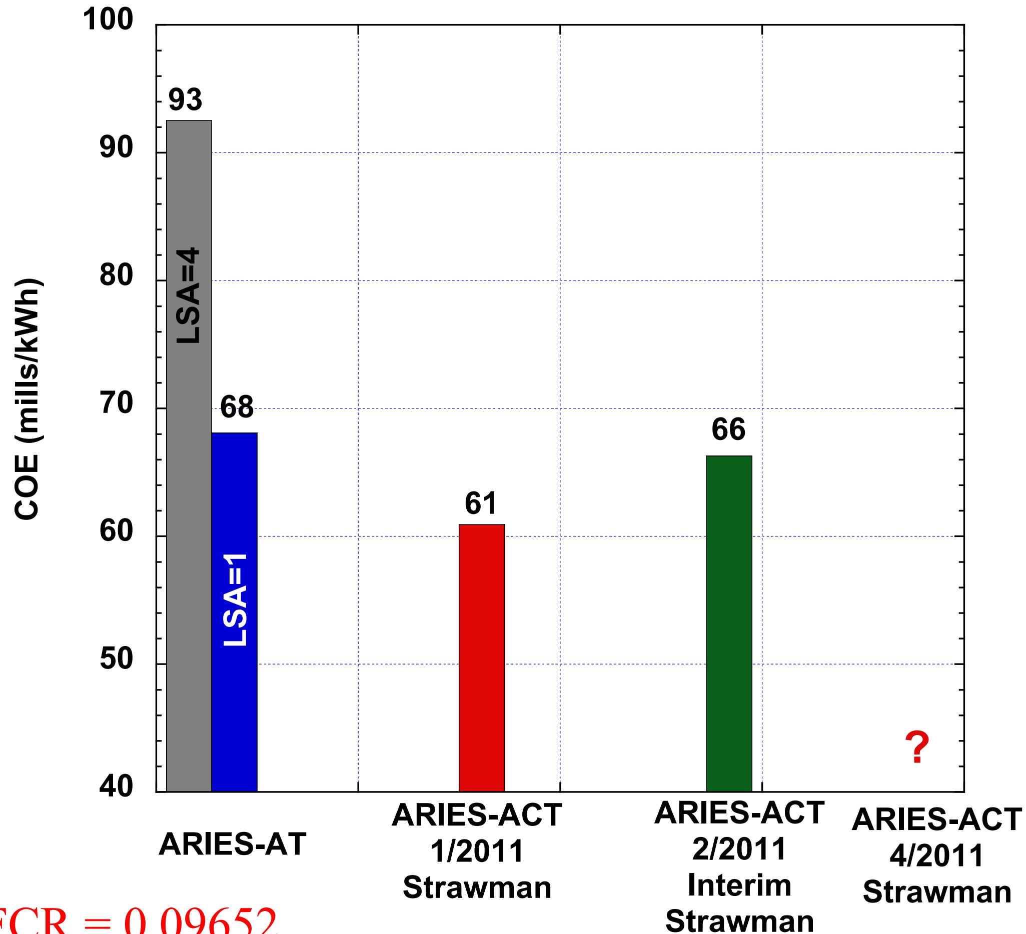
ARIES-ACT vs. Other Sources of Energy



Fusion cheaper than fission ?!

ARIES-ACT
2/2011 Strawman
COE = 66 mills/kWh

Cost of Electricity (in 2009 $)

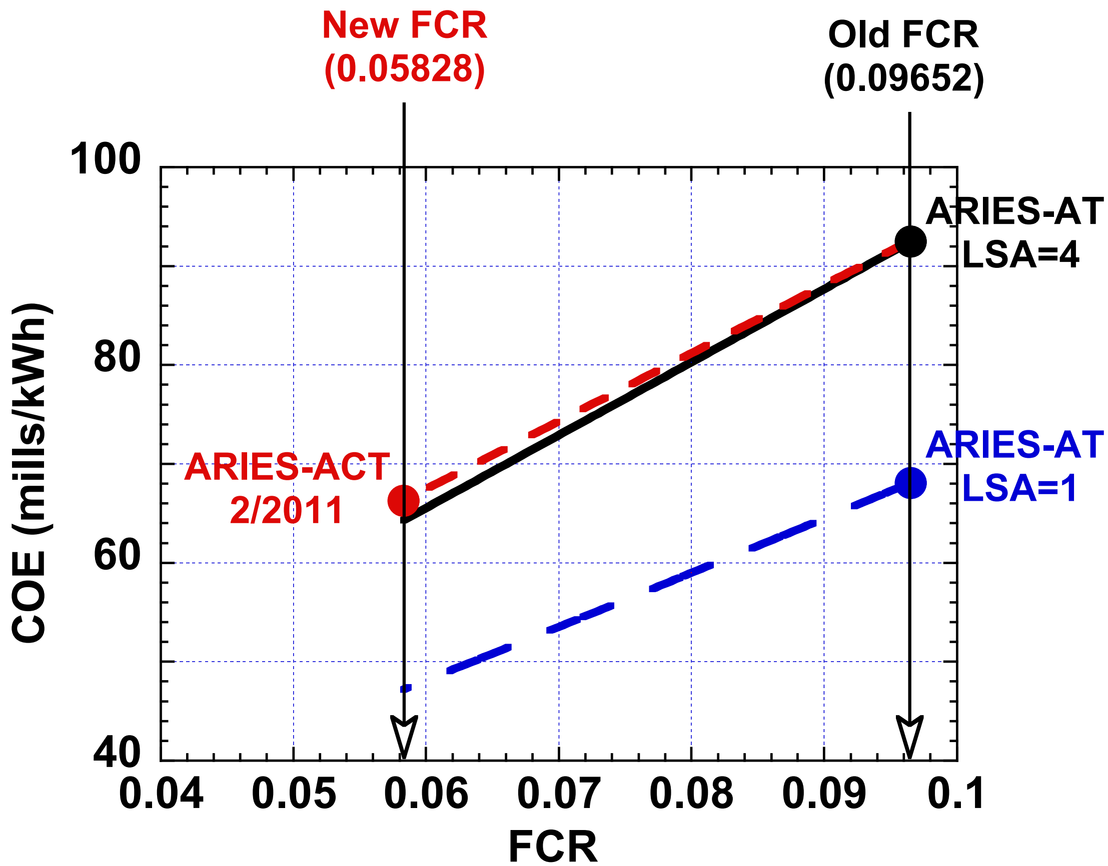


FCR = 0.09652

FCR = 0.05828

FCR is Fixed Charge Rate.

Impact of FCR on COE



For same FCR of 0.05828, 2/2011 ARIES-ACT:

- Is more expensive than ARIES-AT with LSA=1
- Has comparable COE to ARIES-AT with LSA=4.

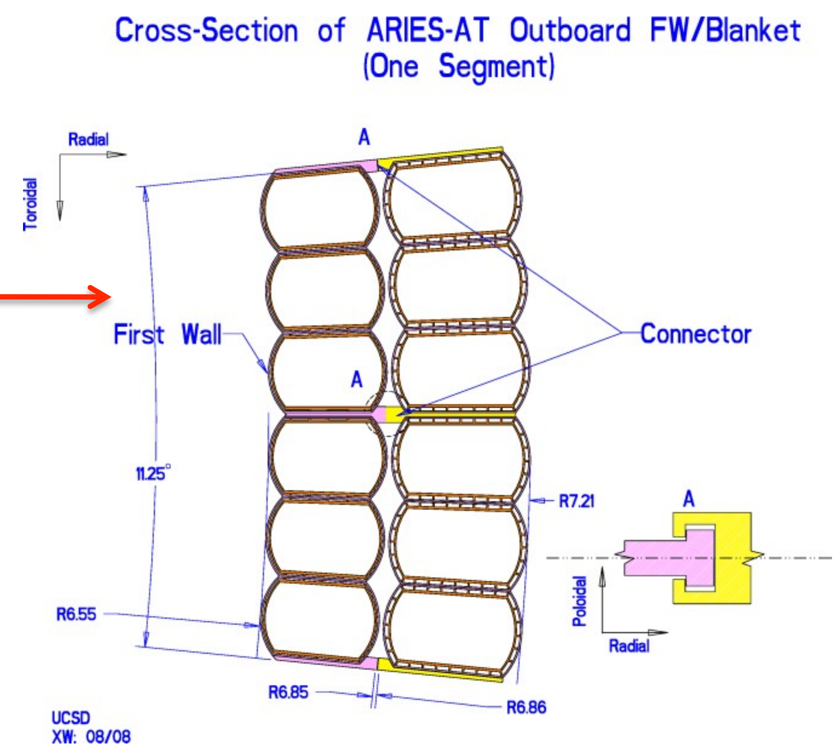
“Place Holders” for ARIES-ACT Strawman

(to be updated as design evolves)

- Radial build:
  - ARIES-AT SiC/LiPb FW and blanket design
  - No thermal shield for TF magnets
  - 18 MWy/m2 EOL fluence for replaceable components
  - 40 FPY lifetime of permanent components.
- Neutron power distribution: 65% to OB, 25% to IB, 10% to divertor
- 20/80 power split for He loop of divertor and LiPb loop of FW/blanket/shield
- 65 MW P_{aux} (need nuclear heat load to LHe thermal shield and TF magnets)
- 2 mills/kWh for D&D cost (need new algorithm for Class A and Class C LLW)
- Cost of startup, stability control, and plasma fueling systems
- Economic life = 40 y; Design lifetime = 47 y; Consider 50 or 60 y life?
- Peak / average NWL = 1.5
- Material unit costs:
  - LiPb with 90% enriched Li and < 50 wppm Bi impurity.
  - Multiplier for nuclear-grade materials (currently 1, meaning industrial/commercial materials)
  - Multiplier for safety-related components (currently 1, meaning no safety-related components).

SiC/LiPb FW and Blanket Design

- Any changes to ARIES-AT FW/blanket design?
- Can FW handle:
  - Peak NWL of 4.7 MW/m^2 ?
  - Disruption
  - High heat flux during transients?

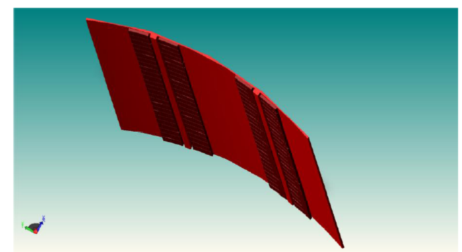


Structure: SiC/SiC Composites

Coolant / Breeder: LiPb

LHe Thermal Shield for ARIES-ACT

- Magnet designers recommend thermal shield between VV (operating @ 200^{o}C) and TF magnets (operating @ 4 K).
- Per Kessel:
  - 4 K magnet cannot face 200^{o}C components
  - 4 K cryogenic LHe cryoplant is <u>never capable</u> of handling such high heat loads
  - It takes so much energy (300 W/W) and coolant capacity to reject high heat at 4 K
  - Rejecting heat at 70-100 K is cheaper and takes less energy (10 W/W).
- ITER LHe thermal shield (ITER Newsline – 2/7/2011 - #163):
  - <u>2 cm thick</u> stainless steel panels coated with low-emissivity silver
  - <u>LHe cooling pipes</u> welded to panels
  - <u>Operates within 80-100 K</u> during plasma operation
  - Korea completed full-scale <u>mock-up of 10° inboard</u> section and tested main procedures of fabrication including cutting, bending, forming, buffing, welding, and machining
  - Korea plans to make another mock-up for <u>outboard</u> 10° section, which will be assembled with inboard section.



- Will include ITER's 2 cm thick LHe thermal shield in ARIES-ACT radial build.

LiPb Cost

- Per Waganer, 90% enriched LiPb could cost ~$9/kg based on:
  - Current cost of 99.97% pure Pb with 300 wppm Bi ($3/kg)
  - Predicted cost for 90% enriched Li of $1000/kg
  - LiPb material cost = Pb unit cost x LiPb mass x Pd-wt%
    + Li unit cost x LiPb mass x Li-wt%.

- Q: Besides Pb and Li material costs, what are associated costs for:
  - Mixing tons of Li an Pb to make `6300 tons of $Li_{15.7}Pb_{84.3}$ eutectic?
  - Control Bi impurity below 50 wppm?
  - Purification system to remove byproducts?

- Waganer's suggestions:
  - MHTT Account should reflect additional cost for:
    - Mixing Li and Pb to make $Li_{15.7}Pb_{84.3}$ eutectic
    - Online purification system to remove:
      - Pb byproducts (Bi, Po, Hg radioisotopes)
      - Corrosion products (Fe, Ni, Cr radioisotopes)
  - Fuel Handling and Storage Account should include cost of:
    - T separation
    - Replenishment of Li.

- Incremental cost increase to MHTT Account? (currently ~$200M – low compared to > $450M in ARIES-ST and CS)

- Need industrial quote for tons of 30-90% enriched Li and LiPb.

Li and Pb Mixing Process Should Avoid High Melting Phases

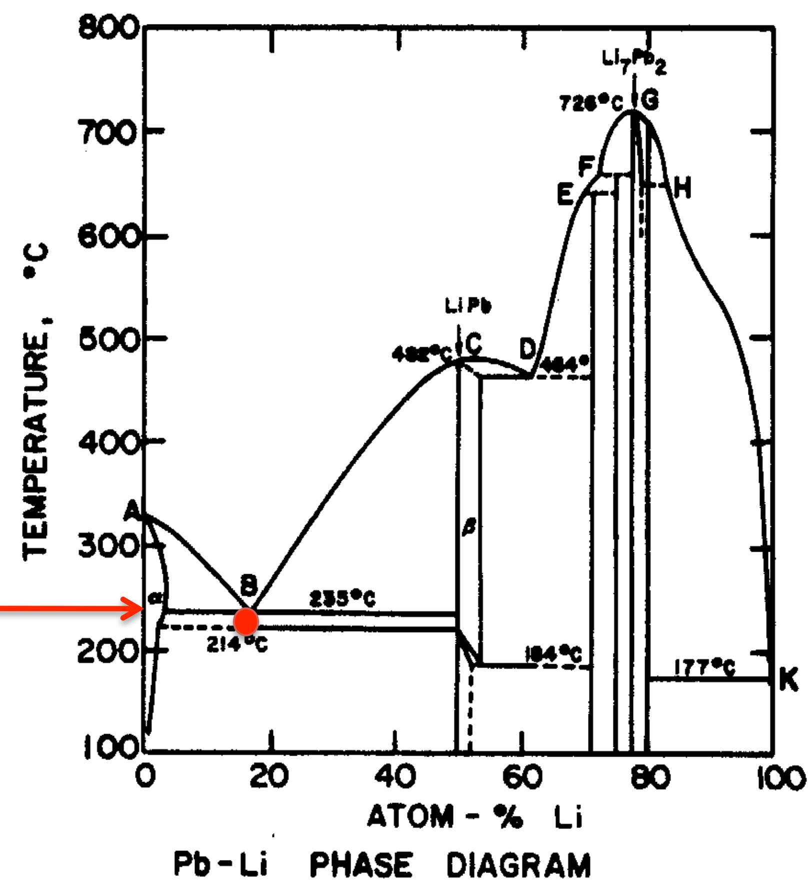
Concerns:
- Non-uniform mix
- Formation of hard melting phases (with $T_m > 235^oC$)

~ 6270 ton Pb
($11.3\ g/cm^3$)

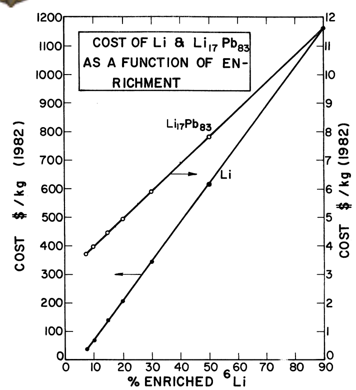
~ 40 ton Li
($0.53\ g/cm^3$)

ARIES-ACT Volumes
(2/2011)

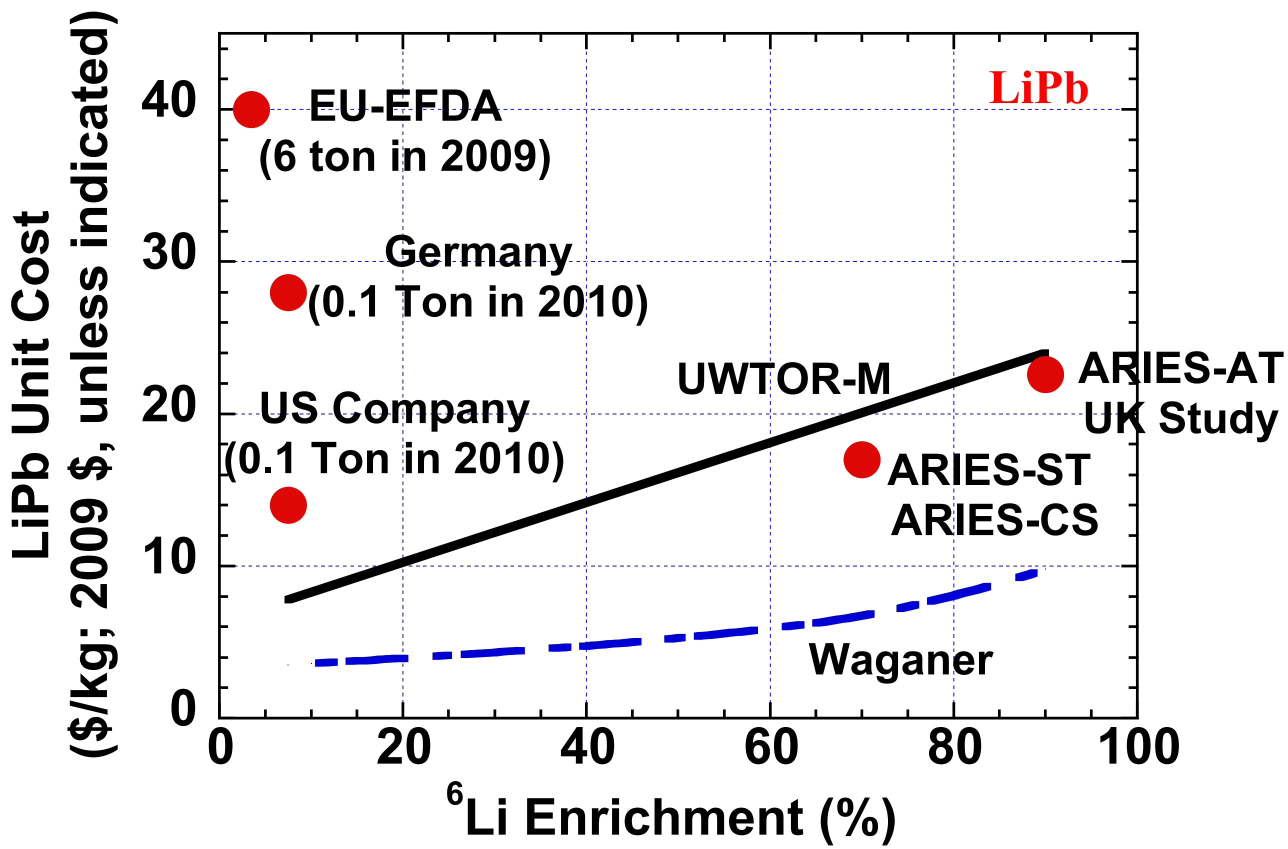
235°C - melting point of
$Li_{15.7}Pb_{84.7}$ eutectic
(formerly known as $Li_{17}Pb_{83}$)



LiPb Unit Cost

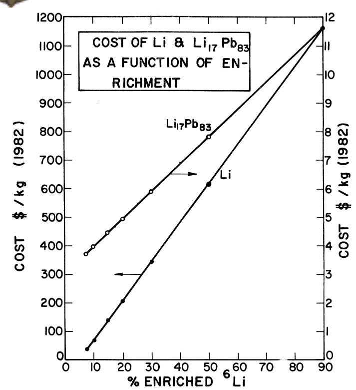


Original
1982 UWTOR-M Cost Estimate
Based on COLEX Enrichment
Process (by ORNL)



American and German companies sell LiPb at much higher prices than predicted by UWTOR-M and Waganer

Cost of Li Enrichment



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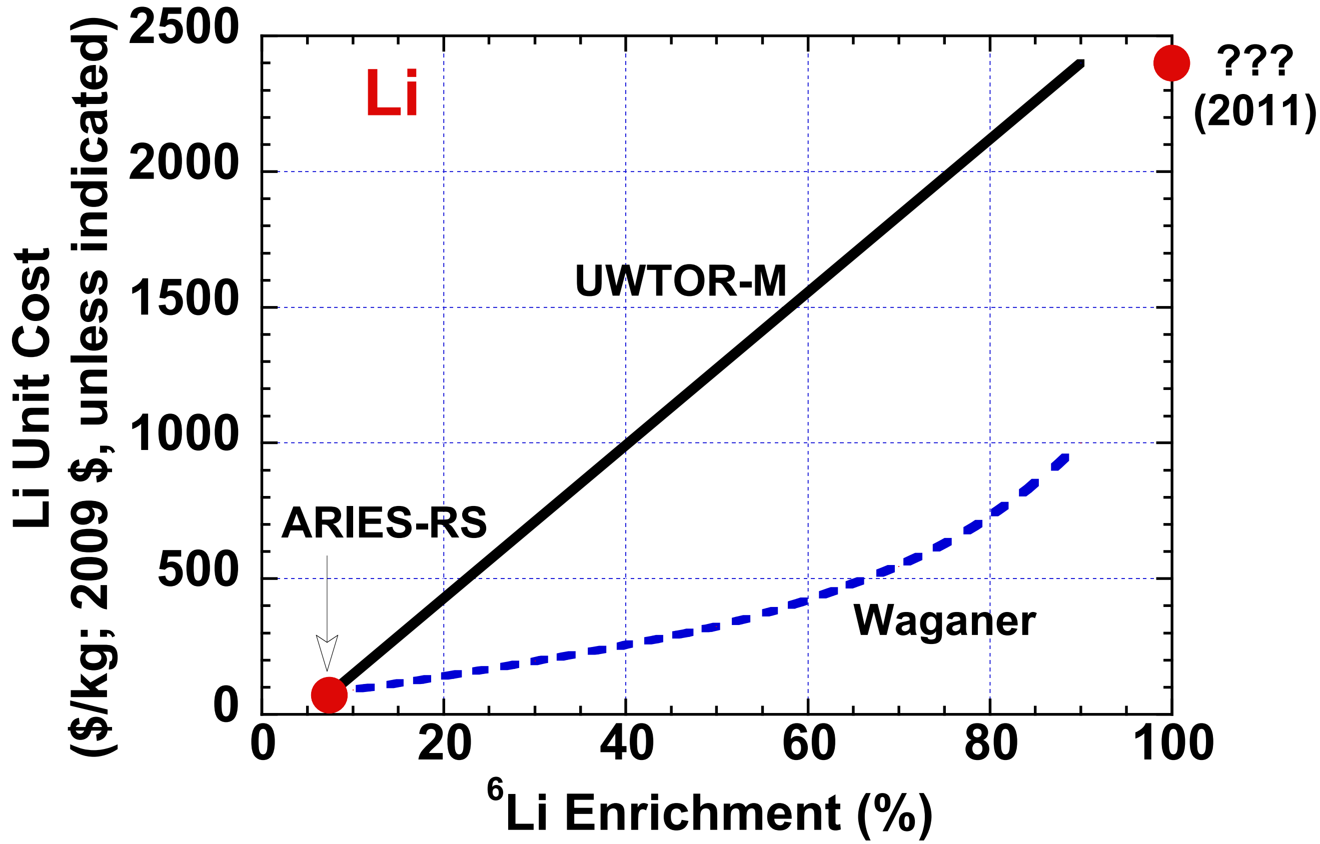
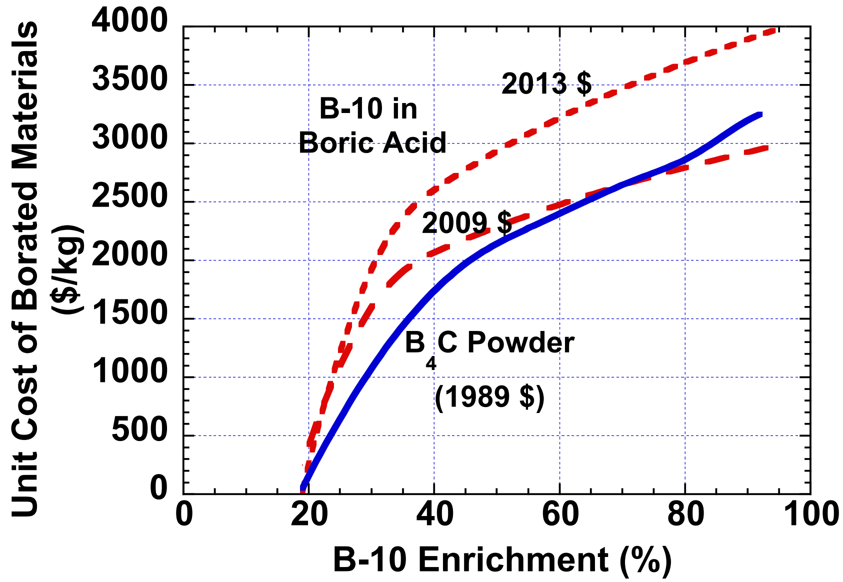


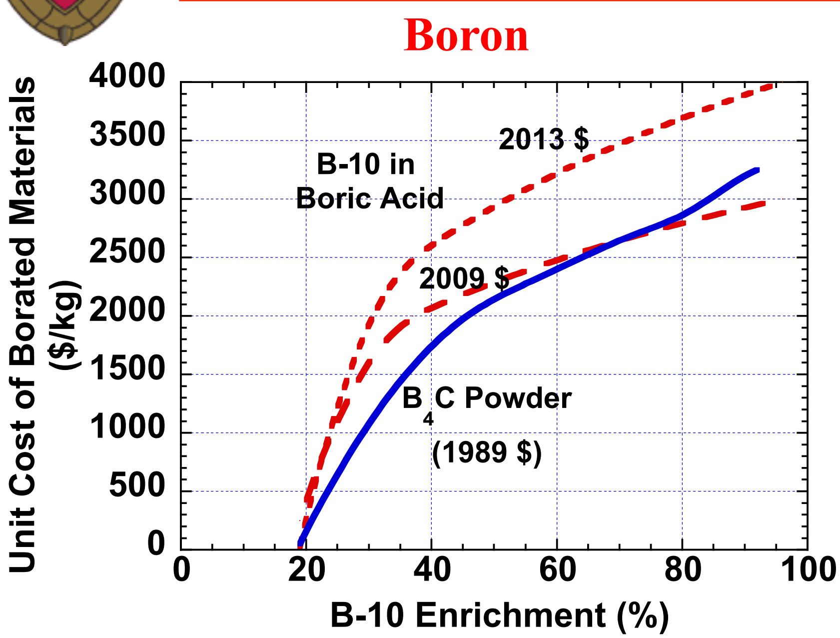
Shape of curve? Straight as in UWTOR-M?
Convex as proposed by Waganer? Or Concave?

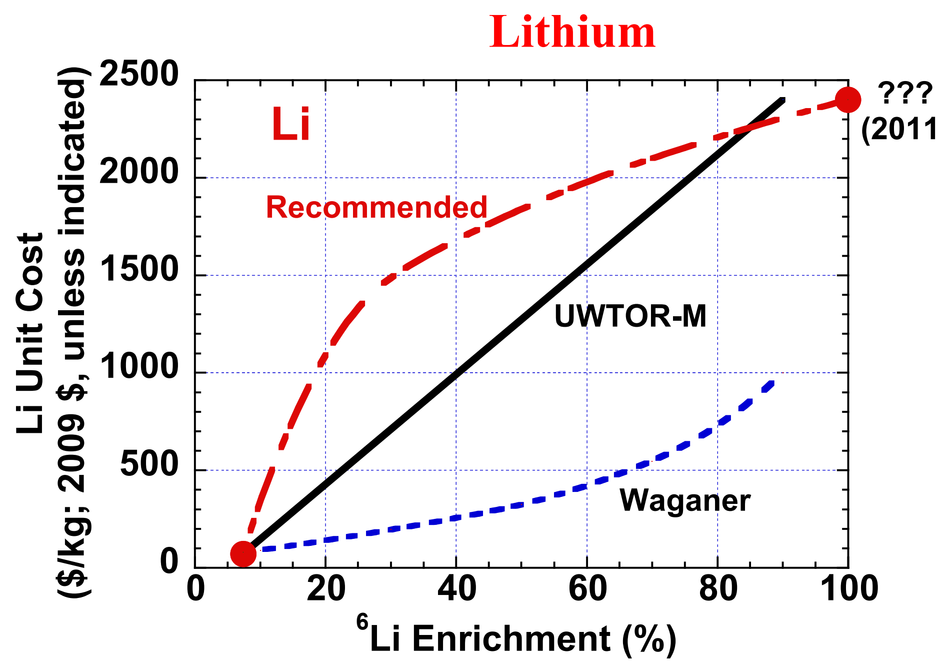
Boron Enrichment Provides Guidance



- Ceradyne, Inc. (formerly Eagle Picher): US company for B enrichment
- **Concave** enrichment curve (not straight nor convex) .
- Large cost for **any** enrichment.
- Pricing based on volumes > 1 Ton. Much larger quantity has slightly lower unit cost (< 10%).
- 30% price increase over 4 years (not just proportional to inflation rate).

Recommended Li Enrichment Cost





- Concave (not convex) enrichment curve for Li.
- LiPb unit cost will be estimated accordingly.

Nuclear-Grade Components

(12/2009 ARIES Presentation by El-Guebaly)

- Besides **technical side** for any material (functions, complex/simple shape, etc.), **administrative side** (inspections, qualified suppliers, material certifications, etc.) **cost more in nuclear industry** because of added quality assurance, documentation, and controlled manufacturing processes that are different from commercial industry type of activities.
- Nuclear standards costs 2-10 times commercial standards due to QA, lots of inspections, records, and field work:
  - Complete traceability of items from raw material to finished product (paper work can cost more than item!):
    - » **Material** constituents must meet ASME specs and impurity level, with documentation
    - » **Designers** should follow Section III rigorous design rules, use FEA, and analyze it exhaustively, with documentation
    - » Plans drawn for **fabricators,** with documentation
    - » Fabricator has "hold points" to allow inspection, with documentation
    - » Welding must be performed by **Certified Nuclear Welders**, inspected, radiographed, and documented
    - » After assembly, the vessel is pressure tested to ~125% pressure, test is witnessed by **Certified Inspector**, and documented
    - » If all documentations, inspection, and pressure test results are satisfactory, component receives N-stamp status and is documented.
    - » Documentation is kept on file for the life of the vessel
  - Extensive quality assurance standards (big cost item)
  - Stringent testing requirements.
- Suggest applying nuclear-grade to structural elements (not fillers):
  - SiC/SiC composites of FW, blanket, shield, and divertor
  - W alloys of FW and divertor
  - FS structure of FW, blanket, shield, and divertor
  - Pipes carrying radioactive He and LiPb coolants.

Safety-Related Components
(12/2009 ARIES Presentation by El-Guebaly)

Besides basic function, these N-stamp components implement safety function, such as:

- Confine radioactivity
- Limit public/workers exposure to radiation.

ARIES safety-related components:

- **Vacuum vessel, maintenance ports, penetrations for plasma heating/control, and pumping ports** (1st confinement barrier for radioactivity and ultimate heat sink for removing decay heat)
- Pipes penetrating VV, unless isolation valves separate VV from externals
  - LiPb system (pipes penetrate VV and contains highly radioactive LiPb)
- **Cleanup/isolation/monitoring systems**:
  - Isolation valves for He
  - Rupture disks (to guarantee pressure remains below limit)
  - Monitors for loss of coolants
  - Monitors for Po-210 detection
  - Monitors in detritiation system building (e.g., T monitors that send signal to building HVAC system to isolate building if T air concentration becomes too high and T cleanup system shifts into high efficiency mode to remove T)
- **Confinement building** (2nd confinement barrier for radioactivity).

NOT Safety-related systems:

- All in-vessel components: FW, blanket, divertor, shield, manifolds (not required for confinement of radioactivity; not needed to ensure public or plant safety)
- Helium system (providing that isolation valves placed on helium lines at VV and He contains small amounts of T).

Open safety-related question: Could failure of FW/blanket/shield endanger the VV (safety-related component) that in turn endangers workers/public?

Economic Impact

Recommendations:

- Nuclear-grade materials:
  - Increase unit cost of structural elements by factor of 1.5 (10th-of-a-kind):
    - SiC/SiC composites of FW, blanket, and shield, and divertor
    - W alloys of FW and divertor
    - FS structure of FW, blanket, shield, and divertor
    - Pipes carrying radioactive He and LiPb coolants (in MHTT Account).

- Safety-related components:
  - Increase unit cost of structural elements by factor of 2 (10th-of-a-kind):
    - Vacuum vessel
    - Maintenance port enclosures
    - Pumping port enclosures
    - Penetration enclosures (for plasma heating/control).