What Fusion Wanted To Be

A systems engineering perspective of a thorium energy economy

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Dr. Joseph Bonometti

Aerospace, defense and power technology development manager

Outline

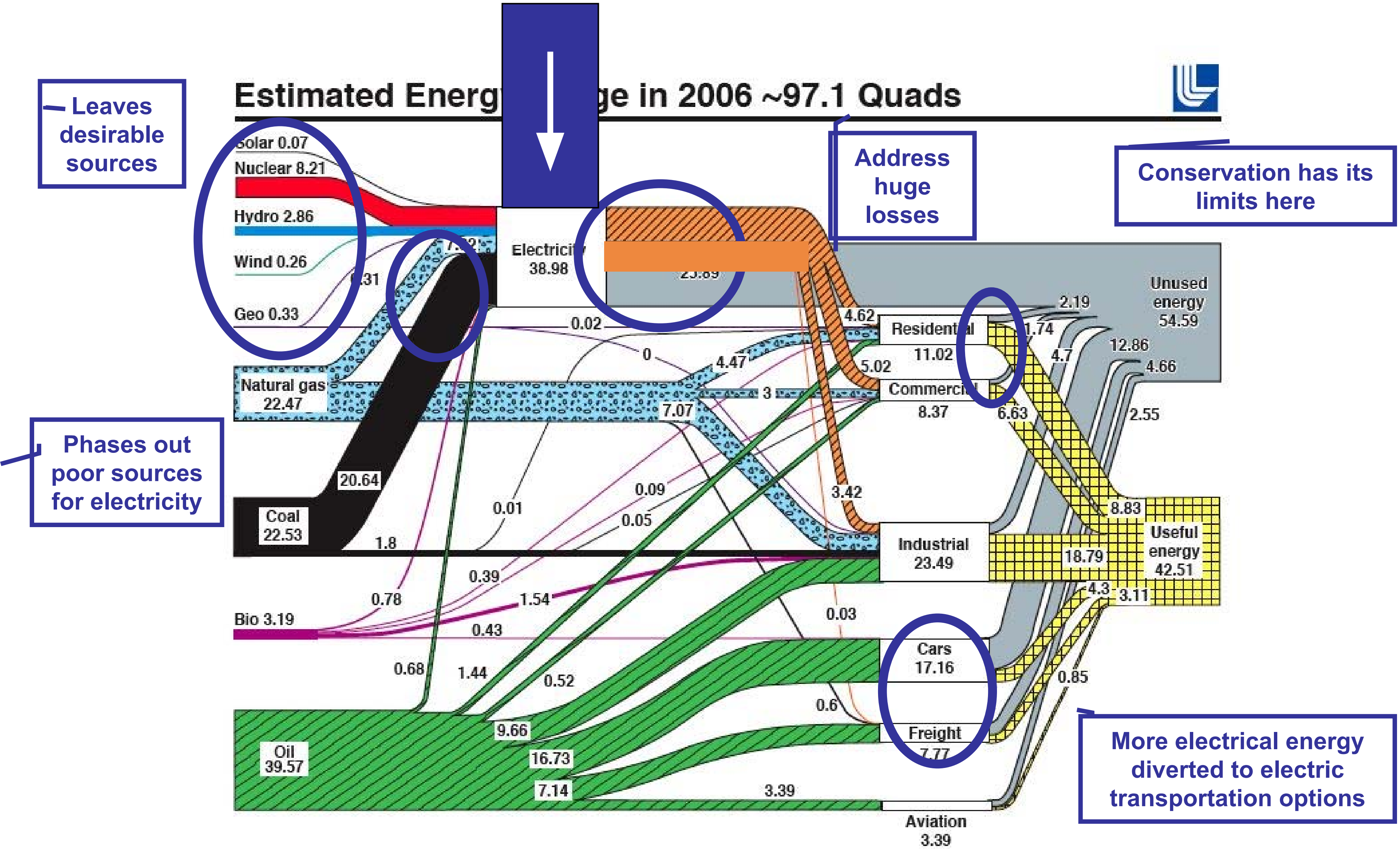
1. Highlights of pervious talk:
    - Illustrate where the largest global problem actually resides
    - Highlight Systems Engineering ideas important to global energy in light of
        - What fusion wanted to be!
3. Make Systems Engineering case for LFTR as the best method to exploit thorium and rapidly meet the energy crisis
4. Present a preliminary look at a LFTR Work Breakdown Structure

Assumptions

1. Basic background of thorium
2. Idea of LFTR
3. Limited Systems Engineering knowledge
4. Still need some convincing that thorium is “right” answer

Energy consumption directly correlates to standard of living and for good reason…

Where largest global problem actually resides…



Leaves desirable sources

Phases out poor sources for electricity

Address huge losses

Conservation has its limits here

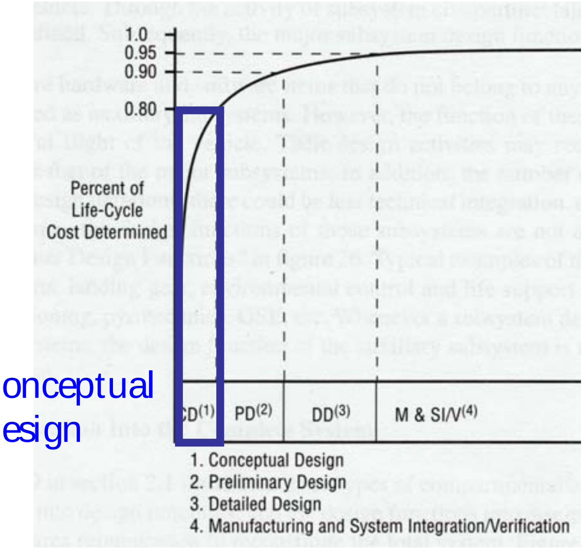
More electrical energy diverted to electric transportation options

Source: LLNL 2008; data is based on DOE/EIA-0384(2006), June 2007. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include small amounts of electricity imports or self-generation. Energy flows for non-thermal sources (i.e., hydro, wind, and solar) represent electricity generated from those sources. Electricity generation, transmission, and distribution losses include fuel and thermal energy inputs for electric generation and an estimated 9% transmission and distribution loss, as well as electricity consumed at power plants. Total lost energy includes these losses as well as losses based on estimates of end-use efficiency, including 80% efficiency for residential, commercial, and industrial sectors, 20% efficiency for light-duty vehicles, and 25% efficiency for aircraft. LLNL-MI-402223

Conceptual Design Stage

It is estimated that at ~ 80 percent of a project's life-cycle cost is locked in by the initial concept that is chosen.

In a similar manner, all benefits are locked in…



Conceptual Design

The conceptual design sets the theoretical limits.

⇩

The conceptual design has the least real-world losses quantified.

⇩

Therefore, there MUST be significant inherent advantages to avoid erosion of all the benefits.

"One can not figure to add margin and be assured an advantage over the existing concept, if there is no inherent, and thus <u>untouchable, growth factor</u>."

Conceptual Design Selection Criteria:

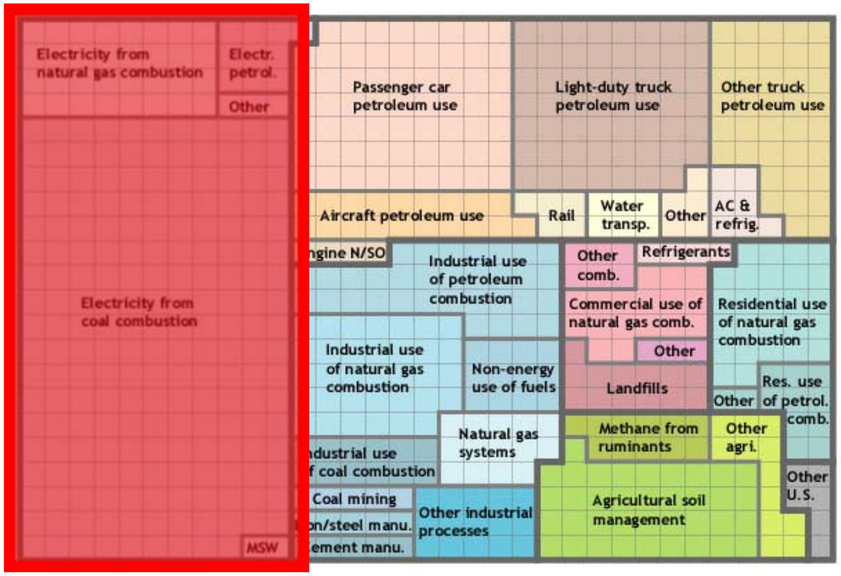
Conventional Nuclear Technology

Pros

- High power-density source
- Availability of massive amounts of energy
- No green house emissions
- Minimal transportation costs
- Low $/kW baseload supply

Cons

- Safety fears
- High capital costs
- Proliferation & terrorist target
- Long term waste disposal
- Uranium sustainability
- Unsightly, bad reputation



~1/3 of CO2 comes from electricity production

Inherently nuclear power produces essentially no CO2

Power Density & Efficiency

Why is it important?

- Land usage
  - cost of the land (lost opportunity for its use)
  - loss of natural environment
- Flexibility in relocation
  - minimal infrastructure expense
  - lower transportation cost
  - recoup investment should site be closed
- Environment independent
  - weather, temperature, under/over/no water, even seismic effects are easily minimize
  - lower cooling requirements (air or water)
- Manufacturing costs
  - multiple unit production
  - reduced material costs
  - effective human-size operations
- Maintenance costs
  - less manpower intensive
  - minimal parts and size

"Smaller":
It is not just for convenience,
but essential to reducing costs

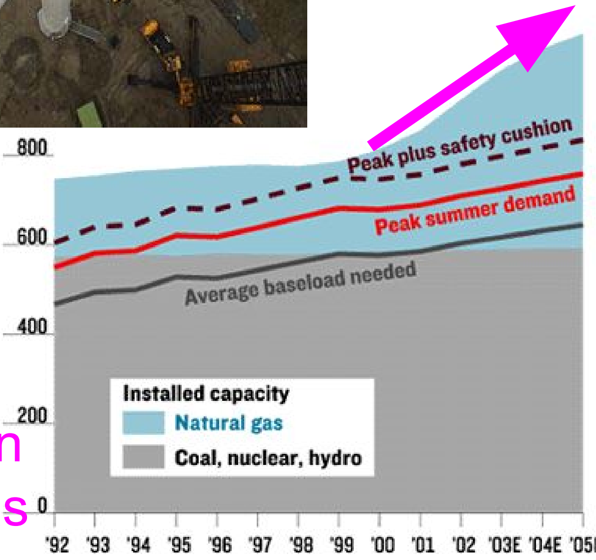
Power Generation Resource Inputs

- Nuclear: 1970’s vintage PWR, 90% capacity factor, 60 year life [1]
  - 40 MT steel / MW(average)
  - 190 m3 concrete / MW(average)
- Wind: 1990’s vintage, 6.4 m/s average wind speed, 25% capacity factor, 15 year life [2]
  - 460 MT steel / MW (average)
  - 870 m3 concrete / MW(average)
- Coal: 78% capacity factor, 30 year life [2]
  - 98 MT steel / MW(average)
  - 160 m3 concrete / MW(average)
- Natural Gas Combined Cycle: 75% capacity factor, 30 year life [3]
  - 3.3 MT steel / MW(average)
  - 27 m3 concrete / MW(average)

Distance from end user, prime real estate, energy intensity, etc…

Cost of:

- **materials**
- **labor**
- **land**
- **tools**
- **etc…**



Recent increase in natural gas plants

Sources: North American Electric Reliability Council; Department of Energy Information Administration.

What is LFTR?

Liquid Fluoride Thorium Reactor or **LFTR** (pronounced “Lifter”) is a specific fission energy technology based on thorium rather than uranium as the energy source. The nuclear reactor core is in a liquid form and has a completely passive safety system (i.e., no control rods). Major advantages include: significant reduction of nuclear waste (producing no transuranics and ~100% fuel burnup), inherent safety, weapon proliferation resistant, and high power cycle efficiency.

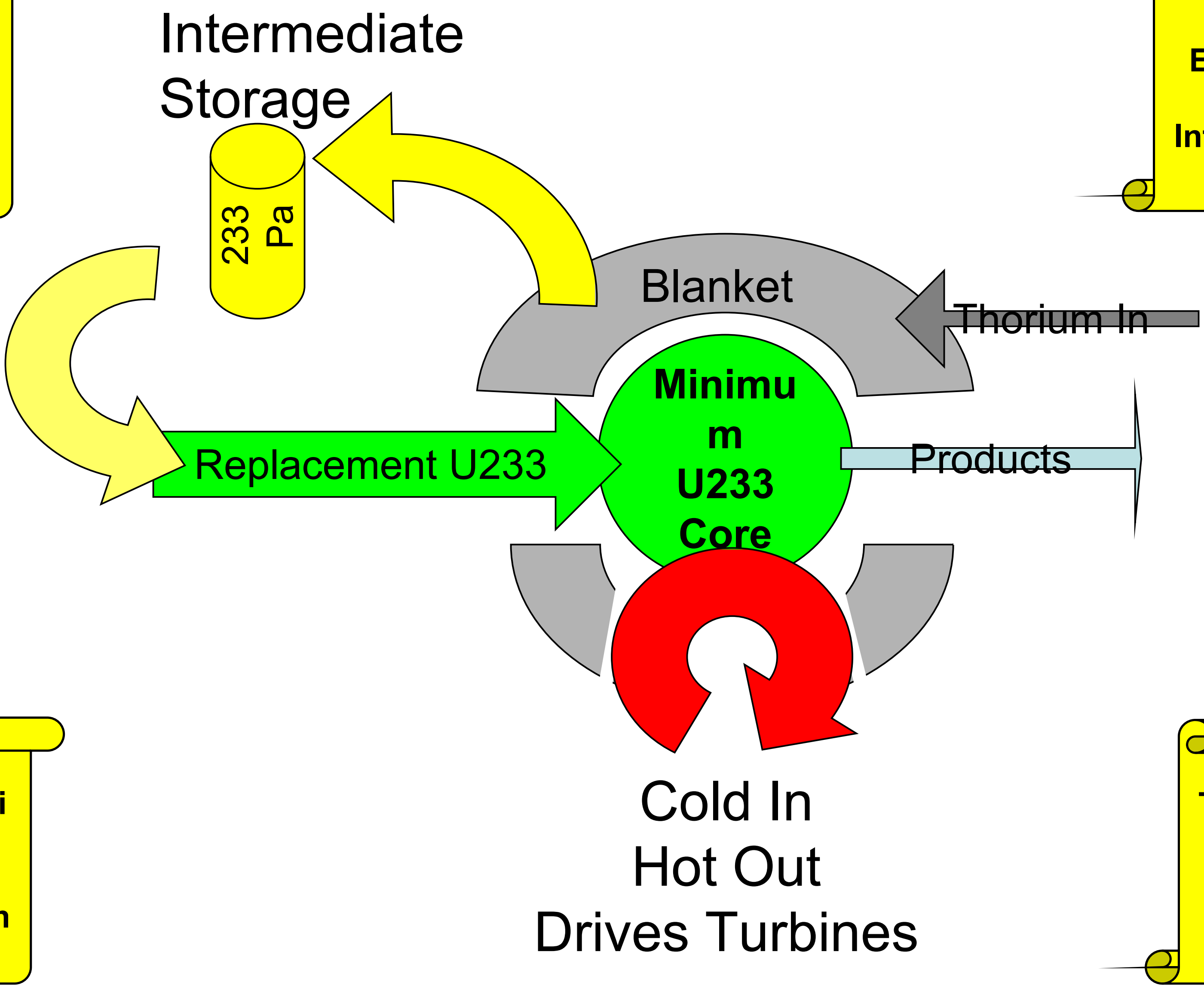
- The best way to use thorium.
- A compact electrical power source.
- Safe and environmentally compatible energy.
- A new era in nuclear power.

What fusion promises someday…

Fundamental Process & Objectives

Safety & Compact/ Mobile

Cost Effective & Grid Interfacing



Intermediate Storage

233 Pa

Blanket

Thorium In

Minimum U233 Core

Replacement U233

Products

Cold In
Hot Out
Drives Turbines

Proliferation & Waste Reduction

Timeliness & Covers Energy Gap

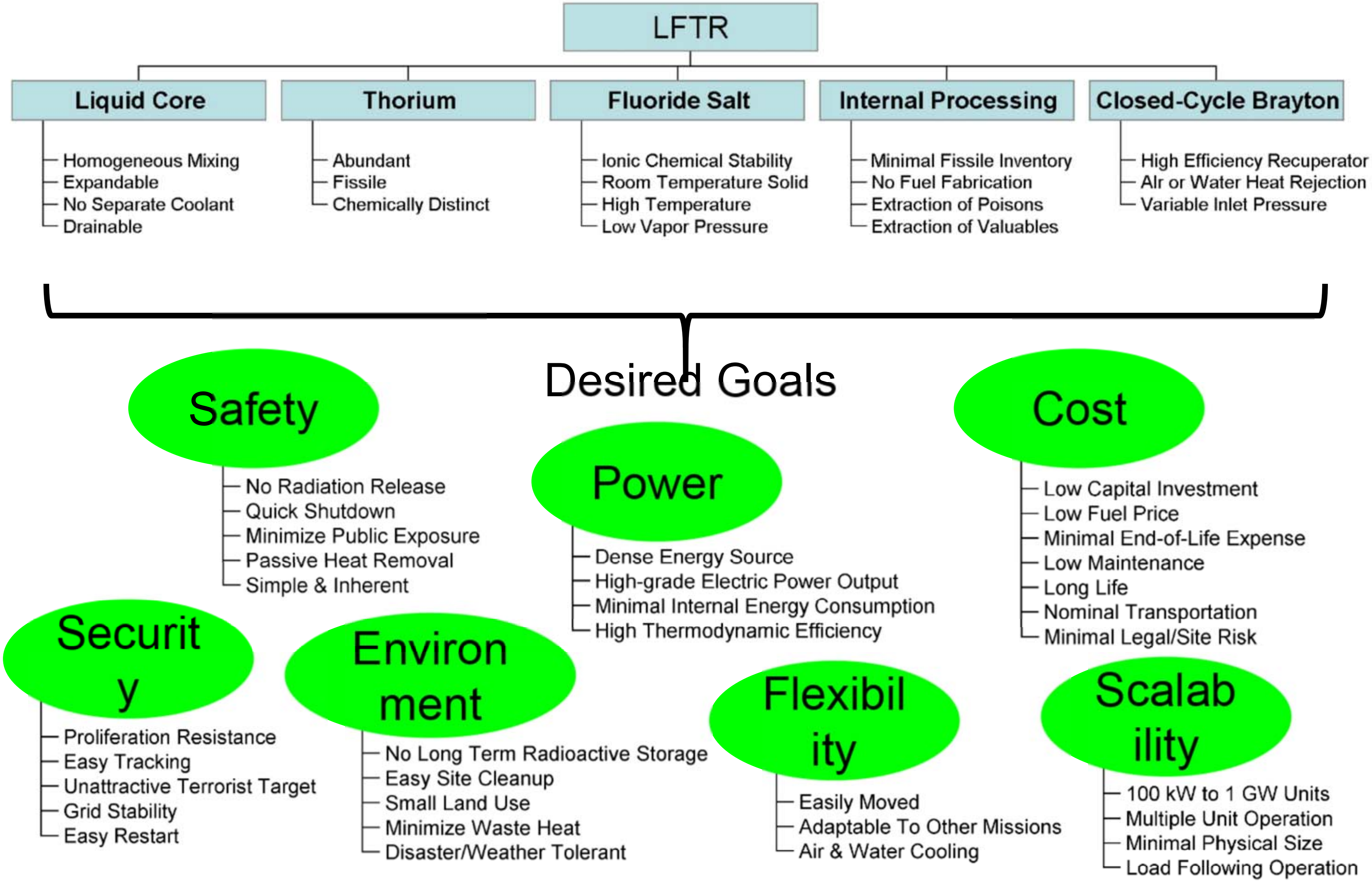
Technical Details

- **Liquid Fluoride Thorium Reactor** …
  - A type of nuclear reactor where the nuclear fuel is in a liquid state, suspended in a molten fluoride-based salt, and uses a separate fluid stream for the conversion of thorium to fissionable fuel to maintain the nuclear reaction.

- It is normally characterized by:
  - Operation at atmospheric pressure
  - High operating temperatures (>>600K)
  - Chemical extraction of protactinium-233 and reintroduction of its decay chain product, uranium-233
  - Thermal spectrum run marginally above breakeven
  - Closed-Cycle Brayton power conversion

"It is the melding of the nuclear power and nuclear processing industries; surprisingly, something that does not occur naturally."

LFTR Inherent Advantages



- LFTR
  - **Liquid Core**
    - Homogeneous Mixing
    - Expandable
    - No Separate Coolant
    - Drainable
  - **Thorium**
    - Abundant
    - Fissile
    - Chemically Distinct
  - **Fluoride Salt**
    - Ionic Chemical Stability
    - Room Temperature Solid
    - High Temperature
    - Low Vapor Pressure
  - **Internal Processing**
    - Minimal Fissile Inventory
    - No Fuel Fabrication
    - Extraction of Poisons
    - Extraction of Valuables
  - **Closed-Cycle Brayton**
    - High Efficiency Recuperator
    - Air or Water Heat Rejection
    - Variable Inlet Pressure

Desired Goals

- Safety
  - No Radiation Release
  - Quick Shutdown
  - Minimize Public Exposure
  - Passive Heat Removal
  - Simple & Inherent
- Power
  - Dense Energy Source
  - High-grade Electric Power Output
  - Minimal Internal Energy Consumption
  - High Thermodynamic Efficiency
- Cost
  - Low Capital Investment
  - Low Fuel Price
  - Minimal End-of-Life Expense
  - Low Maintenance
  - Long Life
  - Nominal Transportation
  - Minimal Legal/Site Risk
- Securit y
  - Proliferation Resistance
  - Easy Tracking
  - Unattractive Terrorist Target
  - Grid Stability
  - Easy Restart
- Environ ment
  - No Long Term Radioactive Storage
  - Easy Site Cleanup
  - Small Land Use
  - Minimize Waste Heat
  - Disaster/Weather Tolerant
- Flexibil ity
  - Easily Moved
  - Adaptable To Other Missions
  - Air & Water Cooling
- Scalab ility
  - 100 kW to 1 GW Units
  - Multiple Unit Operation
  - Minimal Physical Size
  - Load Following Operation

LFTR Work Breakdown Structure

WBS Primer

- System Engineering Tool
  - Usually one of the first tasks completed
  - Define the project parts, i.e., ‘products’
  - Important that it identifies products:
    - Largest or costly
    - Most complex
    - Critical to investigate (known or unknown)
- First place to layout the interrelationships of pieces that make up the system
- Sets the tone on how the System Engineer wants to “orchestrate” the game plan
- Used by Program management, budget, contract and business office personnel as a convenient shopping list to track work, designate funding, allocate resources, etc…

Draft LFTR WBS

Level 1:

- LFTR Prototype Development Reactor
  - Non-production
  - Full-scale mobile unit class
  - Not optimized for efficiency or minimum volume

Level 2 and beyond are engineering driven

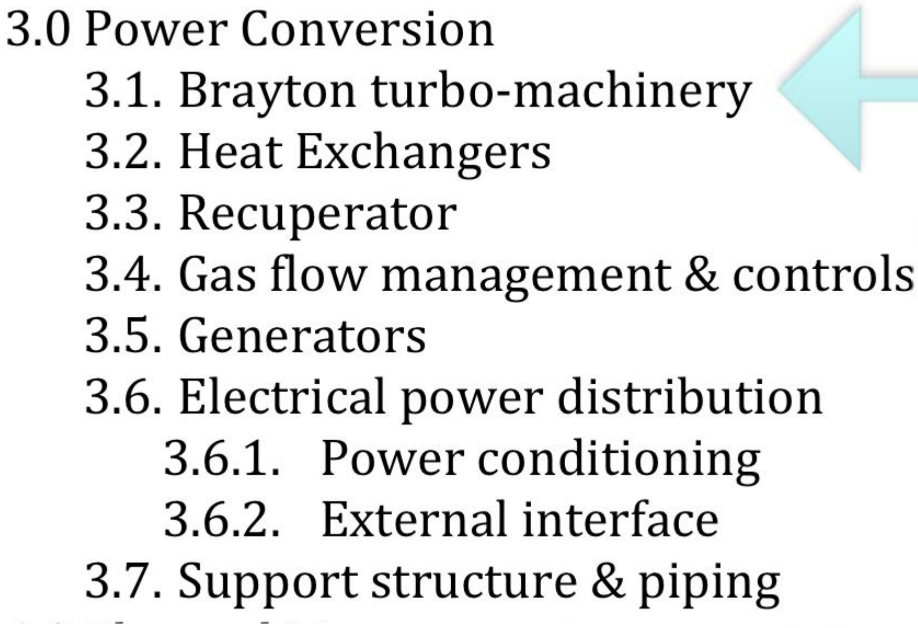
LFTR WBS

- 2.0 Systems Engineering
- 3.0Reactor
- 4.0Power Conversion
- 5.0Thermal Management
- 6.0Chemical Process Engineering
- 7.0Proliferation Security
- 8.0Project Management

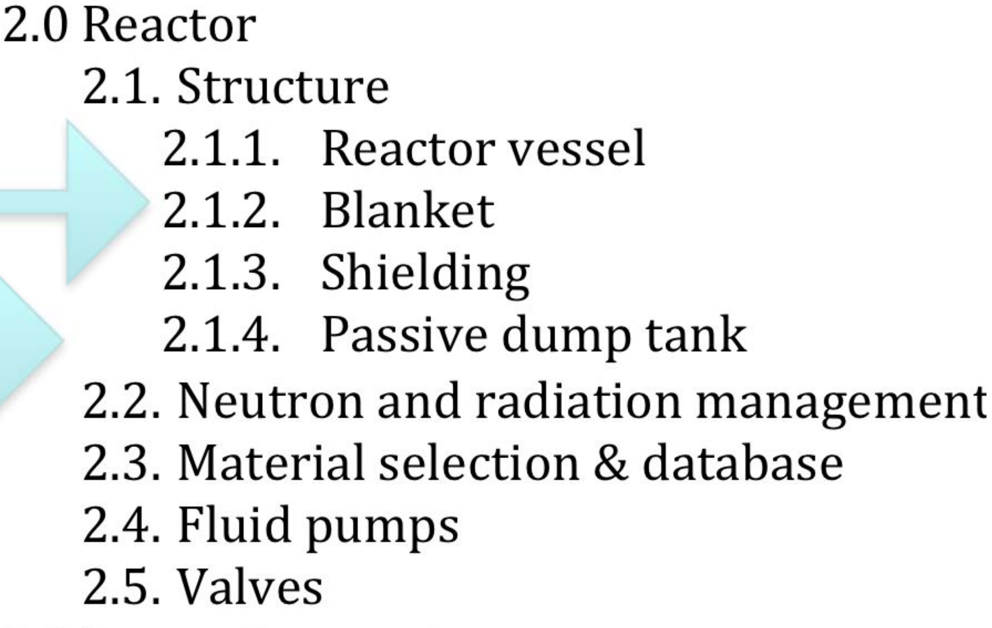
“Orchestra Conductor”

1.0 Systems Engineering
1.1. System performance analysis and trades
1.1.1. Thermal efficiency
1.1.2. Volume
1.1.3. Mass
1.1.4. Cost
1.2. System interface control
1.2.1. Documentation
1.2.2. Trade studies
1.2.3. Test-bed interoperability
1.3. Configuration management
1.4. Inherent safety configuration
1.5. Engineering Data Collection
1.5.1. Diagnostics
1.5.2. Data analysis
1.5.3. Data archive

“Main Instruments”

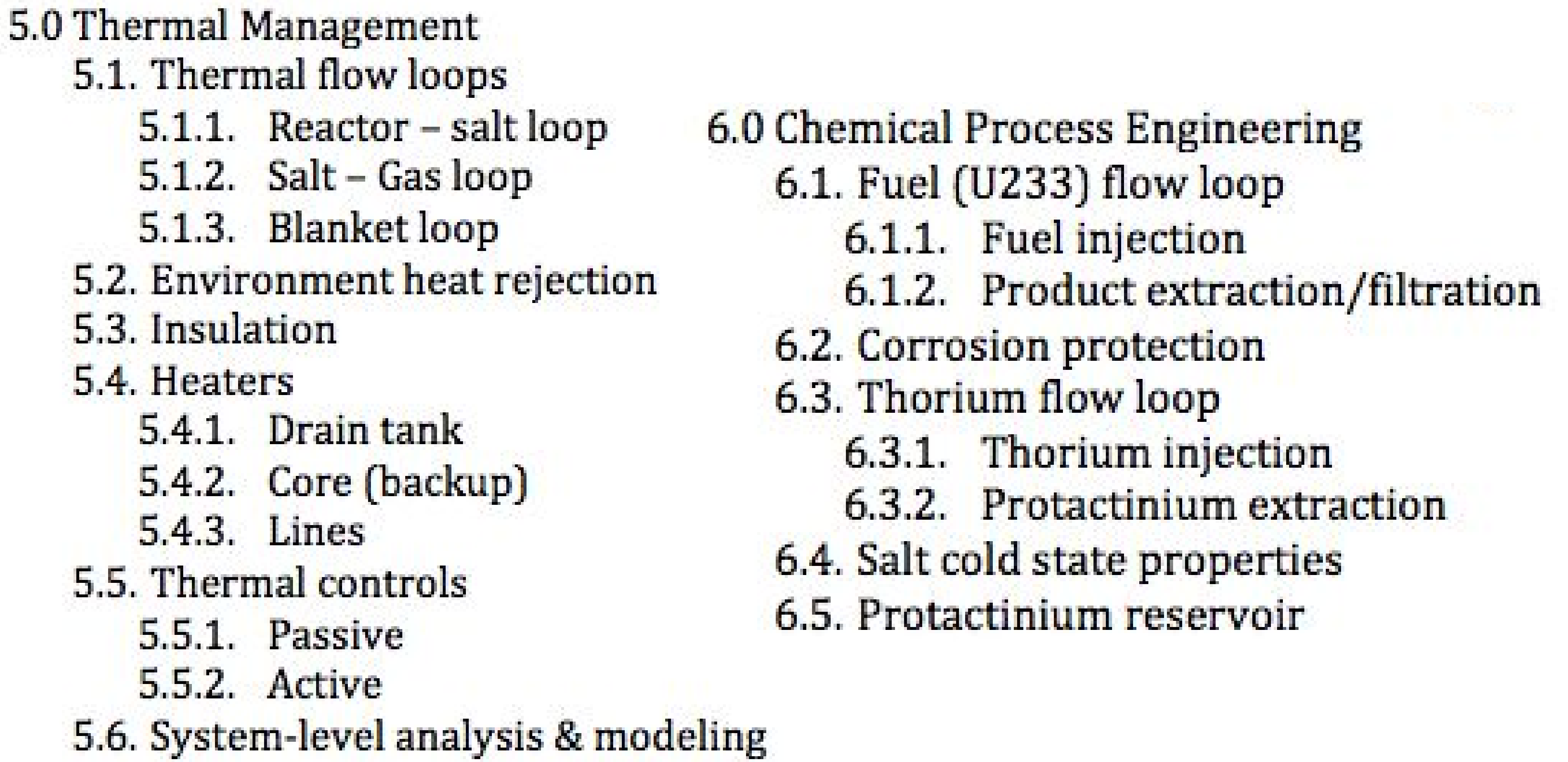


3.0 Power Conversion
  - 3.1. Brayton turbo-machinery
  - 3.2. Heat Exchangers
  - 3.3. Recuperator
  - 3.4. Gas flow management & controls
  - 3.5. Generators
  - 3.6. Electrical power distribution
    - 3.6.1. Power conditioning
    - 3.6.2. External interface
  - 3.7. Support structure & piping



2.0 Reactor
  - 2.1. Structure
    - 2.1.1. Reactor vessel
    - 2.1.2. Blanket
    - 2.1.3. Shielding
    - 2.1.4. Passive dump tank
  - 2.2. Neutron and radiation management
  - 2.3. Material selection & database
  - 2.4. Fluid pumps
  - 2.5. Valves

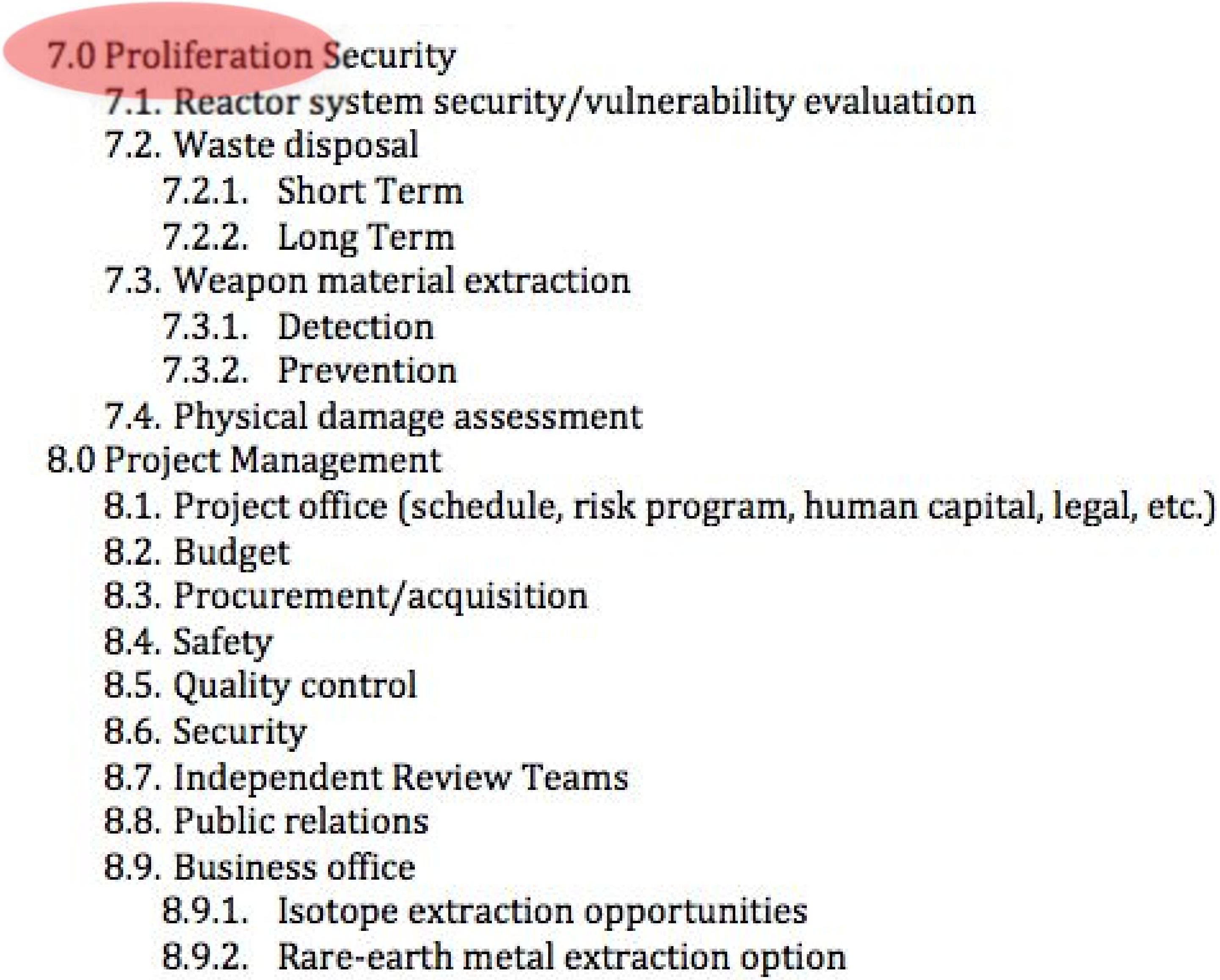
“Sheet Music”



5.0 Thermal Management
  5.1. Thermal flow loops
    5.1.1. Reactor – salt loop
    5.1.2. Salt – Gas loop
    5.1.3. Blanket loop
  5.2. Environment heat rejection
  5.3. Insulation
  5.4. Heaters
    5.4.1. Drain tank
    5.4.2. Core (backup)
    5.4.3. Lines
  5.5. Thermal controls
    5.5.1. Passive
    5.5.2. Active
  5.6. System-level analysis & modeling

6.0 Chemical Process Engineering
  6.1. Fuel (U233) flow loop
    6.1.1. Fuel injection
    6.1.2. Product extraction/filtration
  6.2. Corrosion protection
  6.3. Thorium flow loop
    6.3.1. Thorium injection
    6.3.2. Protactinium extraction
  6.4. Salt cold state properties
  6.5. Protactinium reservoir

“Orchestra Pit”



7.0 Proliferation Security
  7.1. Reactor system security/vulnerability evaluation
  7.2. Waste disposal
    7.2.1. Short Term
    7.2.2. Long Term
  7.3. Weapon material extraction
    7.3.1. Detection
    7.3.2. Prevention
  7.4. Physical damage assessment
8.0 Project Management
  8.1. Project office (schedule, risk program, human capital, legal, etc.)
  8.2. Budget
  8.3. Procurement/acquisition
  8.4. Safety
  8.5. Quality control
  8.6. Security
  8.7. Independent Review Teams
  8.8. Public relations
  8.9. Business office
    8.9.1. Isotope extraction opportunities
    8.9.2. Rare-earth metal extraction option

What Fusion Wanted To Be

Fusion promised to be:

1. Limitless (sustainable) energy
2. Safe
3. Minimum radioactive waste
4. Proliferation resistant
5. Environmentally friendly
6. Power dense
7. Little mining, transportation, or land use
8. Low cost

Thorium can be:

1. Near limitless (sustainable for 100s of years) with supplies easily found throughout the solar system
2. In liquid form (e.g. LFTR), thorium has analogous safety
3. Limited radioactive wastes makes thorium comparable
4. Equivalent proliferation resistant
5. As environmentally friendly
6. Much greater power density
7. Equivalent mining, transportation & land use
8. Much lower cost

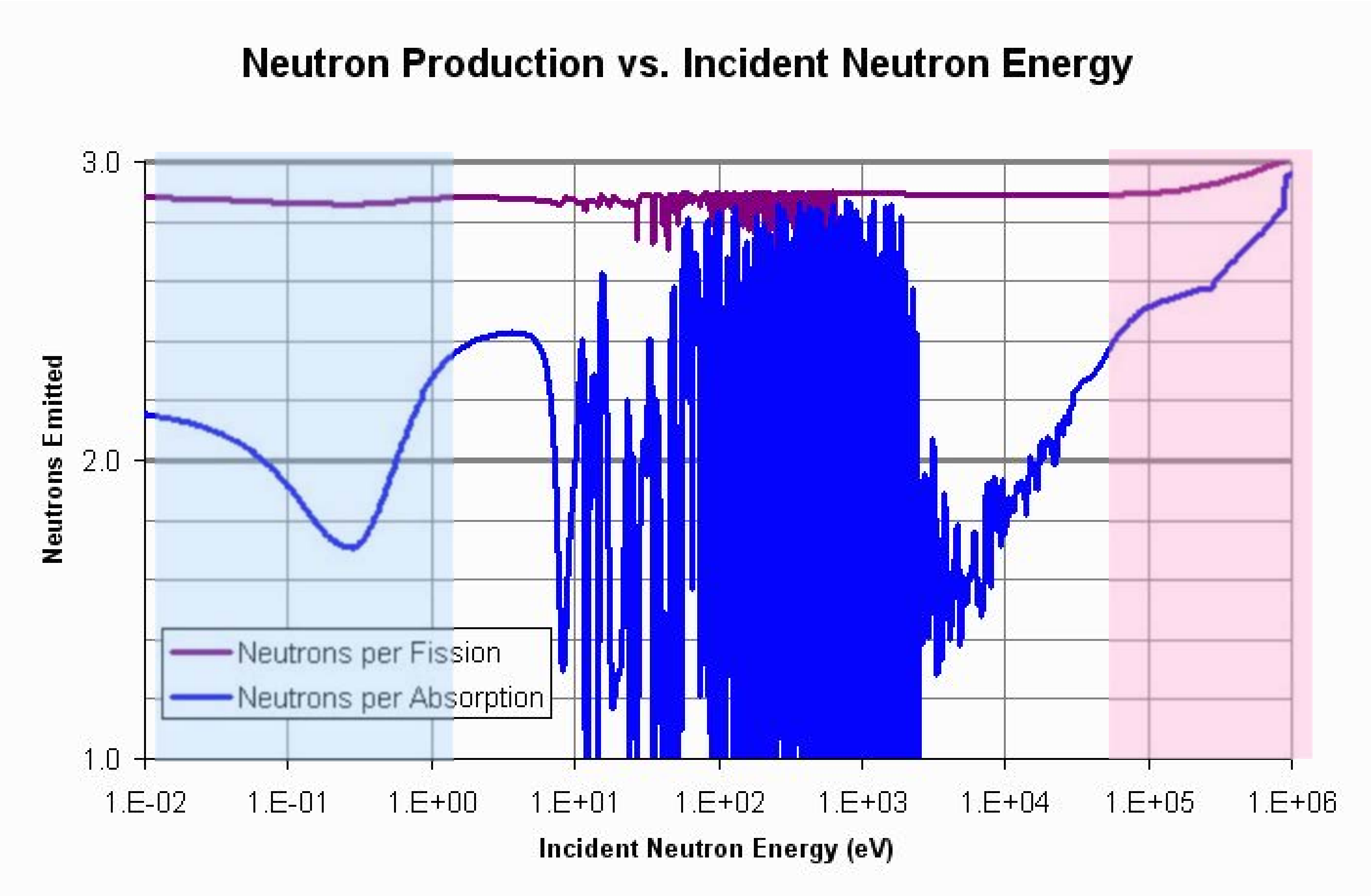
Summary

- **Think about the entirety of the global energy crisis:**
  - Required Resource Intensity
  - Diminishing Returns (producing the next **10 Quads**….)
  - Power Density relation to cost, applicability, flexibility, etc.
  - The speed to produce on the order of **100 Quads** worldwide
  - Vulnerabilities (storms, attacks, environment)

- **Systems Engineering is the "next step"**
  - **What needs to be done**
  - **Order of tasks**
  - **Identify what is dominant**

Hyperlinks

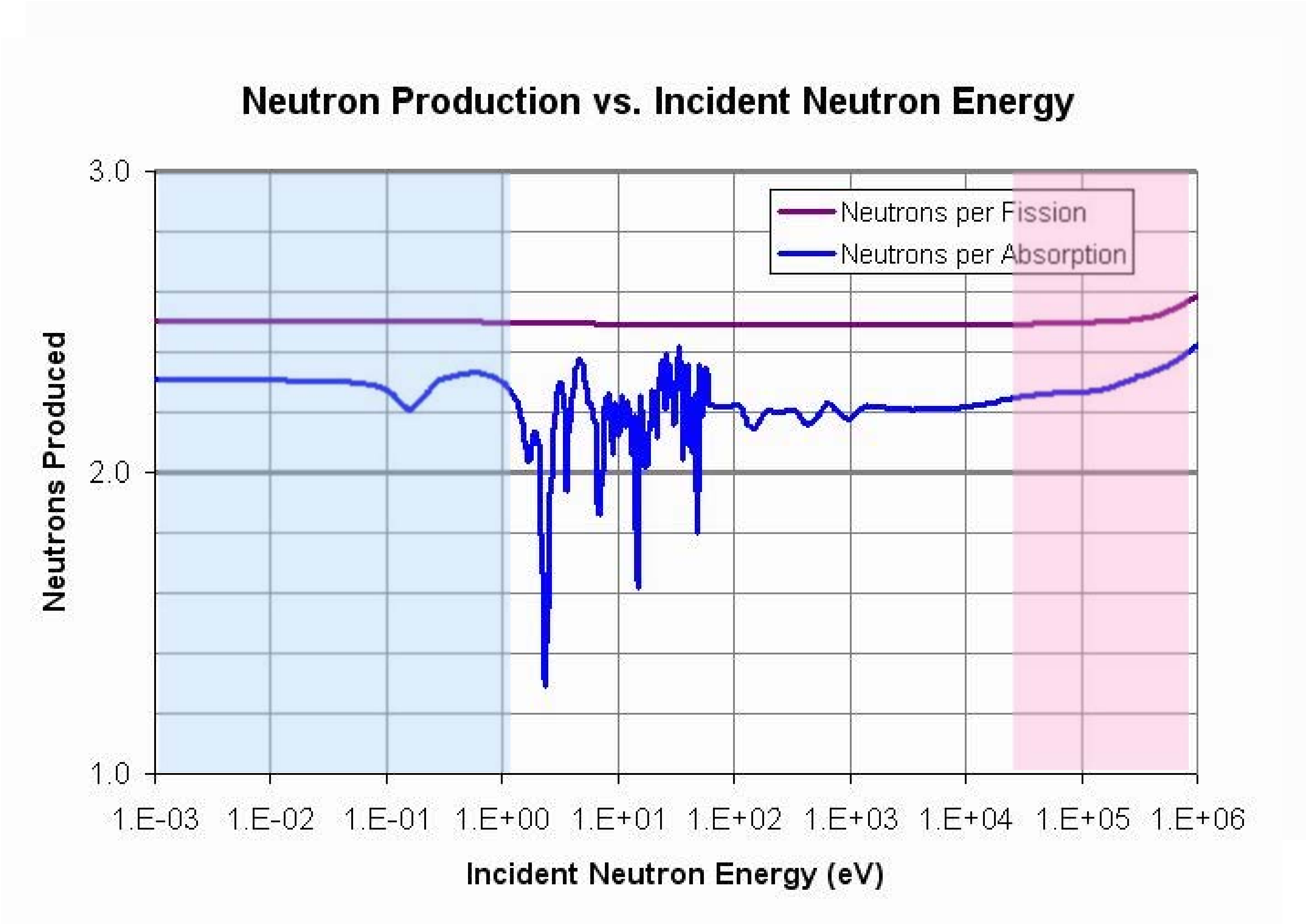
Can Nuclear Reactions be Sustained in Natural Uranium?



Not with thermal neutrons—need more than 2 neutrons to sustain reaction (one for conversion, one for fission)—not enough neutrons produced at thermal energies. Must use fast neutron reactors.

Retur
n

Can Nuclear Reactions be Sustained in Natural Thorium?



Yes! Enough neutrons to sustain reaction produced at thermal fission.
Does not need fast neutron reactors—needs neutronic efficiency.

Retur
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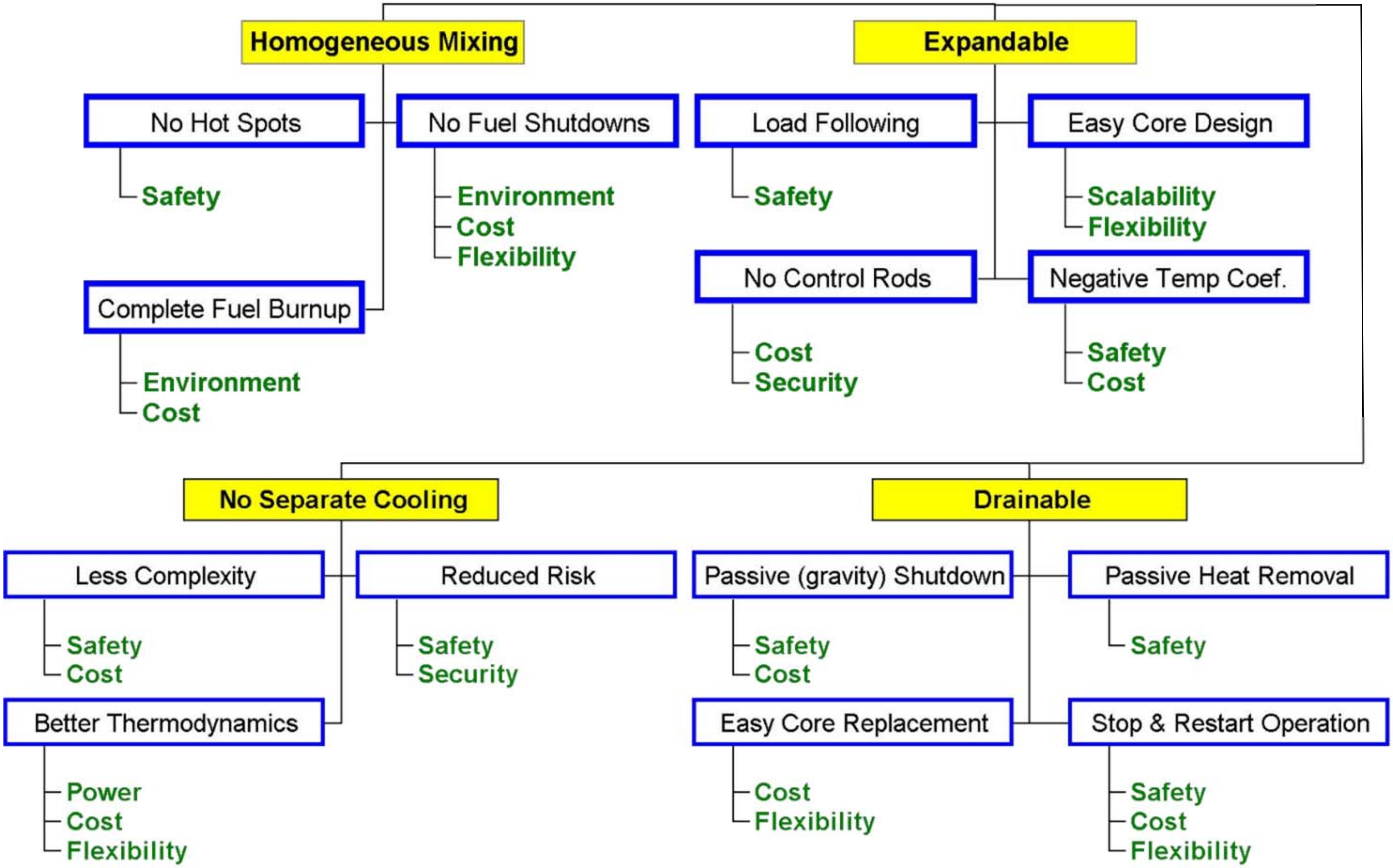
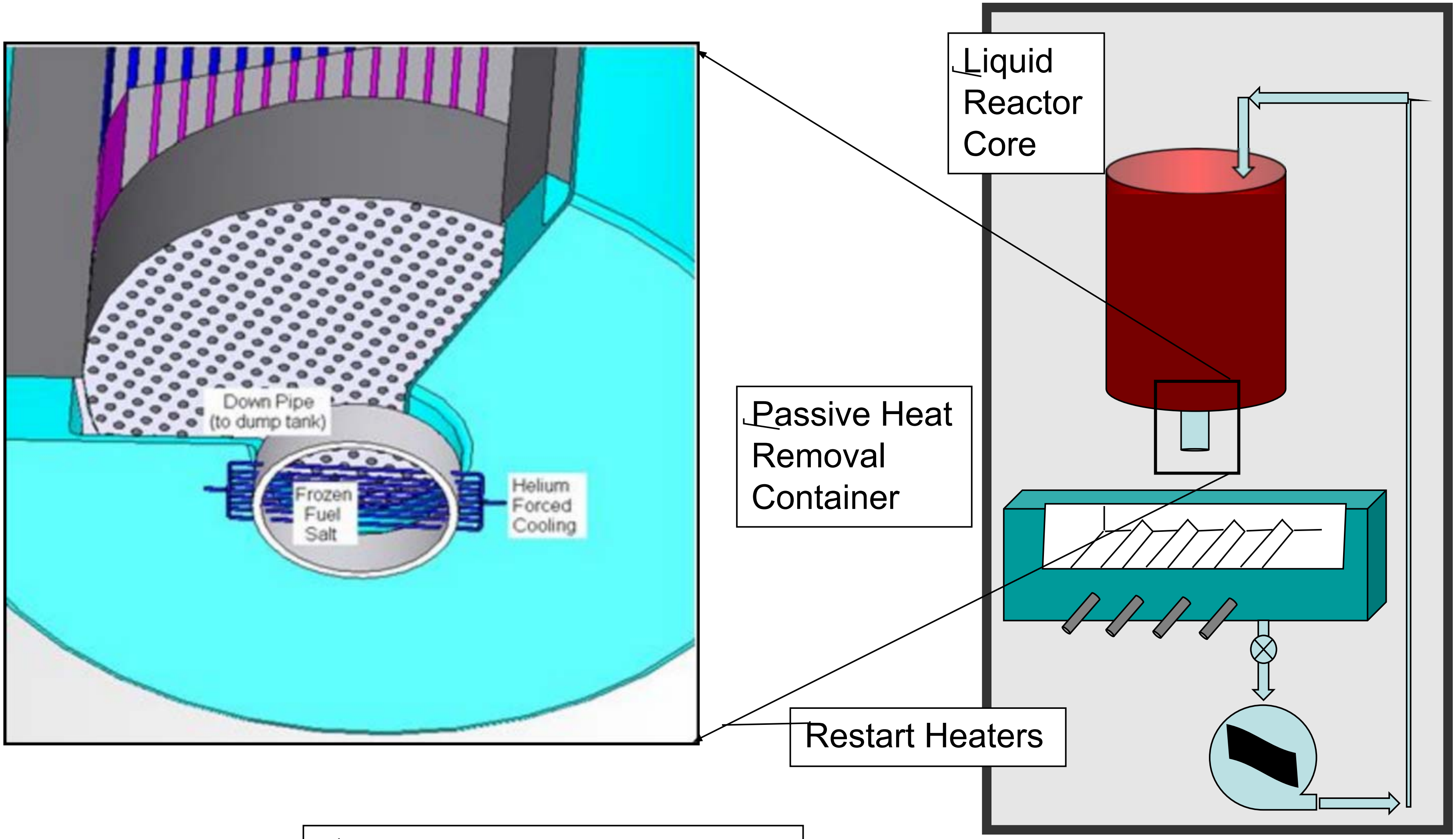
Liquid Core Advantages



- **Homogeneous Mixing**
  - No Hot Spots
    - Safety
  - No Fuel Shutdowns
    - Environment
    - Cost
    - Flexibility
  - Complete Fuel Burnup
    - Environment
    - Cost
- **Expandable**
  - Load Following
    - Safety
  - Easy Core Design
    - Scalability
    - Flexibility
  - No Control Rods
    - Cost
    - Security
  - Negative Temp Coef.
    - Safety
    - Cost
- **No Separate Cooling**
  - Less Complexity
    - Safety
    - Cost
  - Reduced Risk
    - Safety
    - Security
  - Better Thermodynamics
    - Power
    - Cost
    - Flexibility
- **Drainable**
  - Passive (gravity) Shutdown
    - Safety
    - Cost
  - Passive Heat Removal
    - Safety
  - Easy Core Replacement
    - Cost
    - Flexibility
  - Stop & Restart Operation
    - Safety
    - Cost
    - Flexibility

Passive Decay Heat Removal thru Freeze Valve



Liquid Reactor Core

Passive Heat Removal Container

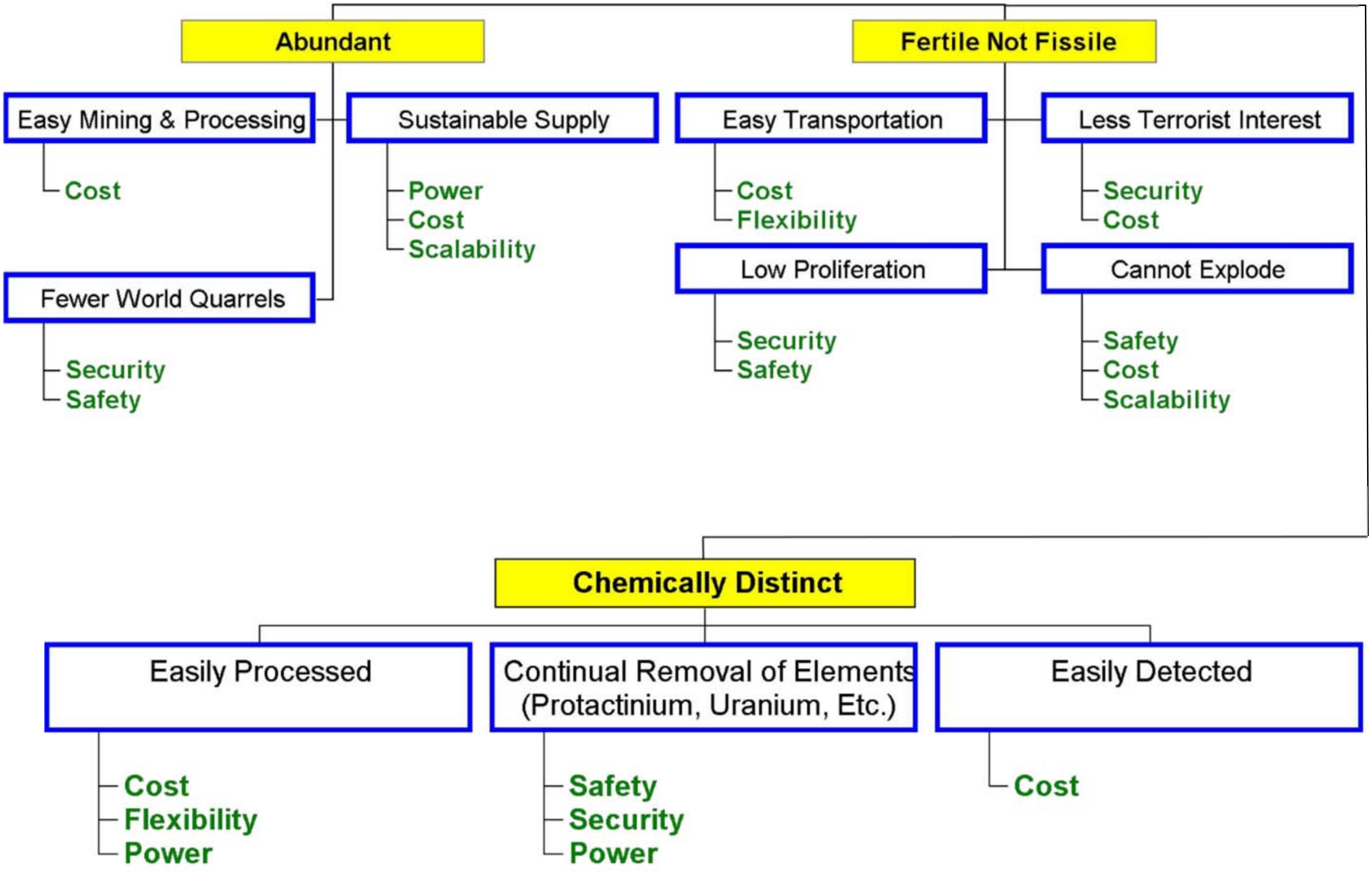
Restart Heaters

Secondary Containment Drum

Restart Pump

Return

Thorium Advantages



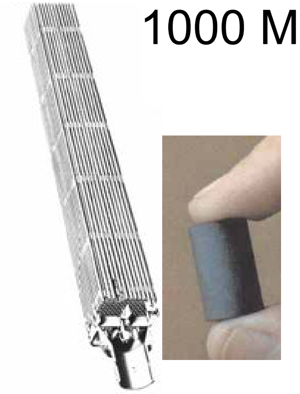
- **Abundant**
  - Easy Mining & Processing
    - Cost
  - Sustainable Supply
    - Power
    - Cost
    - Scalability
  - Fewer World Quarrels
    - Security
    - Safety
- **Fertile Not Fissile**
  - Easy Transportation
    - Cost
    - Flexibility
  - Less Terrorist Interest
    - Security
    - Cost
  - Low Proliferation
    - Security
    - Safety
  - Cannot Explode
    - Safety
    - Cost
    - Scalability
- **Chemically Distinct**
  - Easily Processed
    - Cost
    - Flexibility
    - Power
  - Continual Removal of Elements (Protactinium, Uranium, Etc.)
    - Safety
    - Security
    - Power
  - Easily Detected
    - Cost

Uranium Fuel Cycle vs. Thorium

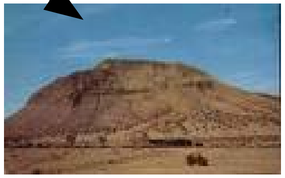
1000 MW of electricity for one year

800,000 tons Ore

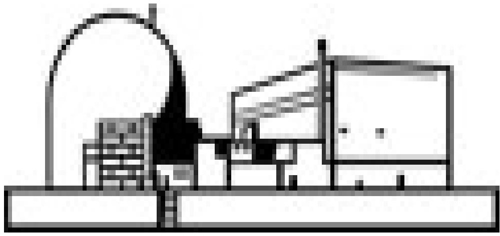
250 tons
Natural uranium



35 tons
Enriched Uranium
(Costly Process)



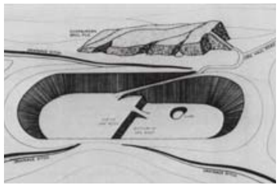
215 tons
depleted uranium
-disposal plans uncertain



Uranium-235 content is "burned" out of the fuel; some plutonium is formed and burned

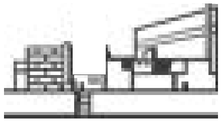
35 tons Spent Fuel
Yucca Mountain
(~10,000 years)

- **33.4 t uranium-238**
- **0.3 t uranium-235**
- **0.3 t plutonium**
- **1.0 t fission products**



200 tons Ore

1 ton
Natural Thorium



Thorium introduced into blanket of fluoride reactor; completely converted to uranium-233 and "burned"

1 Ton
Fission products; no uranium, plutonium, or other actinides

Within 10 years, 83% of fission products are stable and can be partitioned and sold.

The remaining 17% fission products go to geologic isolation for ~300 years.

Is the Thorium Fuel Cycle a Proliferation Risk?

- When U-233 is used as a nuclear fuel, it is inevitably contaminated with uranium-232, which decays rather quickly (78 year half-life) and whose decay chain includes thallium-208.
- Thallium-208 is a “hard” gamma emitter, which makes any uranium contaminated with U-232 nearly worthless for nuclear weapons.
- There has never been an operational nuclear weapon that has used U-233 as its fissile material, despite the ease of manufacturing U-233 from abundant natural thorium.
- U-233 with very low U-232 contamination could be generated in special reactors like Hanford, but not in reactors that use the U-233 as fuel.

U-232 Formation in the Thorium Fuel Cycle

$$^{232}\mathrm{Th} \xrightarrow{n,2n} {}^{231}\mathrm{Th} \xrightarrow[25.5\ \mathrm{h}]{\beta^-} {}^{231}\mathrm{Pa} \xrightarrow{n,\gamma} {}^{232}\mathrm{Pa} \xrightarrow[1.31\ \mathrm{days}]{\beta^-} {}^{232}\mathrm{U}$$

$$^{233}\mathrm{U} \xrightarrow{n,2n} {}^{232}\mathrm{U}$$

$$^{230}\mathrm{Th} \xrightarrow{n,\gamma} {}^{231}\mathrm{Th} \xrightarrow[25.52\ \mathrm{h}]{\beta^-} {}^{231}\mathrm{Pa} \xrightarrow{n,\gamma} {}^{232}\mathrm{Pa} \xrightarrow[1.31\ \mathrm{days}]{\beta^-} {}^{232}\mathrm{U}$$

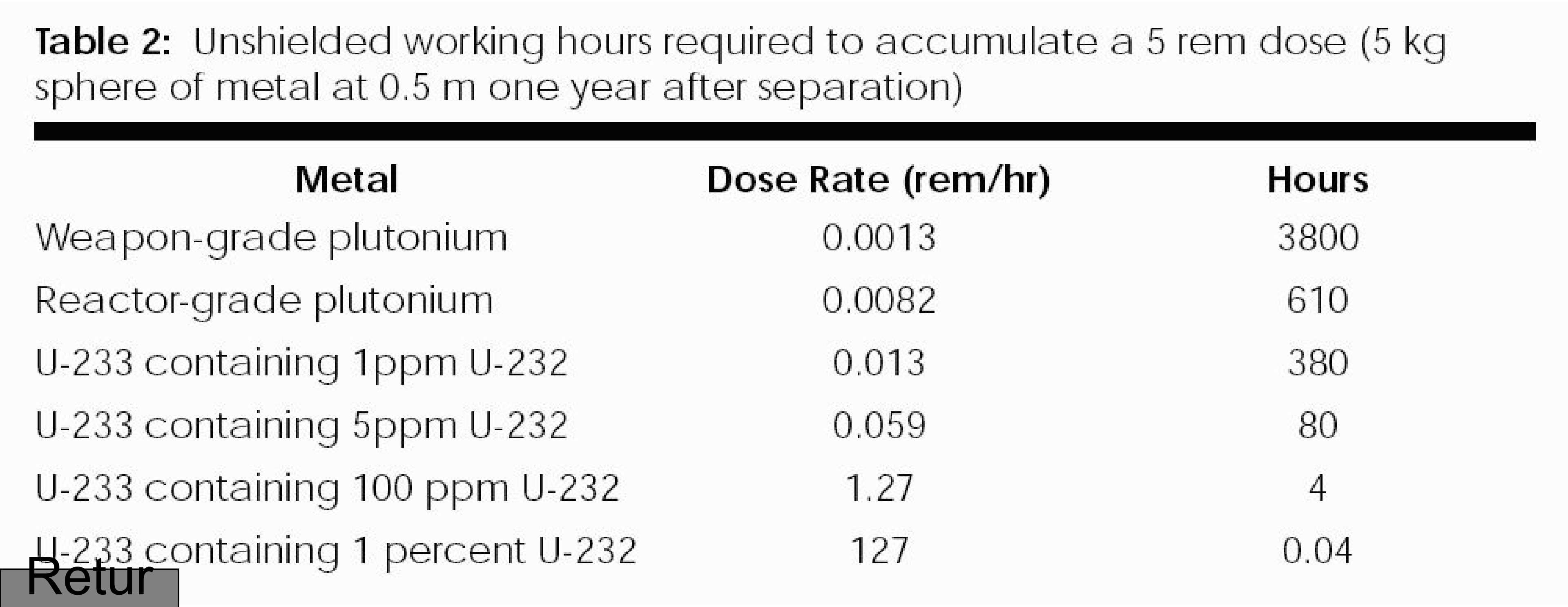


Table 2: Unshielded working hours required to accumulate a 5 rem dose (5 kg sphere of metal at 0.5 m one year after separation)

Metal	Dose Rate (rem/hr)	Hours
Weapon-grade plutonium	0.0013	3800
Reactor-grade plutonium	0.0082	610
U-233 containing 1ppm U-232	0.013	380
U-233 containing 5ppm U-232	0.059	80
U-233 containing 100 ppm U-232	1.27	4
U-233 containing 1 percent U-232	127	0.04

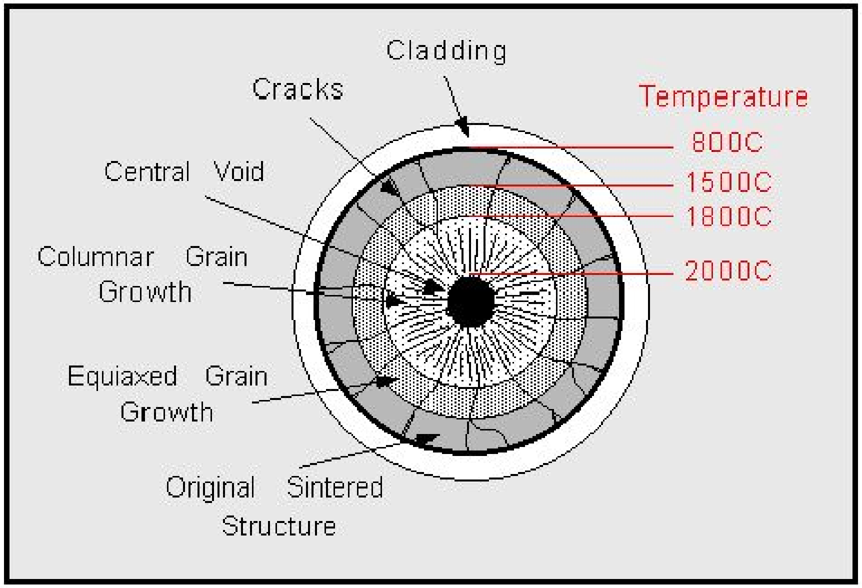
Return

Fluoride Salt Advantages

- **Ionic Chemical Stability**
  - Insensitive to Radiation Damage
    - **Safety**
  - High Bond Strength
    - **Environment**
  - Compatibility With Different Mixtures
    - **Environment**
    - **Security**
- **Room Temperature Solid**
  - Nonvolatile When Cool
    - **Safety**
  - Leak Resistant
    - **Flexibility**
    - **Safety**
  - Easy shipping and Handling
    - **Cost**
    - **Security**
  - Easy Spill Cleanup
    - **Safety**
    - **Cost**
- **High Temperature**
  - Good Thermodynamics
    - **Power**
    - **Cost**
  - No Temperature Limitations
    - **Safety**
    - **Flexibility**
  - Corrosion Resistance
    - **Cost**
    - **Safety**
- **Low Vapor Pressure**
  - Gas Buildup Readily Comes Out
    - **Safety**
    - **Cost**
  - Salt Components Remain
    - **Security**
    - **Cost**

Radiation Damage Limits Energy Release

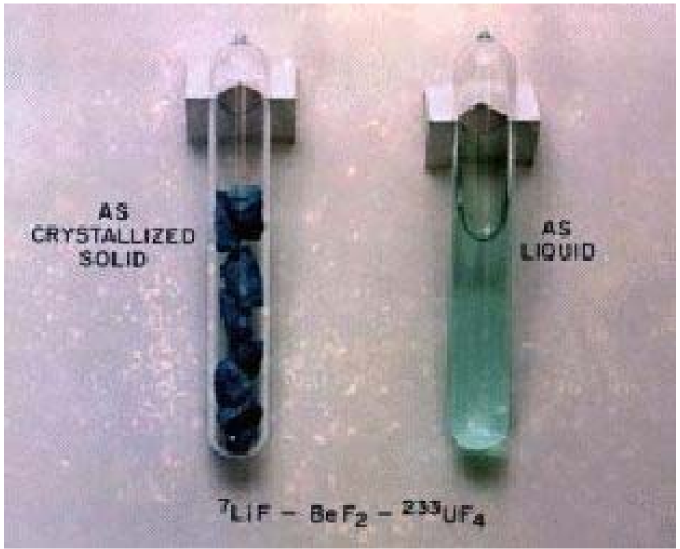
- Does a typical nuclear reactor extract that much energy from its nuclear fuel?
  - No, the “burnup” of the fuel is limited by damage to the fuel itself.
- Typically, the reactor will only be able to extract a portion of the energy from the fuel before radiation damage to the fuel itself becomes too extreme.
- Radiation damage is caused by:
  - Noble gas (krypton, xenon) buildup
  - Disturbance to the fuel lattice caused by fission fragments and neutron flux
- As the fuel swells and distorts, it can cause the cladding around the fuel to rupture and release fission products into the coolant.

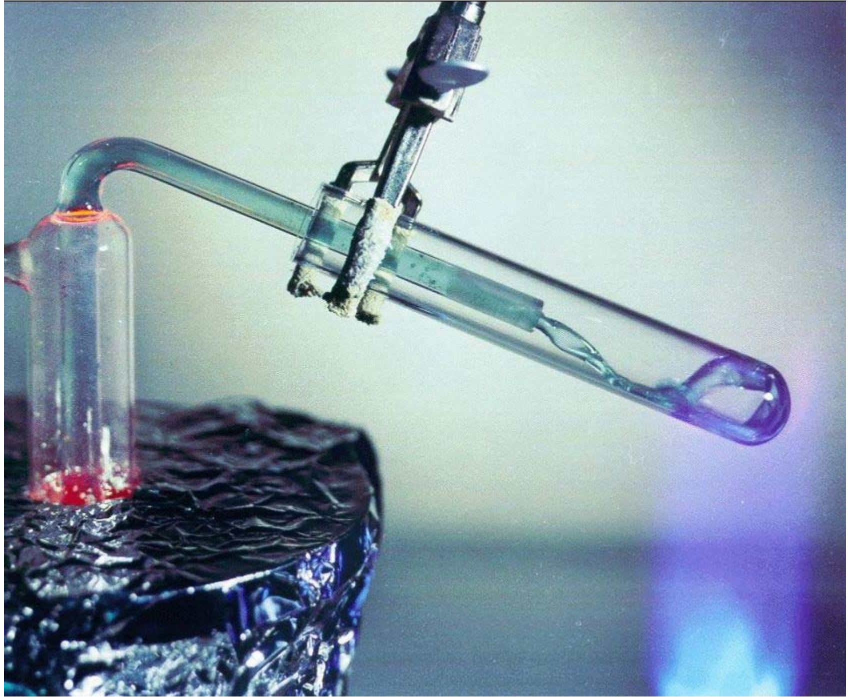


Ionically-bonded fluids are impervious to radiation

- The basic problem in nuclear fuel is that it is covalently bonded and in a solid form.

- If the fuel were a fluid salt, its ionic bonds would be impervious to radiation damage and the fluid form would allow easy extraction of fission product gases, thus permitting unlimited burnup.





Corrosion Resistance at Temperature

- Fluoride salts are fluxing agents that rapidly dissolve protective layers of oxides and other materials.
- To avoid corrosion, molten salt coolants must be chosen that are thermodynamically stable relative to the materials of construction of the reactor; that is, the materials of construction are chemically noble relative to the salts.
- This limits the choice to highly thermodynamically-stable salts.
- This table shows the primary candidate fluorides suitable for a molten salt and their thermo-dynamic free energies of formation.
- The general rule to ensure that the materials of construction are compatible (noble) with respect to the salt is that the difference in the Gibbs free energy of formation between the salt and the container material should be >20 kcal/(mole °C).

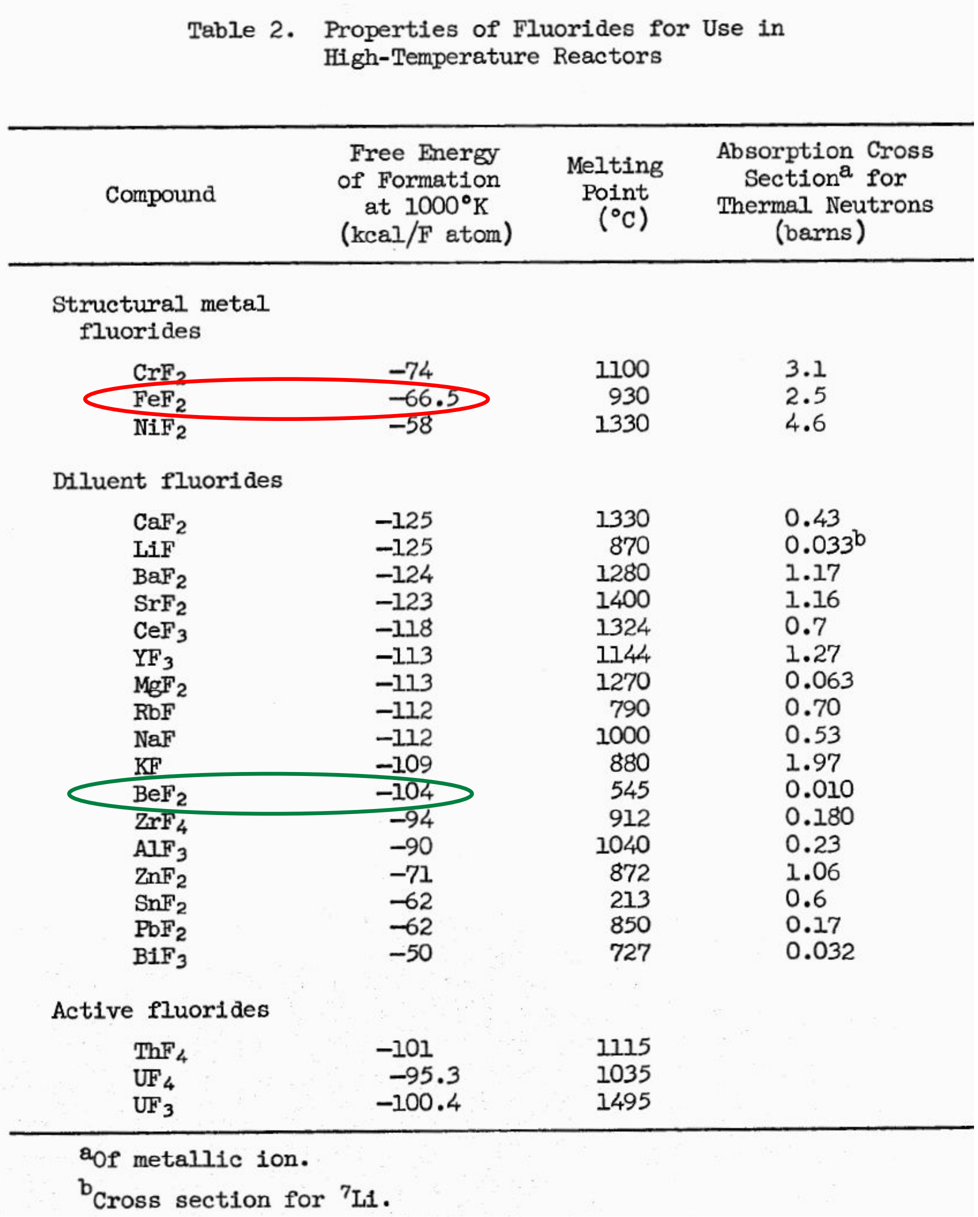


Table 2. Properties of Fluorides for Use in High-Temperature Reactors

Compound	Free Energy of Formation at 1000°K (kcal/F atom)	Melting Point (°C)	Absorption Cross Section[a] for Thermal Neutrons (barns)
Structural metal fluorides			
CrF_2	−74	1100	3.1
FeF_2	−66.5	930	2.5
NiF_2	−58	1330	4.6
Diluent fluorides			
CaF_2	−125	1330	0.43
LiF	−125	870	0.033[b]
BaF_2	−124	1280	1.17
SrF_2	−123	1400	1.16
CeF_3	−118	1324	0.7
YF_3	−113	1144	1.27
MgF_2	−113	1270	0.063
RbF	−112	790	0.70
NaF	−112	1000	0.53
KF	−109	880	1.97
BeF_2	−104	545	0.010
ZrF_4	−94	912	0.180
AlF_3	−90	1040	0.23
ZnF_2	−71	872	1.06
SnF_2	−62	213	0.6
PbF_2	−62	850	0.17
BiF_3	−50	727	0.032
Active fluorides			
ThF_4	−101	1115	
UF_4	−95.3	1035	
UF_3	−100.4	1495	

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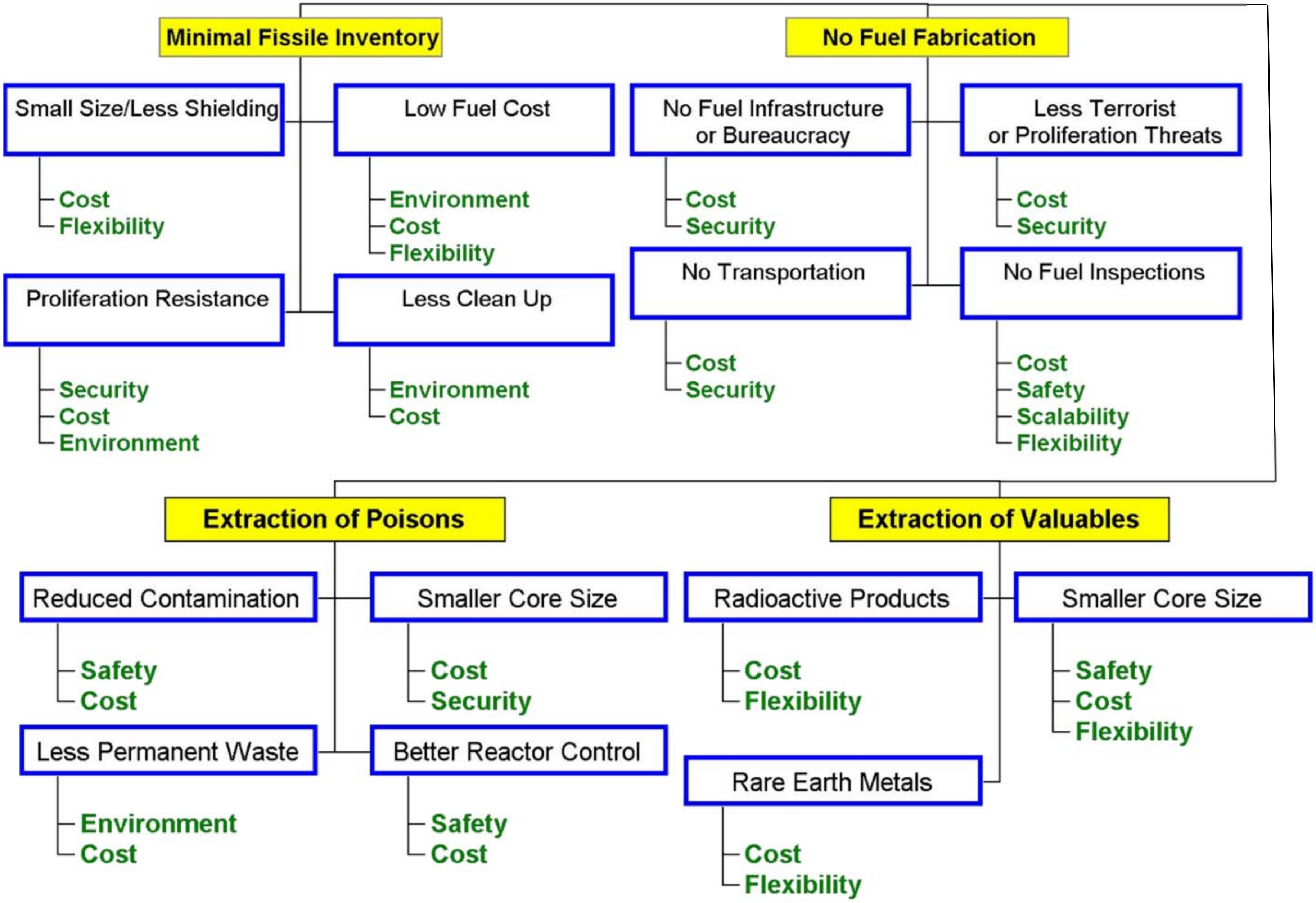
[a] Of metallic ion.

[b] Cross section for ^7Li.

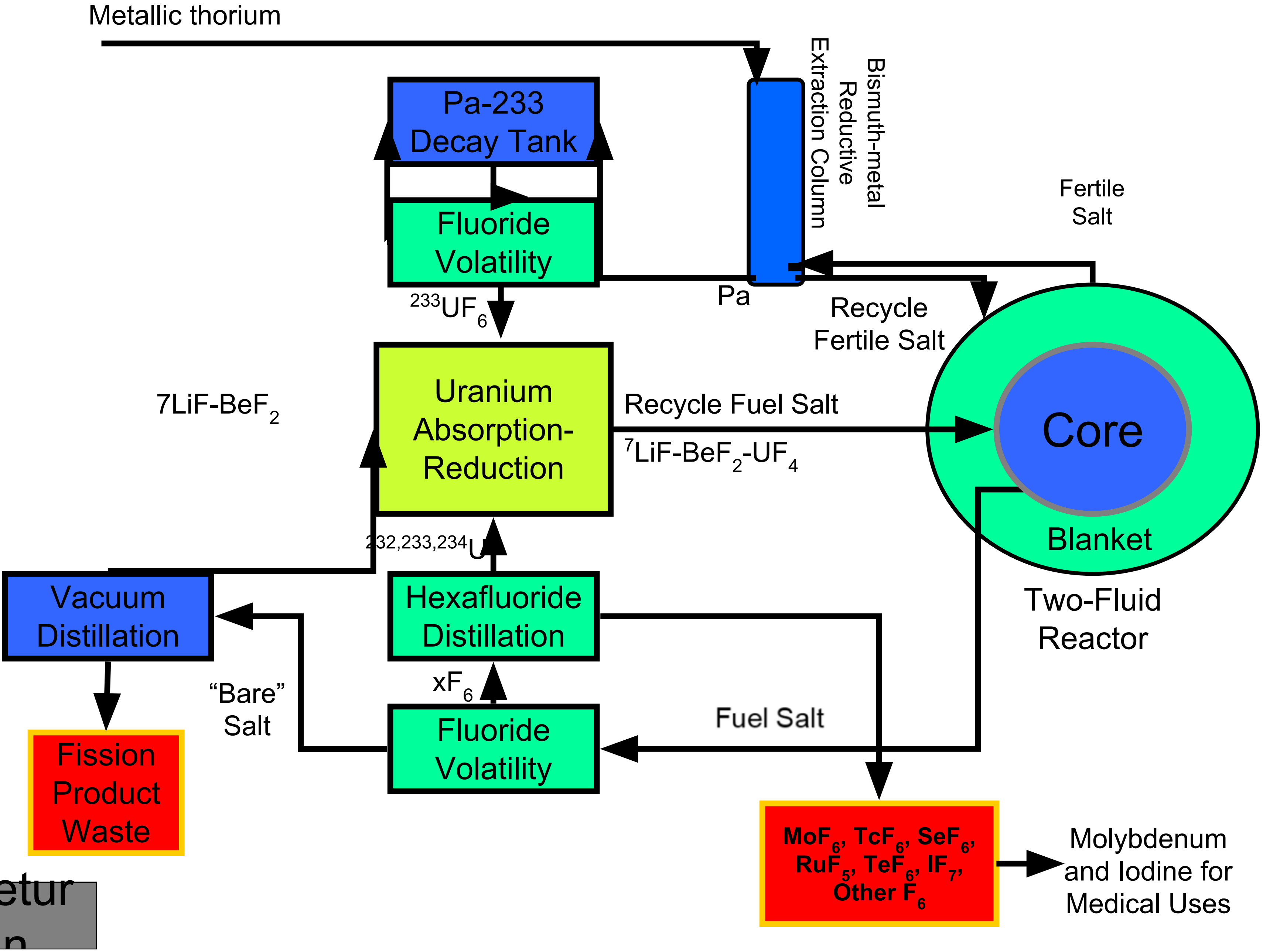
Return

Internal Processing Advantages



- **Minimal Fissile Inventory**
  - Small Size/Less Shielding
    - **Cost**
    - **Flexibility**
  - Low Fuel Cost
    - **Environment**
    - **Cost**
    - **Flexibility**
  - Proliferation Resistance
    - **Security**
    - **Cost**
    - **Environment**
  - Less Clean Up
    - **Environment**
    - **Cost**
- **No Fuel Fabrication**
  - No Fuel Infrastructure or Bureaucracy
    - **Cost**
    - **Security**
  - Less Terrorist or Proliferation Threats
    - **Cost**
    - **Security**
  - No Transportation
    - **Cost**
    - **Security**
  - No Fuel Inspections
    - **Cost**
    - **Safety**
    - **Scalability**
    - **Flexibility**
- **Extraction of Poisons**
  - Reduced Contamination
    - **Safety**
    - **Cost**
  - Smaller Core Size
    - **Cost**
    - **Security**
  - Less Permanent Waste
    - **Environment**
    - **Cost**
  - Better Reactor Control
    - **Safety**
    - **Cost**
- **Extraction of Valuables**
  - Radioactive Products
    - **Cost**
    - **Flexibility**
  - Smaller Core Size
    - **Safety**
    - **Cost**
    - **Flexibility**
  - Rare Earth Metals
    - **Cost**
    - **Flexibility**

LFTR Processing Details



Metallic thorium

Bismuth-metal Reductive Extraction Column

Pa-233 Decay Tank

Fluoride Volatility

$^{233}UF_6$

Pa

Fertile Salt

Recycle Fertile Salt

$7LiF\text{-}BeF_2$

Uranium Absorption-Reduction

Recycle Fuel Salt

$^{7}LiF\text{-}BeF_2\text{-}UF_4$

Core

Blanket

Two-Fluid Reactor

$^{232,233,234}U$

Vacuum Distillation

Hexafluoride Distillation

xF_6

“Bare” Salt

Fluoride Volatility

Fuel Salt

Fission Product Waste

MoF_6, TcF_6, SeF_6, RuF_5, TeF_6, IF_7, Other F_6

Molybdenum and Iodine for Medical Uses

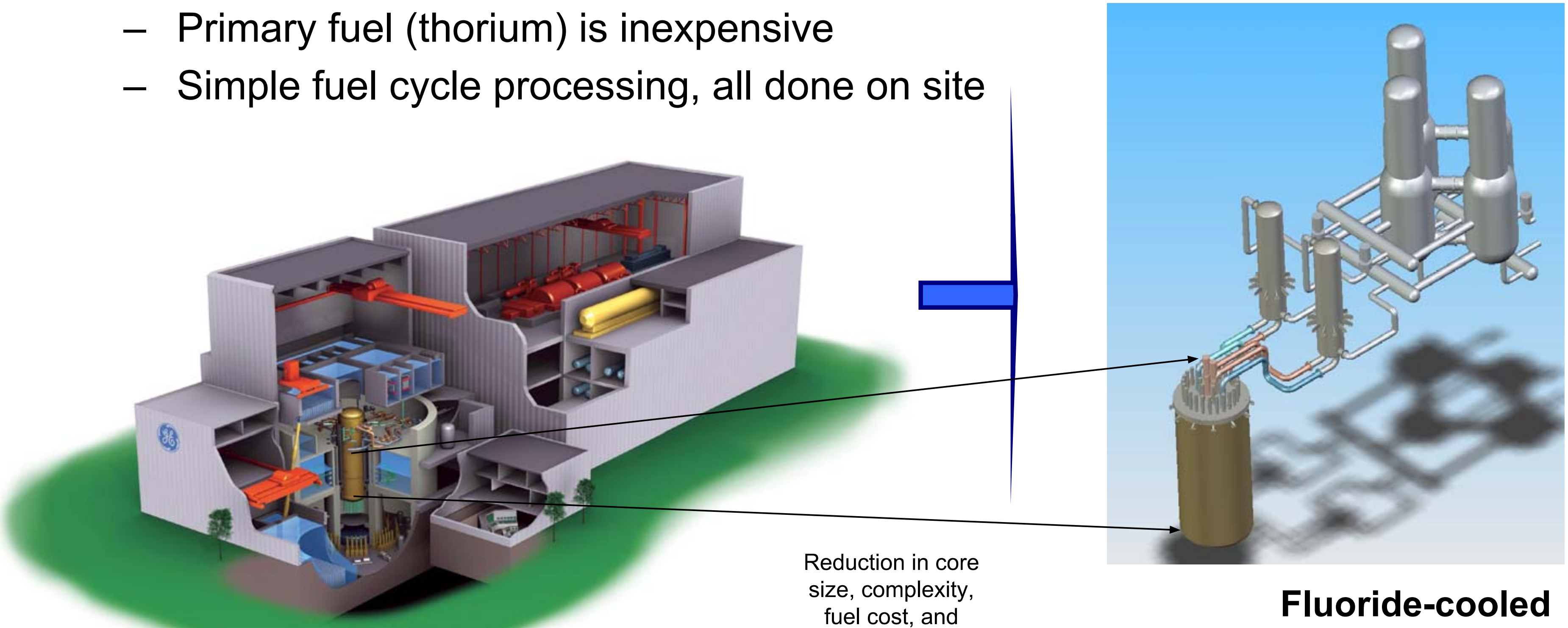
Retur
n

Closed-Cycle Brayton Advantages

- **Air or Water Heat Rejection**
  - Location Independence
    - **Flexibility**
    - **Cost**
  - Best Match to Sink Temperature
    - **Power**
    - **Environment**
- **High Efficiency Recuperator**
  - High Thermodynamic Efficiency
    - **Power**
    - **Cost**
  - Jet Aircraft Turbo Machinery Technology
    - **Cost**
    - **Power**
- **Variable Inlet Pressure**
  - Smaller Physical Size
    - **Scalability**
    - **Cost**
  - Match Optimum Gas Thermodynamic Properties
    - **Scalability**
    - **Flexibility**
  - Cleaner With Less Maintenance
    - **Cost**

Cost advantages come from size and complexity reductions

- Cost
  - Low capital cost thru small facility and compact power conversion
    - Reactor operates at ambient pressure
    - No expanding gases (steam) to drive large containment
    - High-pressure helium gas turbine system
  - Primary fuel (thorium) is inexpensive
  - Simple fuel cycle processing, all done on site



Reduction in core size, complexity, fuel cost, and turbomachinery

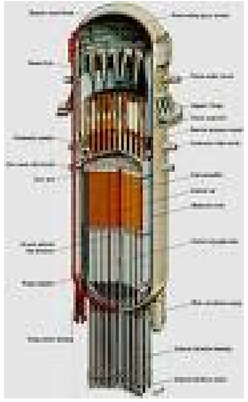
GE Advanced Boiling Water Reactor (light-water reactor)

Fluoride-cooled reactor with helium gas turbine power conversion system

Thorium Reactor could cost 30-50% Less

(Cost Effective & Grid Interfacing)

- No pressure vessel required
- Liquid fuel requires no expensive fuel fabrication and qualification
- Smaller power conversion system
    - Uses higher pressure (2050 psi)
- No steam generators required
- Factory built-modular construction
  - Scalable: 100 KW to multi GW
- Smaller containment building needed
    - Steam vs. fluids
- Simpler operation
    - No operational control rods
    - No re-fueling shut down
    - Significantly lower maintenance
    - Significantly smaller staff
- Significantly lower capital costs
- Lower regulatory burden
- No grid interfacing costs:
  - Inherent load-following
  - No power line additions/alterations
  - Minimum line losses
  - Plant sized by location/needs



Plant Size Comparison: Steam (top) vs. CO2 (bottom) for a 1000 MWe plant

Return