U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Current Status of Molten Salt Reactor R&D Activities in the U.S.

GIF MSR Provisional Steering Committee Meeting at Delft, Netherlands

November 8, 2011

David Holcomb

U.S. Recently Completed Small-Scale Fast Spectrum MSR Options Evaluation

- **Separate projects sponsored by DOE-NE Advanced Reactor Concepts and Fuel Cycle Technology programs**
  - Rationale for evaluation is to develop comparative metrics for different fuel cycle and energy generation technology options
- **Project report available for download from OSTI – "Fast Spectrum Molten Salt Reactor Options" (ORNL/TM-2011/105)**
- **FY12 DOE budget does not include specific funding for MSRs**

Oak Ridge National Laboratory
Managed by UT-Battelle for the Department of Energy

ORNL/TM-2011/105

Fast Spectrum Molten Salt Reactor Options

July 2011

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FY12 U.S. Nuclear Energy Research Program Does Not Feature MSRs

DOE is not currently pursing the development of MSRs. However, the US had a large, active MSR development program from the 1940s-70s that included the operation of two test reactors, and DOE realizes that MSRs can have desirable characteristics and thus has not foreclosed pursuing the technology in the future.

Cooperative Research Between U.S. DOE-NE and Czech Ministry of Industrial Technologies Beginning

- ORNL and NRI are the lead performing institutions
- ORNL is providing 75 kg of highly lithium isotopically separated FLiBe salt to NRI
- NRI will perform criticality testing using LR-0 critical facility
- Joint modeling will be performed to establish the reactivity worth of the salt
- Specific experiments are still being agreed upon
- Fluoride volatility processing identified as potential area for future cooperation
- Planning workshop scheduled for January 2012

FS-MSR Evaluation Initial Focus Was on LWR Derived TRU Disposition

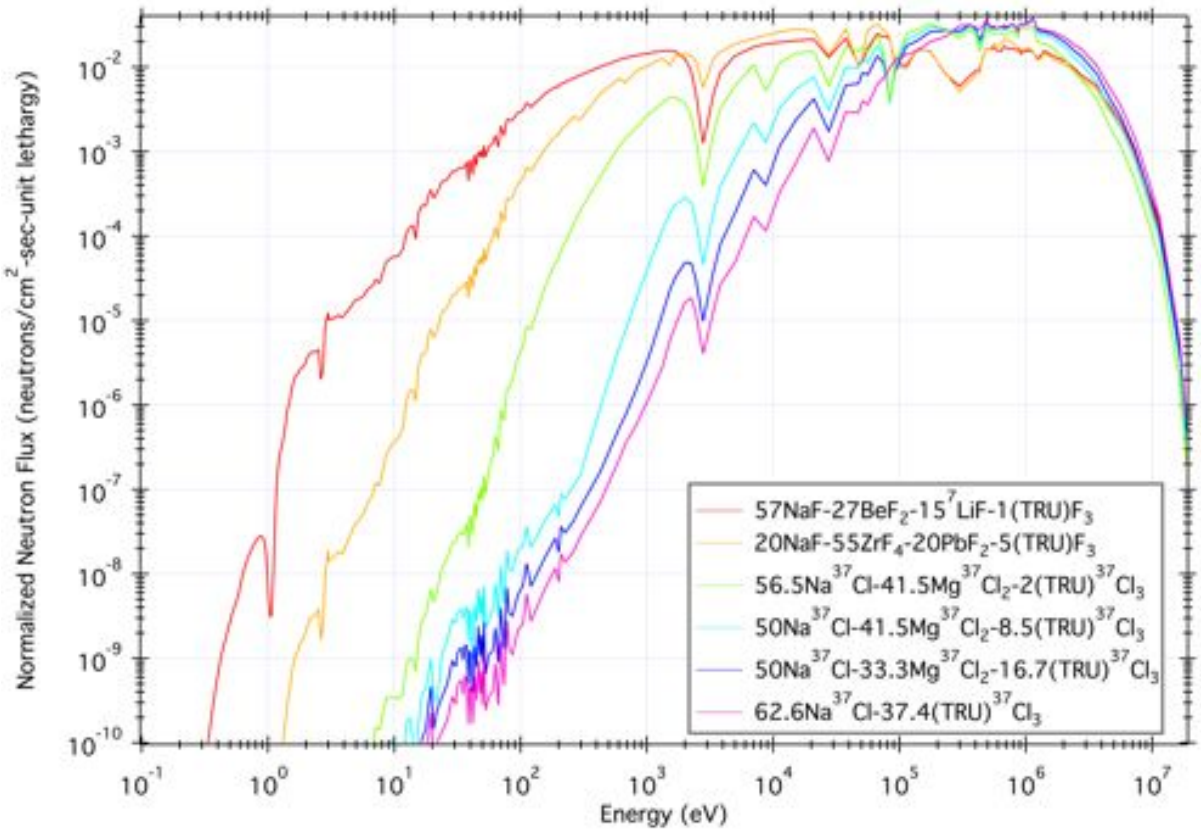
- **First phase process was to**

1. **Select candidate salts**
2. **Calculate neutron consumption per TRU fission (D-factor) as a comparison metric of actinide burning capability***
   - Metal fueled SFR used as a comparison basis
3. **Assess salt processing technology**
4. **Initiate evaluation of materials issues**
5. **Evaluate potential reactor configurations**

*R. N. Hill, *Comparison of Fast Reactor Transmutation Potential*, ANL-AFCI-115, 2003

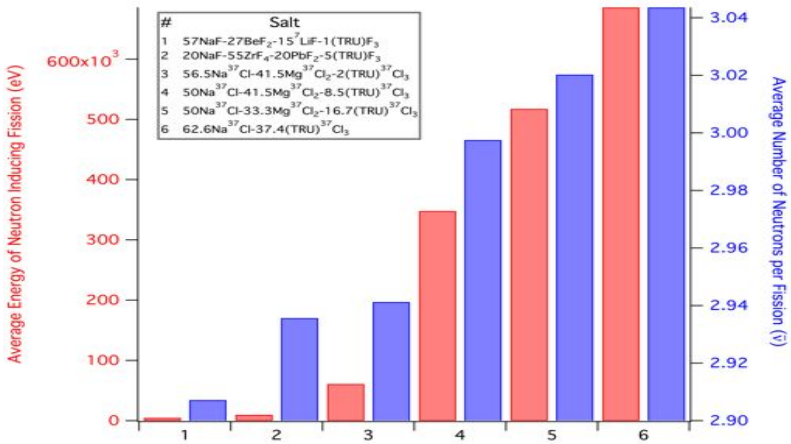
FS-MSRs Have Very Few Thermal Neutrons Enabling Different Design Concepts

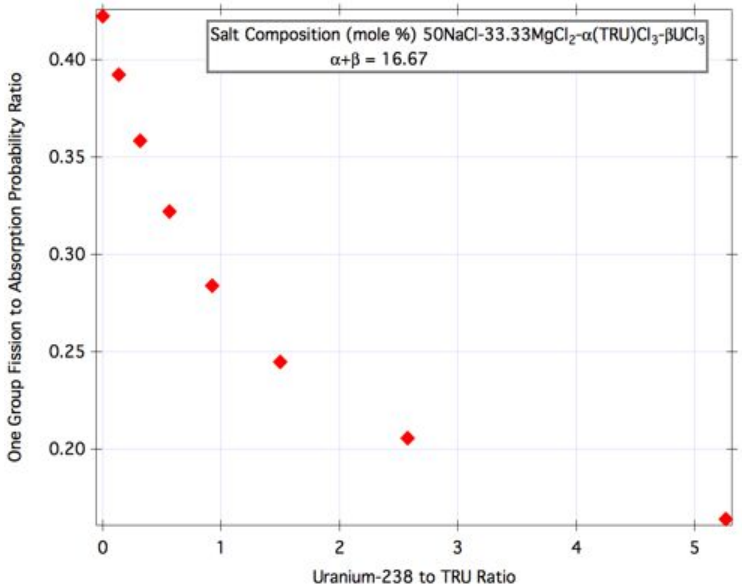
- **Fission products generally have large thermal, but small fast cross-sections**
- **May be possible to operate for extended periods without any processing**



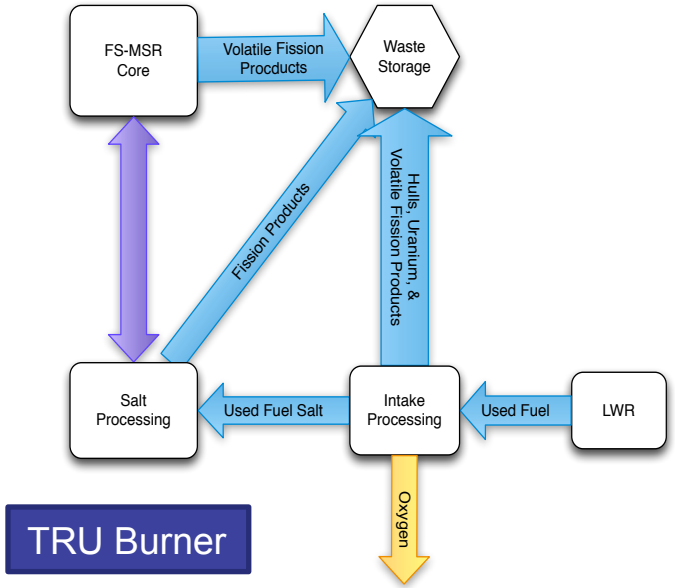
Conversion Ratio Depends on Carrier Salt Atomic Mass, TRU Composition, and TRU Loading

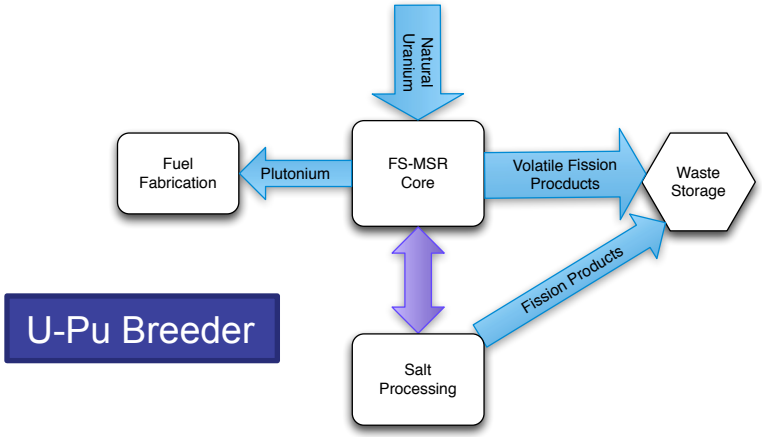
- Increasing fraction of heavy atoms by changing the carrier salt or increasing the TRU loading hardens neutron spectrum
- Harder neutron spectrum increases the breeding rate
- Substituting ^{238}U for TRU enables shifting from a TRU burning to breeding mission

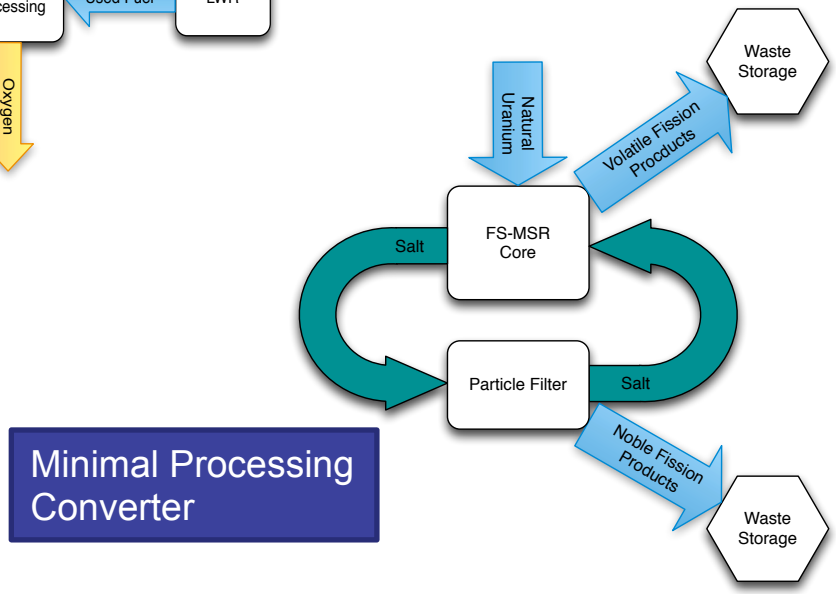




Fast Spectrum Enables Multiple Fuel Cycles With Similar Core Configuration





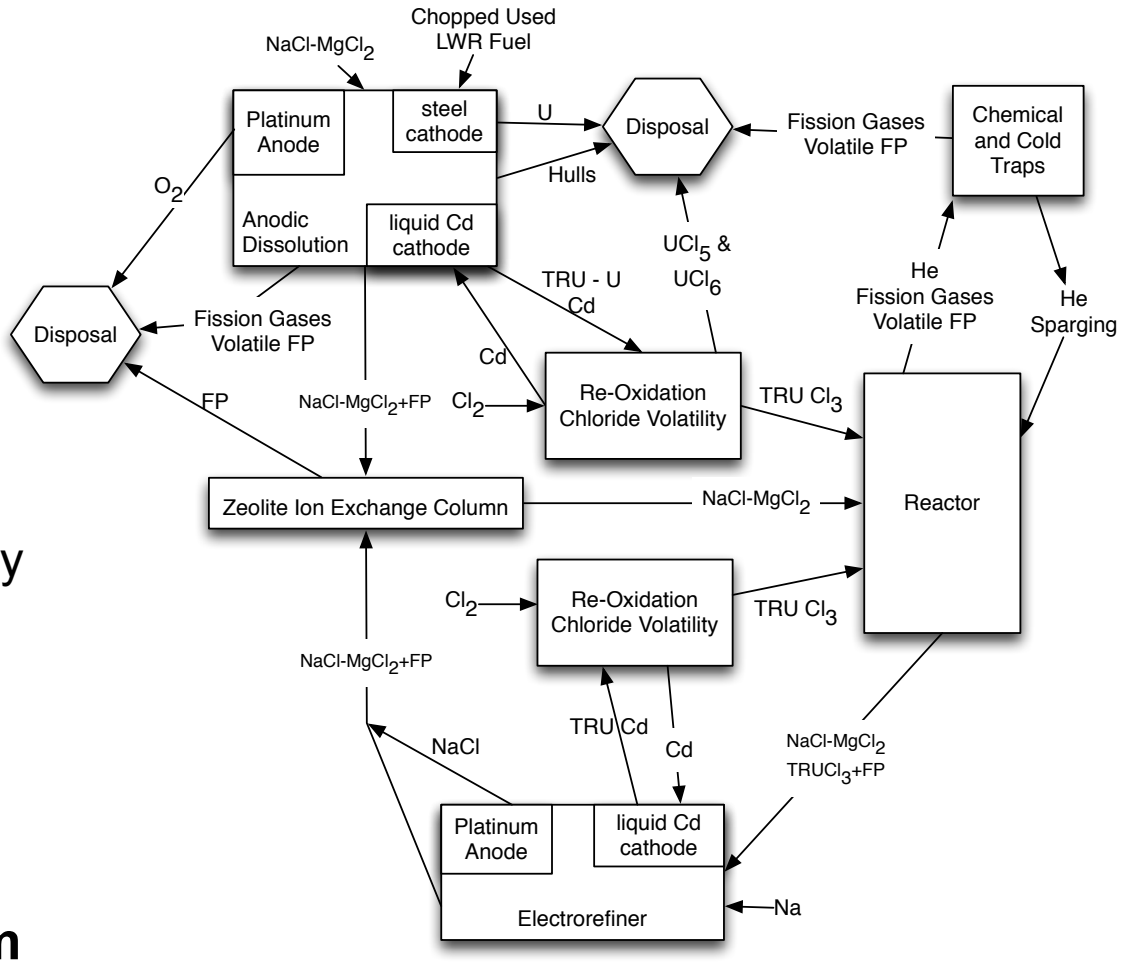


Used LWR Fuel Can Either Be Processed at a Reprocessing Facility or Directly Sent to the MSR

- **Centralized fuel recycling facility would produce TRU oxide that would be reduced and fluoridated or chlorinated at the MSR site**
- **Nitrogen trifluoride and sulfur hexafluoride based fluoride volatility separations processes are currently under investigation**
  - Nitrogen Trifluoride-Based Fluoride-Volatility Separations Process: Initial Studies (PNNL-20775, FCR&D-SWF-2011-000390) recently published – available from PNNL
- **Direct acceptance of used LWR fuel avoids the requirement for large, centralized reprocessing facilities**
- **Economy of scale and simplicity of processing are key design issues**

Reprocessing Technologies Have Been Demonstrated For Both Chloride and Fluoride Salts

- **Fluoride salt processing based upon technology developed under the thermal-spectrum MSR program**
  - Combination of fluoride volatility and reductive extraction
  - Ongoing process technology development in US and the Czech Republic
- **Chloride salt processing closely follows approach developed under Integral Fast Reactor (IFR) program**
  - EBR-II fuel reprocessed using chloride salt based technology



IFR Derived Chloride Salt Reprocessing

Reactor Concept Remains Too Immature for Confident Economic Analysis

Attribute	Impact	Cost Implications
Liquid fuel	• No solid fuel fabrication or qualification • Wide tolerance of isotopic variation • Passive melt plug core dump possible • Easier on-line fuel addition	• Much lower fuel fabrication and development costs • Active decay heat removal systems not required
Large fuel salt coefficient of thermal expansion	• Negative thermal reactivity feedback	• Limited (no?) active safety systems
High primary coolant volumetric heat capacity	• Low fluid pumping requirements • Near-constant-temperature energy transport	• Compact coolant and heat transport loops (small pipes, pumps, heat exchangers)
Highly active primary coolant	• Remote handling required	• More complex and expensive maintenance
Low primary system pressure	• Low pipe break / LOCA energetics • Low source term driving pressure	• Thin-walled vessel and piping • Smaller, simpler containment
Transparent coolant with low chemical activity	• Visible operations • Low pipe break / LOCA energetics	• Smaller containment
High primary system temperatures	• High cycle efficiency • High temperature fluid – materials corrosion and strength performance	• Lower capital cost and fuel costs • Higher materials cost • Thermochemical cycles possible
Integrated fuel reprocessing possible	• Necessitates chemical processing plant • Increases proliferation concerns	• Higher capital cost • Limited export market

FS-MSRs Have Strong Potential Safety Characteristics, But Significant Licensing Challenges

- **Inherent high degree of passive safety – unique for a fast spectrum reactor**
  - Negative void and temperature reactivity feedback due to fuel thermal expansion
  - Melt plug draining into subcritical decay tanks with passive decay heat removal
- **Liquid fuel and fuel reprocessing involves more frequent manipulation of highly radioactive liquids increasing likelihood of small spills**
- **Current licensing process is not oriented towards liquid fueled reactors**
  - Recent homogenous aqueous reactors for medical isotope production provide example licensing path
- **Both licensing strategy and safety analysis methodology need to be developed**
- **Concept needs to be matured to enable reasonable safety evaluation**
  - Reactor and heat transfer system require baseline design
  - Concept of operations and required technologies remain largely unknown
  - Qualified structural alloys are not available (chloride salt option presents larger unknowns)
- **Reactor configurations including fissile material separation may not be licensable for export**

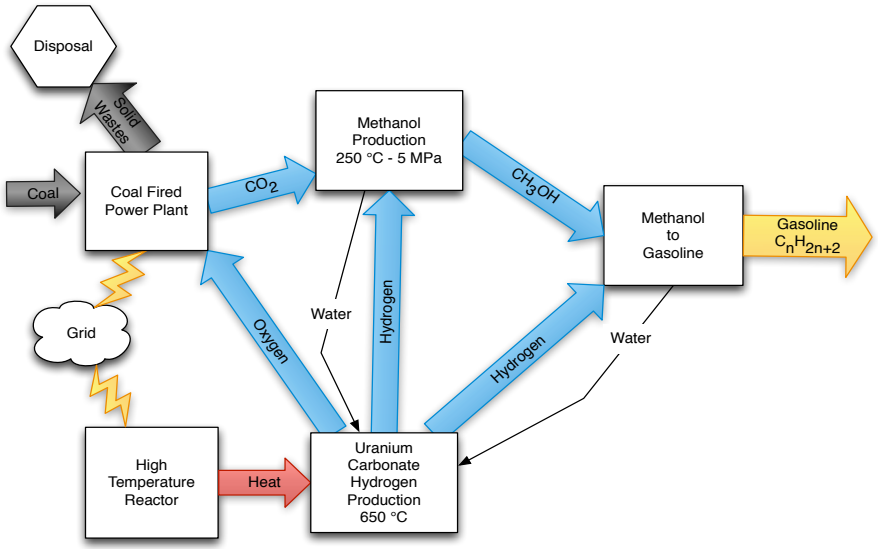
Structural Materials Appear To Be Available for MSR Components

STRUCTURAL MATERIAL	COMPONENT	USAGE TEMPS (550-650°C)	FLUORIDE SALT RESISTANCE*	CHLORIDE SALT RESISTANCE*	RADIATION RESISTANCE	FABRIC-ABILITY
High Nickel Alloy or Cladding	RPV, Piping, HXs, Pumps	Good	Excellent	Uncertain	Poor	Good
Stainless Steels	RPV, Piping, HXs, Pumps	Good	Variable	Uncertain	Okay	Excellent
Ferritic Martinsitic Steels	RPV	Limited	Unknown	Uncertain	Excellent	Excellent
Refractory metals	Shields, Pumps	Excellent	Variable	Uncertain	Variable	Poor
Graphite	Shields	Excellent	Excellent	Uncertain	Okay	Good
Carbon-Carbon Composites	RPV, Piping, Shields	Excellent	Excellent	Uncertain	Good	Okay
Silicon Carbide	Shields, HXs	Excellent	Excellent	Uncertain	Excellent	Okay
SiC-SiC Composities	Shields, HXs	Excellent	Excellent	Uncertain	Excellent	Okay

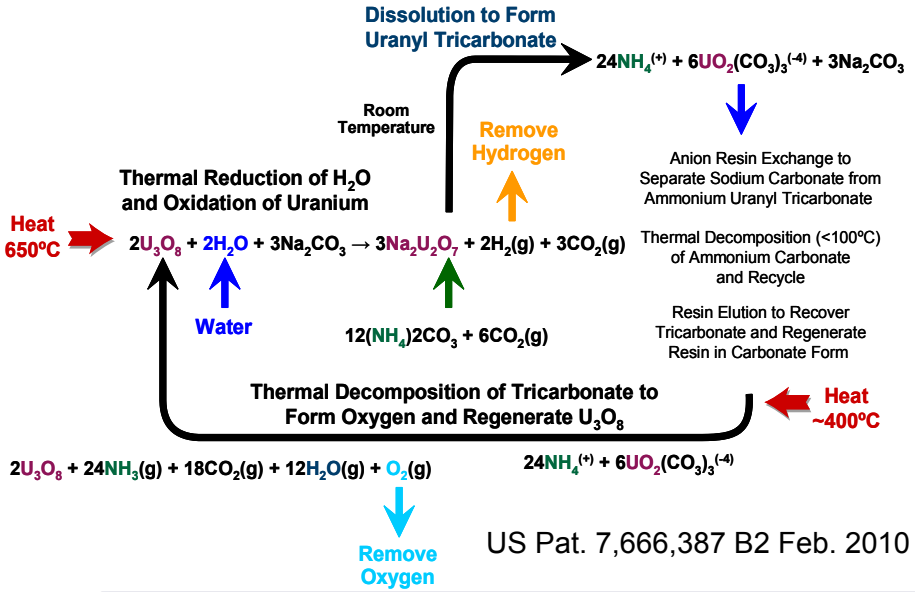
*With chemistry control

MSRs Are High Temperature Reactors and Can Support Industrial Process Heat Production

- **High temperature reactors can efficiently produce large quantities of hydrogen**
- **Hydrogen production is key to enabling nuclear reactors to participate in the hydrocarbon energy cycle**



High temperature reactors can produce gasoline while removing carbon dioxide from the atmosphere



US Pat. 7,666,387 B2 Feb. 2010

Carbonate thermochemical hydrogen cycle efficiently couples to FHR heat

FS-MSR Options Summary

- **FS-MSRs build upon the large national investment in molten salt reactors**
  - Prior operation of molten salt reactors significantly increases the concept practicality
- **A modified open fuel cycle format (capture fission gasses and mechanically filter out noble metal particles) may enable a non fuel cycle state exportable fast spectrum reactor**
- **Avoidance of a solid fuel (capable of accommodating the wide range of isotopic compositions of used LWR fuels) development and qualification effort appears to accrue substantial economic benefits to the FS-MSR concept**
- **Due to lack of detailed system design information, evaluation of most fuel cycle performance parameters is cursory**