High-Temperature Reactors for In Situ Recovery of Oil from Oil Shale

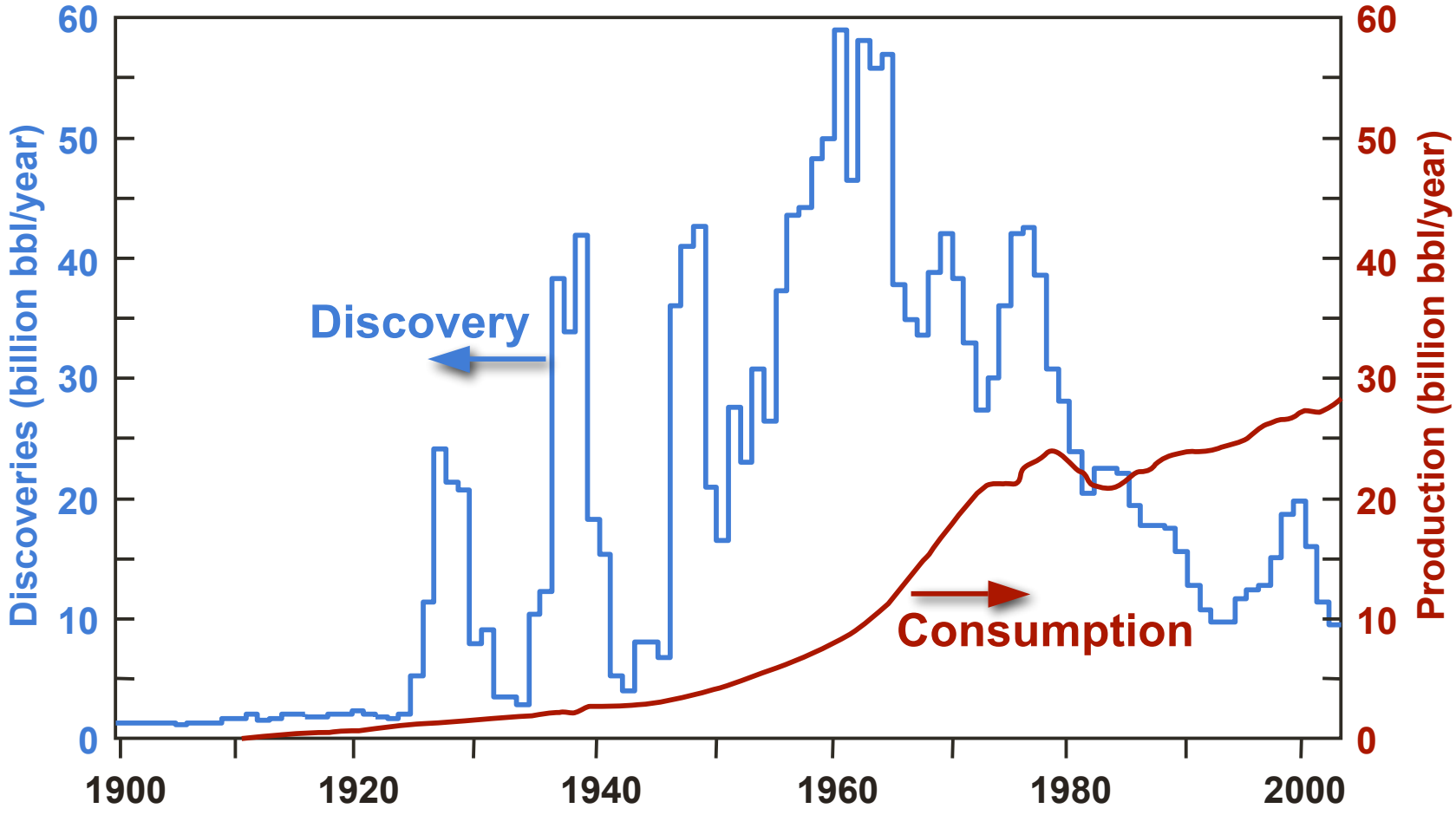
Charles W. Forsberg

Oak Ridge National Laboratory*
P.O. Box 2008; Oak Ridge, TN 37831-6165
Tel: (865) 574-6783; e-mail: forsbergcw@ornl.gov

ICAPP'06; Session 9.03; Paper 6104
2006 International Congress on Advances in Nuclear Power Plants
1:00 P.M., Wednesday, June 7, 2006
Reno, Nevada

*Notice: This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. File name: Hydrogen: ICAPP06 Oil Shale

The Era of Oil for Fuels Is Ending



Oil and Gas J.; Feb. 21, 2005

Conventional Futures: Liquid Fuels from Heavy Oils and Tar Sands

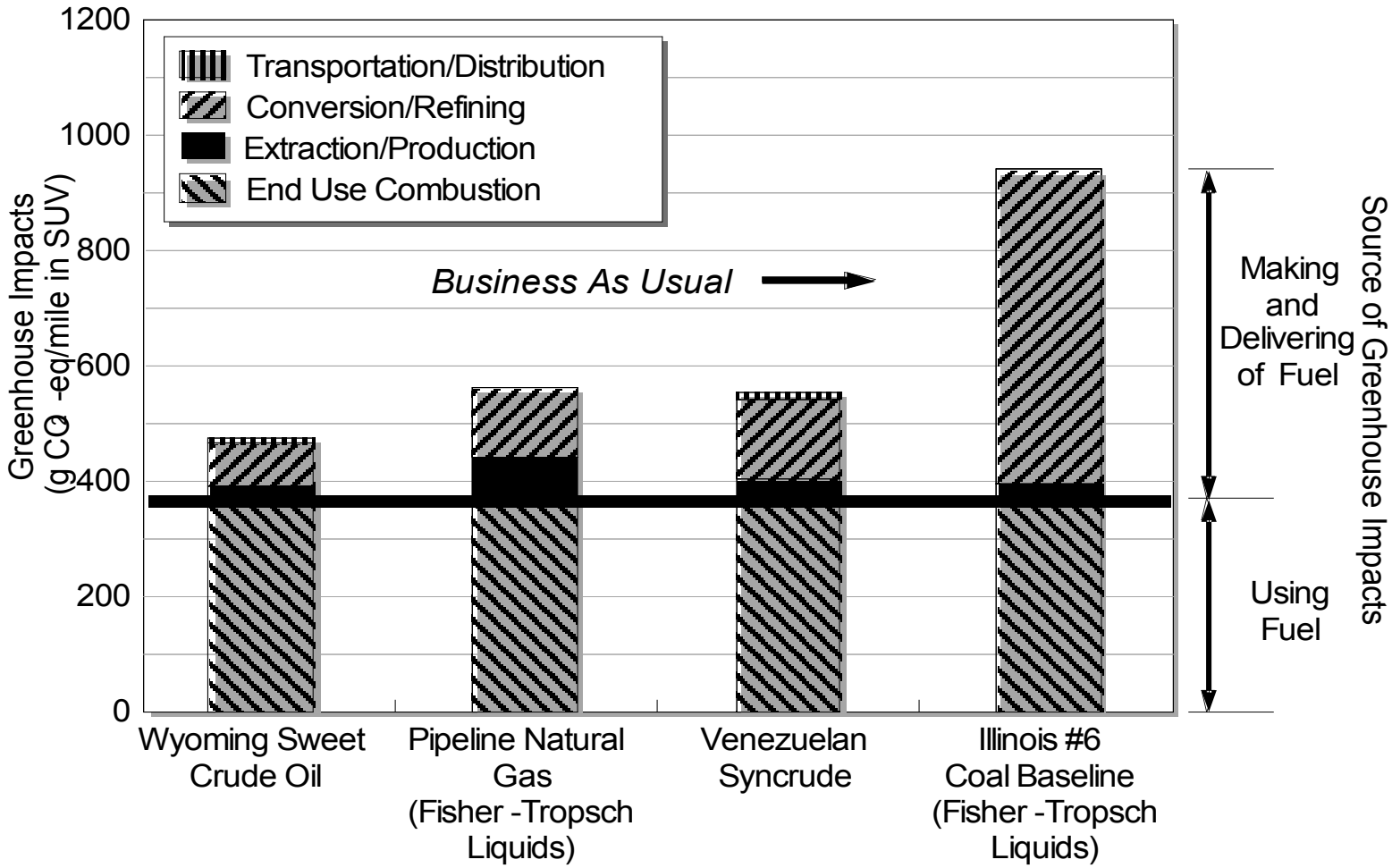
(Lower Hydrogen-to-Carbon Ratios)

Syncrude Canada Ltd.
Tar Sands Operations

- **Tar sands and heavy oils are converted to liquid fuels by:**
  - **Addition of hydrogen**
  - **Removal of carbon (usually with CO_2 to the atmosphere)**
- **Traditional technologies imply major increases in CO_2 releases per vehicle mile (greenhouse-gas concern)**

Business-as-Usual Liquid Fuels Imply Increased Greenhouse-Gas Releases

(Alternative Liquid-Fuel Feedstocks Increase CO_2 Releases from the Production Process)

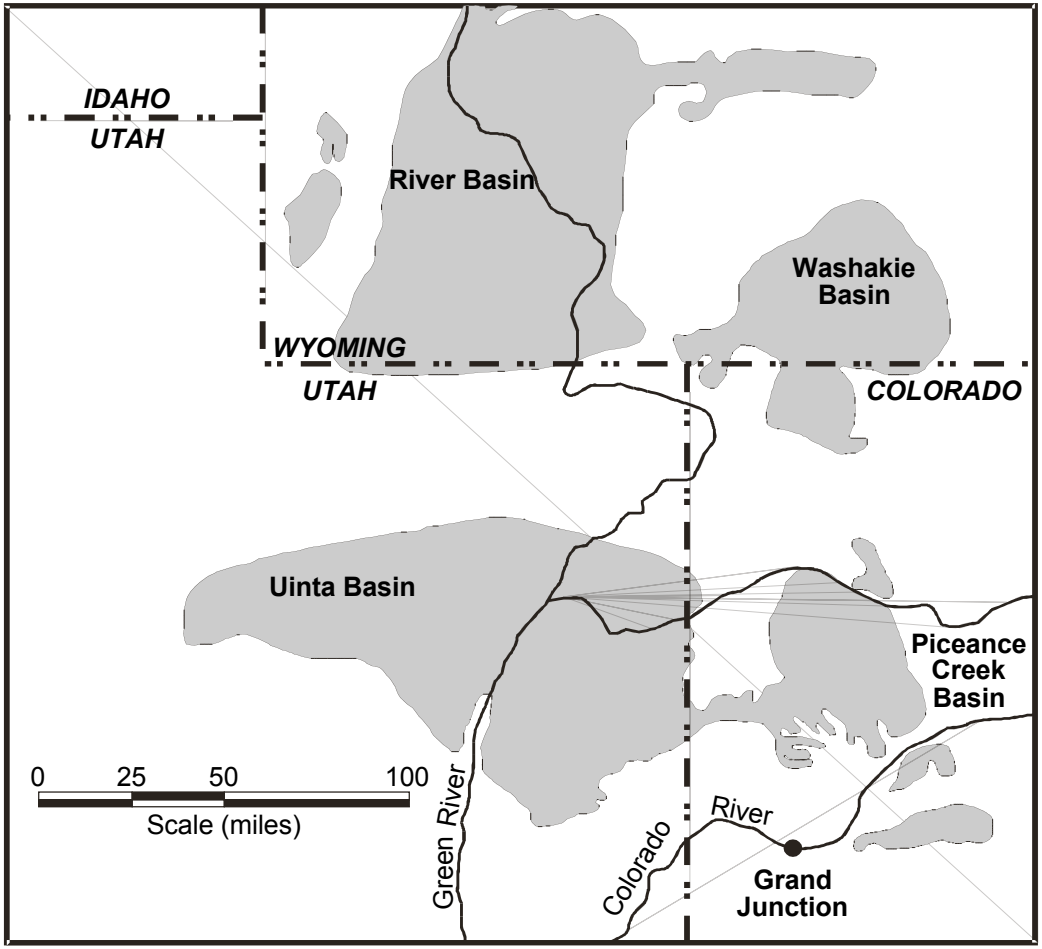


An Alternative

Shale Oil Produced Using High-Temperature Nuclear Heat

Shale Oil Is a Massive American Resource for High-Quality Crude Oil

- ~800 billion barrels of oil
- Oil resources 3 times those of Saudi Arabia
- ~100-year oil supply for the United States



Traditional Shale Oil Production

- Heat oil shale by burning with oxygen
  - High temperatures cause chemical reactions that yield shale oil
  - The oil shale is heated rapidly
  - The process produces a low-quality, unstable oil that requires major refining operations
  - Large carbon dioxide releases
- The process is expensive
  - Projected first-generation commercial plants: $70 to $95 per barrel of oil
  - Long term: $30 to $40 per barrel of oil

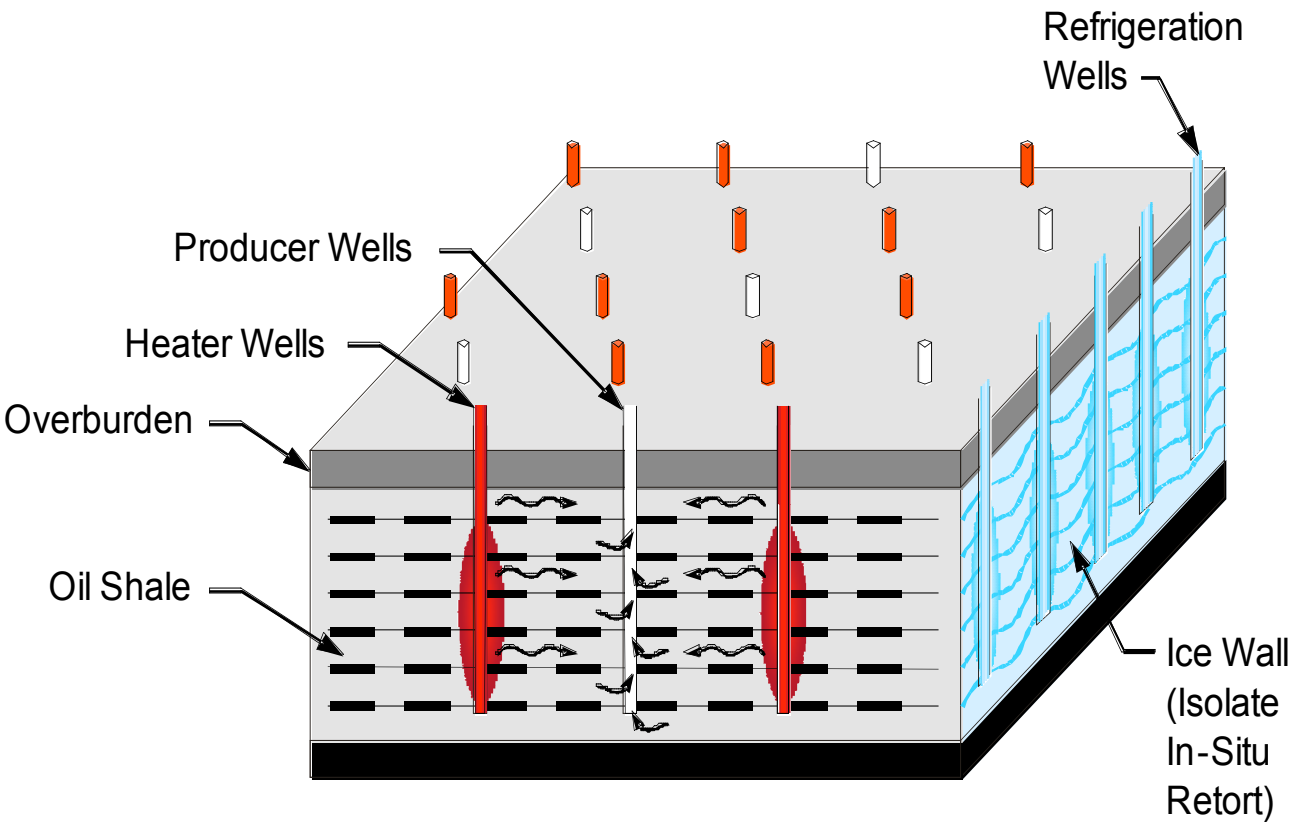
New Shale Oil Process

Shell Oil-Shale Process

- Oil shale is heated slowly over many months under chemically reducing conditions
  - In situ heating of oil shale to high temperatures using electrical heaters
  - Process parameters produce a high-quality stable light-crude oil with limited refining requirements
- To produce 5 million barrels of oil per day will require 60,000 MW(e)
  - Equals one quarter of U.S. crude oil demand
- Economics
  - ~$30/barrel
  - Half the cost is electricity [$0.05/kW(e)-h]
- Primary environmental impact is electricity production

The Shell In Situ Conversion Process:

Heat Oil Shale Electrically to High Temperatures to Release Liquid Fuel



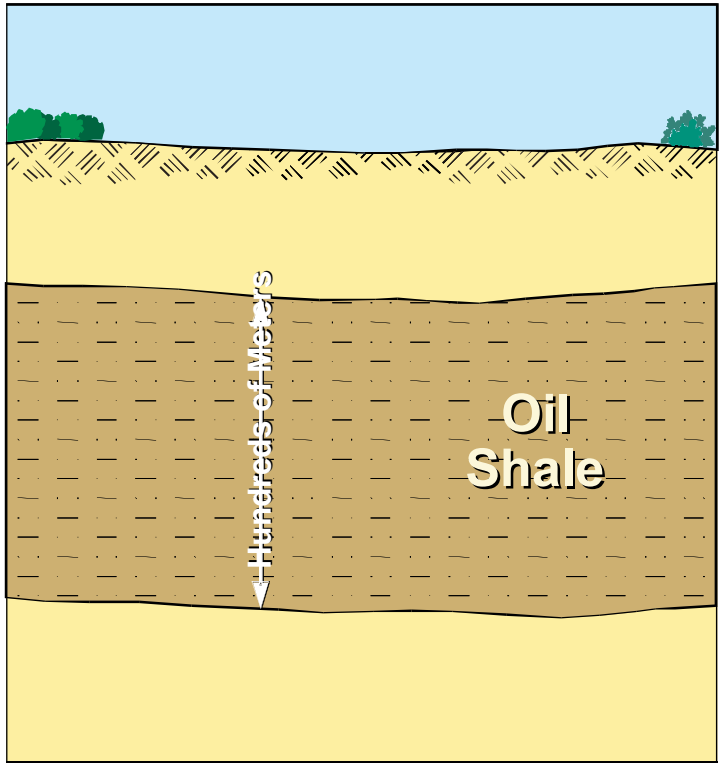
Incentives to Replace Electric Heat with Nuclear High-Temperature Heat

- **Economics**
  - **Electricity to heat the shale to high temperatures is half the production cost of the shale oil**
  - **A high-temperature nuclear reactor can directly produce this heat**
  - **Direct use of heat rather than electricity avoids losses in converting heat to electricity and then back to heat**
    - **Energy requirements are reduced by a factor of 2 to 3**
    - **Lower capital investments**
    - **Low water requirements (local water shortages)**
- **Avoids the greenhouse-gas impacts from burning fossil fuels to produce electricity**

The Characteristics of Oil Shale Deposits Make Nuclear Heat Viable

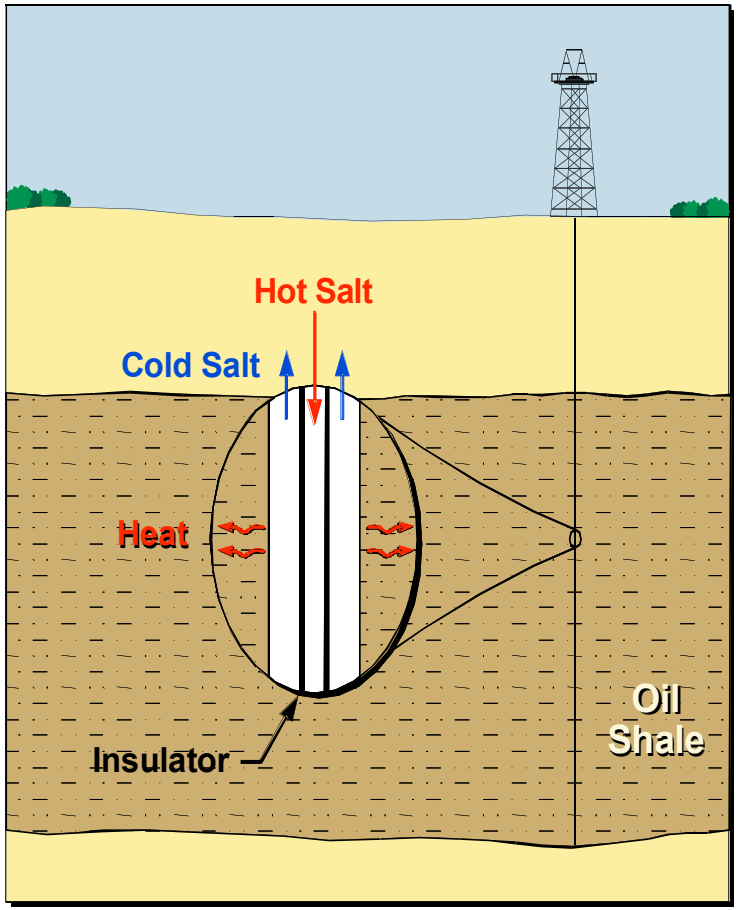
(Most-Concentrated Fossil Resource on the Planet)

- Heat transmission distances are limited
- Oil shale deposits
  - Thick
  - 10^6 barrels of oil per acre
  - 250-300 kW-h/barrel
- For a 600 MW(t) reactor
  - 40 years of operation
  - <2-km piping distance to well head



Key Challenge: Down-Hole Heat Transport

- Heater wells are bayonet heaters
  - Insulated inner pipe
  - Kilometer-long pipe
- Heat-transfer-fluid requirements
  - High volumetric heat capacity
  - Low pumping costs
  - Low pressures



Liquid Salts May Be Required for the Heat Transport System

- Characteristics
  - Chemically stable
  - High volumetric heat capacity
  - High boiling point
- Candidate systems
  - Fluorides
  - Chlorides
- Same salts being considered for other systems
  - Molten Salt Reactor
  - Heat transport system between high-temperature reactors and hydrogen production facilities
  - Advanced High-Temperature Reactor
    - Salt coolant
    - Coated-particle fuel

Comparison of Heat Transfer Liquids

Coolant[a]	T_{melt} (°C)	T_{boil} (°C)	ρ (kg/m³)	C_p (kJ/kg °C)	ρC_p (kJ/m³ °C)
LiF-NaF-KF (46.5-11.5-42)	454	1610 (est)	2,020	1.89	3820
$NaF-NaBF_4$ (8-92)	385	700	1,750	1.51	2640
$NaNO_3-KNO_3$ (66.3-33.7)	221	*b*	1772	1.53	2710
Sodium	97.8	883	790	1.27	1000
Water (7.5 MPa)	0	100	732	5.5	4040

[a]Composition in molar percent; [b]Nitrates decompose near 600ºC

Conclusions

- Oil shale is an American mega-oil source
- Shell process projected to dramatically lower shale-oil production costs
- Electricity is the primary production cost
- Incentives for use of nuclear high-temperature heat versus electricity
  - Avoid conversion loses of heat to electricity and then back to heat
  - Low greenhouse-gas emissions
  - Low water consumption (local water shortages)
- Several technical challenges remain