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Past, Present, and Future of Molten Salts for Nuclear Reactors

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Changing the World's Energy Future

David Eugene Holcomb

Idaho National Laboratory

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David Holcomb
Molten Salt Reactor Technology Lead

Molten Salt Reactor PROGRAM

Past, Present, and Future of Molten Salts for Nuclear Reactors

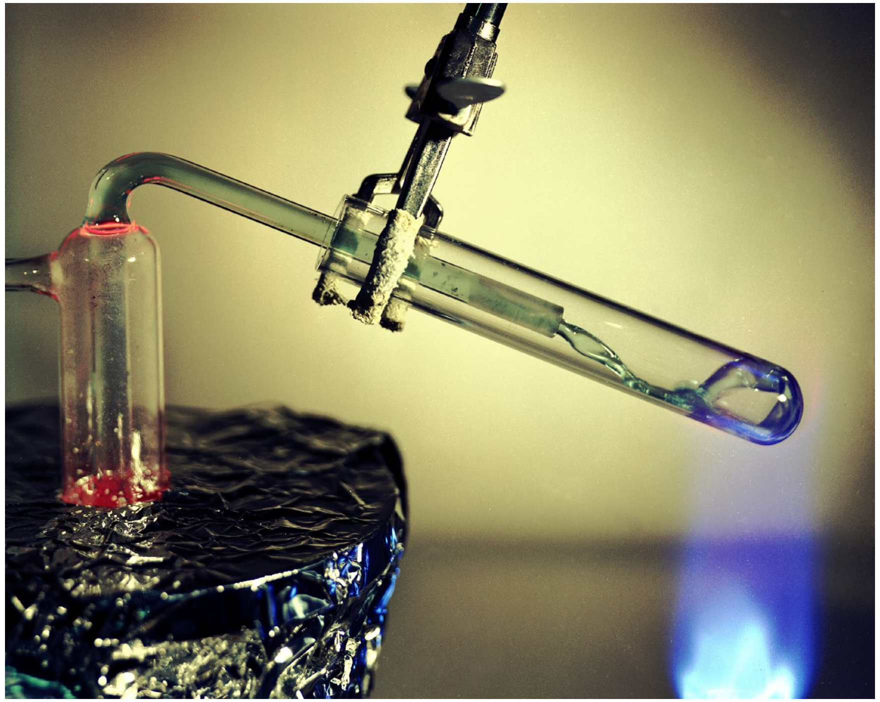
Molten Salt – Powering the Future Workshop

Idaho Falls, ID

INL Idaho National Laboratory

What Are Salts Useful for at Nuclear Reactors?

- Fuel
- Coolant
  - Transfer of fission and decay heat
- Thermal storage
  - Decouple reactor from balance-of-plant (BOP)
    - BOP becomes industrial grade
  - Buffers supply–demand imbalance
- Chemical separations
  - Actinides, fission products, and contaminants from carrier
  - Valuable isotopes

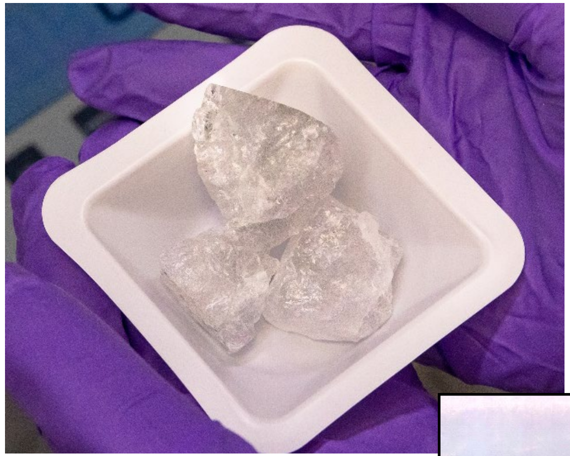


Molten Salt Flow

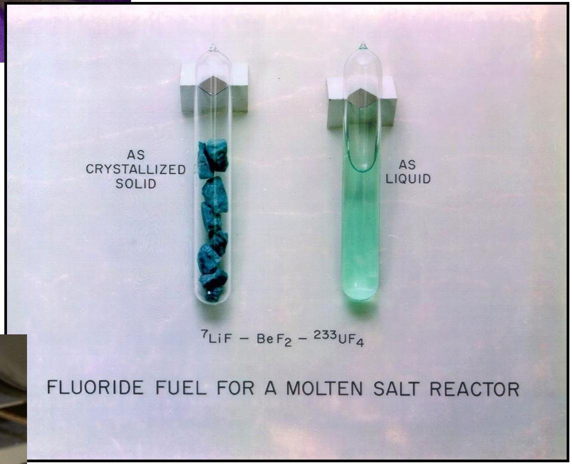
ORNL Photo 93359 – Approved for public release

What Is So Special About Salts (Versus Water, Liquid Metals, Gas)?

- High solubility for uranium, plutonium, and thorium
- Stable thermodynamically
  - No radiolytic decomposition at elevated temperature
- Low chemical potential energy (no vigorous reactions with air or water)
- Excellent heat transfer
  - Forced and natural circulation
  - Large heat capacity
- Very high boiling points
  - Low vapor pressure at operating temperatures
- Adequately compatible with nickel-based structural alloys and graphite
- Compatible with chemical processing



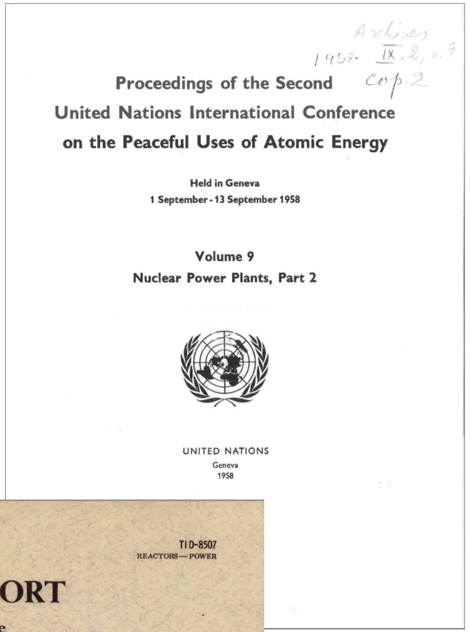
FLiBe Salt



Plutonium Chloride

Advantages of Salts for Liquid Fuels Were Recognized Early On

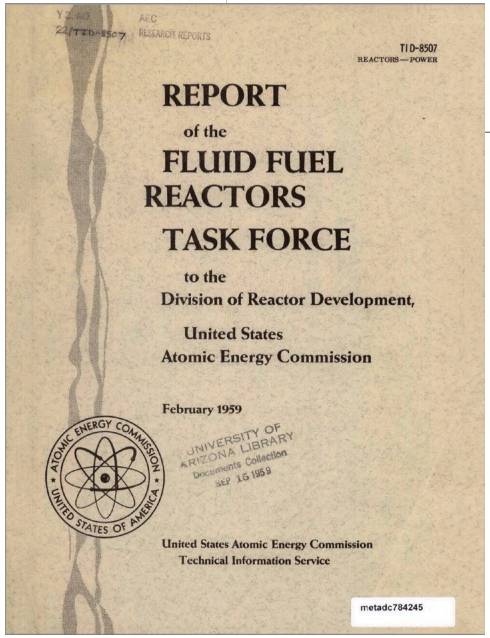
- Water radiolysis resulted in gas bubbling—hydrogen
- Much higher boiling points
- First salts were hydroxides
  - Small thorium solubility
  - Unacceptable corrosion
- Alkali halide salts adopted by 1950
- Presented by the United States to the world at the second Atoms for Peace conference in 1958
- Variant of *Fluid Fueled Reactors* selected as having the “highest potential for achieving technical feasibility”
  - Th-U breeding fuel cycle in a homogeneous reactor first described in 1944


Proceedings of the Second
United Nations International Conference
on the Peaceful Uses of Atomic Energy

Held in Geneva
1 September - 13 September 1958

Volume 9
Nuclear Power Plants, Part 2

UNITED NATIONS
Geneva
1958


AEC RESEARCH REPORTS

TID-8507
REACTORS—POWER

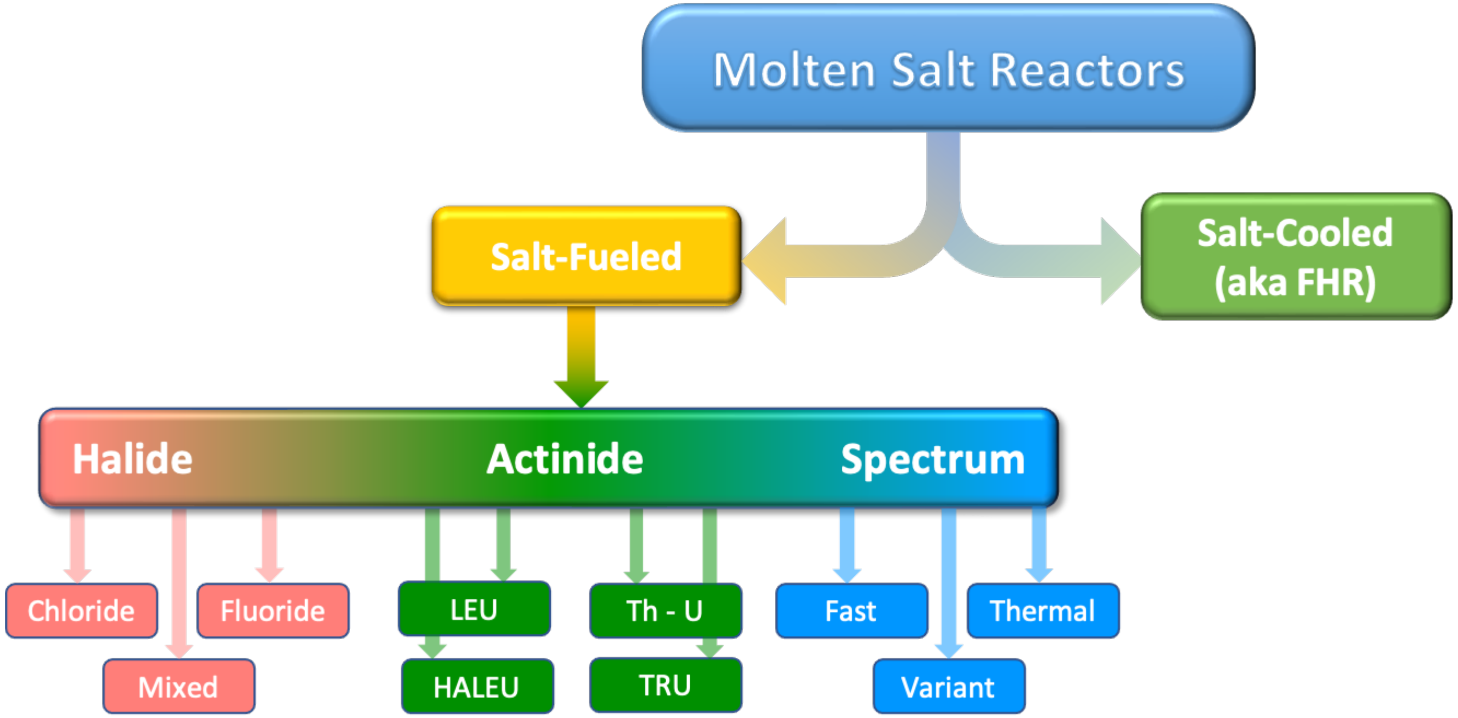
REPORT
of the
FLUID FUEL
REACTORS
TASK FORCE
to the
Division of Reactor Development,
United States
Atomic Energy Commission

February 1959

ATOMIC ENERGY COMMISSION · UNITED STATES OF AMERICA

United States Atomic Energy Commission
Technical Information Service

Molten Salt Reactors (MSRs) are Nuclear Reactors in Which Molten Salt Performs a Significant Function in Core



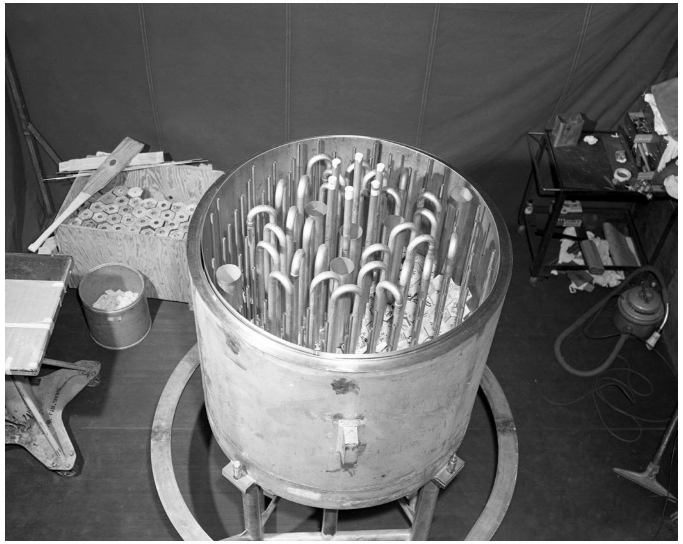
- Liquid- and solid-fueled variants
- Chloride-, fluoride-, and mixed halide-based fuel salts
- Salt and liquid-metal coolants
- Thermal, fast, time-variant, and spatially variant neutron spectra
- Wide range of power scales
- Intensive, minimal, or inherent fuel processing
- Multiple different primary system configurations
- Nearly all fuel cycles

Molten-salt breeder reactors are MSRs that produce more fissile material than they consume.

Aircraft Reactor Experiment (ARE) Successfully Demonstrated Liquid Salt Concept in 1954

- Demonstrated ability to build and operate a high-temperature (860°C), low-power circulating fuel reactor
  - Operated from 11/03/54 to 11/12/54
- Liquid fluoride salt circulated through beryllium oxide reflector in Inconel tubes
- $^{235}UF_4$ dissolved in NaF-ZrF_4
- Nuclear operation over 221 h period
  - Last 74 hours were in MW range
  - Up to 2.5 MW_t
- Produced 96 MW-h of nuclear energy
- Gaseous fission products were removed naturally through pumping action

ARE Core During Assembly



- Very stable operation due to high negative reactivity coefficient
- Demonstrated load-following operation without control rods
- Low-power experiments
  - Reactor power calibration
  - Rod calibration
  - Preliminary measurement of the temperature coefficient
- High-power experiments
  - Power levels: 10 kw, 100 kw, 500 kw, and 1 MW
  - Temperature coefficient of reactivity
  - Reactor power calibration from process instrumentation
  - 25 h ^{135}Xe buildup experiment—no build up in salt
  - Reactor temperature cycling—21 times between high and low power
  - Time lags, temperatures, transit time of fuel

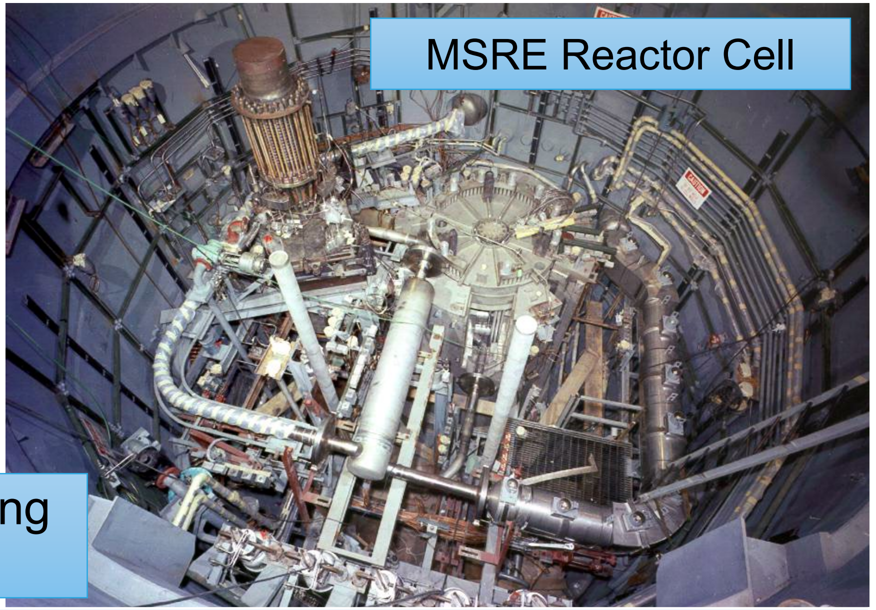
ORNL Successfully Demonstrated Key MSR Technology at the MSRE

- Design of MSRE commences: **1960**
- ORNL receives directive to construct and operate MSRE: **April 28, 1961**
- Construction begins: **1962**
- Salt loaded into tanks: **Oct. 24, 1964**
- Salt first circulated through core: **Jan. 12, 1965**
- First criticality (U^{235}): **June 1, 1965**
- First operation in megawatt range: **Jan. 24, 1966**
- Full power reached: **May 23, 1966**
- Nuclear operation with U^{235} concluded: **March 26, 1968**
- Strip uranium from fuel salt: **Aug. 23–29, 1968**
- First criticality with U^{233}: **Oct. 2, 1968**
- Full power reached with U^{233}: **Jan. 28, 1969**
- Nuclear operation concluded: **Dec. 12, 1969**

"MSRE stands for not only molten salt reactor experiment but also for mighty smooth-running experiment…"
–Alvin Weinberg

"So far the Molten Salt Reactor Experiment has operated successfully and has earned a reputation for reliability."
– USAEC Chairman, Glenn T. Seaborg

MSRE Reactor Cell

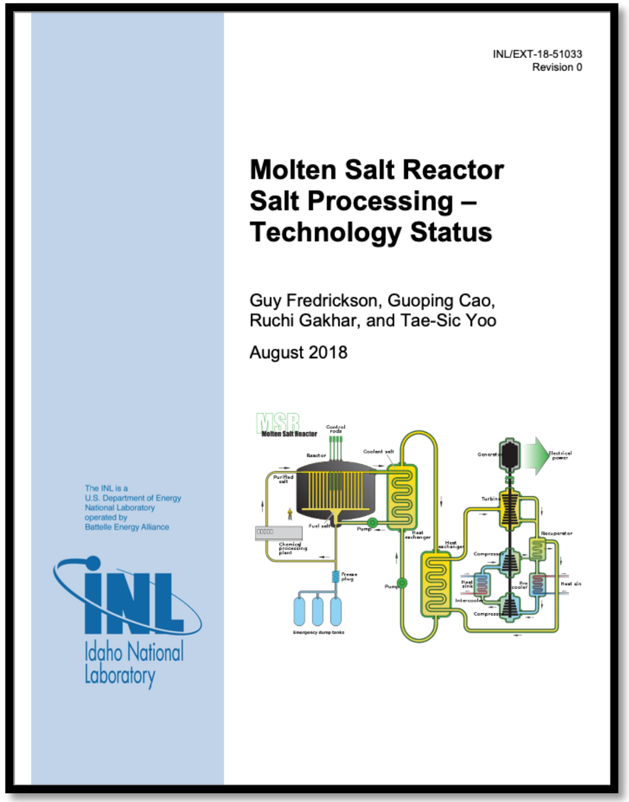


MSRE Operating Statistics

Full power	13,172 h ^{235}U 9,005 h ^{233}U 4,167 h
Fuel salt circulation time	21,788 h
Coolant salt circulation time	26,076 h
Availability during planned reliability testing period (final 15 months with ^{235}U)	86%
Availability during final runs with ^{235}U	98.6%
Availability during final runs with ^{233}U	99.9%

Salts and Water are Carrier Options for Nuclear Fuel Separations

- Multiple different separations methods possible in salt
  - Distillation, reductive extraction, oxidative precipitation, selective crystallization, electrowinning, etc.
- Separations enable nuclear fuel recycling, efficient waste for development, fissile material breeding, isotope extraction
- Not yet on industrial scale for nuclear fuel
  - Application-specific scale-up issues
- Aluminum production using Hall-Héroult cells at industrial scale for a century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Revision 0

Molten Salt Reactor Salt Processing – Technology Status

Guy Fredrickson, Guoping Cao, Ruchi Gakhar, and Tae-Sic Yoo

August 2018

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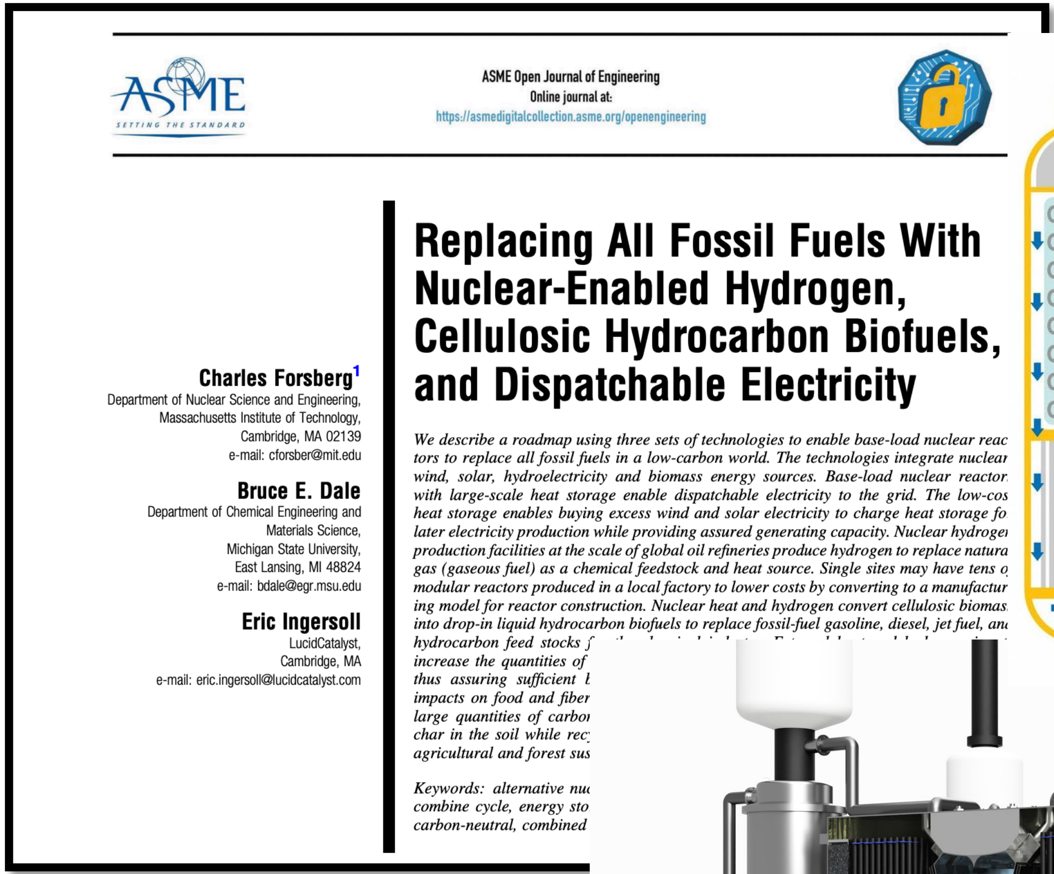
Molten Salts Broaden What Nuclear Power Plants Can Do



ASME Open Journal of Engineering
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https://asmedigitalcollection.asme.org/openengineering

Replacing All Fossil Fuels With Nuclear-Enabled Hydrogen, Cellulosic Hydrocarbon Biofuels, and Dispatchable Electricity

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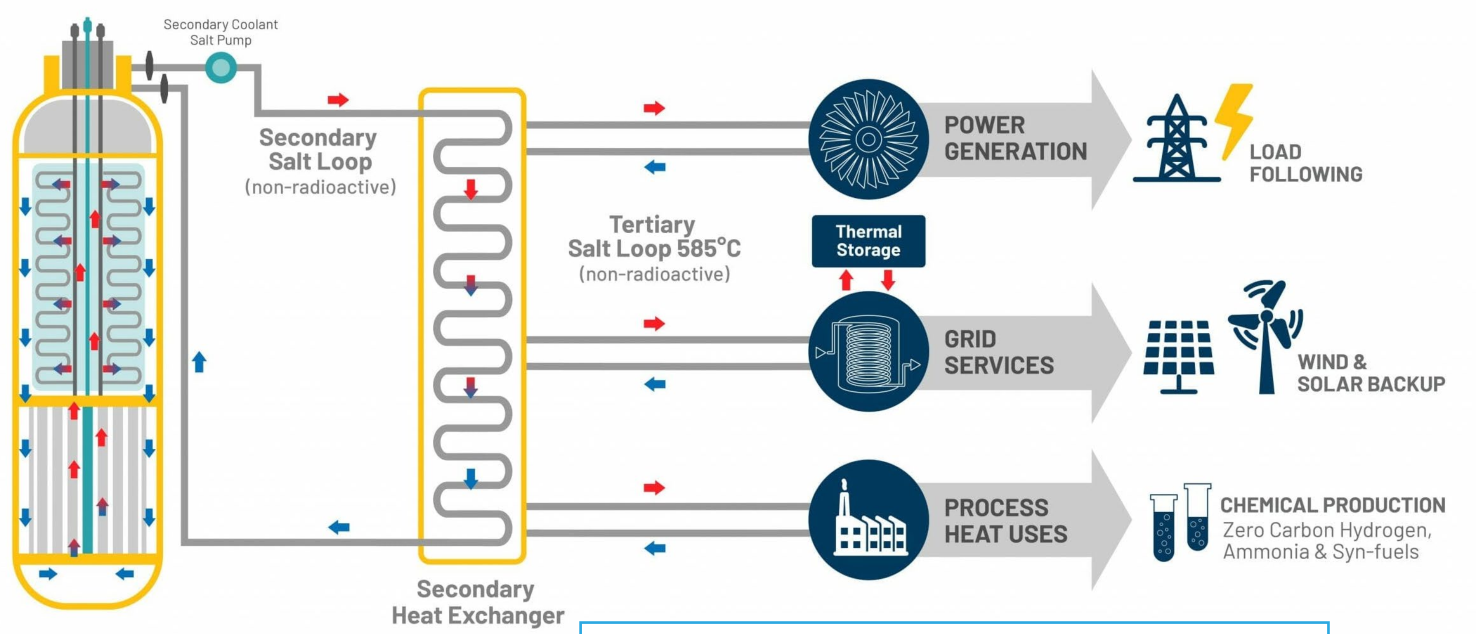
We describe a roadmap using three sets of technologies to enable base-load nuclear reac tors to replace all fossil fuels in a low-carbon world. The technologies integrate nuclear wind, solar, hydroelectricity and biomass energy sources. Base-load nuclear reactor with large-scale heat storage enable dispatchable electricity to the grid. The low-cos heat storage enables buying excess wind and solar electricity to charge heat storage fo later electricity production while providing assured generating capacity. Nuclear hydroge production facilities at the scale of global oil refineries produce hydrogen to replace natura gas (gaseous fuel) as a chemical feedstock and heat source. Single sites may have tens o modular reactors produced in a local factory to lower costs by converting to a manufactur ing model for reactor construction. Nuclear heat and hydrogen convert cellulosic biomas into drop-in liquid hydrocarbon biofuels to replace fossil-fuel gasoline, diesel, jet fuel, an hydrocarbon feed stocks f increase the quantities of thus assuring sufficient b impacts on food and fiber large quantities of carbo char in the soil while rec agricultural and forest sus

Keywords: alternative nu combine cycle, energy sto carbon-neutral, combined

https://doi.org/10.1115/1.4064592



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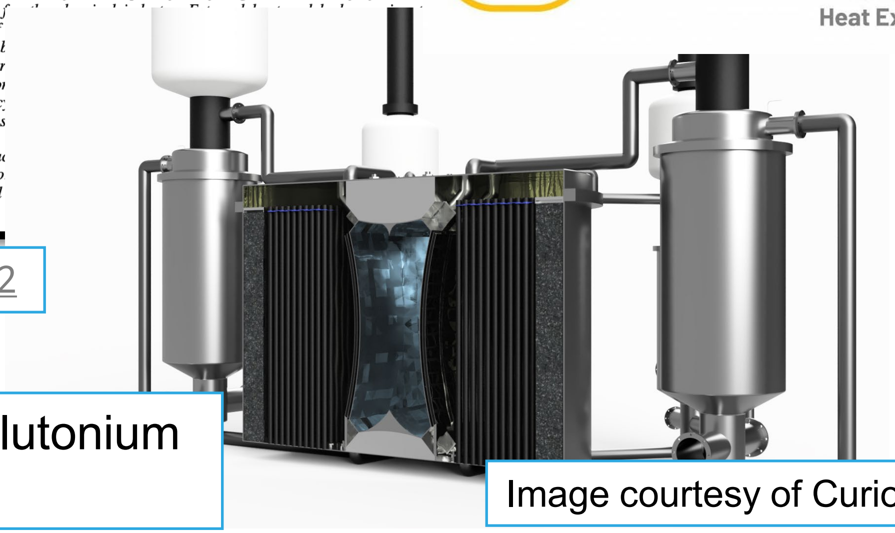

hope® – Homogeneous Plutonium Eliminating Reactor

Image courtesy of Curio Legacy

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