URANIUM-THORIUM LIQUID-SALT REACTOR FOR PRODUCING VALUABLE RADIOISOTOPES

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BOTTOM LINE

- **Valuable radioisotopes – such as tritium, He-3, Mo-99, and Np-237**

- **could be produced and separated most efficiently and profitably**

>> in a single,
>> small,
>> fluid thorium or uranium fuel,
>> liquid-salt-cooled reactor (LSR)
>> most likely situated on a government reservation

SCOPE OF PRESENTATION

- **Survey of current and changing status**

- **For such valuable byproducts, specifically:**

  >> utilization,
  >> supply,
  >> shortages,
  >> and production options

- **Ralph Moir and I gave a longer, more technical version of this presentation**

  >> yesterday
  >> at Argonne National Laboratory

RADIOISOTOPE PRODUCTION AND APPLICATIONS

- **Some radioisotopes indispensable**

  >> for applications in medicine, industrial research, nuclear weapons, national security, and outer space

- **Special considerations**

  >> their rarity,
  >> production cost,
  >> and handling requirements

- **Radioisotopes are valuable commodities on the open market**

MOLYBDENUM-99 RADIOISOTOPE

- **The most common medical radioisotope**

  >> technetium-99
  >> half-life 6 hours (short, medically-efficient lifetime)

- **~ 30 million medical procedures per year**

  >> accounting for 80% of all nuclear diagnostic procedures worldwide.

- **Derived from**

  >> molybdenum-99 nuclear-reactor fission product
  >> half-life 66 hours (manageable lifetime for production and shipment)

PRODUCTION OF RADIOISOTOPES

- **Almost all diagnostic and therapeutic radioisotopes**

- **Produced in nuclear reactors,**

    >> mostly being byproducts of the fission process
    >> either in reactor fuel
    >> or in specifically designed targets
    >> that contain fissile materials

- **Nuclear accelerators have a small specialized role**

NUCLEAR-WEAPON TRITIUM REQUIREMENTS

- **Require tritium**

  >> that must be replenished
  >> after an unknown fraction — perhaps half —
  >> of tritium having decayed with its 12.3 year half-life

- **In addition,**

  >> research and development
  >> of controlled fusion calls for considerable tritium

HELIUM-3

- **The decay product of tritium is the very rare gas helium-3**

  >> Supply dependent on recovery from nuclear weapons
  >> (Not the same issue as shortage in conventional helium gas)

- **Helium-3 especially useful now in neutron detectors,**

  >> especially those deployed for homeland security throughout the world

- **Also important basic research applications**

Plutonium-238

- **The heavy non-fissile radioisotope plutonium-238**

  >> produced from neptunium-237 in high-power reactors,
  >> ideal for thermoelectric generators,
  especially for long missions in outer space
  >> not usable for nuclear explosives

- **In U.S. national-security and non-proliferation restrictions**

  >> for radioisotopes tritium, helium-3, and Plutonium-238
  >> require government control and processing
  >> in government facilities

NATIONAL-SECURITY AND NON-PROLIFERATION CONSTRAINTS

- **Radioisotopes tritium, helium-3, and plutonium-238**

  >> require government control and processing
  >> in government facilities

SHORTFALLS
IN MEDICAL-RADIOISOTOPE PRODUCTION

- **Ongoing and emerging shortfalls**

  >> in supplies of valuable radioisotopes
  >> recognized by various international and national commissions

- **At present, there are no major producers in the United States**

  >> of molybdenum-99 for medical use
  >> for medical use in the United States

- **Most of current molybdenum-99 world production**

  >> by inefficient irradiation of solid targets
  >> low-enriched uranium
  >> in research and test reactors

LONGER-TERM RADIOISOTOPE SHORTFALLS

- **In the distant future:**

  >> additional demand likely from thermonuclear fusion breeders
  >> require a large tritium inventory for startup.

- **Near term:**

  > United States and the surrounding world
  > far more viable applications than forthcoming supply
  > for these and some other rare radioisotopes.

PROPOSED LIQUID-SALT REACTOR FOR RADIOISOTOPE PRODUCTION

- **Small nuclear reactor proposed**

  >> to supply specialized radioisotopes
  >> in a timely, cost-effective, and secure manner

- **Mixed liquid-salt combination of fuel and coolant.**

  >> reactor could be quite similar in many respects
  >> to circulating molten-salt reactors
  >> developed at Oak Ridge National Laboratory

- **Mutually constructive role**

  >> liquid-salt reactor
  >> small, modular
  >> fissile/fertile fuel adaptable
  >> conservative design parameters
  >> abundant radioisotope production

GOVERNMENT SITING OF FACILITY

- **To meet near-term requirements**

- **New, dedicated facility**

  >> in a remote area
  >> on a government reservation
  >> with state-of-the-art safety and security features

- **Government siting recommended**

  >> for timeliness and national security
  >> more rapid licensing of reactor
  >> lower cost because of reduced construction delay
  >> non-government organizations supportive

ABOUT MOLTEN-SALT REACTORS

- **Basically simple, reliable nuclear reactor**

  >> can function at low, near-atmospheric pressures
  >> reduced mechanical stress endured by the system
  >> simplified reactor design, improved safety

- **Oak Ridge researched liquid-fueled and cooled reactors up through the 1960s**

  >> included uranium-233 and thorium

MOLTEN-SALT BREEDER REACTOR EXPERIMENT

- **Oak Ridge work culminated with the Molten-Salt Reactor Experiment**

  >> 7.4 Megawatt (thermal) test reactor
  >> started operation in 1965
  >> operated safely and reliably
  >> maintained without excessive difficulty.
  >> one-fluid reactor
  >> four-year experiment, about 1.5 years of full-power operation.

- **Simulated basic neutronic characteristics**

  >> epithermal liquid-fluoride thorium breeder reactor.

- **Primarily two fuels:**

  >> first uranium-235
  >> later uranium-233 bred from thorium in other reactors

SCHEMATIC OF MSRE
HEAT-CIRCULATION AND CHEMICAL-PROCESSING

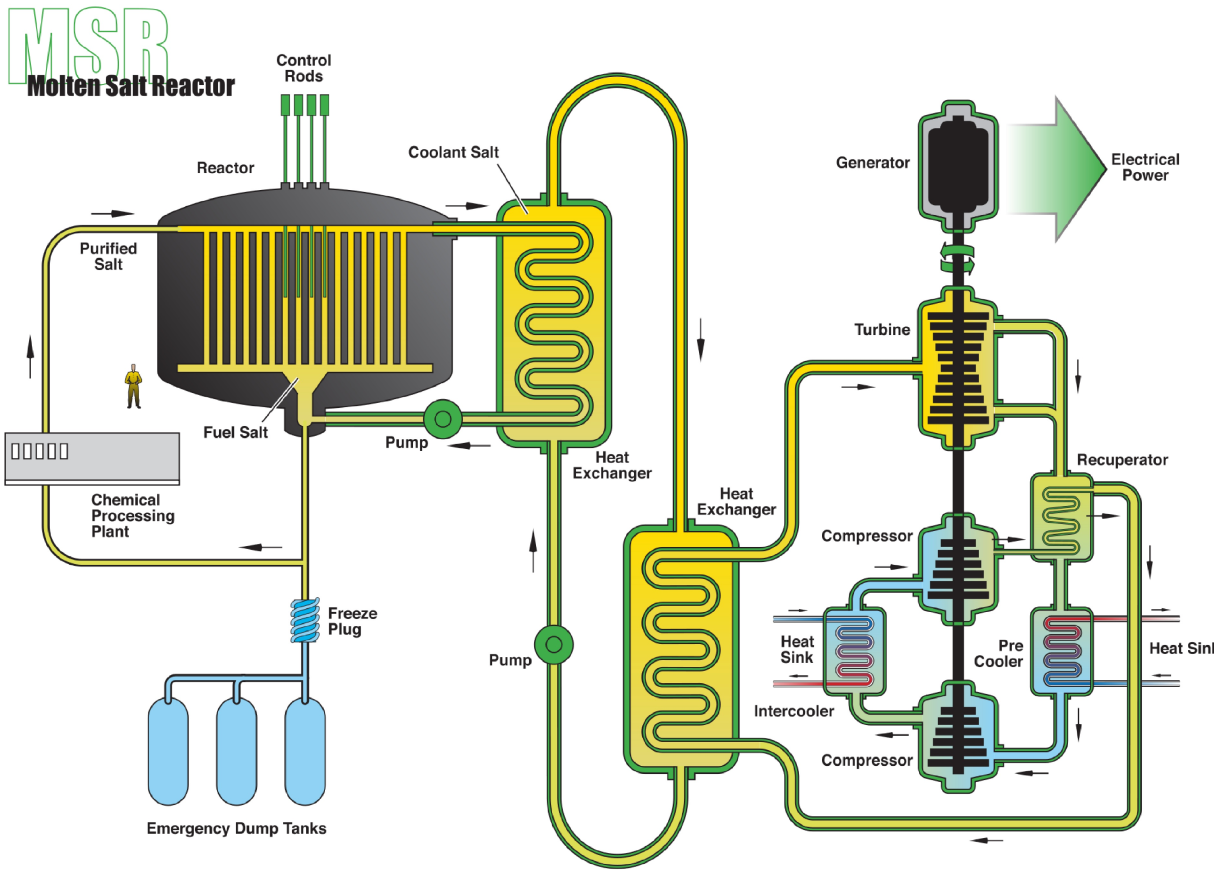

Figure 1. Schematic diagram of a molten-salt reactor based on 1960's experiment at Oak Ridge.

KEY FEATURES OF MSRE

- **Graphite moderator**

- **Continuous circulation of molten salt**

- **Online, continuous chemical processing**

  >> gaseous and solid fission products
  >> other extraneous coolant-transported materials

- **Solid control/safety rods**

- **Additional safety with a drain plug**

  >> kept solid by actively freezing plug
  >> provides passive safety system
  >> in case of electric-supply failure or overheating
  >> would melt and drain solution into “nuclear-safe” geometries

FLIBE

- **A fluid solution used as a coolant and carrier**

  >> FLIBE = FLuorine - LIthium - BEryllium
  >> chemically compatible mixture
  >> of liquid salts

- **Oak Ridge MSREreactor combined primary coolant and fuel**

  >> FLIBE and uranium

- **MSRE secondary coolant was FLIBE**

  >> provides very good, reactor-compatible properties

- **FLIBE lithium content needed for tritium production**

- **FLIBE acts as solvent and carrier for tritium and fission products**

  >> for on-line, continuous chemical extraction
  >> optimum efficiency for high yield production

AIRCRAFT REACTOR EXPERIMENT

- **First molten-salt reactor**

    >> at Oak Ridge in early, mid-1950s
    >> 2.5 MW(th)
    >> military experiment designed to attain a high power density
    >> for use as an engine in a nuclear-powered bomber

- **Used molten-fluoride salt in core zone**

    >> and liquid sodium as a secondary coolant

- **Operated successfully and sufficiently for a 1000-hour cycle in 1954**

FEATURES OF NEW PROPOSAL FOR PRODUCTION OF VALUABLE RADIOISOTOPES

- **A single solution-type reactor**

  >> specializing in radioactive-materials production
  >> short-lifetime fission products, extracted in as brief a time as possible

- **Tritium production in FLIBE**

- **Yield of other commercial radioisotopes**

  >> should effectively ease the forthcoming shortfall
  >> at reduced cost of valuable medical radioisotopes

- **Np-237 can be extracted too**

  >> to make valuable Plutonium-238 used for thermoelectric generators

ESTIMATING COMMERCIAL VALUE

- **rough estimates of the annual commercial value and government savings**

  >> 70% capacity factor
  >> 100MW(thermal)

- **From tritium production of about 210g/yr**

  >> valued at $40,000/g
  >> offsets significant portion of current federal tritium budget outlay
  >> cost significantly less than current government production

- **Molydenum-99: 50 g/yr**

  >> At 0.5MCi/g, this would correspond to 340 MCi/yr
  >> Assuming a 1% extraction yield in processing
  >> at a price of $200/Ci (for a 6-day Curie),

- **Tritium extraction (and He-3 accumulation) simultaneous with Mo-99 production**

  >> respective product yields fully independent of each other
  >> government budget outlays significant

- **Additional market value for heat and power produced**

SUMMARY OF PRODUCTION EXPECTATIONS

- **Tritium production for U.S. government**

  ~210g/yr ➜ ~$8.4M/yr

- **molybdenum-99 6-day-Curie fission-product market value**

  ~50g/yr ➜ ~$140M/yr

- **Marketable power**

  ~100MWth ➜ ~$12M/yr

- **Estimates necessarily have large uncertainties**

  >> product-yield
  >> market-value

- **No monetary credit assumed for helium-3 production**

LICENSING AND SITING ISSUES

- **Reactor licensing**

    >> known to be a financial and procedural show-stopper
    >> for nuclear reactors
    >> especially in the United States
    >> and especially for non-traditional concepts.

- **No applications for solution-reactor facilities in isotope production**

    >> known to have been submitted for approval in United States

- **Nuclear regulatory bodies have not developed regulations**

    >> to facilitate solution reactors for commercial isotope production

- **The two such reactors previously described were licensed**

    >> by the U.S. Atomic Energy Commission
    >> but not as isotope-production facilities

EXPEDITED LICENSING POTENTIAL

- **Expedited licensing might be achievable**

  >> national-security priority in production of tritium
  >> homeland-security considerations in production of He-3

- **Might reduce construction costs and delays significantly**

  >> by siting on a government reservation
  >> especially Oak Ridge or Savannah River
  >> compared to an equivalent publically-sited plant

INHERENT-JUSTIFICATION POTENTIAL

- **Proposed liquid-fueled/liquid-cooled reactor**

  >> appears to amply and quickly pay for itself
  >> provide near-term economic and national value
  >> more than enough to motivate government and commercial initiative
  >> especially in the United States

- **Reactor could be fueled with uranium, thorium, and/or plutonium**

  >> would satisfy multiple goals and professional interests
  >> including more efficient burnup, less byproduct waste

DEVELOPMENT WORK REQUIRED

- **Government and/or commercial development work needed**

- **Optimize production and separation**

  >> fission products, tritium, helium-3, and neptunium-237
  >> financially self-supporting
  >> providing public service national-security value
  >> meet or exceed current national requirements for full cost-recovery

- **Computations needed:**

  >> design-specific radiation-transport/nuclear-production

- **Even if sited on a government reservation**

  >> licensing issues will again need to be addressed,
  >> deserve to be expedited as much as possible

SOME POINTS OF EMPHASIS

Here are some takeaway points of emphasis:

● NNSA and DOE

>> paying high cost for production
>> of tritium and helium-3

● Shortfall emerging in special radioisotope production

>> medical diagnostics and treatment
>> industrial research.

● Current medical-isotope production methods insufficient

>> production reactors around the world are aging
>> new reactors discouraged by proliferation concerns

● Small liquid-fueled reactor

>> could produce all the tritium
>> help resolve the medical-radioisotope availability
>> proven, extremely safe design
>> national-security and non-proliferation benefits

● Only one small specialized reactor needed
>> located at U.S. government site is needed
>> could be built and operated by private industry

MORE POINTS TO EMPHASIZE

- **Government facilities have had significant role**

  >> Oak Ridge National Laboratory reactor-development experience
  >> Savannah River National Laboratory existing tritium processing

- **Reactor products should readily compensate for the investment**

  >> tritium yield reduces federal government costs
  >> rare radioisotopes sold commercially
  >> steam, heat, electricity fungible byproduct

- **Siting on a government reservation expedites/resolves**

  >> availability of the reactor
  >> and its important radioisotope products
  >> siting, licensing, and non-proliferation problems

ADDITIONAL RELEVANT FACTORS

- **At 100MWth, the reactor can be small, possibly modular**

- **Liquid-fueled reactors very efficient**

    >> in their use of low-enriched uranium as fuel
    >> can consume natural uranium or thorium
    >> fuel continuously recycled
    >> good neutronic features

- **Liquid-salt coolant/carrier**

    >> continuous circulation
    >> enables very efficient on-line radioisotope extraction
    >> allows removal of reactor poisons such as xenon

- **Fluid fuels compared to solid fuels**

    >> much less radiation damage and thermal stress
    >> consumed fuel replaced on-line during operation

- **Operational features**
    >> atmospheric pressure
    >> comparatively thin containment vessels
    >> liquid fuel is continuously circulated
    >> heat transferred at high temperature

- **Enhanced safety characteristics are intrinsic to design**

MORE POINTS OF EMPHASIS

- **Very safe reactor concept**

  >> liquid solution safely expands as temperature increases
  >> reactivity control is intrinsic to design
  >> passive safety valve from a solid meltable salt plug

- **Concept indifferent to type of fuel**

  >> versatile fuel cycle
  >> any combination of uranium, thorium, or plutonium

- **Not a proliferation issue**

  >> especially if sited on a government reservation
  >> especially if high-enriched uranium not needed

SUMMARY

The molten-salt reactor of this concept:

- **Fueled with thorium or uranium**
- **Would appear to produce timely and sufficient radioisotopes**
- **To meet or exceed current national requirements**
- **At the very least on a full cost-recovery basis, more likely at a profit**
- **With a potential commercial market product value**

    >> of many billions of dollars per year

APPENDIX

ABSTRACT

Uranium-Thorium Liquid-Salt Reactor for Producing Valuable Radioisotopes

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Valuable and indispensable radioisotopes – such as tritium, helium-3, molybdenum-99, and neptunium-237 – could be produced, separated, and extracted most efficiently and economically in a single, small liquid-salt reactor optimally situated on a government reservation.

Various international and national commissions have recognized looming shortfalls in some radioisotopes designated as essential. At present, nearly 80% of all nuclear-medicine procedures worldwide are derived from radioactive molybdenum-99, but there are no major producers in the United States. Much of the world's medical-isotope production is inefficiently carried out by irradiating uranium targets in aging specialized solid-fuel reactors. Production of tritium and helium-3 for national-security purposes has becomes increasingly expensive.

Much better sustained radioisotope production could be obtained from a liquid-salt reactor, an enterprising approach satisfying near-term high-priority goals for valuable and rare radioactive substances. One such small 100MWth reactor should suffice to meet domestic requirements for tritium, as well as international needs for medical radioisotopes, with a commercially profitable near-term return on investment.

The proposed reactor would be similar to the circulating molten-salt reactor originally developed at Oak Ridge National Laboratory. The isotope-production reactor's primary coolant would consist of F/Li/Be compounds that provide very good and relevant reactor-compatible properties, functioning with near-atmospheric pressure, reduced mechanical stress, simplified reactor design, and inherently safe operation. Mixed and circulated with the coolant would be criticality-sustaining fuel that could function with any of several fissile and fertile material combinations, primarily uranium and thorium.

Under typically constrained domestic circumstances — wherein national or commercial reactor funding, development, and construction options are limited — this particular concept offers near-term benefits while avoiding most shortcomings. Because of national-security considerations, the proposed liquid-salt radioisotope-production reactor likely would have to be federally endorsed, prioritized, and located on a government reservation.

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