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Alternative Cooling Systems for the Thorium Fuel Cycle Molten Salt Breeder

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ABSTRACT

This work considers alternative cooling methods that would enhance the performance of the designs of future thorium molten salt breeder reactors; specifically the use of the Dissociating Gases and the Kalina dual-fluid cycles.

The use of dissociating gases as a replacement of typical gaseous coolants such as helium or carbon dioxide with gases that dissociate upon heating and recombine upon cooling such as nitrogen tetroxide, aluminum chroride and aluminum bromide, results in a decreased work input during compression , higher overall efficiency and minimizes the volume and weight of the associated turbomachunery.

The Kalian Cycle uses a binary working fluid of water and ammonia, which allows for heat rejection and addition in the cycle at varied temperatures for greater heat recovery over a wide temperature range, including during phase changes. This increases the overall thermal efficiency compared with the Rankine (Steam) Cycle, for which phase changes occur at uniform temperatures as a result of the use of single component working fluids.

The consideration of these cooling methods would result in future molten salt reactors with more favorable performance and economics compared with current standards.

Historical Perspective

Historically, the thorium fission fuel cycle was investigated over the period 1950-1976 in the liquid fuel Molten Salt Breeder Reactor (MSBR) at the Oak Ridge National Laboratory (ORNL) as well as in the solid fuel seedand blanket pilot Shippingport fission reactor plant.

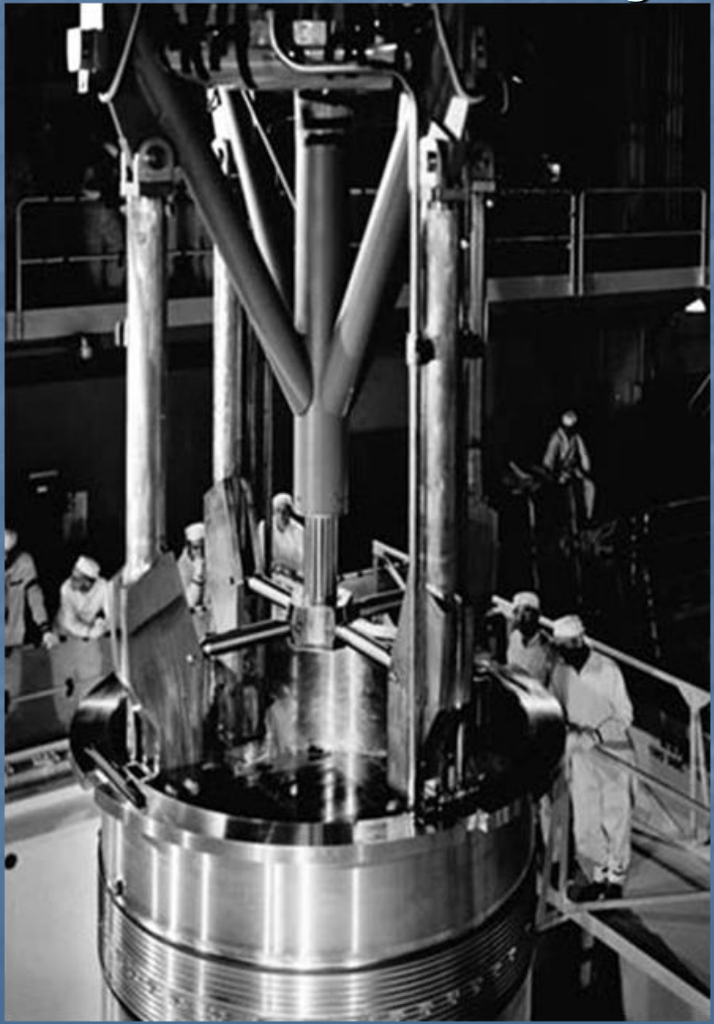
It has also been used in the High Temperature Gas Cooled Reactor (HTGR) in a pebble bed and a prismatic moderator and fuel configurations. The General Atomics (GA) Company built two thorium reactors over the 1960-1970 period. The first was a 40 MWe prototype at Peach Bottom, Pennsylvania operated by Philadelphia Electric. The second was the 330 MWe Fort St. Vrain reactor for Public service of Colorado which operated between 1971 and 1975.

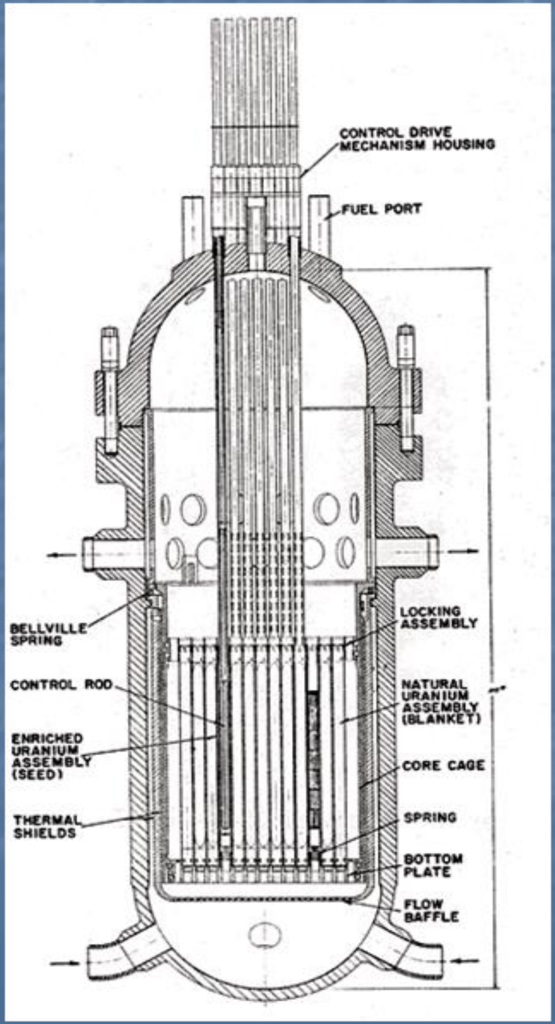
Solid fuels

The Shippingport reactor was the first commercial and experimental nuclear power plant in the USA and second in the world after Calder Hall in the UK.

Initial Seed and Blanket core design

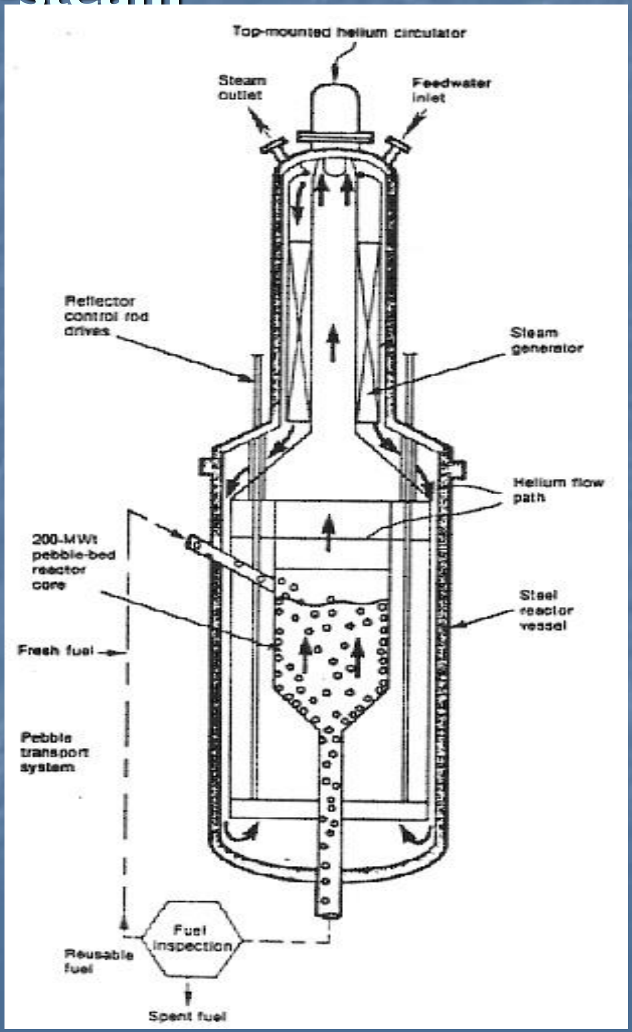
Coolant: Light Water



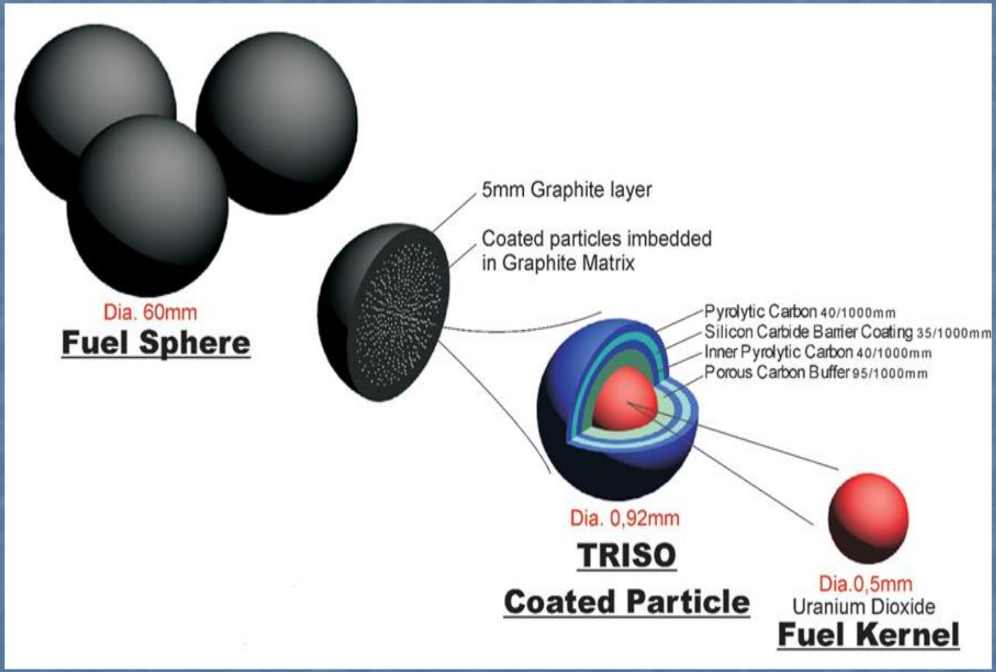


Solid fuels
Fort Saint Vrain He cooled graphite moderated reactor, Colorado.
Coolant: Helium - steam

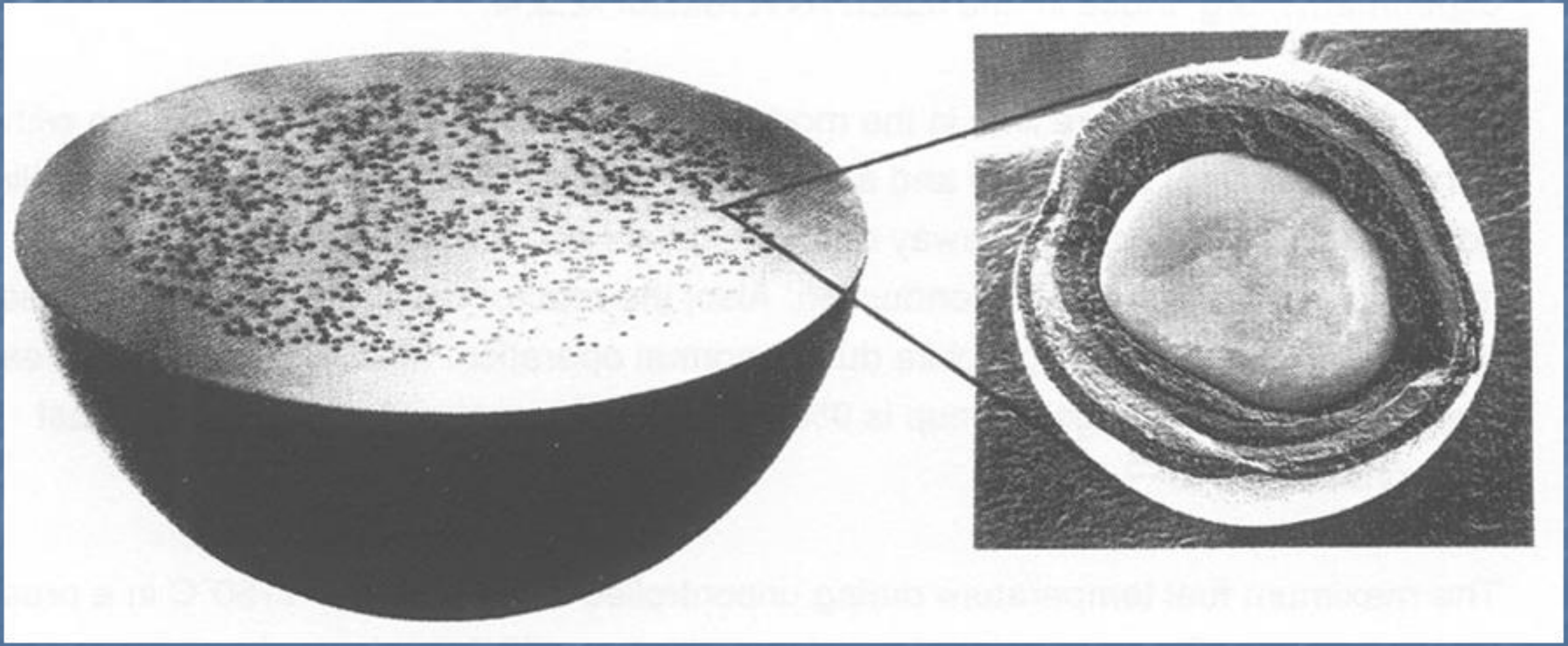
Solid fuels
The TFTR-300 Thorium high temperature pebble bed reactor used a 180 m high dry cooling tower. AVR reactor, Germany. Coolant: He-steam



Solid fuels
Fuel kernel, coated triso fuel particle and pebble fuel sphere design.

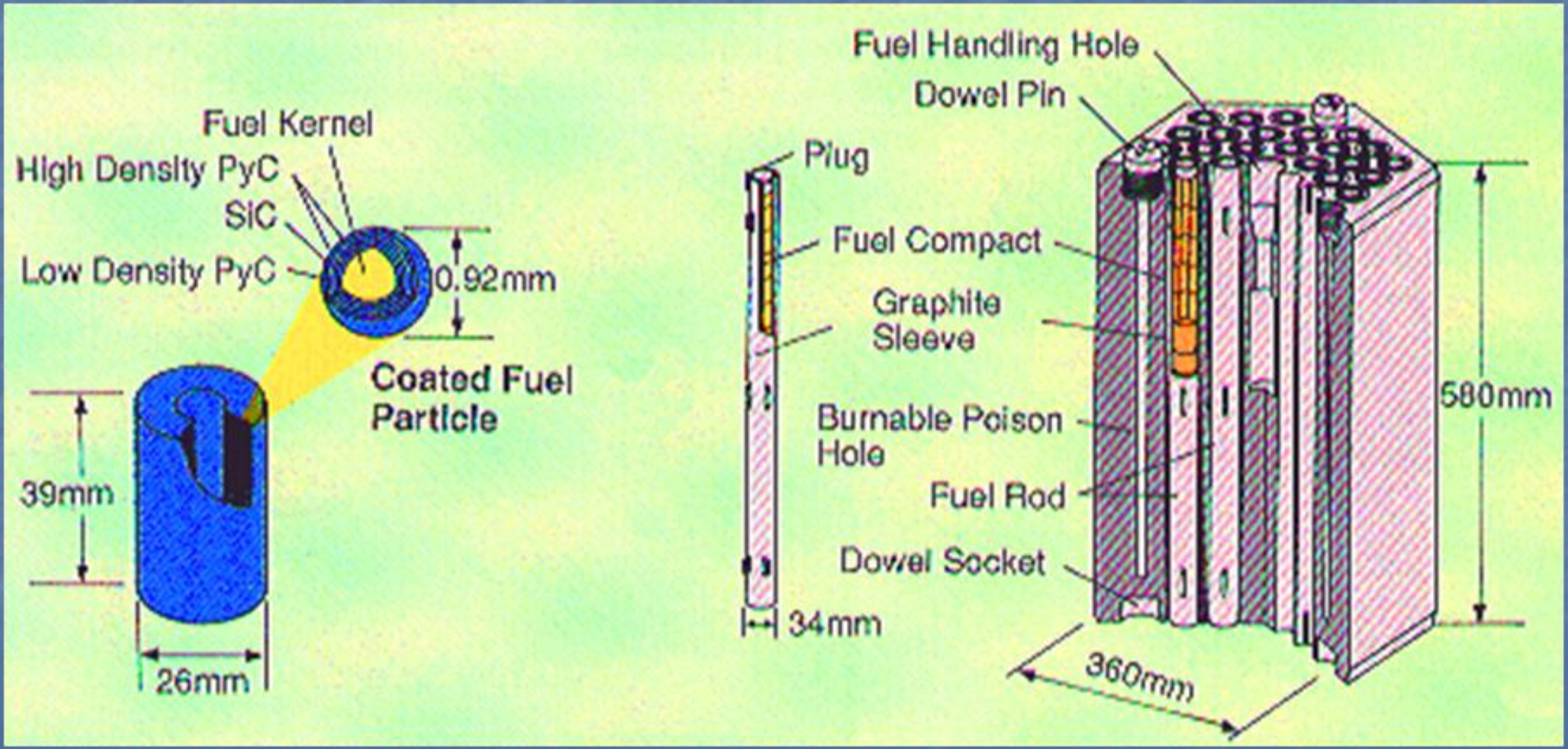


Solid fuels
Fuel particles used in the pebble bed and the prismatic fuel designs.

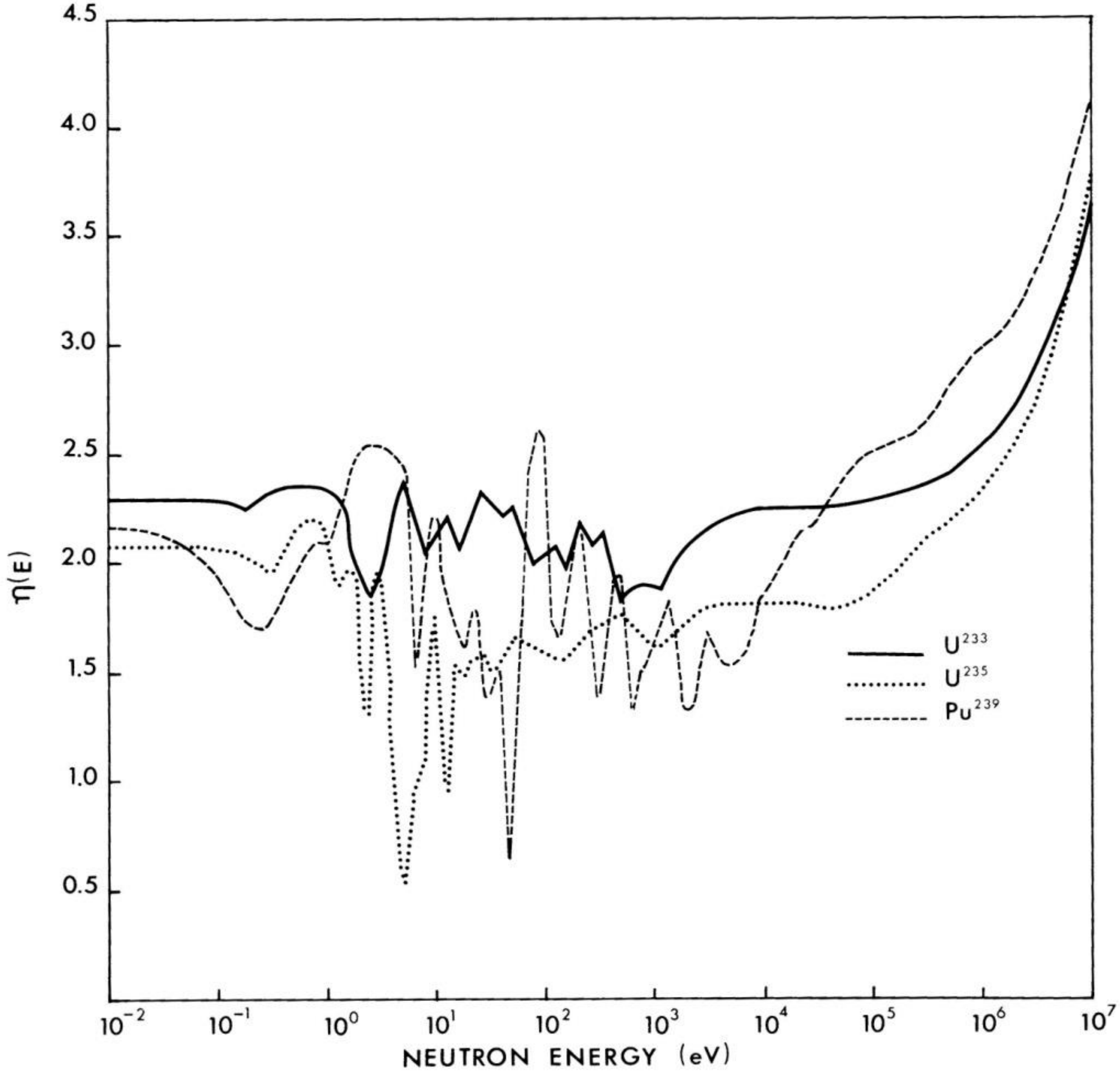


Solid fuels
Prismatic hexagonal graphite fuel block.

High Temperature Engineering Test Reactor (HTTR) is a 30 MW(th) prismatic core HTGR designed, constructed and operated by the Japan Atomic Energy Research Institute (JAERI).



Regeneration factor as a function of neutron energy for the different fissile isotopes. Breeding in the Thorium-U^{233} fuel cycle can be achieved with thermal or fast neutrons.



Comparison of U and Th breeding

Long half life of Pa233 implies a need for liquid fuels

$$ {}_{0}n^{1} + {}_{90}Th^{232} \rightarrow {}_{90}Th^{233} + \gamma $$

$$ {}_{90}Th^{233} \rightarrow {}_{91}Pa^{233}(T_{1/2}=27 \text{ days}) + {}_{-1}e^{0} + \nu^{*} + \gamma $$

$$ {}_{91}Pa^{233} \rightarrow {}_{92}U^{233} + {}_{-1}e^{0} + \nu^{*} + \gamma $$

$$ {}_{0}n^{1} + {}_{90}Th^{232} \rightarrow {}_{92}U^{233} + 2\,{}_{-1}e^{0} + 2\nu^{*} + 3\gamma $$

$$ {}_{0}n^{1} + {}_{92}U^{238} \rightarrow {}_{92}U^{239} + \gamma $$

$$ {}_{92}U^{239} \rightarrow {}_{93}Np^{239}(T_{1/2}=2.35 \text{ days}) + {}_{-1}e^{0} + \nu^{*} + \gamma $$

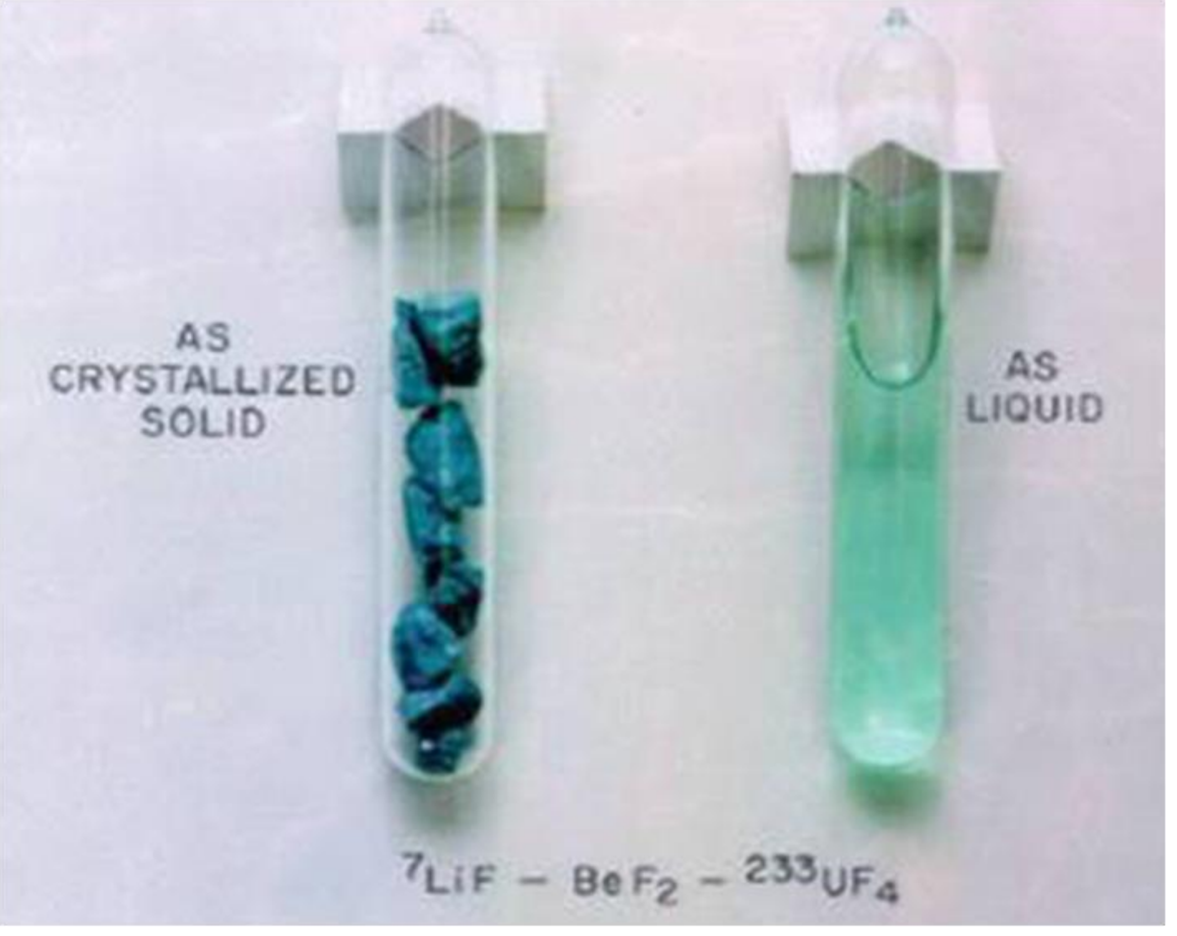
$$ {}_{93}Np^{239} \rightarrow {}_{94}Pu^{239} + {}_{-1}e^{0} + \nu^{*} + \gamma $$

$$ {}_{0}n^{1} + {}_{92}U^{238} \rightarrow {}_{94}Pu^{239} + 2\,{}_{-1}e^{0} + 2\nu^{*} + 3\gamma $$

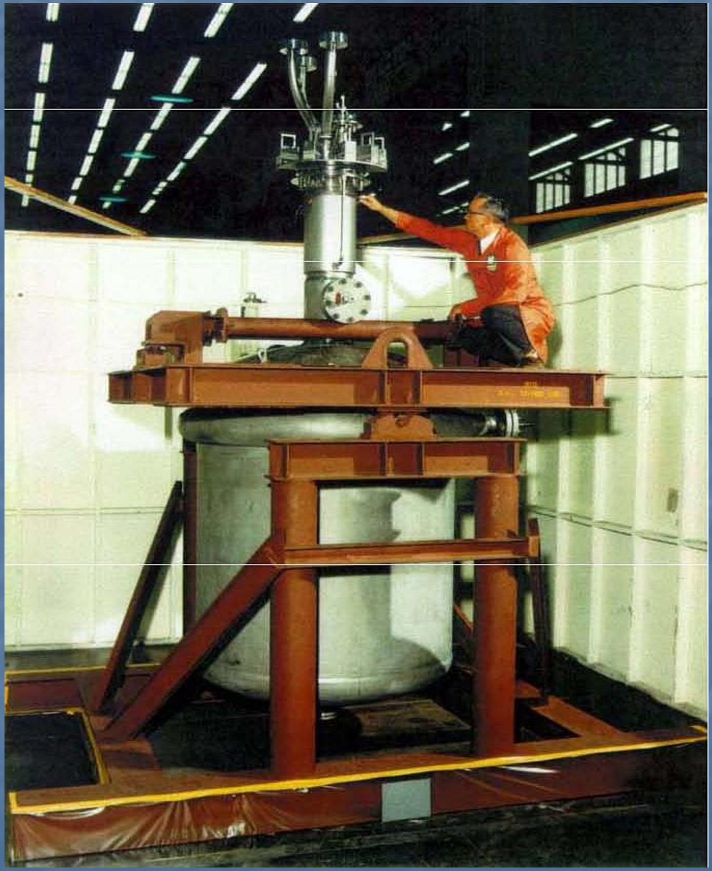
Liquid Fuels

${}_{3}Li^{7}F$-BeF_2-${}_{92}U^{233}F_4$ salt

cold solid and hot liquid states.



Molten Salt Reactor Experiment, 8MWth



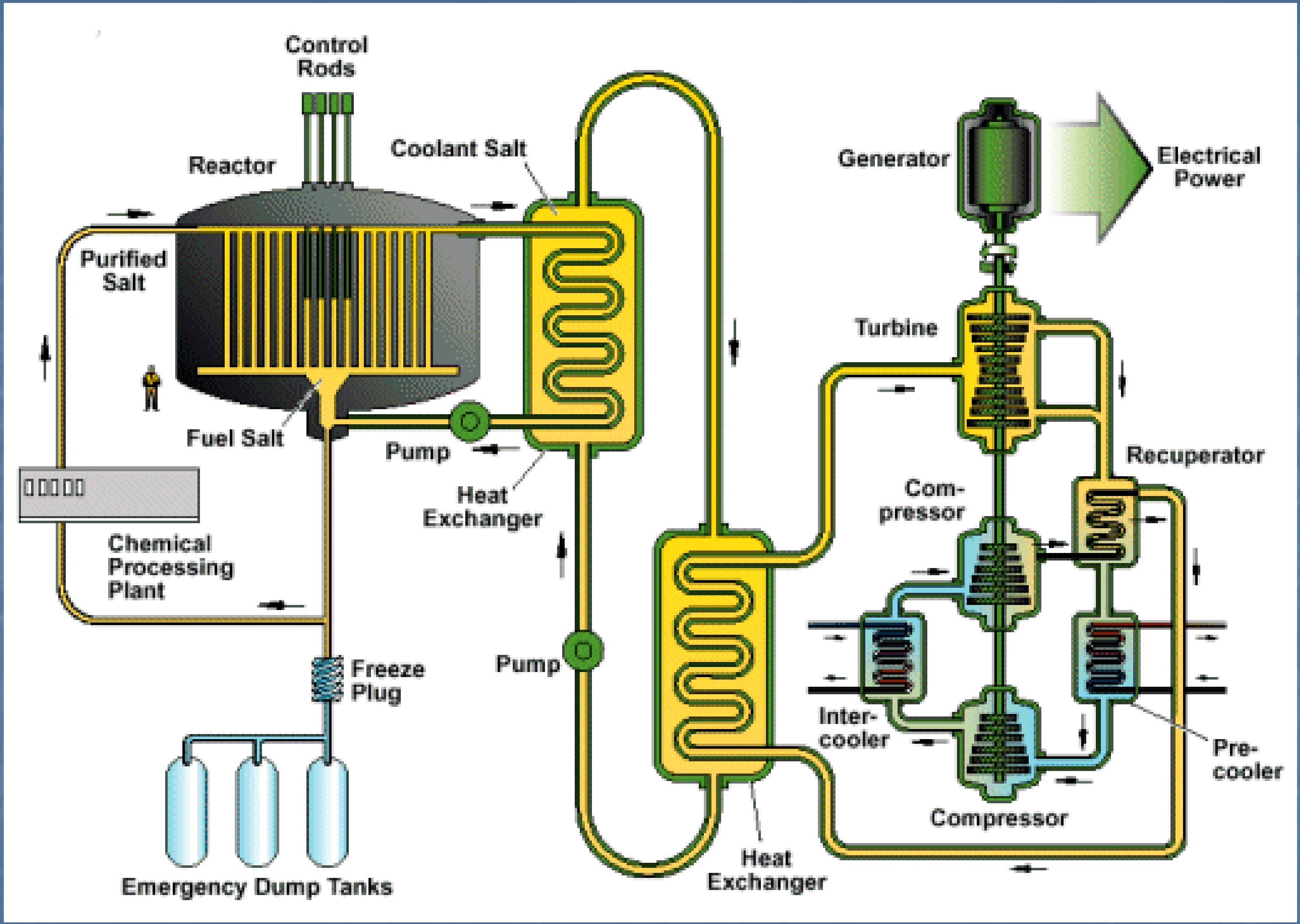


Figure 9. Molten Salt Reactor, MSR using a Brayton, Joule gas turbine cycle.

In the MSR system, the fuel is a circulating liquid mixture of sodium, zirconium, and uranium fluorides.

The molten salt fuel flows through graphite core channels, producing an epithermal spectrum.

The heat generated in the molten salt is transferred to a secondary coolant system through an intermediate heat exchanger, and then through a tertiary heat exchanger to the power conversion system.

The reference plant had a power level of 1,000 MWe. The system had a coolant outlet temperature of 700 ^{o}C, possibly ranging up to 800 ^{o}C, affording improved thermal efficiency.

Table 7. Specific heat and γ for gaseous coolants at 68 ^{o}F.

Gas	Specific heat, c_p [BTU/(lb_m.^{o}F)]	γ [c_p/c_v]
Hydrogen, H_2	3.420	1.405
Helium, He	1.250	1.659
Carbon dioxide, CO_2	0.202	1.290
Air	0.240	1.400
Nitrogen, N_2	0.248	1.400

HELIUM SHORTAGE

Helium is being depleted as an unprecedented rate and reserves could dwindle to virtually nothing within a generation. Nobel laureate Robert Richardson, professor of physics at Cornell University in Ithaca, New York, , who won his Nobel prize for his work on He^3, discusses the issue at meeting of the Nobel Prize laureates in Lindau, Germany::

> “In 1996, the US Congress decided to sell off the strategic reserve and the consequence was that the market was swelled with cheap helium because its price was not determined by the market. The motivation was to sell it all by 2015. The basic problem is that helium is too cheap. The Earth is 4.7 billion years old and it has taken that long to accumulate our helium reserves, which we will dissipate in about 100 years. One generation does not have the right to determine availability for ever. As a result of that Act, helium is far too cheap and is not treated as a precious resource. It is being squandered. They could not sell it fast enough and the world price for helium gas is ridiculously cheap. You might at first think it will be peculiarly an American topic because the sources of helium are primarily in the US but I assure you it matters of the rest of the world also. Once helium is released into the atmosphere in the form of party balloons or boiling helium it is lost to the Earth forever.”

He believes the price for helium should rise by between 20- and 50-fold to make recycling more worthwhile. He suggests that party balloons filled with He are too cheap, and they should really cost about $100 (£75) to reflect the precious nature of the gas they contain.

NASA makes no attempt to recycle the He used to clean its rocket fuel tanks, one of the single biggest uses of the gas.

DISSOCIATING GASES CYCLE

Dissociating gases which dissociate upon heating and recombine upon cooling can be used in nuclear power plants to considerably reduce the weight of the heat exchange and rotating machinery. Such a reaction can occur in nitrogen tetroxide:

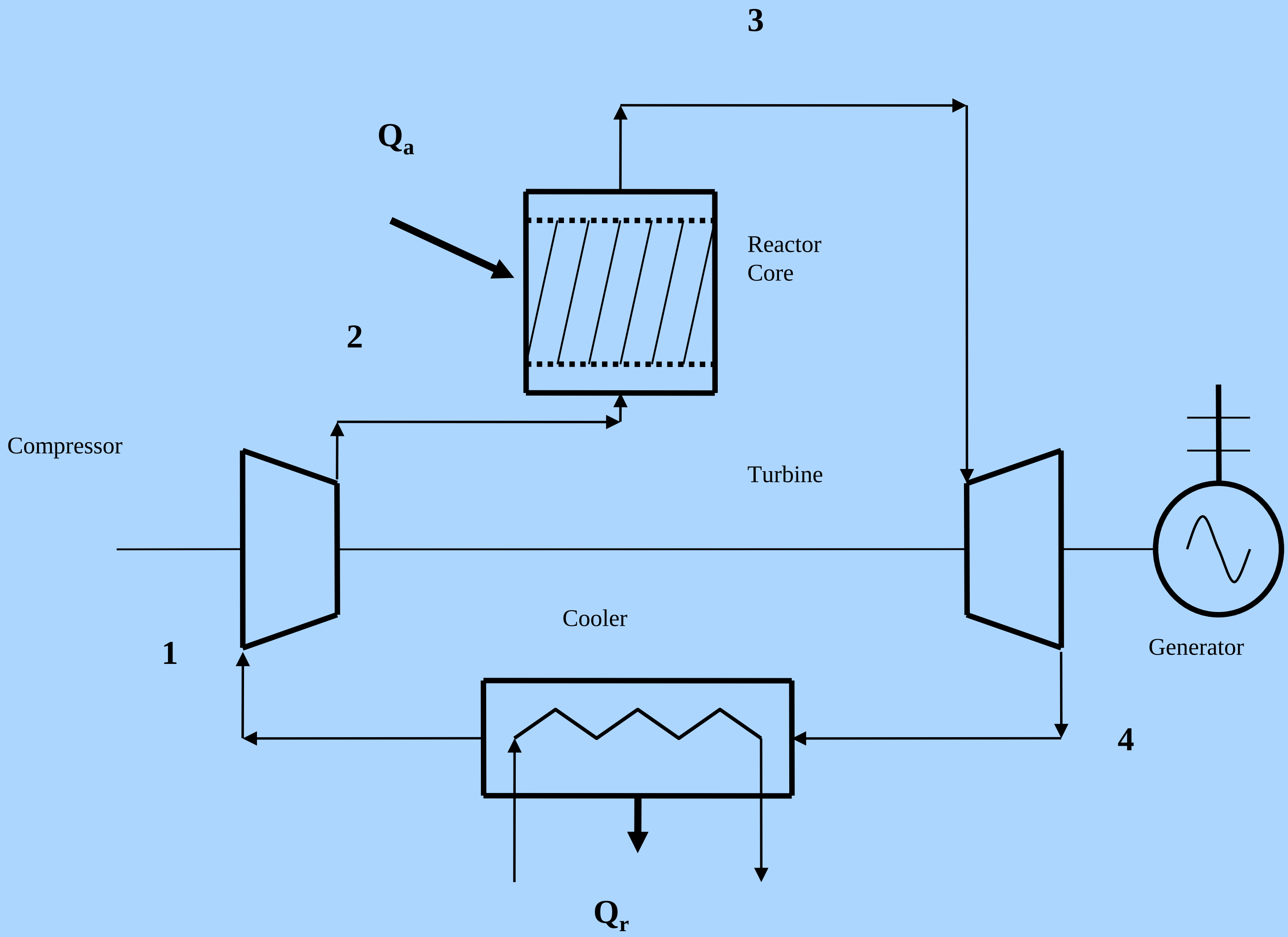
$$N_2O_4 \rightleftharpoons 2NO_2 \tag{2}$$

The doubling of the number of molecules in the working gas from n to 2n, doubles the amount of work per unit mass in the ideal gas equation:

$$PV = 2nRT \tag{3}$$

The resulting doubling of the work done per unit mass of the working fluid allows the use of smaller size and weight turbines, compressors and heat exchangers. As proposed by Ragheb and Hardwidge, if used in the propulsion system of a nuclear submarine, it can increase its power to weight ratio and consequently its attainable speed by 30 percent for the same reactor power. The weight reduction makes it also suitable for space power applications. Other gases such as aluminum chloride and aluminum bromide can be used.

The ideal direct gas turbine or Brayton cycle



Direct Brayton cycle PV and TS diagrams

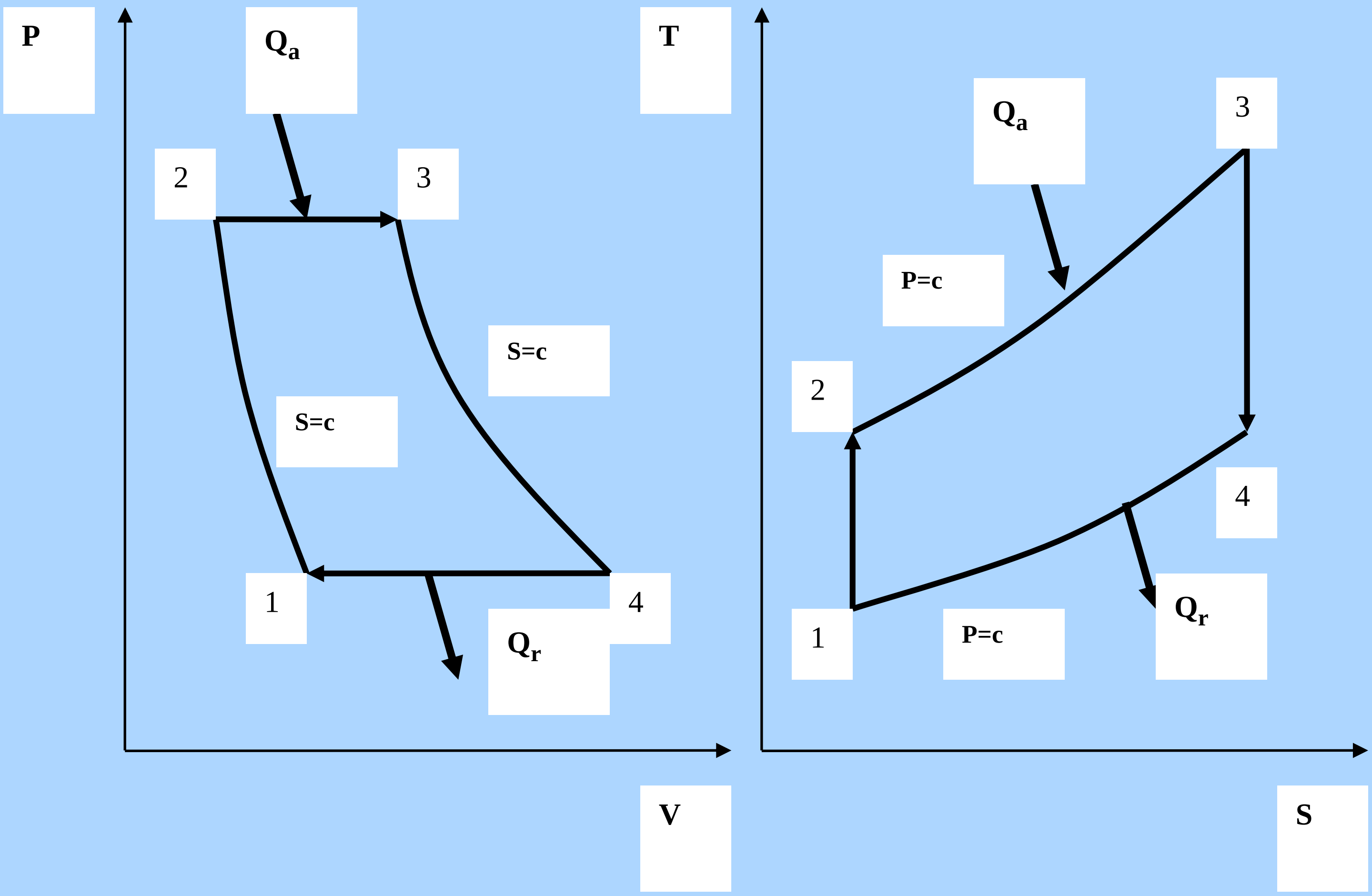


Table 5. Candidate dissociating gas systems.

Dissociating gas	Increase factor in gas constant	Thermal release from reaction [Kcal/mole]	Temperature Range °C
$N_2O_4 \rightleftharpoons 2NO_2$	2	13.7	25-170
$2NO_2 \rightleftharpoons 2NO + O_2$	1.5	27.0	140-850
$Al_2Br_6 \rightleftharpoons 2AlBr_3$	2	30.0	300-1,400
$Al_2Cl_6 \rightleftharpoons 2AlCl_3$	2	29.8	200-1,100
$Al_2I_6 \rightleftharpoons 2AlI_3$	2	26.4	230-1.200
$2NOBr \rightleftharpoons 2NO + Br_2$	1.5	-	25-500
$2NOCl \rightleftharpoons 2NO + Cl_2$	1.5	-	25-900
$Al_2Cl_6 + 4Al(liquid) \rightleftharpoons 6AlCl$	6	263.8	670-1,200
$Al_2Br_6 + 4Al(liquid) \rightleftharpoons 6AlBr$	6	282.4	670-1,400
$Al_2I_6 + 4Al(liquid) \rightleftharpoons 6AlI$	6	196.4	670-1,300
$HgCl_2 + Hg(liquid) \rightleftharpoons 2HgCl$	2	70.4	280-700
$HgBr_2 + Hg(liquid) \rightleftharpoons 2HgBr$	2	63.7	250-700
$SnCl_4 + Sn(liquid) \rightleftharpoons 2SnCl_2$	2	38.6	-
$SnBr_4 + Sn(liquid) \rightleftharpoons 2SnBr_2$	2	65.3	-
$Ga_2Cl_6 \rightleftharpoons 2GaCl_3$	2	20.0	10-1,000
$Ga_2Br_6 \rightleftharpoons 2GaBr_3$	2	18.5	150-1,200
$Ga_2I_6 \rightleftharpoons 2GaI_3$	2	11.0	250-1,300
$Ga_2Cl_6 + 4Ga(liquid) \rightleftharpoons 6GaCl$	6	58.8	100-1,000

Table 6. Characteristics of different turbines using steam and dissociating gases.

	Working Fluid			
	H_2O Steam Turbine	H_2O Steam Turbine	Al_2Cl_6 Gas Turbine	Al_2Br_6 Gas Turbine
Output, MWe	500	300	555	340
Pressure, turbine inlet, ata	240	240	80	80
Temperature, turbine inlet, ^oC	580	580	600	750
Pressure, turbine exhaust, ata	0.035	0.035	5	5
Mass flow rate, metric tonne/hr	1,495	880	17,900	21,900
Turbine revolutions, rpm	3,000	3,000	3,000	3,000
Number of exhausts	4	3	2	4
Total number of turbine stages	42	39	6	12
Mean diameter of last stage, m	2.550	2.480	1.338	0.915
Height of last stage blade, m	1.050	0.960	0.495	0.250
Internal efficiency				
High pressure cylinder	-	80.0	89.9	90.0
Intermediate pressure cylinder	-	89.5	-	-
Low pressure cylinder	-	82.0	-	-
Number of turbine shafts	1	1	1	1
Turbine length, m	29.1	21.3	9.0	7.6
Weight of turbine, metric tonnes	964	690	55	90
Power to weight ratio, [MWe/Metric tonne]	0.52	0.43	10.09	3.78

The dramatic advantage of using dissociating gases is a reduced size and weight in the turbo machinery.

A 500 MWe steam turbine would measure 21.3 meters in length compared with just 9 meters for a 555 MWe Al_2Cl_6 turbine.

This is associated with an increase by a factor of 10.09/0.52 = 19.4 in the power to weight ratio.

The reduced weight in the other associated heat transfer equipment makes dissociating gases a promising choice for space, naval propulsion, space applications, as well as central station applications.

KALINA CYCLE

The Kalina cycle can be used in nuclear power applications increasing the efficiency up to 30 percent. It is simple in design and can use readily available, off the shelf components.

It is similar to the Rankine cycle except that it heats two fluids, such as a mixture of ammonia and water, instead of one.

The dual component vapor consisting for instance of 70 percent ammonia and 30 percent water is directed to a distillation subsystem which creates three additional mixtures. One is a 40/60 mixture, which can be completely condensed against a normal cooling source. After condensing, it is pumped to a higher pressure, where it is mixed with a rich vapor produced during the distillation process. This recreates the 70/30 working fluid.

The elevated pressure completely condenses the working fluid and returns it to the heat exchanger to complete the cycle.

The mixture's composition varies throughout the cycle with the advantages of variable temperature boiling and condensation, and a high level of recuperation. Its main use has been so far in geothermal heat extraction.

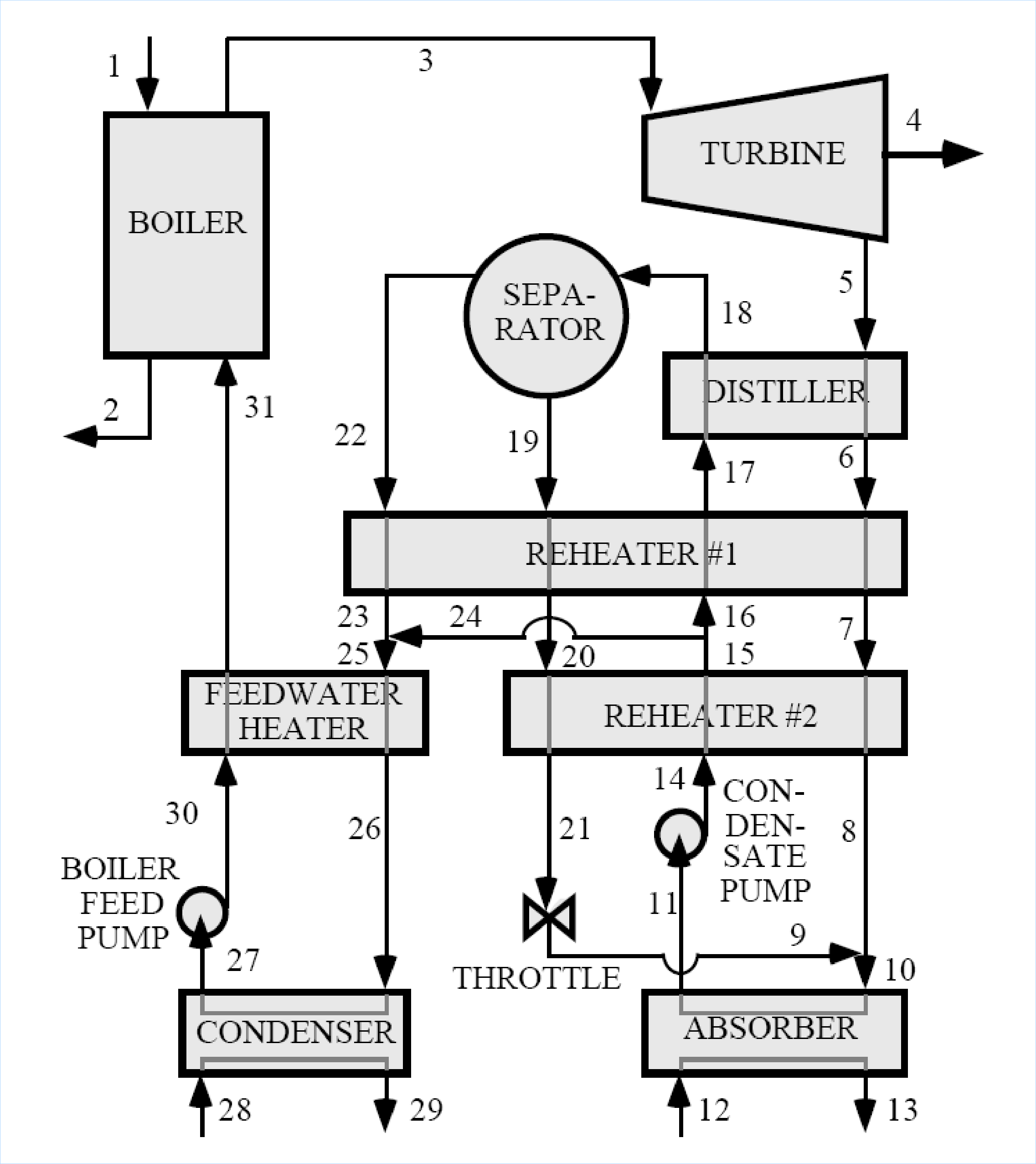


Figure 21. Simplified Kalina cycle using exhaust gases to a boiler.

COMPARISON OF THE KALINA AND STEAM CYCLES

The Kalina cycle is a new concept in heat recovery and power generation, which uses a mixture of 70 percent ammonia and 30 percent water as the working fluid with the potential of significant efficiency gains over the conventional Rankine cycle.

Basically this concept is suitable for medium to low gas temperature heat recovery systems with gas inlet temperatures in the range of 400 to 1000 ^{o}F, offering more gains, over the Rankine cycle, as the gas temperature decreases.

Gas turbine based combined cycles using this concept have 2-3 percent higher efficiency over multi pressure combined cycle plants using steam and water as the working fluid.

In low gas temperature heat recovery systems such as diesel engine exhaust or fired heater exhaust, the energy recovered from the hot gas stream is more significant and Kalina cycle output increases by 20-30 percent.

The main reason for the improvement is that the boiling of ammonia water mixture occurs over a range of temperatures, unlike steam and hence the amount of energy recovered from the gas stream is much higher.

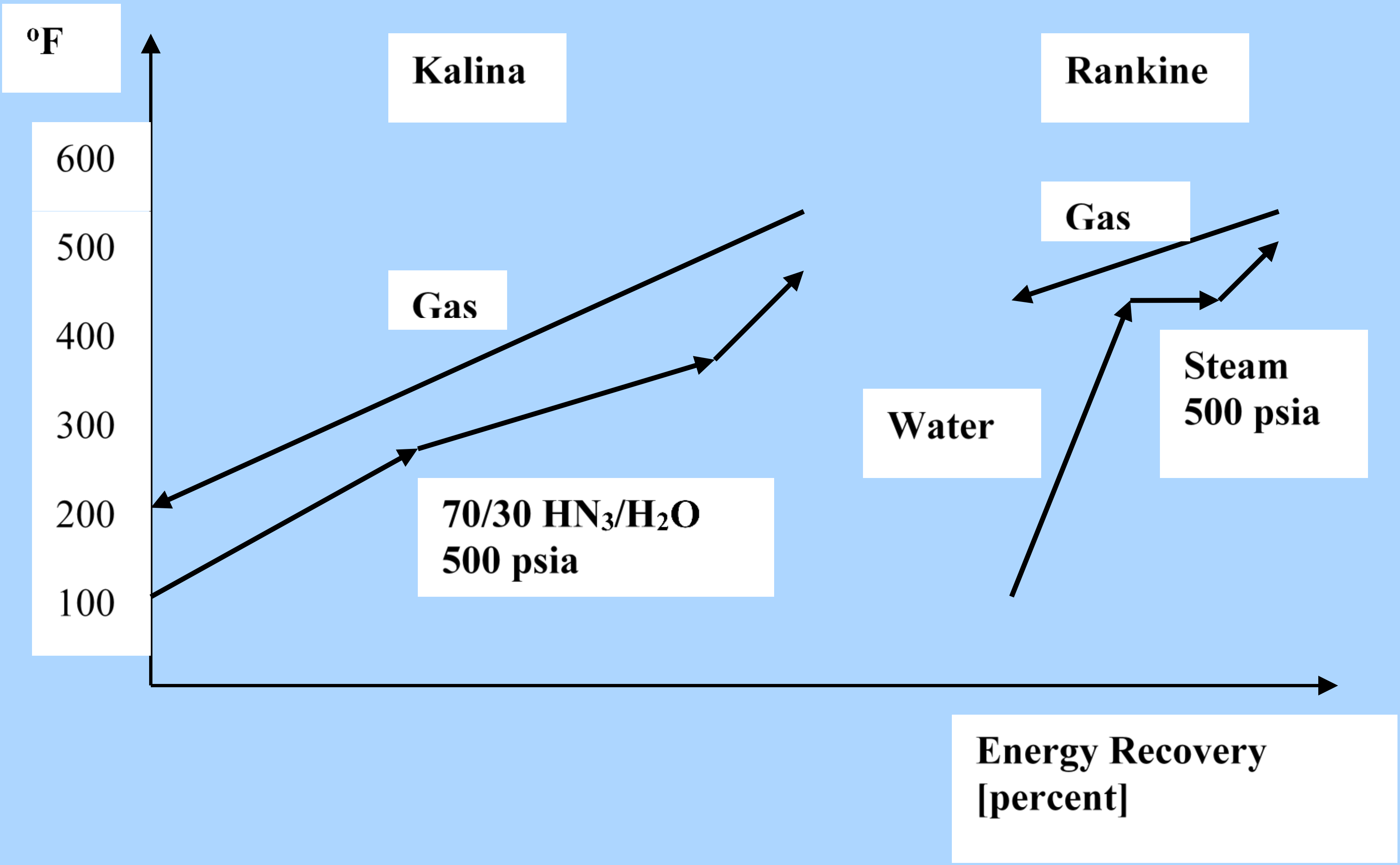


Figure 22. Comparison of the heat recovery in the Kalina and Steam cycles.

Considering a 550 ºF gas temperature source with a cold end fluid temperature of 100 ºF and 70/30 NH_3/H_2O mixture at 500 psia, by virtue of its varying boiling point, is able to match or run parallel to the gas temperature line while recovering energy and hence the exit gas temperature can be as low as 200 ºF.

The steam-water mixture at 500 psia, on the other hand, due to pinch and approach point limitations and a constant boiling point of 467 ºF, cannot cool the gases below about 400 ºF. Only about 15-20 percent of the energy is recovered, compared with 100 percent in the Kalina cycle.

The condensation of ammonia-water also occurs over a range of temperatures and hence permits additional heat recovery in the condensation system, unlike the Rankine cycle, where the low end temperature, affected by ambient conditions, limits the condenser back pressure and power output of the system.

If the cooling water temperature is say 100 ^{o}F, less power is generated by the steam turbine compared to say 40 ^{o}F cooling water.

The condenser pressure can be much higher in a Kalina cycle, and the cooling water temperatures does not impact the power output of the turbine as in the Rankine cycle.

The thermo-physical properties of ammonia-water mixture can also be altered by changing the concentration of ammonia. This helps to recover energy in the condensation system. Modifications to the condensing system are also possible by varying the ammonia concentration and thus more energy can be recovered from the exhaust gases.

Expansion in the turbine produces a saturated vapor in the Kalina cycle compared with wet steam in the Rankine cycle, which requires protection of the turbine blades in the last few stages.

Also due to the higher pressure of vapor and lower specifc volume, the exhaust system size can be smaller compared to steam.

For example the specific volume of a 70 percent ammonia water mixture exhausting from a turbine at its dew point of 240 F is 5.23 ft^3 / lb, while steam at its condensing temperature of 70 F(saturation pressure = 0.36 psia) has 868 ft^3/lb.

Thus the equipment size can be smaller with a Kalina system

Dissociating Gases Cost Analysis

- **In terms of cost implications, the Dissociating Gases alternative yields lower specific volumes, enabling the construction of gas-turbine units of higher capacity and lower weight as compared with modern steam turbines.**

  Positive impacts on the useful life of equipment associated with the utilization of dissociating gas systems also represent a cost benefit over thelife of the plant.

  Helium as a coolant medium may become so depleted that it would cease to offer a viable alternative for a fleet of future He cooled reactors.

Kalina Cycle Cost Analysis

- In terms of the Kalina Cycle, ammonia (NH_3) is one of the most produced inorganic chemicals, with production totaling 131 million metric tonnes in 2010; thus in combination with relatively low costs, its incorporation into the working fluid of the Kalina Cycle does not represent a substantial expenditure. Additionally, no significant enhancements in current equipment are required.
- Overall, utilization of the Kalina Cycle or Dissociating Gases will decrease plant size, resulting in lessed capital cost in the construction of new power plants.

Safety Considerations

- In conjunction with the Kalina Cycle, NH_3 is widely used, with uses ranging from pH control in current fluid systems, to household cleaner, to fertilization in the agricultural industry.
- Extensive use has led to well-established safety standards. When handled properly, ammoia is considered as an ecologically safe industrial chemical, with reported environmental benefits with respect to neutralization of acidic pollutants in the air.
- In terms of plant presence, pungent odor and irritant properties make ammonia self-alarming, essentially its own warning agent.
- Ammonia, like gasoline, is flammable and thus does present some fire and explosion potential, though it is somewhat difficult to ignite and is easily ventilated.

“You never change anything by fighting the existing reality. To change something, build a new model and make the existing model obsolete.”

Bucky Fuller, inventor of the geodesic dome concept.

SUMMARY

This work considers alternative cooling methods that would enhance the performance of the designs of future thorium molten salt breeder reactors; specifically the use of the Dissociating Gases and the Kalina dual-fluid cycles.

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REFERENCES

1. M. M. H. Ragheb, R. T. Santoro, J. M. Barnes, and M. J. Saltmarsh, "Nuclear Performance of Molten Salt Fusion-Fission Symbiotic Systems for Catalyzed Deuterium and Deuterium-Tritium Reactors," Nuclear Technology, Vol. 48, pp. 216-232, May 1980.
2. M. Ragheb and C. W. Maynard, "On a Nonproliferation Aspect of the Presence of U^{232} in the U^{233} fuel cycle," Atomkernenergie, 1979.
3. M. M. H. Ragheb, M. Z. Youssef, S. I. Abdel-Khalik, and C. W. Maynard, "Three-Dimensional Lattice Calculations for a Laser-Fusion Fissile Enrichment Fuel Factory," Trans. Am. Nucl. Soc., Vol. 30, 59, 1978.
4. S. S. Rozhkov and G. E. Shatalov, "Thorium in the Blanket of a Hybrid Thermonuclear Reactor," Proc. U.S.-USSR Symp. Fusion-Fission Reactors, July 13-16, 1976, CONF-760733, p. 143, 1976.
5. Jungmin Kang and Frank N. von Hippel, "U-232 and the Proliferation Resistance of U-233 in Spent Fuel," Science and Global Security, Volume 9, pp. 1-32, 2001.
6. J. D. Lee, "The Beryllium/molten salt blanket-a new concept," UCRL-80585, Lawrence Livermore Laboratory, 1979.
7. Alexander I. Kalina, "Process and Power System utilizing potential of Ocean Thermal Energy Conversion, U. S. Patent 8,561,406, October 22, 2013.
8. Henry A. Mlcak, " An Introduction to theKalina Cycle," Proceedings of the International Joint Power Generation Conference, Vol. 30, pp. 1-11, 2004.
9. A. K. Krasin, " Prospects of using the Dissociating Gasesin Large Power Stations," Dissociating Gases as Hear-Transfer Media and Working Fluids in Power Installations, A. K. Krasin, ed., "Dissociating Gases as Heat Transfer Media and Working Fluids in Power Installations," Academy of Sciences, Belorussian SSR, Institute of Nuclear Power, Nauka and Tekhnica Press, Minsk, 1970.
10. B. I. Lomashev and V. B. Nesterenko, "Gas turbines with Dissociating Working Fluids," A. K. Krasin, ed., "Dissociating Gases as Heat Transfer Media and Working Fluids in Power Installations," Academy of Sciences, Belorussian SSR, Institute of Nuclear Power, Nauka and Tekhnica Press, Minsk, 1970.
11. V. B. Nesterenko, "Thermodynamic Schemes and Cycles of APS using The Dissociating Gases," A. K. Krasin, ed., "Dissociating Gases as Heat Transfer Media and Working Fluids in Power Installations," Academy of Sciences, Belorussian SSR, Institute of Nuclear Power, Nauka and Tekhnica Press, Minsk, 1970.
12. M. Ragheb "Nuclear Reactor Concepts and Thermodynamic Cycles," http://www.mragheb.com/NPRE%20402%20ME%20405%20Nuclear%20Power%20Engineering/Nuclear%20Reactors%20Concepts%20and%20Thermodynamic%20Cycles.pdf, May 28, 2014.

ADVANTAGES OF THE THORIUM FUEL CYCLE

1. Breeding is possible in both the thermal and fast parts of the neutron spectrum with a regeneration factor of $\eta > 2$. The implication is a virtually inexhaustible energy source.

2. Expanded nuclear fuel resources due to the higher abundance of the fertile Th232 than U238. The USA proven resources in the state of Idaho amount to 600,000 tons of 30 percent of Th oxides. The probable reserves amount to 1.5 million tons. There exists about 3,000 tons of already milled thorium in a USA strategic stockpile stored in Nevada.

3. The hazard of core meltdown as a result of decay heat generation is eliminated since the fission products as well as the actinides are continuously extracted.

4. Solid fuel pool storage at the reactor sites and their associated cooling needs are eliminated.

4. Lower nuclear proliferation concerns due to the reduced limited needs for enrichment of the U235 isotope that is needed for starting up the fission cycle and can then be later replaced by the bred U233. The fusion fission hybrid totally eliminates that need. An attempted U233 weapon test was reported as a fizzle because the U232 contaminant concentration and its daughter products could not be reduced enough.

4. A superior system of handling fission products wastes than other nuclear technologies and a much lower production of the long lived transuranic elements as waste. One ton of natural Th232, not requiring enrichment, is needed to power a 1,000 MWe reactor per year compared with about 33 tons of uranium solid fuel to produce the same amount of power. The thorium just needs to be purified then converted into a fluoride. The same initial fuel loading of one ton per year is discharged primarily as fission products to be disposed of for the fission thorium cycle.

ADVANTAGES OF THE THORIUM FUEL CYCLE

5. Ease of separation of the lower volume and short lived fission products for eventual disposal.

6. Higher fuel burnup and fuel utilization than the U235-Pu239 cycle.

7. Enhanced nuclear safety associated with better temperature and void reactivity coefficients and lower excess reactivity in the core. Upon being drained from its reactor vessel, a thorium molten salt would solidify shutting down the chain reaction,

8. With a tailored breeding ratio of unity, a fission thorium fuelled reactor can generate its own fuel, after a small amount of fissile fuel is used as an initial loading.

9. The operation at high temperature implies higher thermal efficiency with a Brayton gas turbine cycle (thermal efficiency around 40-50 percent) instead of a Joule or Rankine steam cycle (thermal efficiency around 33 percent), and lower waste heat that can be used for desalination or space heating. An open air cooled cycle can be contemplated eliminating the need for cooling water and the associated heat exchange equipment in arid areas of the world.

10. A thorium cycle for base-load electrical operation would provide a perfect match to peak-load cycle wind turbines generation. The produced wind energy can be stored as compressed air which can be used to cool a thorium open cycle reactor, substantially increasing its thermal efficiency, yet not requiring a water supply for cooling.

ADVANTAGES OF THE THORIUM FUEL CYCLE

11. The unit powers are scalable over a wide range for different applications such as process heat or electrical production. Units of 100 MWe each can be designed, built and combined for larger power needs.

12. Operation at atmospheric pressure without pressurization implies the use of standard equipment with a lower cost than the equipment operated at high pressure in the LWRs cycle.

13. In uranium-fuelled thermal reactors, without breeding, only 0.72 percent or 1/139 of the uranium is burned as U^{235}. If we assume that about 40 percent of the thorium can be converted into U^{233} then fissioned, this would lead to an energy efficiency ratio of 139 x 0.40 = 55.6 or 5560 percent more efficient use of the available resource.

14. Operational experience exists from the Molten Salt reactor experiment (MSRE) at oak Ridge National Laboratory (ORNL) at Oak Ridge, Tennessee. A thorium fluoride salt was not corrosive to nickel alloy: Hastelloy-N. Corrosion was caused only from tellurium, a fission product.

Actinides and Fission products radiotoxicity

Source: Sylvain David, Institut de Physique Nucléaire d'Orsay