

Inherently Safe Reactor with Boiling Sodium in Contact with Fuel

W. Van Snyder
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Abstract

Using new ideas and novel combinations of old ideas, it is possible to construct an inherently and passively safe compact boiling sodium reactor. Fuel is metal nitride ceramic particles. Liquid sodium coolant enters at the bottom, flows around fuel particles, and sodium vapor exits at the top, circulated by its boiling, not by pumps. The device consists of a reaction region, connected to a storage region in which criticality is impossible. It has no moving parts other than paste fuel, coolant, and pumps and valves to control gas pressures above the regions. There are no control rods: Power output depends upon the amount of fuel in the reaction region, which is controlled by gas pressure or electromagnetic pumps. If the gas pressure or electromagnetic pump fails, fuel flows passively under the influence of gravity from the reaction region to the storage region and the reaction stops. The reaction region is small. The volume of circulating coolant is small. Power output can be changed rapidly. If electricity is produced by magnetohydrodynamic generators, the entire plant has essentially no moving parts. External electrical power is not necessary for safety. Small volumes of fuel slurry are removed continuously for processing, which eliminates the “iodine pit” startup control instability. There is no need to shut down the reactor for refueling. The capacity factor should well exceed 95%.

1 Conceptual outline

In the mobile paste fuel reactor concept described by Atomic Power Development Associates (APDA) in 1961 [5] [4], fuel is a bulk penetrated by coolant tubes rather than fuel being in pins surrounded by flowing coolant.

In the limiting case as coolant tubes become smaller and more numerous, they are eliminated and coolant flows directly through fuel. This concept, which has largely been abandoned, is known as a pebble-bed reactor, a fluidized-bed reactor, or a slurry reactor, depending upon whether coolant flows through a stable bed of fuel particles, levitates them in equilibrium, or carries them away.

Sodium coolant does not react with metallic or metal nitride fuel. It is not necessary to encapsulate fuel in a coating to prevent interaction, as was done in earlier concepts with fuel in contact with coolant. In a fast neutron reactor, it is unnecessary, indeed undesirable, to include a moderator in the fuel particles. This allows to use small fuel particles that are easy to fabricate.

Early homogeneous reactor concepts used aqueous solutions of uranium salts, usually uranyl sulfate or uranium trifluoride, in heavy water. Those solutions were corrosive. Using water as the coolant required high pressure and low temperature, which complicated construction and reduced thermal efficiency. Water is decomposed by radiation, which required re-combining hydrogen with oxygen, usually used to pre-heat water for the steam generator. Later concepts used molten salts, which also corrode reactor materials. The present concept does not use water directly as a coolant. Actinide nitrides do not significantly corrode reactor materials. Therefore, the corrosion problems that prevented progress of those earlier concepts do not exist in the present concept.

The advantage of small uncoated fuel particles is explained in [27]: The surface-to-volume ratio is larger. Inert fission gases do not diffuse through metal. Rather, they move through microcracks and along grain boundaries, or accumulate in sealed pores that eventually expand, interconnect, and break open at the surface. With smaller particles, the distance to the surface from a pore, grain boundary, or microcrack is less. Therefore, it is more likely that a microcrack or grain boundary will initially be directly open to the surface, and there is a smaller limit to the size a sealed pore can attain before it breaks open at the surface: Small particles expand less than large solid slugs, and endure less thermal strain.

In addition to moving along grain boundaries and microcracks, iodine and many fission-product metals diffuse through fuel, are soluble in sodium [13, Table 1, p. 98], and are insoluble in fuel [6]. Their diffusion rates from fuel into sodium depend upon the surface area. Their production rates depend upon volume. The ratio of diffusion rate to production rate is therefore greater with greater surface-to-volume ratio, and the surface-to-volume ratio is greater with smaller particles. With large volumes of coolant flow, coating

particles prevents contaminating the large volume of coolant with fission products. As shown in Section 4, however, with a small volume of coolant, contamination is a virtue that reduces fuel reprocessing cost.

In a settled paste with uniform-size spherical fuel particles, the maximum fuel density is 74 vol.% ($\pi/\sqrt{18}$).^a With random close packing, the settled fuel density of particles having a polydisperse log normal size distribution with $0 \leq \sigma \leq 3$ is in the range from 60 vol.% to 97 vol.% [8]. The number of fissions per second is given by $N(t)\sigma_f\bar{v}n(t)$, where $N(t)$ and σ_f are the number density and fission cross section of fissionable atoms, \bar{v} is the average velocity of neutrons, and $n(t)$ is the number of neutrons [18, § 5.2]. With higher volumetric fuel density, specific power output (watts per liter) is larger. Density sufficiently high to cause prompt criticality must be avoided. The density of fuel atoms can be reduced by adding zirconium or molybdenum, or increasing the proportion of non-fissionable heavy metal; the latter would increase breeding.

Fuel composed of very small particles is agitated if coolant flows through it. Depending upon coolant flow rate and state (liquid or gas), the volume fraction of fuel is reduced and the mixture becomes a slurry rather than a settled paste. Power output depends upon volume and fuel volume fraction, and therefore upon coolant flow rate. Early slurry-fuel reactor concepts assumed the amount of fuel is constant and always within the same container perimeter, with density profiles that depend upon coolant flow conditions. If coolant flow fails, fuel settles into the containment vessel and assumes the density of a solid paste. Oscillations might set in. These cause control instabilities. Therefore, flowing slurry-fueled reactor concepts were rejected.

The boiling-sodium concept shown in schematic form in Figure 1 is either a pebble-bed, fluidized-bed, or slurry reactor, depending upon coolant velocity, which depends upon the relationship between the vessel diameter and its power output. There are important distinctions that overcome objections to earlier such concepts: Sodium has much higher heat capacity and thermal conductivity than the gases (usually helium) proposed in those earlier concepts; the enthalpy of vaporization of sodium is large, but gases proposed in those earlier designs did not undergo phase transitions. These phenomena result in a much smaller coolant flow rate than in earlier concepts.

This concept embodies two connected regions. Reaction takes place in a compact region, which is connected to a storage region in which criticality is impossible, for example, several thin concentric cylindrical shells connected to a thin conical bottom and separated by neutron shields, shown in cross section in Figure 1. The storage volume is larger than necessary to contain the entire fuel mixture.

Rather than using control rods, power output is determined by the amount of fuel within the reaction region, and the fuel volume fraction, which depends upon coolant velocity. The bottom of the reaction region is conical (1) to allow operation at low power, (2) to flow fuel toward the connector to the storage region, (3) to control density distribution and thereby eliminate oscillations [25], and (4) to produce a vertical profile with reducing coolant velocities. The relationship of the levels of the fuel mixture within the reaction and storage regions is controlled either by the relationship of gas pressures above fuel in the reaction and storage regions, or by electromagnetic pumps.

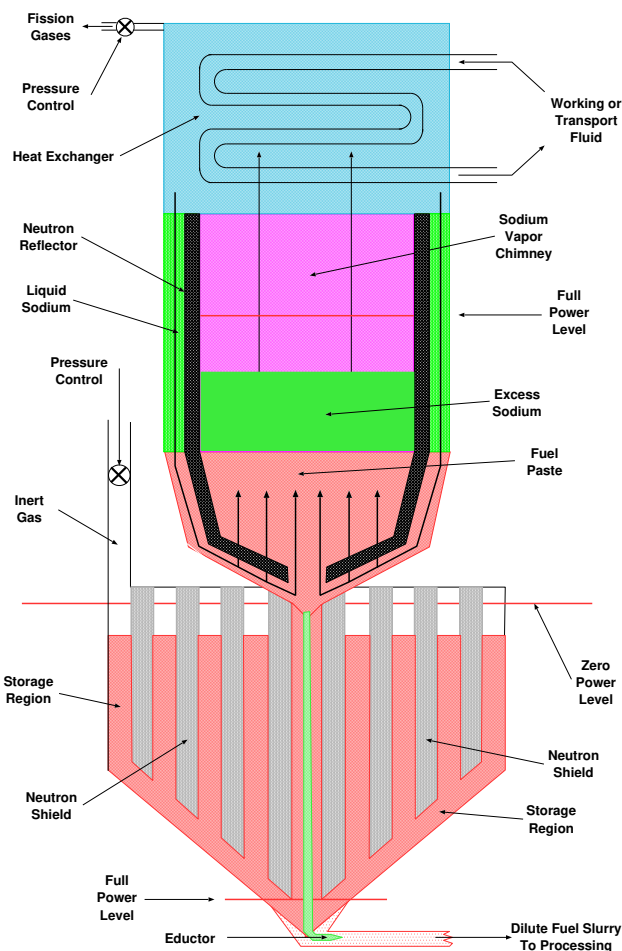


Figure 1: Reactor at Partial Power

^aThis result was conjectured by Johannes Kepler in 1611. Thomas Hales published a proof 10 August 2014.

When pressure is reduced in the storage region, or increased in the reaction region, fuel flows passively, under the influence of gravity, from the reaction region to the storage region, reducing power. This constitutes a negative-reactivity feedback mechanism. Pressure is maintained above the storage region by several redundant normally-open valves that must be actively closed. Pressure is maintained above the reaction region by an adjustable flow rate valve to remove fission gases from above the heat exchanger. When valves for both regions are open, fuel flows passively, under the influence of gravity, into the storage regions and the reaction region is empty. If fuel particles are sufficiently small to form a viscous paste or colloidal suspension rather than a settled slurry, pressure above the storage region drives fuel into the reaction region. If fuel particles are large, gas pressure above the storage region simply drives sodium through the fuel and into the reaction region; an electromagnetic pump is necessary to lift fuel from the storage region to the reaction region.

The reaction and storage regions, and most of the vapor chimney, are submerged within a sodium pool.

2 The reactor in operating condition

In one PRISM design taken as an example [31], the fuel load is 26 tonnes (1,000 kg/T), the fuel volume fraction is 28.3%, and the power output is 840 MWth. It was not specified whether the fuel volume fraction is the volume fraction of metallic fuel alloy, or the volume fraction of the interior of fuel pins, about 75% of which is occupied by fuel.^b Coolant is liquid sodium. The sodium inlet temperature is 360°C (633°K) and the outlet temperature is 499°C (772°K). The coolant flow rate is 5.4 m³/s = 4,685 kg/s.^c The average heat capacity of liquid sodium coolant is therefore $C_p^\ell = 840,000 / 4,685 / (772 - 633) = 1.290$ kJ/kg/°K. Fuel is contained within pins; sodium coolant is not contaminated with fission products (unless a fuel pin ruptures).

Assuming the volume fraction for random close packing of uniform spherical particles is 60%, and metallic particles with a density of 19 g/cm³, 26 tonnes of fuel would occupy a cylinder having diameter and height about 1.5 meters, and a bottom area of 1.77 m². The 5.4 m³/s PRISM coolant flow through 1.77 m² would have an upward velocity of 3 m/s. As shown by Equation (2), particles smaller than 2.35 cm diameter would be carried out of the reaction region. To maintain a settled bed, particles as large as 20 cm diameter might be needed. Such large particles would be damaged by excessive thermal strain.

Allowing coolant to boil reduces the necessary flow rate. The energy W necessary to heat a liquid of mass m from temperature T_1 to T_2 at constant pressure, then boil it at T_2 , then heat the vapor from T_2 to T_3 is

$$W = m [C_p^\ell (T_2 - T_1) + \Delta H_{\text{vap}} + C_p^v (T_3 - T_2)] . \quad (1)$$

Sodium heat of vaporization ΔH_{vap} is 96.96 kJ/mol, or 4,218 kJ/kg.^d Sodium vapor heat capacity C_p^v at 1,175°K is 2.53 kJ/kg/°K [9]. 840 MWth would be sufficient to heat 168 kilograms of sodium per second from 633°K to 1154.7°K, boil it, and heat the vapor to 1,200°K – about 0.2 kg s⁻¹ MW⁻¹. At 633°K, the volume of 168 kilograms of liquid sodium is 193.7 liters.^e

Uranium-plutonium alloys would need to include excessive amounts of zirconium or molybdenum so as not to melt in boiling sodium. For example the solidus temperature of U-10Pu-30Zr (atomic percent) is below 1,200°K [7, P. 184]. Ceramic fuels are necessary.^e Nitride fuels would react less with sodium and structure than would carbide, oxide, or silicate fuels. Uranium-20% plutonium mononitride melts at 3,045±30°K [19]. A disadvantage of nitride fuels is that nitrogen-14 has a significant neutron absorption cross section, which decreases neutron economy and causes production of carbon-14. It would be necessary to use expensive nitrogen-15, which is only 0.366% of the atmosphere [16]. To the extent nitrogen is recovered when fuel is reprocessed [20], this cost is only incurred for the initial fuel load.

The uranium density observed in uranium nitride prepared by Johnson et al [15] was 13.55 g/cm³. The overall density was 14.25 g/cm³. Assuming 60% volume packing ratio for uniform spherical particles, the uranium volume fraction in a settled bed of uniform-size uranium nitride particles would be 57.1%.

^bThis assumes that fuel in PRISM is fabricated with an initial 75% smear density, as in EBR-II [13].

^cThe density of liquid sodium at 633°K is 867.4 kg/m³ [9].

^dThe molar mass of sodium is 0.022989769 kg.

^eIf a colloidal suspension of 10 nm metallic fuel particles does not separate, and if melted metallic particles do not consolidate, metallic fuels might be possible. Such small particles would be entrained in vapor flow, as shown in section 3.

Assuming simplistically that power density is linearly related to fuel volume fraction, and that the PRISM fuel volume fraction is the uranium volume fraction, the same power could be obtained with $28.3\%/57.1\% \times 26 \approx 12.9$ tonnes of uranium as uranium nitride ≈ 905 liters. With 60 vol.% fuel particles, the minimum sodium amount would be 600 liters, and the total volume would be about 1,500 liters. Assume for simplicity that the reaction region is a cylinder with diameter and height approximately 1.25 meters. The surface area of the bottom is 1.23 m^2 . Additional sodium in a taller vessel would ensure that fuel is always covered by sodium, even if working fluid flow to the heat exchanger is interrupted.

Coolant circulation is driven by coolant boiling. There are no pumps. The density of sodium vapor at $1,200^\circ\text{K}$ is 0.394 kg/m^3 [9]. Boiling 168 kilograms of sodium per second at $1,200^\circ\text{K}$ would produce $168 / 0.394 = 426 \text{ m}^3/\text{s} = 426,000$ liters of sodium vapor per second.

Because the amount of circulating coolant is small, and the reaction volume is small, thermal inertia is small and power output can be changed rapidly.

In the present concept, the entire volume of sodium used for flowing coolant through fuel becomes contaminated with fission products and must be purified continuously. In PRISM, sodium in the pool is used as coolant, to eliminate a separate heat exchanger and associated pumps. The PRISM sodium pool contains about 840 cubic meters of sodium [31]. Purifying that volume of sodium would be prohibitive. The amount of sodium in an isolated circulating entirely-liquid sodium cooling system, a loop-within-pool design, would be less, but still large.

The heat exchanger is shown in more detail in Figure 2. After sodium is condensed to transfer its heat to the working fluid, it flows downward, around the outside of the reaction region, thence between the neutron reflector and sodium pool so as to remain a liquid, thence through the fuel to boil again.

The fluid that passes through the heat exchanger might be a transfer fluid, or the working fluid. If the fluid exits the heat exchanger at the same temperature as the entering sodium vapor, and if the fluid is sodium, it will enter the heat exchanger as a liquid and leave as a vapor. The heat exchanger is therefore not conceptually different from a steam generator in a more conventional system. The alternative to boiling sodium in the heat exchanger is to use a sufficiently high working fluid flow rate, or a sufficiently high pressure, that it does not boil. This would reduce total plant thermal efficiency, require pumps, and increase plant cost. In the PRISM design, the rate is 5,400 liters per second [31]. In either case, the balance of plant could be similar to the PRISM design.

The sodium pool would contain a heat exchanger, but of significantly less capacity than in the PRISM design, because most of the reaction heat is carried by the separately-circulating and boiling coolant.

Coolant that returns from the plant's cooling tower would pass first through the pool heat exchanger before entering the chimney heat exchanger.

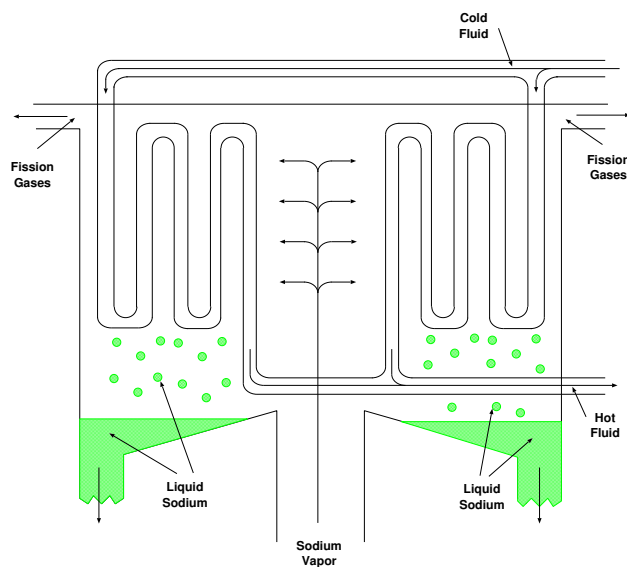


Figure 2: Heat Exchanger in More Detail

3 Flow

Equating the drag force on a particle to the force of gravity determines the velocity at which particles are suspended in equilibrium with upward fluid flow:

$$\begin{aligned}
 F_d &= \frac{1}{2} C_d \rho_s U_t^2 \pi \frac{d_f^2}{4} = F_g = \frac{4\pi}{3} \frac{d_f^3}{8} \rho_f g, \text{ or} \\
 U_t &= \sqrt{\frac{4g}{3C_d} \frac{\rho_f}{\rho_s} d_f} = 22.81 \sqrt{d_f} \text{ m/s for liquid sodium and uranium nitride, or} \\
 U_t &= 1031 \sqrt{d_f} \text{ m/s for sodium vapor and uranium nitride,}
 \end{aligned} \tag{2}$$

where

g = acceleration of gravity = 9.81 m/s²,

d_f = fuel particle diameter, meters,

ρ_f = fuel particle density = 14.25 kg/liter,

ρ_s = sodium density = 0.805 kg/liter for liquid sodium at 900°K and 0.394×10^{-3} kg/liter for sodium vapor at 1200°K [9, Table 1.3-1],

C_d = the Reynolds-number dependent drag coefficient (Kloosterman et al [17] used $C_d = 0.445$), and

U_t = upward coolant equilibrium terminal flow velocity, m/s.

A 1.25 meter diameter reaction cylinder with a bottom cross section of 1.23 m² would be filled to a depth of about 1.25 meters by 1,500 liters of settled fuel paste. The upward velocity of 5.4 m³/s of liquid sodium would be 4.4 m/s. The upward velocity of 193.7 liters per second of liquid sodium would be 0.158 m/s. The upward velocity of 426 m³/s of sodium vapor would be 347 m/s. The speed of sound in sodium vapor at 1,200°K is 802 m/s,^f so this is subsonic flow at Mach 0.43. Table 1 shows the relationship of particle sizes to terminal velocity.

Table 1: Particle sizes

U_t	d_f
4.4 m/s liquid	3.72 cm
0.158 m/s liquid	48.0 μ m
347 m/s vapor	11.3 cm

The void fraction of particles ϵ_v , coolant flow velocity U , and the terminal velocity U_t , the velocity above which particles would be entrained in coolant and carried away, are related by the Richardson-Zaki relation [3]:

$$\epsilon_v = \left(\frac{U}{U_t} \right)^{\frac{1}{n}} \text{ or } U_t = U \epsilon_v^{-n}, \tag{3}$$

where the Richardson-Zaki constant $n \approx 2.4$, assuming the Reynolds number^g is greater than about 500. The minimum possible void fraction with uniform-size particles is 0.4. Solving Equation (3) for U with $\epsilon_v = 0.4$ gives the velocity for a stable fuel bed $U_s = 0.111 U_t$.

There are three possible regimes for fuel in the reaction region:

^fThe speed of sound is given by $v_s = \sqrt{\frac{C_p R T}{C_v M}}$ where $C_p = 1.279$ is the heat capacity of sodium vapor at constant pressure at 1200°K, $C_v = 0.862$ is the heat capacity of sodium vapor at constant volume at 1200°K [9, Table 1.1-5], $R = 8.314$ J/(mol K) is the gas constant, $T = 1200$ is temperature in kelvins, and $M = 0.022989769$ kg is the molar mass of sodium.

^gThe Reynolds number is $Re = \frac{\rho U D}{\mu}$. With $\rho = 743$ kg/m³ at 1154°K, $U = 0.109$ m/s, $D = 1.5$ m, and $\mu = 1.49 \times 10^{-5}$ Pa-s, the Reynolds number for liquid sodium is about $Re = 8.15 \times 10^6$.

$U > U_t$ Fuel is entrained in coolant and carried out of the reaction region (this is called a *slurry reactor*). Slurry reactors were studied and rejected because of reactivity instability caused by slurry collapsing to a higher density settled bed if coolant flow ceases. With coolant flow caused by coolant boiling rather than by pumps, coolant flow rate is proportional to power output, assuming the coolant does not all boil, and a slurry reactor might be feasible. Fuel entering the heat exchanger would contaminate it, and might damage it by abrasion. Fuel particles, except ones very much smaller than the design size, could be separated from vapor by a cyclone separator, which would reduce efficiency and move the abrasion problem from the heat exchanger to the much simpler separator.

$U_s < U < U_t$ Fuel is levitated but not carried out of the reaction region (this is called a *fluidized bed reactor*). Fluidized bed reactors have been described [25] [17], but not deployed commercially. In some designs, they would have the same reactivity instability as slurry reactors, but might also be feasible if coolant flow is caused by boiling. With a sufficiently tall chimney, only tiny fuel particles would enter the heat exchanger.

$U < U_s$ Coolant flows around fuel without significantly levitating it (this is called a *pebble bed reactor*). Pebble bed reactors were developed in South Africa, but not widely used. They would not have a reactivity instability caused by slurry or fluid collapse.

The coolant velocity, and therefore the regime in which the reactor operates, is determined by the relationship of coolant flow rate to reaction region diameter. By equating $U_t = F/A$ to Equation (2), where F is coolant volumetric flow rate and A is the area through which it flows, the diameter d_r of the reaction region aperture for which the coolant velocity is U_t can be computed as a function of particle diameter:

$$\begin{aligned} d_r &= \frac{1}{2} \sqrt{\frac{F}{c\pi}} \frac{1}{\sqrt[4]{d_f}} = \frac{0.1813}{\sqrt[4]{d_f}} \text{ (vapor at } F = 426 \text{ m}^3/\text{s)} \\ &= \frac{0.0259}{\sqrt[4]{d_f}} \text{ (liquid at } F = 0.1927 \text{ m}^3/\text{s)}, \text{ or} \\ &= \frac{4.340}{\sqrt[4]{d_f}} \text{ (liquid at } F = 5.4 \text{ m}^3/\text{s)}, \end{aligned} \tag{4}$$

where d_f is particle diameter in meters and c is the constant in Equation (2) (1031 or 22.81). Table 2 shows reaction region diameters for several particle diameters and several vapor and liquid flow rates.

Table 2: Vessel Diameters d_r (meters) for $U = U_t$
Flow rates m^3/s

d_f	426 (v)	0.193 (l)	5.4 (l)
10 nm	18.13	2.59	434.0
50 μm	2.15	0.308	51.6
100 μm	1.81	0.259	43.4
1 mm	1.02	0.146	24.4
1 cm	0.573	0.082	13.7

To reduce the velocity to $U_s = 0.111 U_t$, it is necessary to increase d_r by a factor of $1/\sqrt[4]{0.111} \approx 3$.

There is a tension between small particle size, coolant velocity, and vessel diameter. Smaller particle sizes result in more fission-product diffusion into sodium, thereby reducing fuel processing cost, but require a larger vessel to avoid entraining fuel particles. If a slurry reactor remains stable with boiling coolant, the best particle size is the smallest one.^h

With a cylindrical region, a ‘‘pancake’’ shape results for small particles. Achieving criticality might not be possible except with a much larger fuel load per watt of output. A pancake would have poor neutron economy, and breeding would be much reduced. Alternatively, the vessel can have a divergent shape, such

^hSmall particles are less damaged by thermal strain, swell less, and allow more fission products to diffuse to sodium.

as a cone ($d_r = 2h \tan \alpha$), paraboloid ($d_r = 2\sqrt{h/a}$), or intermediate shape ($d_r = 2(h/a)^\alpha$, $1/2 < \alpha < 1$) that might have better neutron economy, so that liquid entering at the bottom does not entrain (or levitate) particles, and gas exiting at the top of the sodium above fuel does not entrain (or levitate) particles. Excess sodium above fuel, beyond the 40% volume mixing ratio for a settled paste, would prevent fuel particles from being entrained into vapor.

Sefidvash proposed a conical vessel in a fluidized-bed reactor concept description [25].

Three-phase flow calculations, or experiments, would be necessary to choose an appropriate shape and particle size such that the fuel mixture remains stable and does not oscillate, and such that vapor escapes from fuel uniformly and does not “burp.” These experiments could be done at small scale using various vessel shapes, induction heating, and depleted uranium nitride.

4 Processing sodium and fuel

Alkali metal, alkaline earth, antimony, arsenic, cadmium, gallium, germanium, indium, sodium iodide, small amounts of tellurium, and tin fission products are soluble in sodium at operating temperatures. Nitride ceramics, actinides, lanthanides, noble metals, and inert gases do not dissolve in or react with sodium [6]. Gases and soluble fission products, especially those that are not soluble in uranium, diffuse from fuel particles into sodium. Metals that have boiling points below 1154.7°K can be removed from coolant by condensing from vapor. Metals that have boiling points above 1154.7°K can be separated by boiling liquid sodium drawn from the liquid region or the eductor stream using heat from the vapor, or by a cold trap. Temperatures higher than the operating temperature would be needed to distill high boiling-point fission products, e.g., to separate strontium (1655°K) from barium (2170°K).

As shown in Figure 1, fuel slurry is continuously removed for processing from the bottom of the connection between the reaction and storage regions, by an eductor powered by coolant sodium. Circulating and processing fuel, even during shutdown, continuously removes ^{135}I , the precursor to the powerful neutron poison ^{135}Xe , thereby reducing or eliminating the “iodine pit” startup control instability.

Sodium and fuel are processed as described in [27]. Purified or replacement fuel is returned to the reaction region as a dilute slurry. To summarize:

1. Separate sodium from particles.
2. Return insufficiently consumed fuel particles to the reaction vessel.
3. Distill sodium to purify it and separate sodium-soluble fission products.
4. Remove fission products that have not diffused into sodium from sufficiently consumed fuel particles using the pyroelectric process developed for the Experimental Breeder Reactor II (EBR-II) [30].
5. Create particles from purified or replacement fuel.

A reactor similar to PRISM would produce about 956 grams of fission products per day. Sodium-soluble fission products constitute 12.2 wt.%, or 116 grams per day. With 2,000 liters of liquid sodium in the reaction vessel, the rate of increase of their concentration in circulating liquid coolant is less than 0.07 wt.% per day. Fission product gases constitute 16.4 wt.%, or 157 grams per day. Other fission products amount to 690 grams per day.ⁱ

Purify sodium continuously to remove sodium-soluble fission products from 2,000 liters = 1,464 kg of liquid sodium per day. As vapor at 1,200°K, 1,464 kilograms of sodium would occupy about 3,700 cubic meters. Withdrawing 0.043 m³/s, or about 0.01% of the sodium vapor flow, and passing it through a distillation column, would remove caesium (943.3°K), selenium (957.6°K), and rubidium (961.2°K). A cold trap can remove tellurium (melting point 934.2°K), sodium iodide (934.2°K), barium (1,000°K), and strontium (1,050°K) from sodium separated from fuel slurry sent to processing. Alternatively, sodium separated from the reprocessing slurry can be heated by vapor, further heated to boil more of the fission products, and then passed through a distillation column. It might be impractical to remove cadmium (boiling point 1,040°K, melting point 594°K) by a cold trap. If not removed, cadmium would accumulate at the rate of 1.43 kg/GWe-yr, but the only significantly radiotoxic cadmium isotope, ^{113m}Cd , has a half life of 14.10 years, and

ⁱOutput from the ORIGEN 2 computer program [1].

is produced at the rate of 3.2 grams per GWe-yr [1]. Cadmium might damage fuel particles by forming low melting point alloys, decreasing the fraction of particles that can be returned without processing. Additional sodium-soluble fission products are produced in only millimole quantities per GWe-yr. Processing about 13.2 kg, about one liter, per day, about 4.8 tonnes per year, of fuel particles would maintain 5 wt.% concentration of fission products [28].

Even though sodium-soluble fission products diffuse from fuel into sodium, some remain within fuel particles. In “high” but unspecified burnup solid metallic fuel slugs from EBR-II, only 70% of alkali-metal products and 20% of alkaline earth fission products had diffused into bond sodium [13]. With smaller particles, more sodium-soluble fission products would diffuse from fuel into sodium. Caesium and strontium, the two fission products that produce 99.4% of radiotoxicity but constitute only 9.26 wt.% of fission products, are sodium soluble. It would be desirable to remove them before pyroelectric processing, to avoid incorporating them into the ceramic waste form [10]. Till and Chang wrote [30, p. 241] that removing them would “increase repository space utilization by the huge factor of 225. . . . In the absence of these two activities. . . there would simply be no need for a highly engineered repository.” One way is to distill fuel as described in [27]. Another is to flow hydrogen through a hot fuel/sodium paste or slurry. All fuel and fission product metals form hydrides, which decompose at various modest temperatures. For example, formation and decomposition of uranium hydride are in equilibrium at 225°C [11], and cadmium hydride decomposes at -20°C. As hydrides form and decompose, fuel particles are re-formed with different distributions of fuel and fission products. The process gives more opportunities for soluble fission products to dissolve into sodium rather than to be incorporated into fuel particles. Sodium-soluble fission products can then be separated from fuel particles by filtering and washing with clean sodium, or by a sequence of centrifugal contactors with a countercurrent sodium flow. Oxidation of fuel particles at the anode in a pyroelectric processor is necessarily a surface phenomenon. Therefore, the larger surface-to-volume ratio of small particles, as compared to solid slugs, allows pyroelectric processing to proceed more rapidly.

5 Inherent safety

The first line of defense is, of course, the active control system, and its human operators who continuously monitor temperatures, pressures, and flow rates, and adjust pressures above the reaction and storage regions or adjust power to electromagnetic pumps that lift fuel from the storage region to the reaction region.

Fuel, coolant, and structure expansion as temperature increased contributed to inherent passive safety in EBR-II [30]. That mechanism would be operative but less effective in the concept proposed here. Very high thermal conductivity of metallic fuel, very high thermal conductivity of sodium coolant, and very large heat capacity of the sodium pool were more important [29]. Those mechanisms would be at work here. Indeed, the thermal conductivity of paste or slurry is greater than the thermal conductivity of solid metal because the thermal conductivity of sodium ($\kappa_{Na} \simeq 62.9 \text{ Wm}^{-1}\text{K}^{-1}$ [9, p. 101]) is greater than the thermal conductivity of uranium ($\kappa_f \simeq 35 \text{ Wm}^{-1}\text{K}^{-1}$ [12]).

The thermal conductivity of uranium nitride is less than metal, but still quite large. Ross developed the correlation $\kappa_f = 1.37 T^{0.41} \text{ Wm}^{-1}\text{K}^{-1}$ [24]. The thermal conductivity of paste fuel, $\kappa_p \approx 34.3 \text{ Wm}^{-1}\text{K}^{-1}$ at 630°K and $\kappa_p \approx 38.4 \text{ Wm}^{-1}\text{K}^{-1}$ at 1200°K, was estimated using Equation (6.4) from [14]:

$$\frac{\kappa_p}{\kappa_{Na}} = 1 + 3\beta\phi + 3\beta^2\phi^2 \left(1 + \frac{9\beta}{16(\beta+5)} + \frac{\beta}{4} + \frac{\beta^2}{2^6} + \dots \right) + O(\phi^3), \quad (5)$$

where $\alpha = \kappa_f/\kappa_{Na} \simeq 0.397$, $\beta = (\alpha - 1)/(\alpha + 2) \simeq -0.251$, and $\phi = 0.6$, the volume fraction occupied by fuel in settled paste. Above 711°K, the thermal conductivity of uranium nitride paste remains greater than the thermal conductivity of uranium metal. Because $\beta < 0$, as ϕ decreases, i.e., in a fluidized bed or slurry, thermal conductivity increases. Thermal conductivity of sodium vapor is significantly less, but vapor rises through liquid coolant and carries away heat by convection instead of conduction.

The first additional safety mechanism proposed here is the connection between the reaction and storage regions described in Section 1 and the relationship of the gas pressures above them.

When coolant boils, it creates sodium vapor. When the temperature of sodium vapor increases, its pressure

increases. Both phenomena drive fuel from the reaction region into the storage region, producing negative feedback that decreases power output. Increasing reactivity increases temperature and pressure in the reaction region, and therefore reduces the amount of fuel in the reaction region. To maintain reactivity, it is necessary to increase gas pressure above the storage region. Not doing so results in reducing the amount of fuel in the reaction region, which reduces power output, which reduces the temperature and pressure in the reaction region, which allows fuel to return to the reaction region. The viscosity of settled paste results in a strongly damped system without oscillations. Equilibrium is reached quickly.

There is sufficient sodium that fuel in the reaction region is always covered with sodium. Before power output becomes sufficient to boil all the sodium, vapor pressure in the reaction region is sufficient to drive all the fuel out of the reaction region and the connector, and into the storage region. Vapor would then flow through fuel to the plenum above the storage region, where it would be condensed, and its pressure reduced, by the enormous heat capacity of the sodium pool. With reaction stopped, the reaction vessel would also be cooled by the enormous heat capacity of the sodium pool, and remaining sodium vapor therein would condense. After the sodium vapor is condensed, the reaction region is empty, the level in the storage region would be the same as in the connector, and with large particles, fuel would be settled below excess sodium.

In addition to its several redundant gas pressure control valves, all of which must actively be held closed, the storage region is fitted with several redundant emergency pressure-relief valves of the rupturing diaphragm type. One accident scenario would be for a valve that controls pressure above the reaction region to be open, all valves that control pressure above the storage region to be closed, and all of the pressure-relief valves are blocked or have failed to rupture. This would allow fuel to flow unimpeded into the reaction region, and increase the reaction rate. To counteract this, the mechanisms that actively close the pressure control valves above the storage region are thermally connected to the reaction region. The connection consists of several redundant small vessels of sodium contained within the reaction region, each connected via a tube to a switch that controls power to the pressure control valves. Each switch is held closed by a spring. The switches are wired in series. If the temperature increases above a predetermined level, and therefore pressure within any of those vessels exceeds a predetermined value, its switch is opened, power to the valves that control storage region pressure ceases, the valves are opened, and pressure above the storage region is released. It would be necessary for all of these devices to fail in such a way that their switches remain closed, in order for all the pressure control valves to remain closed in the event of excessive temperature.

A further line of defense is slugs of actively-frozen paste that separate the reaction region from additional connections to an unpressurized emergency “dump” region (not shown in Figure 1), as was used in the Molten Salt Test Reactor [23]. If power to the plugs’ coolers fails, or the temperature of the reaction region becomes sufficient to overcome their coolers, or the pressure exceeds their strength, the plugs melt or break and fuel flows passively into the emergency dump region. Temperature might become excessive if, for example, a leak allows sodium vapor to escape, eventually boiling away excessive coolant without increasing pressure in the reaction region.

If an emergency dump region separate from the storage region is undesirable, rather than using gas pressure to move fuel from the storage region to the reaction region, use an electromagnetic pump, power to which is enabled by the series-connected thermal switches. With constant pump power and constant pressure within the reaction region, the level of fuel would be stable. Increasing pressure within the reaction region would drive fuel back through the pump into the storage region. Separate connectors that bypass the pump would connect the actively-frozen plugs to the storage region.

Releasing boron into the reaction region in response to excessive temperature or pressure would quench the nuclear reaction, but this would require to purify all the fuel, or at least all the sodium. In APDA-146, Blessing et al [4, §IV.I.3.b] remarked that a fluid poison might be vulnerable in a reactor accident. They recommended sintered boron carbide slugs in a hydraulic cylinder, moved by sodium; such a device would not contaminate fuel with boron.

Many of the inherent safety mechanisms of PRISM [2, § 6], for example the Reactor Vessel Auxiliary Cooling System (RVACS), would also be used. The maximum hypothetical accident, a complete reaction and storage vessel disruption, would have the same result as in PRISM: natural dispersion into a porous easily-cooled non-critical mass at the bottom of the sodium pool. This would be an expensive mess, but not a significant safety hazard.

6 Alternative balance of plant

Figure 3 shows an alternative balance of plant concept.

Theoretical calculations using equations by Shair and Cristinzio [26] (Figure 4) show that a sodium-vapor magnetohydrodynamic (MHD) generator might have very large power density at modest magnetic field strength. With an inlet temperature of 1,400°K, inlet pressure of 1.36 atm (20 psia), and Mach number 2.0, the power density can be 1 kW/cm³ with a magnetic field of 0.125 Tesla, and 100 kW/cm³ with a magnetic field of 0.15 Tesla.

If the magnets in a sodium vapor MHD generator could be operated at the temperature within the sodium vapor chimney, it can replace the vapor chimney heat exchanger.

Sodium condenses at 1154.7°K, so a second generator would be necessary to extract energy between that temperature and the usual power plant outlet temperature. There are several possibilities for the second generator. One is a mercury vapor MHD generator. Higher magnetic field strength is required in a mercury vapor MHD generator, about 0.325 Tesla to achieve one kW/cm³ and 0.5 Tesla to achieve 100 kW/cm³, because of mercury's larger atomic weight and higher first gas ionization potential. U.S. patent number 3,430,081 [32] proposes that adding a small amount of barium would increase ionization, thereby increasing power density. Mercury circulation is driven by boiling. There are no pumps. A sodium-mercury heat exchanger is necessary because sodium and mercury combine explosively.

For any metal vapor MHD generator, an externally supplied electric field applied before the vapor enters the MHD generator would ionize the vapor, further increasing power density.

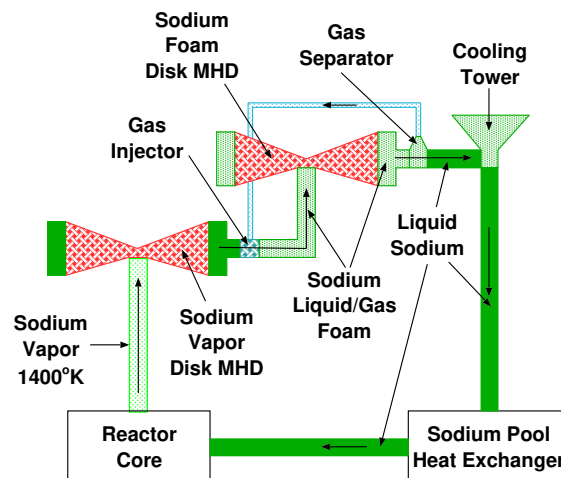


Figure 3: Balance of Plant Concept

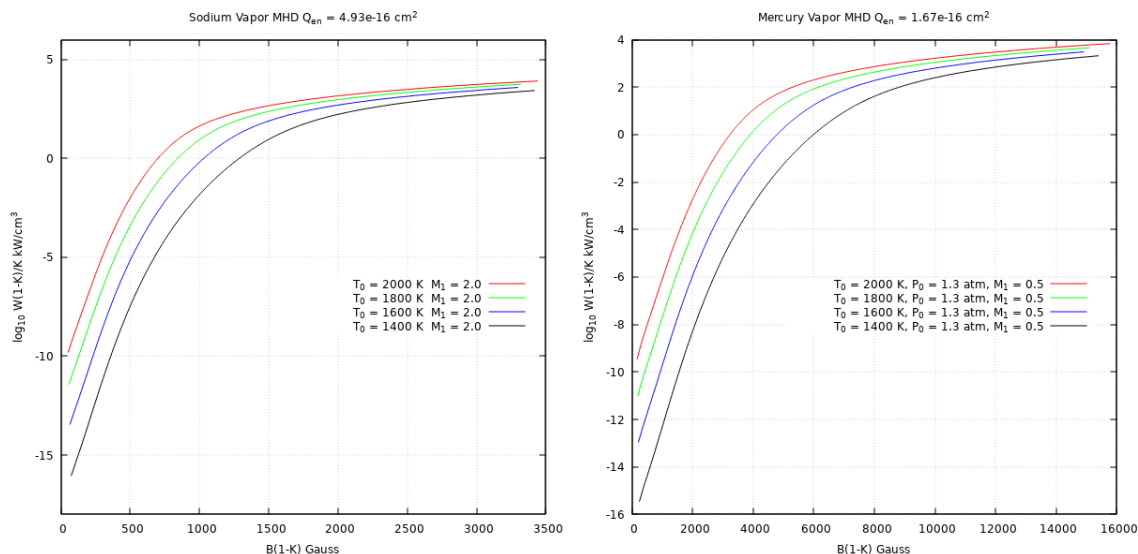


Figure 4: Magnetohydrodynamic generators' theoretical power densities ($K = E_{load}/E_{open \text{ circuit}}$)

A second concept is to inject an inert gas or a low boiling point liquid that is immiscible with sodium and does not react with sodium, into liquid sodium leaving the sodium-vapor MHD generator, producing a liquid-sodium/gas foam to use in a two-phase MHD generator. Gas would act as an accelerant. An injection pump might be needed. Argonne National Laboratory investigated two-phase MHD generators [21] [22]. It

might be possible to combine both concepts into a single device by injecting accelerant into the condensation region in a larger generator.

Finally, a conventional steam system could be used. This puts water in proximity to sodium. It would require a heat exchanger within the reactor, and a water pump and a pump to supply the sodium pool heat exchanger. This is the same as in the PRISM design.

7 Conclusions

This is only a concept description, not an engineering design. There is no pretence of detailed neutronic, structural, or thermal-hydraulic analysis. The purpose of this monograph is to stimulate those analyses. There are at most two new ideas here – but the combination of ideas has not appeared.

The inherently safe boiling-sodium reactor is compact. The concept consists of connected reaction and storage regions. It has no moving parts other than fuel and gas-pressure control valves. It has no control rods. It has no coolant circulation pumps. Operating temperature is higher, and therefore thermal efficiency is greater. Power output is controlled by the amount of fuel in the reaction region, which is controlled by the relationship of pressures above reaction and storage regions, or by an electromagnetic pump. If power to the devices that control fuel levels fails, the reaction stops because fuel flows passively from the reaction region to the storage region.

The reaction region is small. The volume of circulating primary coolant is small. Thermal inertia is small. Power output can be changed rapidly.

If electricity is produced by magnetohydrodynamic generators, the entire plant has essentially no moving parts.

Fuel can be processed continuously. It is not necessary to shut down the reactor for refueling. The capacity factor should well exceed 95%. The “iodine pit” startup control instability is eliminated.

Auxiliary power is not needed to maintain safety during shutdown.

The concept could be evaluated in miniature at low cost.

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