

Revisiting Mobile Paste Reactor Fuel

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Abstract

In April 1961, Atomic Power Development Associates produced *Summary of the APDA Fuel Development Programs*. Chapter XVII described a *Paste Fuel Concept*. The report noted that there are “advantages inherent in a mobile-fueled reactor.” Patent number 3,169,117, entitled *Nuclear Reactor Paste Fuel Composition*, was filed on May 9, 1961. In May 1964, Argonne National Laboratory produced *Catalog of Nuclear Reactor Concepts*. The chapter concerning paste fuels concluded “The few paste-fuel concepts developed to date and the present early stages of such developments show that considerably more work probably will be required before the paste-fuel concept can be considered for commercial development.” This monograph enlarges upon and quantifies the APDA concept, which appears not to have been pursued. Additional passive safety concepts, that might also eliminate the need for control assemblies, are described. Several important consequences of continuously-processed fuel that are not discussed in the APDA report are described, in particular, that the “iodine pit” startup control instability can be eliminated.

1 Introduction

In 1845, Edgar Allan Poe wrote

*Once upon a midnight dreary, while I pondered, weak and weary,
Over many a quaint and curious volume of forgotten lore . . .*

The first volume of forgotten lore that I pondered was the *Summary of the APDA Fuel Development Programs*, produced in April 1961 by Atomic Power Development Associates [1]. Chapter XVII described a *Paste Fuel Concept*. The report noted that there are “advantages inherent in a mobile-fueled reactor.”

The second was *Conceptual Design of a 300 MWe Paste-Fueled Fast Breeder Power Reactor* [2]. The abstract [3] appears in Appendix B.

The third was patent number 3,169,117, entitled *Nuclear Reactor Paste Fuel Composition*, filed on May 9, 1961 [4]. It was assigned to Los Alamos National Scientific Laboratory. References to the use of that patent in a reactor design have not been found.

The fourth was *Catalog of Nuclear Reactor Concepts* [5], produced by Argonne National Laboratory in May 1964. Concerning paste fuels, it described only the APDA concept, the Los Alamos Molten Plutonium Reactor Experiment (LAMPRE), the KEMA reactor concept from the Netherlands, and the RAPTUS reactor concept from Italy. Some tests were done to investigate the flow characteristics of the APDA concept. Some development was done on LAMPRE. The other concepts were only paper studies. The chapter concluded “The few paste-fuel concepts developed to date and the present early stages of such developments show that considerably more work probably will be required before the paste-fuel concept can be considered for commercial development.”

The mobile paste fuel concept does not appear in the literature of nuclear power reactor development after 1964, except in references to earlier work: *Quoth the Raven* Nevermore.

First it must be emphasized that the term “paste” does not necessarily imply a viscous homogeneous mixture such as toothpaste with 50 μm particles. It means instead “a settled particle bed” or “not a slurry.” This monograph enlarges upon the APDA concept, and quantifies several factors. Additional passive safety concepts, that might also eliminate the need for control assemblies, are described. Several important consequences of continuously-processed fuel that are not discussed in the APDA report are described, in particular, that the “iodine pit” startup control instability can be eliminated.

Concepts developed for fuel elements are applied to reactor design as a whole, and balance-of-plant design.

2 The APDA fuel element concept

The following is extracted directly from [1], which is a summary of [2]. Figure 1 was Figure 67 in the original. The footnotes are added by the present author.

The paste-fueled reactor concept evolved from fuel cycle cost studies made by APDA. These studies indicated that a liquid-metal-cooled, fast neutron breeder reactor, employing a high burnup fuel, with low inventory and minimum fuel and blanket fabrication, would give truly low-cost nuclear power. It was concluded that such a reactor should use mobile fuel and blanket¹ systems which would move continuously into and out of the reactor during full-power operation, and which would be reprocessed and fabricated on the site in an integrated facility. It was further concluded that the core should be internally cooled by a separate cooling system since transporting of the mobile fuel material through an external heat exchanger to remove all of the reactor heat would involve prohibitive fuel inventories. Consideration of these various requirements led to the concept of using pastes for the fuel and blanket material. Aside from the core itself, the major components of the paste-fueled reactor power plant are almost identical to the corresponding components of existing solid-fueled fast reactor designs, and they are arranged in a similar manner. Hence, the major developmental problems are associated with the core and the fuel and blanket material.

Recognizing the advantages inherent in a mobile-fueled reactor, APDA initiated the development of the paste-fueled reactor concept in 1955. The fuel and blanket consist of small spherical particles containing fissionable or fertile material settled in a liquid metal. These settled, two-phase fuel systems are called “pastes” to distinguish them from “slurries,” i.e., two-phase fuel systems in which the particles are dispersed in the liquid by fluid-dynamic forces.² The concentration of solids in the pastes is maintained at the settled density of approximately 60 per cent by volume of solids, irrespective of paste movement.³ A conceptual drawing of a paste-fueled-core subassembly is shown in Figure 1. A dilute slurry of fuel particles in liquid metal is fed to a cyclone separator at the top of the core. Concentrated paste from the separator is introduced into the top of each fuel subassembly and flows slowly down through the small passages formed by the spacing between the coolant tubes (paste in the tubes and coolant in the surrounding space is an alternative arrangement). The bottom portion of each subassembly is conical. Paste flows through orifices in this portion into an eductor. Carrier liquid (sodium), which is introduced into a central pipe in each subassembly connected to the eductor, dilutes the paste and fluidizes the particles, which are then carried out to the processing cell adjacent to the reactor vessel. A portion of the

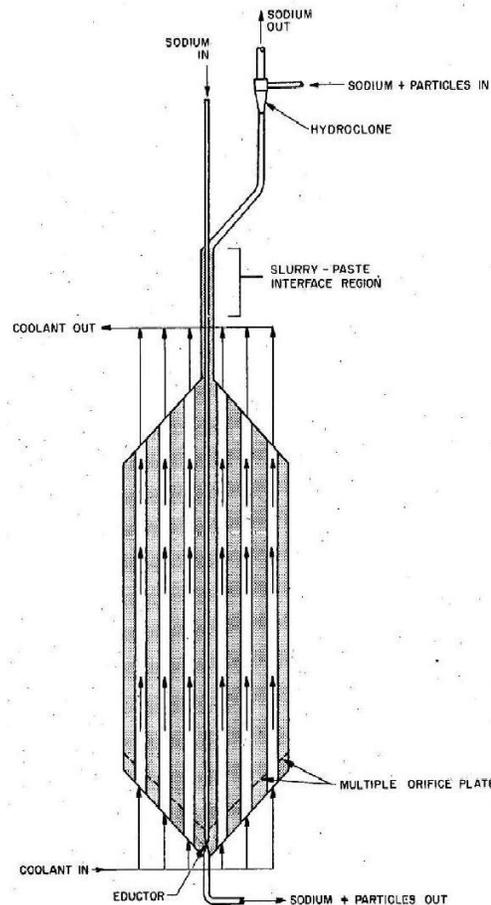


Figure 1: Schematic Drawing of Paste Fueled Reactor Subassembly

¹Nelson and Chasanov [6] describe advantages of paste as blanket fuel, the primary one being that blanket fuel assemblies would not need to be shuffled or rotated, as would be the case using static-fuel blanket assemblies. They argue that paste would not be appropriate for axial blankets, but that argument is based upon an assumption that driver assemblies contain static fuel and are frequently replaced. With mobile fuel, for both driver and blanket, one could use the same replacement schedule for both assemblies.

²Chon et al [7] mention “instability that is inherent in a slurry fuel system” but do not give a reference. Loss of slurry circulation would allow the slurry to settle, causing control instabilities due to changing fuel concentration and distribution.

³Farr and Groot [8] report random close packing densities from 64% to 97% for spheres having polydisperse log-normal size distributions with $0 < \sigma < 3$.

fuel particles is reprocessed. Oversized particles, which might result from the sintering of several particles or swelling under irradiation, are screened out. The remaining fuel particles together with fresh particles are returned in a slurry to the reactor vessel and to the cyclone separator, completing the circuit.

The paste-fueled reactor can be controlled by any of the methods applicable to solid fueled reactors. The total out-of-core fuel inventory in the fuel circulating system can be limited so that its total reactivity worth is less than the worth of the safety controls; therefore, no more fuel can conceivably be added to the core than the controls can accommodate. The paste-fuel system conceived by APDA is distinguished by several features which appear to have overcome the principal technological obstacles that have impeded the successful development of other mobile-fueled reactor concepts. Most notable among these features are the following:

1. Fuel is not used to transport heat from the reactor. Thus, small volumes of fuel can be moved external to the reactor at very low velocities [quantified in section 5 below].
2. The use of a noncorrosive liquid metal, such as sodium, to transport the fuel and blanket particles largely eliminates problems of container corrosion and mass transport.
3. The low velocities required in the fuel system minimize the erosion of containers by the particles and breakdown of particles by attrition.
4. Loss of pumping power⁴ does not affect fuel concentration in the dynamically stable paste-fuel system, in which fuel particles are at settled density in the reactor core.

In comparison with static bed systems, wherein no throughput of fuel is involved, the paste-fuel system has several advantages. This system allows homogenized burnup and breeding by the continuous intermixing of the particles. It also provides continuous reprocessing of the fuel and continuous removal of fission gases. These features should allow higher mean burnups and breeding ratios than other systems. Further, clogging of the bed by fission gases should cause less difficulty in the paste-fuel system since only the gases released in a single pass through the core are of concern. In addition, the paste-fuel concept retains all the advantages expected of mobile-fueled reactors over conventional solid-fuel systems. These advantages include increased resistance of fuel to irradiation damage and dimensional change; ease of fuel and blanket fabrication; simplification of reactor loading and unloading, which can be a continuous process without interruption of operation; continuous on-site reprocessing; and simplification and improved performance of certain nonfuel portions of the reactor complex.

3 Additional advantages not claimed in APDA report 146

The following advantages are inherent in a mobile paste fueled reactor, but were not claimed in APDA report 146.

- In a static-fuel reactor, burnup is a significant consideration because higher burnup reduces the frequency of fuel assembly replacement. The primary limitation to fuel burnup in Experimental Breeder Reactor II (EBR-II) was fuel pin cladding durability, and bundle-duct interaction due to radial fuel pin strain [9, p. 116] [10] [11, p. 2], i.e., damage to or deformation of the container. Fuel mobility and fission gas removal reduce or eliminate container strain and creep, and container-duct interaction. Fuel motion reduces or eliminates container damage due to formation of iron-uranium and iron-plutonium eutectics.⁵ APDA report 146 [2, Appendix Sec. 3.a] found that eutectic formation was not a significant problem until temperatures significantly exceeded operating temperatures. The fuel container can remain in the reactor substantially longer than in a static-fuel system. Service life would be limited by thermal-cycling stress, neutron swelling and embrittlement, erosion, and “noble” metal deposition.⁶

⁴Pumping power for fuel circulation, not coolant circulation.

⁵Uranium nitride is the preferred alternative to metallic fuel if motion does not sufficiently reduce eutectic formation [6, Sec. II.B.3].

⁶Nelson and Chasanov [6, Sec. II.C.5.c] estimated a 6–10 year lifetime for fuel elements.

- Sodium iodide can be removed from the sodium carrier by a cold trap, thereby removing a source of xenon, further reducing the possibility of clogging caused by gas bubbles. This removes only iodine that has diffused from fuel into carrier. With smaller particles, the surface-to-volume ratio is larger, and more fission products diffuse from fuel into carrier.
- Continuous removal of ^{135}Xe , and its precursor ^{135}I as NaI, especially when the reactor is shut down, eliminates the “iodine pit” startup control instability.
- Transmuting the powerful neutron poison ^{135}Xe to essentially non-radioactive ^{136}Xe by circulating fission gases within the neutron reflector reduces production of radioactive ^{135}Cs that results from beta decay of ^{135}Xe , the cost to store fission products, and neutron load on the shield.
- Continuous online fuel processing increases capacity factor because it is not necessary to shut down the reactor. APDA report 146 estimated that fuel cycle costs would be 37% of the cost for a static fuel plant [2, Table IX]. This estimate does not, of course, take into consideration the lower fuel processing cost possible using the pyroelectric processing method developed for EBR-II [9] [12].
- There is no transfer tunnel and no transfer coffin [13, p. 3-38]. Fuel is transferred between the reactor and the processing facility as a dilute slurry in a small pipe.
- The solid metal fuel slugs used in EBR-II were fabricated at 75% smear density. They swelled, primarily due to fission-gas voids in the size range 5–75 μm [10], until burnup reached 1.6%. Figures 4 and 9 in [10] show that swelling stopped, and thermal conductivity abruptly increased, at about 1.6% burnup. This was attributed to gas pores connecting and opening to the surface, followed by intrusion of sodium. A paste of small fuel particles would initially be in a state of essentially open porosity. Large pores are not possible, and small ones open to the surface earlier. More grain boundaries and microcracks reach the surface. Fewer and smaller sealed gas-filled pores reduce swelling, and increase fuel thermal conductivity compared to solid fuel slugs.
- Continuous online fuel processing maintains constant fuel composition, which eliminates burnup reactivity swings. Eliminating burnup reactivity swings reduces the required control worth [14, p. 83].
- The thermal conductivity of paste fuel is greater than the thermal conductivity of solid metal slugs at all fuel densities because the thermal conductivity of sodium is greater than that of uranium (Sec. 9 infra). Thermal conductivity would change less, if at all, and gradually rather than abruptly. Control would be simpler and safer.
- Section IV of *Integral Fast Reactor Program Summary Progress Report* [15] describes one safety hazard, even present with solid metallic fuel: “Under accident conditions, transient heating of metallic fuel produces cladding loading dominated by plenum pressure.” This effect is essentially nonexistent in a fuel assembly filled with mobile fuel, operated at the same pressure as coolant, and connected to an external system for fuel transport, fuel processing, and fission gas release.
- If fuel elements can be made to be sufficiently robust that their service lifetime is the same as the reactor as a whole, there need be no mechanical systems to remove and replace fuel assemblies. The cover of the reactor is simplified by not needing a rotating plug.

4 Proposed revisions to the APDA 146 concept

Figure 1 shows sodium flowing downward to power an eductor, where particles are entrained into a slurry, which is then removed from the bottom of the fuel assembly by a tube departing horizontally from the fuel element. A connection below a fuel element would be difficult to manipulate when it is necessary to remove a fuel element. In this proposal, the slurry is returned to the top of the fuel element by a tube through its center.

APDA report 146 claims that fuel flow blocking by the accumulation of fission gases would not be a problem because of the limited fuel residence time within the fuel element – at most a few hours – before it, and its

entrained fission gases, are removed [2, Sec. III.B.4]. Calculations by the ORIGEN 2 computer program⁷ [16] show that after 1387 days of operation of a reactor at 36.542 MWth/tonne for 1387 days, with neutron flux of $3.14 \times 10^{14} \text{ n cm}^{-2} \text{ s}^{-1}$, out of each tonne (1000 kg) of heavy metal fuel, 52.18 kilograms would have fissioned, producing 59.83 moles of xenon and 6.474 moles of krypton, mostly from decay of very short-lived isotopes of iodine and bromine. Some isotopes of xenon and krypton also have very short half lives. The gas production rate would be 2 millimoles per hour per tonne of fuel. At standard temperature and pressure, one mole of ideal gas occupies 22.4 liters. Assuming the fuel element is kept at constant pressure equal to coolant pressure, this gas evolution at 755°K would occupy 0.12 liters per hour per tonne of fuel, or 3.58 liters per hour, at standard temperature and pressure for an initial load of 26.092 tonnes of zero-burnup fuel. Using 19 kg/liter for the density of fuel, and 60% volume mixing ratio of fuel in paste, the reactor would contain 2281 liters of paste. The volume mixing ratio of gas would be at most 0.31% for a fuel residence time of two hours, assuming all gases escape from fuel particles and none decay, uniform gas mixing, the fuel element operates at atmospheric pressure, and essentially zero gas saturation in sodium.

An earlier study [17] that used glass beads, water, and carbon dioxide gas, had suggested gas bubbles might cause problems. The density and viscosity of sodium, the surface tension of fission-gas bubbles in sodium, the density of fuel and fission gases, the propensity of gas to wet fuel, and the saturation of fission gases in sodium, would surely be different.

When studying two-phase helium-NaK flows in liquid-metal-foam magnetohydrodynamic (MHD) generators [18], Argonne National Laboratory found that small amounts (0.11 – 0.44 wt.%) of barium in Na - 0.77 K significantly increased bubble stability and surface tension, which would reduce the tendency of bubbles to combine or cling to surfaces. Barium constitutes 4.21 wt.% of fission products, and diffuses from fuel into solution in sodium [10]. Maintaining 2.39 – 9.45 wt.% fission products in sodium would maintain 0.11 – 0.44 wt.% barium. That study did not remark on bubble stability in pure sodium. Other fission products might increase or decrease bubble stability. NaK might be used for thermal bond and transport, provided its lower boiling point (785° C) and lower thermal conductivity (26.2 W/m/K) are not problems. Further studies would be necessary to quantify the effects on bubble stability in sodium containing fission products.

To address further the gas bubble problem in this proposal, a fine filter at the bottom of the fuel assembly, fed by the same plenum that feeds the eductor, allows sodium to flow slowly upward through fuel while fuel flows downward. This counter-current flow entrains fission gas bubbles and moves them upward, ultimately out of the fuel assembly. Slight turbulence near the bottom reduces fuel stagnation beside coolant tubes. Fuel particles must be sufficiently large, or the sodium flow sufficiently slow, that sodium flows around them instead of lifting them. 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:

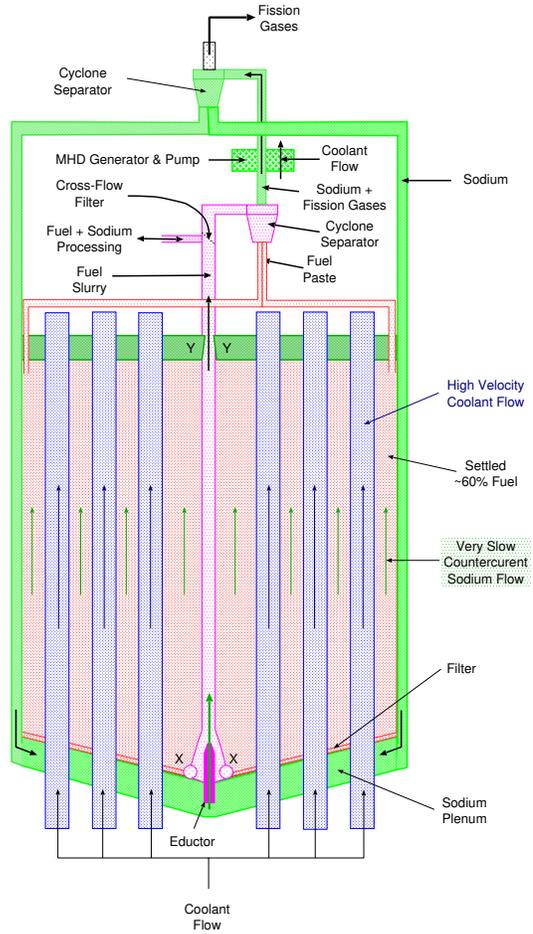


Figure 2: Revised APDA Paste-Fuel Reactor Concept

⁷ORIGEN 2 is a well-validated simulation of reactor operation.

$$\begin{aligned}
F_d &= \frac{1}{2} C_d \rho_s U^2 \frac{\pi}{4} d_f^2 = \frac{4\pi}{3} \frac{d_f^3}{8} \rho_f g, \text{ or} \\
U_t &= \sqrt{\frac{4g d_f \rho_f}{3 C_d \rho_s}} = 26.34 \sqrt{d_f} \text{ m/s},
\end{aligned} \tag{1}$$

where

$$\begin{aligned}
g &= \text{acceleration of gravity} = 9.81 \text{ m/s}^2, \\
d_f &= \text{fuel particle diameter, meters,} \\
\rho_f &= \text{fuel particle density} = 19 \text{ kg/liter,} \\
\rho_s &= \text{sodium density} = 0.805 \text{ kg/liter for liquid sodium at } 900^\circ\text{K [19, Table 1.3-1],} \\
C_d &= \text{the Reynolds-number dependent drag coefficient (0.445 in [20]), and} \\
U_t &= \text{upward coolant flow terminal velocity.}
\end{aligned}$$

With $U_c = U_t$, where U_c is the upward velocity of sodium carrier, a slurry is formed by fuel particles that are suspended in equilibrium with carrier flow. Using the Richardson-Zaki equation

$$\epsilon^{2.4} = \frac{U_c}{U_t}, \tag{2}$$

where ϵ is the void fraction, together with the observation that $\epsilon \gtrsim 0.4$ with uniform-size randomly close packed particles, when $U_c < 0.11 U_t$, gas is entrained but fuel particles are not lifted. From Equation (1), even with particles as small as $100 \mu\text{m}$, $U_t = 0.2634 \text{ m/s}$. Sodium, fission gases, and very small particles are drawn from above the fuel into the fuel slurry stream, by orifices labeled Y in Figure 2.

In the APDA 146 concept, the paste fuel flow rate was controlled by a multiple-orifice plate below the fuel. Below the plate, fuel flowed to the apex of the bottom cone, where it was entrained and diluted by the eductor. In the revised concept shown in Figure 2, fuel flows to the apex of the cone bounded by the bottom filter, and the rate of paste entrainment in slurry is controlled by the orifices labeled X that feed the eductor and remove paste from the fuel volume. These orifices would be larger, and less likely to clog, than in the APDA 146 design. Absent gas bubble problems, a counter-current sodium flow is not needed, and a solid bottom can be used instead of a filter.

With $U_c > U_t$, fuel particles are entrained in the carrier. The tube carrying educted slurry can be very small. Assume its cross section is 1% of the total cross section of fuel in the element, and the slurry contains 10% fuel by volume. A slurry flow rate of ten centimeters per second⁸ would maintain a downward bulk paste flow rate of 36 centimeters per hour. The total fuel content of the slurry return tube is slightly more than 0.1% of the total volume of fuel in the fuel element, depending upon the height of the cyclone separator above the top level of fuel. Therefore, fuel settled in the slurry return tube in the event of circulation failure would cause only a very small change in overall fuel density distribution, which should not cause control stability problems.

Fission gases will be collected with sodium and separated from fuel paste by the first cyclone separator, and removed from sodium by the second cyclone separator. A simpler gas separator might be possible.

After fuel is separated from the slurry, paste returns at the top through a ring header to the outside edges of the fuel volume. Because the fuel is removed at the apex of the bottom cone, this results in a net flow toward the center. This tends to increase homogeneity of fuel composition and physical properties. Sodium returns to the outside edges of the bottom plenum so that tiny particles that pass through the filters are entrained with the sodium that powers the eductor.

In irradiated fuel from EBR-II, alkali metal and alkaline earth fission products were found to have dissolved into bond sodium [10, Table 1, p. 98]. One would also expect to find gallium, germanium, indium, sodium

⁸Equation (1) shows that a sodium flow rate of 10 cm/s would lift particles smaller than $14.4 \mu\text{m}$ in diameter. Faster and more dilute flow would be needed for larger particles.

halides, and perhaps arsenic, antimony, cadmium, tellurium and Na_2Te , and tin [21]. Tiny particles, but not solutions, of noble metals, lanthanides, and fuel will appear. Sodium would need continuous processing, but not perfect purification, using methods described in [22], to maintain an acceptably low concentration of fission products. Radioactive iodine thereby removed would decay to xenon, which ought to be circulated within the neutron reflector to transmute ^{135}Xe to ^{136}Xe , so as to reduce the production of radioactive ^{135}Cs .

The MHD pump for sodium that circulates fuel is combined with and shares a magnet with a MHD generator that uses flow from the main coolant stream. Hydroclone separators and the MHD generator/pump have no moving parts and are integrated into each fuel assembly. APDA 146 proposed using a single hydroclone for all fuel assemblies [2, Sec. IV.B.13]. A separate hydroclone in each fuel assembly would reduce plumbing above the reactor core.

When it becomes necessary to remove a fuel assembly, fuel can first be pumped out by its eductor, reducing its weight substantially. This would also cleanse connecting tubes so that coolant is not contaminated when they are disconnected. In the schematic diagram in Figure 2, physically distinct locations are shown for processing and fission gas tubes. To facilitate fuel element replacement, the tubes should be coaxial, or gathered into a central bundle. Fewer and larger fuel elements would facilitate replacement by requiring fewer connections. One PRISM design proposes 192 fuel assemblies [23, Fig. 8]. The APDA 146 design for the same capacity proposed 19 fuel assemblies [2, Sec. IV.B].

5 Fuel processing

5.1 Will it work?

The first question about fuel processing is “would this actually work?” Miniature experiments concerning successors to LAMPRE used molten plutonium entrained by a sodium eductor and then separated, with the sodium destined for a heat exchanger in a full-size reactor. Just when it appeared that corrosion problems had been solved, funding was withdrawn. A successor direct-contact reactor was proposed, fueled by a paste composed of uranium and plutonium oxides. This eliminated corrosion problems, but the project was abandoned after preliminary experiments found, contrary to experience reported in APDA 146, that the paste was so thick it was impossible to pump. The particle size, physical arrangement, and pumping method were not described [24].

In [2, Appendix Secs. A.2.a-c], APDA 146 described preliminary studies of paste flow and the transitions between paste and slurry. At low temperature and without fission in progress, they reported no flow problems, but recommended high fission density and high power density experiments to obtain data about details of the flow characteristics, such as the relative rates of fluid and solid flows.

5.2 Processing rate

Assuming that paste fuel will flow through the core as described by APDA 146, and that it can be transported as a slurry to a processor, the question becomes “what is the processing rate?”

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 [25, Sec. 5.2]. If the reactor is exactly critical and power output is constant, $n(t)$ and \bar{v} are constant. Let $N(t) = cF(t)$, where c accounts for the total amount of fissionable atoms + fission products, alloying metals in fuel, fissile enrichment, sodium carrier, structure, and coolant. $F(t)$ is the proportion of fuel in a fuel + fission product mixture – a dimensionless quantity that decreases as a consequence of each fission. Let $f(t)$ be the proportion of fission products. Then $F(t) + f(t) = 1$, and

$$\frac{dF(t)}{dt} = -kF(t), \text{ or } \frac{df(t)}{dt} = k(1 - f(t)), \quad (3)$$

where $k = c\sigma_f \bar{v}n(t)$ is a constant that has units of inverse time. Assuming $f(0) = 0$, or $F(0) = 1$, the solutions of Equation (3) are $\ln(F(t)) = -kt$, or $F(t) = e^{-kt}$, and $f(t) = 1 - e^{-kt}$.

Rather than deriving k from properties of a particular reactor design, its operational regime, and principles of physics, one can measure $f(t)$ or $F(t)$ at some time τ in a representative system and compute

$$k = -\frac{1}{\tau} \ln(1 - f(\tau)) = -\frac{1}{\tau} \ln(F(\tau)). \quad (4)$$

Calculations by the ORIGEN 2 computer program [16] show that per tonne of heavy metal, as oxide, irradiated in a light-water reactor operated at 36.542 MWth/tonne for 1387 days with neutron flux of $3.14 \times 10^{14} \text{ n cm}^{-2} \text{ s}^{-1}$, 52.18 kg, or 5.218% of heavy metal, would be converted to fission products.

Substituting $\tau = 1387$ days and $f(1387 \text{ days}) = 0.05218$ into Equation (4) gives $k = 38.64 \times 10^{-6}/\text{day}$. In a metal fueled fast-neutron reactor, k would probably not be different by more than a factor of two. Substituting τ , k , and $F(\tau)$ into Equation (3) gives

$$\left. \frac{dF(t)}{dt} \right|_{t=\tau} = -k F(\tau) = -38.64 \times 10^{-6}/\text{day} \times 0.94782 = -36.62 \times 10^{-6}/\text{day}. \quad (5)$$

One design of a GE/Hitachi S-PRISM (1000 MWth) reactor would have a total initial heavy-metal loading of 26,092 kilograms [26, Table 3.1, p. 15]. Assuming two hour core residence, fuel density of about 19 kg/liter, sodium density of 0.820 kg/liter at 550°C [19], and 10% fuel by volume in slurry, it would be necessary to circulate the amounts shown in Table 1.

Table 1: Material circulation assuming two hour core residence

	Mass		Volume	
	per hour	per second	per hour	per second
Fuel	13,046 kg	3.62 kg	687 l	191 ml
Sodium	5,067 kg	1.41 kg	6,180 l	1.72 l
Slurry	18,113 kg	5.03 kg	6,866 l	1.91 l

Pumping cost is $5.03 \text{ kg/s} \times 9.81 \text{ m/s}^2 h = 49.3 h$ watts, where h is the “head” in meters necessary to circulate slurry, not counting losses to viscosity and friction.

Assume that fission products are not removed until $f(t) = f(\tau)$, and thereafter it is desired to maintain $f(t) = f(\tau)$, which requires that fission products be removed at the same rate as production. To extract $k F(\tau) L$ kilograms of fission products per day, where L is the initial fuel load, it is necessary to purify P kilograms of fuel per day, where $P f(\tau) = k F(\tau) L$. The amounts shown in Table 2 were computed using the values of k , $F(\tau)$, and $f(\tau)$ from above, assuming fuel is to be maintained with $f(t) = f(\tau) = 0.05218$, $L = 26,092 \text{ kg}$, and $k F(\tau) L = 0.956 \text{ kg/day}$. A processing rate of $P = 0.956/0.05218 = 18.3 \text{ kg/day}$ is about 6.68 tonnes per year, not counting blanket fuel.

Table 2: Processing to maintain 5.218% burnup in 26,092 kg of fuel

	Mass			Volume		
	per day	per hour	per second	per day	per hour	per second
Fuel	18.3 kg	763 g	212 mg	963 ml	40.2 ml	11.2 μ l
Sodium	7.11 kg	296 g	82 mg	8.67 l	361 ml	100 μ l
Paste	18.6 kg	776 g	215 mg	1.35 l	56.3 ml	15.6 μ l
Slurry	25.4 kg	1.06 kg	294 mg	9.63 l	401 ml	111 μ l

This fuel processing rate assumes that all fission products remain confined within fuel particles. Hofman et al [10] reported that at 1.6% burnup, solid fuel slugs in EBR-II stopped expanding. They concluded the reason was that fuel reached a state of essentially open porosity, and thereafter all fission gases escaped.⁹ They further reported that in irradiated metallic solid-slug fuel pins with “high” but otherwise unspecified burnup, 70% of alkali metal fission products, i.e., caesium and rubidium, and 20% of alkaline earth fission products, i.e., barium and strontium, had diffused into bond sodium. Fission gases constitute 16.43 wt.% of fission products. Caesium and rubidium constitute 10.41 wt.% of fission products. Barium and strontium constitute 6.756 wt.% of fission products. It is reasonable to assume that with sufficiently small particles, a state of essentially open porosity will be reached, probably at much lower burnup, and that all fission gases, far more than 70% of alkali metals, and far more than 20% of alkaline earth metals, would diffuse into sodium. Cadmium constitutes 0.375 wt.% of fission products and would presumably diffuse into sodium. Tellurium constitutes 1.42 wt.% of fission products, and might diffuse into sodium. It is soluble in sodium in small concentration [21]. At higher concentrations it forms a compound (Na_2Te) that is insoluble in sodium. The actual heavy metal processing rate necessary would probably be in the range of 12.1–15.3 kg/day, depending upon the amount of fission products that escape and can simply be washed away with clean sodium. In fuel slurry delivered to the fuel processor, particles would be separated from sodium, sodium purified, and fuel processed, as described in [22].

If processing is started immediately, when $f(t) = 0$, at the rate P that would be required to maintain $f(t) = f(\tau)$, $f(t)$ would exponentially approach $f(\tau)$ as an asymptote, i.e., $f(t) = (1 - \exp(-kt)) f(\tau)$.

5.3 Continuous processing

The principle of continuous reactor fuel handling, without replacing structures, can be applied to fuel reprocessing as well. In the pyroelectric refiner described by Chang et al in [12], fuel batches are placed in anode baskets. Products collected at cathodes are harvested continuously by scrapers and a conveyor belt. After processing, noble metals remain in the anode baskets, which are removed to process those metals.

The method for moving particles in the reactor can also be used in the electrorefiner.

Rather than a simple basket, fashion anodes with conical bottoms and an eductor below them. Instead of sodium, the transport fluid is molten electrolyte. Eductor power can be provided by a central pump, or by electromagnetic pumps at each eductor. Arrange several anodes in series. Recirculate metal in each anode, and divert a small amount to the next anode. Adjust the number of anodes and the diversion rate so that the metal harvested from the final anode in each sequence has acceptably low amounts of TRU.

Apply the same principle to cathodes. Instead of a conveyor, emplace a conical hopper and eductor below each cathode.

Divert a portion of the electrolyte carrier from a metal output stream, for continuous purification, to remove fission products that are not deposited at cathodes.

Most continuous chemical engineering processes have lower operating cost than batch processes, even when their facilities have greater capital expense.

⁹Inert gases do not diffuse through metals. They escape from fuel along grain boundaries and microcracks, or from interconnected pores that eventually break open at the surface [27].

6 Phase-change accelerant instead of MHD generator/pump

As shown in Figure 3, slurry is accelerated by injecting a liquid, such as a hydrocarbon with a sufficiently high boiling point, but not so high as to pyrolyze easily, that is immiscible with and does not react with sodium, and that is vaporized by high temperature fuel slurry, as it emerges from the reactor core, above a neutron reflector or shield to minimize production of ^{14}C . An inert gas might work, but a phase change is desirable. Vaporization accelerates the low-density fuel + sodium slurry to the first cyclone separator, where fuel particles are separated from sodium + fission gases + accelerant. Fuel paste is returned to the core. Sodium + fission gases + accelerant flow to the second cyclone separator where sodium is separated from gases. Ultimately, fission gases and accelerant are separated by a condenser and heat exchanger.

A temperature-compensated valve at the orifice that admits accelerant to the slurry stream would automatically adjust the flow of accelerant to maintain a roughly-constant temperature in the circulation system.

Other than krypton and xenon, neither sodium nor any fission products have boiling points below the temperature of fuel slurry. Nonetheless, because of their nonzero vapor pressure, very small amounts of metals, especially sodium¹⁰ and caesium,¹¹ would appear as gases in the stream that emerges from the second cyclone separator. They will accumulate in the condenser, requiring it to be cleaned or replaced periodically.

Assuming slurry inlet and outlet temperatures are the same as for coolant in EBR-II [13] (645°K and 755°K), using 1.23 J/g/K as the heat capacity for sodium and 0.12 J/g/K for uranium, assuming fission products and higher actinides are present only in small amounts and the heat transported by them is only slightly more than by uranium (their heat capacities are typically less than twice that of uranium), using the flow rates described above, and using one Watt = one Joule per second, the power gained by slurry passing through the core is about 48 kWth for fuel and 190 kWth for sodium = 238 kWth total. Assuming vaporized accelerant is in thermal equilibrium with sodium, and a turbine with 30% efficiency extracts energy to cool the accelerant to 300°K, the power output would be 71 kWe, less the 49.3 h watts required to raise sodium to a sufficient “head” to power its next cycle through the fuel elements. An optional turbine or MHD generator in the circulation system might produce enough electricity to cold-start a reactor without external power or a standby Diesel generator.

In many MHD studies such as [29] or [18], a two-phase vapor-liquid flow through the generator is envisioned. Energy is harvested by expansion of the vapor and acceleration of the two-phase fluid within the generator proper. The vision here is that the primary purpose of vapor expansion is to circulate sodium, while a turbine or MHD generator would harvest energy not used for circulation.

Metals accumulating in a turbine might be sufficiently troublesome to prevent its use. They could be prevented from entering a turbine by using a heat exchanger. This would increase cost and complexity, and metals would accumulate therein instead. An alternative to a turbine is a MHD generator in the downward-flowing streams or a two-phase MHD generator between the separators [18].

This circulation system has no moving parts (except the optional turbine) and does not need electricity. It

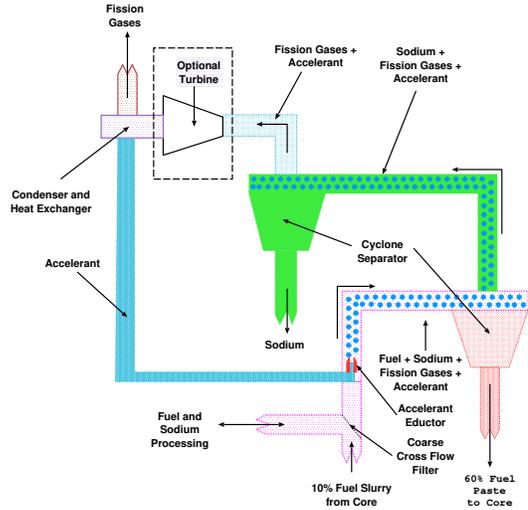


Figure 3: Alternative to MHD Pump for Sodium Circulation

¹⁰ $\ln P_{\text{Na}} = 11.9463 - 12633.73/T - 0.4672 \ln T = \ln(6.29) \text{ mBar}$ as pure metal at 500° C, P is in MPa, T is in K [19].

¹¹ $\log_{10} P_{\text{Cs}} = 3.69576 - 3453.122/(T - 26.829) = \log_{10}(117) \text{ mBar}$ as pure metal at 500° C, P is in Bar = 100 kPa and T is in K [28]. Assuming essentially all caesium created diffuses from fuel particles into sodium, its mole fraction is 0.187%. Its contribution to the partial pressure of metals, compared to sodium, is 0.219 mBar: 3.48% of metal vapor is caesium.

would operate continuously. One advantage of this scheme is that when the reactor is shut down, residual core heat and fission product decay heat would be sufficient to separate fission gases, especially ^{135}Xe , and eliminate the “iodine pit” startup control instability. It might be possible to eliminate the passive bayonet heat exchanger system used in EBR-II to remove decay heat, as described by Koch in [13].

7 Primary coolant as eductor power source

In principle, the eductor could be powered by admitting a small flow of primary coolant. This would eliminate the MHD generator/pumps, but would contaminate coolant with sodium-soluble fission products and small particles that are not separated by the cyclone separators.

If the outlet temperature were raised above the boiling points of caesium (670.2°C), selenium (684.4), and rubidium (688°C), they would escape as fission gases. Tellurium (melting point 449.5°C), sodium iodide (661°C), barium (727°C), and strontium (777°C) can be removed by a cold trap. It is impractical to remove cadmium (boiling point 767°C, melting point 321°C), which 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 is produced at the rate of 3.2 grams per GWe-yr. Additional sodium-soluble fission products are produced in only millimole quantities per GWe-yr.

A loop-within-pool system would reduce the amount of contaminated coolant, which could be periodically purified and replaced more easily than purifying the entire pool contents.

8 Interim storage

Fuel that is removed immediately from the reactor core is intensely radioactive because of fission products that have very short half lives. In EBR-II, spent fuel was stored within the reactor vessel’s sodium coolant tank for 12 – 24 months while those fission products decayed. The same thing is described in [23]. APDA 146 proposed storing fuel removed for processing in a small tank within the fuel processing facility for a few days [2, Sec. VII.B]. In EBR-II and PRISM designs, fuel assemblies containing numerous fuel pins are stored. When decay heat was sufficiently reduced, fuel assemblies at EBR-II were removed and disassembled, and natural circulation in air was then sufficient to cool the individual pins [13].

In the mobile paste fuel system, it might be desirable to store spent fuel within the primary cooling system, to avoid having hot and intensely radioactive materials in the processing facility, but it must be stored in mobile form, not in assemblies that are mechanically removed for processing. Using the assumptions in Table 2, it would be necessary to provide $1.35 D$ liters of storage, where D is the number of days of storage before processing, that is, the amount of time that a parcel of fuel paste takes to work its way through the storage system to the processing facility. Storage elements could be similar to fuel elements without coolant tubes, arranged in series. They would be smaller and of different shapes, and disposed in a dispersed configuration, to avoid criticality. If fuel is stored for more than a few days, it would be necessary to circulate fuel or agitate it with a sodium flow, to prevent fuel particles from agglomerating, and to remove fission gases.

One method is to circulate paste separately within each vertical storage element, and divert a portion of it into the next element, until it reaches the last element and is diverted to the processing facility. Each storage element would have its own sodium eductor, paste-sodium separator, and sodium-gas separator. A common sodium pumping system ought to be possible. Decay heat might be sufficient to use accelerant injection to circulate fuel as it ages.

Another method is to wrap a helix around the inner wall of the sodium pool, with sufficient slope to maintain paste flow, and to flow sodium across the paste, from a coaxial sodium supply sleeve, through holes in the sides of the helix tube, to agitate paste and remove fission gases. A 10 cm diameter tube, about 64 meters long, could accommodate the amount of fuel necessary to process in one year.

The interim storage system would not be subjected to a neutron flux as intensive as core fuel elements, and would not endure significant thermal cycling. Assuming it is not significantly damaged by erosion or

fuel/container chemical interaction, it ought not to need replacement.

9 Safety implications

The most important properties of EBR-II that led to its demonstrated inherent safety [15, § IV] and [14] are

- Metallic fuel thermal conductivity ($\kappa_f \simeq 35$ W/m/K) [30] is much greater than oxide fuel thermal conductivity at 500° C ($\simeq 0.42$ W/m/K) [31],
- sodium thermal conductivity ($\kappa_{Na} \simeq 62.9$ W/m/K) [19, p. 101] is much greater than water thermal conductivity at 500° C ($\simeq 0.650$ W/m/K), and
- the core is submerged in a pool of sodium coolant that has large heat capacity (1.23 J/g/K) [14].

High thermal conductivity and high heat capacity combine to reduce fuel temperature, resulting in low Doppler reactivity.

The thermal conductivity of paste fuel, κ_p , was estimated using Equation (6.4) from [32]:

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

where where $\alpha = \kappa_f/\kappa_{Na} \simeq 0.556$ and $\beta = (\alpha - 1)/(\alpha + 2) \simeq -0.314$. With ϕ , the volume fraction occupied by metallic fuel, ranging from 0.6 to 0.95, as would be possible using spheres having polydisperse log-normal size distributions with $0 < \sigma < 3$ [8], κ_p declines nearly linearly from about 40 to about 36 W/m/K. Small fuel particles would have fewer and smaller sealed pores of fission gases, and therefore higher thermal conductivity than irradiated solid fuel slugs. Paste fuel has stronger negative thermal conductivity feedback than solid uranium at all fuel densities.

In EBR-II, the three accident scenarios described in [15] – loss of coolant flow without scram, loss of heat sink without scram, and transient overpower (withdrawal of control rods) – all result in heating the core, which causes expansion of fuel and structure, which reduces the fuel volume below criticality. The same effects would occur in a core containing fuel elements as described here.

As is the case for static fuel, mobile fuel and structure expand as a consequence of increasing temperature. With mobile fuel, whether axial or radial expansion of the reaction region dominates depends upon the relationship of the thermal expansion coefficients of fuel and structure. (Table 3) If the fuel particles are sufficiently large that fuel is not a homogeneous paste, when sodium expands, it flows around fuel and its level above fuel increases, but the volume occupied by paste is not affected. The relationship of the changes in thermal conductivity and density of both fuel and sodium caused by temperature changes ought to have the same relevance for both static and mobile fuel. APDA 146 addressed the relationship of thermal effects to stability [2, Secs. VI.B.6-12]. If fuel particles are sufficiently small that paste remains homogeneous upon heating, especially upon rapid heating, because sodium expands 3–5 times more than fuel, paste provides significantly more negative thermal feedback than solid metal or ceramic fuel.

Table 3: Thermal expansion coefficients $\mu\text{m}/\text{m}/^\circ\text{K}$

304 SS	18.7	Sodium	71
Uranium	13.9	U-19Pu-10Zr	19.2

Section IV.A.6 in [15] begins “The possibility of core meltdown is exceedingly remote; however, despite all possible design measures taken, a theoretical possibility of core meltdown. . . remains.” It then describes axial extrusion of molten fuel from pins, followed by dispersal of highly porous and coolable resolidified debris in a non-critical configuration at the bottom of the reactor vessel, as a “significant reactivity reduction

mechanism.” Destruction of some fuel pins would not significantly damage the reactor, and would not be a safety hazard, but cleaning the vessel would be expensive.

Intentionally destructive tests of irradiated EBR-II fuel pins in the Transient Reactor Test Facility (TREAT) [15, Secs. IV.A.6, IV.F] showed molten fuel extrusion from pins was caused more by fission gases than by fuel expansion. In a system as envisioned herein, if fuel melts, it would not be extruded by fission gases, because fission gases are continuously removed. The result would be a consolidated, likely non-porous, highly reactive, possibly molten fuel body unless and until the container failed and released fuel into the coolant vessel.

The additional passive safety system shown in schematic form in Figure 4 consists of a storage region into which fuel flows passively under the influence of gravity from the reaction region. The storage region is larger than the reaction region, and of such shape and position that it cannot sustain a fission reaction, for example, tall, thin concentric cylinders connected to a thin cone, as shown in edge view in Figure 4. The reaction and storage regions are both within the sodium pool.

Power output is controlled by the level of fuel in the reaction region. Control and safety assemblies might not be necessary.

Rather than being at the bottom of the fuel element as in Figure 2, the eductor is within the transport tube below the zero power level. After separating sodium, paste is returned to the reaction region. Fuel circulates downward through the transfer tube, then into the storage region through perforated standpipes, and back to the eductor. Fuel composition remains the same in both regions. Iodine and fission gases are continuously removed, no matter the power level.

The total internal and external inventory of fuel in the circulating system (including in transit to and from processing) is never enough to over-fill the reaction or storage regions.

There are at least three ways to control the level of fuel in the reaction region:

- If fuel particles are sufficiently small that fuel forms a viscous homogeneous paste rather than a settled slurry, fuel can be forced from the storage region to the reaction region by gas pressure above the storage region. The relationship of levels in the regions, and therefore power output, can be controlled by the relationship of gas pressures above the regions. If fuel particles are large, paste cannot be forced from the storage region to the reaction region by gas pressure above fuel in the storage region. The density ratio is too large, and sodium viscosity is too small. Gas pressure in the storage region would simply drive sodium down through fuel and into the reaction region.
- The relationship of eductor power and the fuel flow rate it induces, compared to the rate at which fuel sinks passively from the reaction region to the storage region, determines the relationship of fuel levels in those regions, and depends upon the drainage rate necessary to respond to accident scenarios. Although power output declines as fuel sinks from the reaction region into the storage region, fuel residence time might need to be less than the two hours assumed in the APDA 146 concept.
- A MHD generator/pump powered by primary coolant flow moves fuel from the storage region to the reaction region, holds fuel in place, or allows it to flow to the storage region.

In the last two cases, with MHD generator/pumps powered by primary coolant flow, power output is determined by primary coolant flow rate. The relationship between primary coolant flow rate and fuel level is adjusted by controlling the power transfer from the MHD generator to the MHD pump.

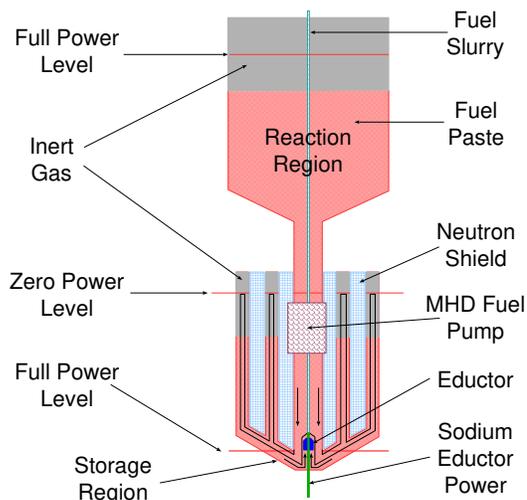


Figure 4: Passive safety

Power failure, gas pressure failure, circulation failure, control systems responding to excessive temperature in the reaction region, or operator control, result in fuel flowing passively under the influence of gravity from the reaction region to the storage region. The reaction region remains empty. By using gas pressure or an electromagnetic pump to hold fuel in the reaction region, orifices to control recirculation rate, as in the APDA 146 proposal [2], might not be needed, which would allow to empty the reaction region rapidly.

The coolant tubes shown in Figure 2 penetrate the storage and reaction regions in Figure 4, but are omitted for clarity. The gas in the plenum above the reaction region will be at the same temperature as the coolant outlet. Even if gas pressure above the storage region is not used to drive fuel into the reaction region, increasing gas pressure above the reaction region due to increasing temperature increases the rate at which fuel flows into the storage region.

These control mechanisms can be combined with an actively-cooled plug consisting of frozen fuel paste, not shown in Figure 4, that retains fuel in the reaction region, as was done in the Molten Salt Reactor Experiment [33]. If plug cooling is stopped by operator control or by power failure, or if fuel temperature or reaction region pressure becomes sufficiently large, the plug melts or breaks and fuel flows passively into the storage region.

The primary advantages of this system are its significant control advantages. As a safety system, the primary purpose of the frozen plug feature is to protect the reactor vessel from the expense resulting from contamination, not for personnel or public safety. Even without this feature, personnel and public safety would be adequately protected by the mechanisms used at EBR-II and proposed for PRISM[13] [23]. In the absence of such a system, if all fuel elements in a reactor core containing about 2,500 liters of paste fuel, within a sodium pool about nine meters in diameter, were to fail simultaneously, their fuel would sink to the bottom and form a sub-critical, porous, easily cooled “pancake” about 4 cm thick. Decay heat could be adequately removed by the Reaction Vessel Auxiliary Cooling System [13] [23]. This is an expensive mess, but not a safety hazard.

10 Whole reactor and balance of plant

The concept of circulating fuel slurry by accelerant injection can be applied to primary coolant and the reactor as a whole. This is not a new idea. The study described in [34] proposed injecting water into lead-bismuth coolant. With sodium coolant, the same accelerant described in Section 6 would be injected into coolant as it emerges from the core, above a neutron reflector or shield so as not to breed ^{14}C . Mobile fuel and a sodium + accelerant system provide the same benefits, and overcome the objections, noted in [34].

Direct injection of liquid accelerant into hot coolant above the core vaporizes the liquid, which forms voids in the hot leg, and accelerates coolant flow. The large difference in density between the hot leg, including its voids, and the cold leg, drives natural circulation. There are no coolant-circulation pumps. Accelerant injection pumps are much smaller than coolant circulation pumps. Vapor is separated and used directly in a turbine. There are no heat exchangers other than a vapor condenser on the cold side of the turbine – the usual power-plant cooling system. Additional energy could be produced by MHD generators, or sodium turbines not unlike the turbines used in hydroelectric generators, in the down leg. This circulation can continue, using a lower accelerant injection rate, powered during reactor shutdown by residual and decay heat. There is no proximity of sodium to water.

One potential disadvantage is that the primary system must be pressurized to drive a turbine. The system described in [34] proposed 70 atmospheres. Pressurization is not, however, used to prevent coolant from boiling, so loss of pressurization is not a safety hazard. If the core is depressurized during shutdown, accelerant injection can be gravity fed, eliminating dependence upon injection pumps for shutdown safety.

A catastrophic rupture of the accelerant feed lines to the injector, caused for example by a seismic event, could inject large amounts of liquid accelerant into both the down leg and up leg of coolant flow, resulting in voids within the reactor core. The core must be designed to have robust inherent safety even in the presence of significant coolant voids. One such safety mechanism is to drain fuel passively into inherently sub-critical storage regions as described in section 9.

In a lead-bismuth system, ^{210}Po , transmuted from bismuth, is a significant radiotoxicity hazard that would appear in steam. Lead also has significant long-lived activation products. An accelerant vapor leak would be a significant radiotoxicity hazard. Sodium has no long-lived activation products. An accelerant vapor leak would not be a significant radiotoxicity hazard.

Lead-bismuth alloys are corrosive to steel [34]. Sodium is not corrosive. The heat capacity of sodium is 8.9 times greater than PbBi eutectic at 500°C . The thermal conductivity of sodium is four times greater than PbBi eutectic at 500°C . The viscosity of PbBi eutectic is 5.3 times greater than sodium at 500°C . The density of PbBi eutectic is twelve times greater than the density of sodium at 500°C .¹² Pumping cost for PbBi is much greater than for sodium. Sodium is a better coolant, especially if electricity can be generated by a turbine powered by accelerant gases, instead of using a sodium-water heat exchanger.

The system proposed in [34] is based upon static fuel in pins. The core includes control rods, and refueling is accomplished by replacing fuel assemblies. Vapor separators above the core complicate refueling and operation of control rods. With mobile fuel, and with control rods eliminated by controlling paste level within the reaction regions of fuel elements,¹³ those complications do not exist, at least not in comparison to the short-term schedule of refueling in static-fuel systems. The complication remains if and when fuel containers must be replaced. Sufficiently robust fuel containers would not need to be replaced during the lifetime of the reactor.

11 Conclusion

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 is at most one new idea here – but the combination of ideas has not appeared.

Mobile fuel has obvious advantages. A settled paste would not have the reactivity instability that a suspended slurry would have. Sodium has high thermal conductivity, high heat capacity, high boiling point, very low neutron absorption cross section, its activation products have very short half lives, its low density and low viscosity reduce pumping power, it moderates neutron energy less than water would, and it does not react with metallic fuel or the container. It is the best carrier for paste fuel. A steel container reacts less with metallic fuel than with carbide, silicate, oxide, or molten salt fuels [6]. Metallic particles are the best fuel, if motion, metals alloyed with fuel, and sufficiently low temperature adequately prevent them from reacting with the container or forming clusters. Uranium nitride is the best alternative, but it is expensive because nitrogen isotope separation is necessary: only ^{15}N (about 0.4% in the atmosphere) can be used because of the large neutron absorption cross section of ^{14}N , and to avoid creating ^{14}C . If nitrogen is recovered when fuel is reprocessed [36], this cost is only incurred for the initial fuel load. An assembly fueled with a mobile metal-sodium paste would have a longer service life than one containing static fuel because it is not necessary to replace it to replenish fuel, there is no container strain due to a pressure differential to coolant, and continuously moving fuel reduces or eliminates fuel/container chemical interaction. Container lifetime would be limited by thermal-cycling fatigue, neutron swelling and embrittlement, erosion, and deposition of “noble” metals, not container strain and creep. External thermal storage would eliminate rapid thermal cycling due to load following. Continuously processing and mixing fuel eliminates changes in fissionable distribution, density, and composition, thereby eliminating burnup reactivity swings and simplifying control. Continuously removing ^{135}Xe , and its precursor ^{135}I in the form of NaI, eliminates the “iodine pit” startup control instability. Inherent safety mechanisms, in addition to those in EBR-II as described in [14], are possible. It might be possible to eliminate control and safety assemblies.

The mobile paste fuel concept apparently disappeared from the literature after 1961 (other than later references to earlier work). Was it rejected as a result of scientific, engineering, and economic studies? There is no evidence of this. Did it simply lose a funding battle, get put on the shelf, and was then forgotten? If the latter, more complete studies should be conducted.

¹²Thermal-hydraulic properties of sodium and PbBi eutectic were taken from [19] and [35], respectively.

¹³APDA 146 [2, pp. 39–46] describes hydraulic control and safety systems that do not require rods to penetrate the cover.

APDA 146 [2] described several areas needing further investigation. Many of those questions have already been answered, and some could now be answered with modern modeling tools, but several still require further investigation. There is no reason that a mobile-fuel assembly could not be made compatible with fuel assemblies in a sodium-cooled reactor designed for static fuel, assuming that nozzles to control and adjust coolant flow are part of the fuel assembly, or ones built into the supporting structure could be accommodated. Assuming a self-contained fuel circulation system powered by primary coolant flow using a MHD generator/pump, the only additional complication would be the plumbing required to remove fission gases, and eventually to connect to a processing system. It should be possible to investigate the physical feasibility and economic viability of this concept, and optimize its dimensions, using only one fuel element in a research reactor such as the proposed Versatile Test Reactor. Experiments to evaluate the concept would therefore not add significant expense to the overall program of research to be conducted at the Versatile Test Reactor.

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Appendix A – Major Technical Problems listed in APDA 146

Appendix A in APDA 146 [2] listed several technological problem areas. These are summarized here, with comments to relate the discussion to the present proposal. The reader is referred to the original for more details.

1. Problem areas related to core structure development

(a) Core design

“The design of the core structure would be based primarily on a quantitative knowledge of paste flow characteristics, fuel and structural temperature limitations, and heat transport capabilities of a sodium coolant system, . . . analysis of thermal gradients, and the mechanical and structural forces to which the structure would be subjected, both under normal and abnormal operations.”

Analytical tools have significantly advanced during the last sixty years. Significant experience with sodium cooled reactors has been gathered from EBR-II, as well as in France, Russia, and Japan. Systems involving paste or slurry flow, but not specifically uranium particles in sodium, have become widely used. Specific investigation of the flow of pastes of uranium and sodium is required.

(b) Fabrication development

“The major fabrication problems are (1) fabricating of the coolant tubes, (2) fabricating of the tube sheets, (3) welding or brazing of the coolant tubes to the tube sheets, (4) welding or brazing of the subassembly shell to the tube sheets, (5) interlocking of the individual subassemblies into a complete structure, and (6) supporting the complete structure in the reactor vessel.”

Significant advances in fabrication, such as electron beam welding, have occurred during the last sixty years. Analytical tools for structural analysis are well developed.

2. Problem areas related to the fuel circulating system

(a) Paste flow mechanics

APDA had sponsored significant research in paste flow mechanics. The effect of bubbles was investigated, but using only glass beads, water, and carbon dioxide. They remarked “An accurate evaluation of the effects of gas bubbles on paste flow would require a high-fission-density flow experiment.”

APDA also “sponsored a preliminary analysis of the effects on paste flow of thermal convection currents which may exist in a paste fuel ligament as a combined result of high power density and the geometry of the fuel ligament. . . . Verification of the validity of this analysis would require a high-power-density flow test upon which fission gas generation would be superimposed.”

Such experiments could be conducted in miniature in a reactor such as the proposed Versatile Test Reactor.

One of the revisions proposed in Section 4 above is a counter-current flow of sodium within the paste to entrain and remove bubbles. Due to the enormous density difference between fuel and sodium, thermal convection might produce the counter-current sodium flow and attendant bubble entrainment. The relationship between thermal convection and bubble transport requires investigation.

(b) Slurry flow mechanics

“The feasibility of circulating a dilute slurry of uranium particles (0.004 to 0.008 inch in diameter) in sodium has been demonstrated. . . . No general correlation is available by which these data can be applied to slurry systems containing large-diameter high-density particles. . . . More extensive and definitive studies are required, however, before a preliminary design of the plumbing system for the slurry would be possible.”

The minimum particle size that is not levitated by counter-current sodium flow should be used, to enhance removal of fission products during operation, as described in [22].

(c) Transition between slurry flow and paste flow

APDA flow experiments demonstrated both transitions. Although a settling tank sufficed for the slurry-to-paste transition, APDA 146 recommended a hydroclone separator, and remarked that detailed studies of dimensions, and the effect of particle abrasion, are necessary both for the separator and eductor.

(d) Particle size classifications

APDA verified that undersize particles can be removed by a hydroclone, and oversize particles caused by stitching can be removed by cross-flow filters. APDA 146 concluded “After preliminary development, both the hydroclones and screening devices should be included in a full-sized mockup of the paste flow system.”

3. Problem areas related to fuel development

(a) Thermal and mechanical stability of the paste fuel

APDA determined that there was no significant sintering below 850°C, and no appreciable interaction with stainless steel at temperatures below the uranium-iron eutectic temperature (725°C). The latter was verified at EBR-II. Fuel motion would further reduce the possibility for this interaction. They observed some particle degradation due to abrasion and attrition, but investigated only pure uranium, not alloy fuels.

(b) Irradiation stability of the paste fuel

APDA sponsored studies at Batelle Memorial Institute in which 0.007 inch uranium - 10 wt.% molybdenum particles were irradiated in a static rather than flowing condition to 0.0007% burnup, which would be achieved by five hours' residence in a mobile paste fuel reactor. They observed no evidence of stitching caused by localized temperature extremes at average temperatures up to 620°C. “APDA believes that the irradiation stability of paste fuels has been demonstrated for the reactor experiments. However, there are no irradiation data at high burnup and high power density.” Such experiments could be conducted in miniature in a research reactor such as the Versatile Test Reactor. The average burnup of particles depends upon the rate of fuel processing as explained in Section 5.

(c) Particle fabrication

APDA sponsored tests at the National Lead Company that successfully produced uranium particles in the size range of 0.004 to 0.008 inches using the spinning disk technique. Batelle Memorial Institute produced particles of 10% enriched uranium - 10 wt.% molybdenum using the same method. Modern methods to produce metal particles, such as gas-powered atomizers, might be more efficient.

(d) Reprocessing of paste fuels

APDA judged that “the pyrometallurgical methods developed by ANL for reprocessing EBR-II fuel would be adaptable for reprocessing of alloy-particle pastes.” This was before development of pyroelectric methods. Paste fuel would be transported to and from an integrated fuel processing facility using small pipes. A transfer crane and coffin would not be needed. Contaminated sodium can be separated from fuel by centrifugal separators that incorporate hot gas injection, then by distillation of the particles to prevent sodium from entering electrolyte. Pyroelectric processing of small particles ought to proceed faster than for solid slugs because of increased surface-to-volume ratio, as explained in [22]. Contaminated sodium could be purified as explained in [22].

4. Problem areas related to control and safety

(a) Fuel accountability

Fuel accountability in a paste fuel reactor is different from that in static fuel reactors. There might be accumulations in unexpected places, such as beside coolant tubes, that might be detectable by reactivity changes, but these might be masked by changes due to burnup. The burnup of particles can be maintained at a roughly constant value by continuous processing. APDA 146 concluded “fuel accountability must be studied first in the full-sized out-of-pile flow loop, then in the in-pile flow loop, and finally in a reactor experiment and prototype reactor.”

APDA did not envision the separate full-size storage region, only a small (10% capacity) holding tank between the reactor and fuel processing facility; this complicates the fuel accountability problem.

(b) Paste expansion

Studies in a static capsule, sponsored by APDA at the Southern Research Institute, showed that under slow heating, “expansion was accommodated by increased volume of the bed rather than by compaction of the bed or expansion of the container. . . . It is expected that the behavior in a flowing paste bed would be no worse since the particles. . . can move to accommodate the expansion.”

“Behavior under a rapid temperature increase is not so clear. Since the sodium expands about six times more than the particles, there must be a rapid displacement of sodium relative to the bed. . . . Further analytical and experimental research on this problem is required.”

(c) Structural stability

Questions of structural stability do not intrinsically depend upon the difference between flowing and static fuel. The primary difference is between a pin-in-duct system such as was well studied at EBR-II, and a tube-in-shell system, in which fuel is a bulk penetrated by coolant tubes. Coolant tube bowing can be ameliorated with internal structure that would not interfere with fuel flow. APDA 146 concluded “Possibly the design may be arranged in such a way that no inherently positive coefficients exist. However, an analytical and experimental program is necessary for verification and numerical evaluation of the reactivity coefficients.” Modern reactor analysis tools can tackle these questions, but reactor experiments would still be valuable.

(d) Operating control system

APDA 146 remarked on the advantage that the “core of a paste-fuel system does not involve mechanical components that present problems of sealing.” In the present proposal, the operating condition is controlled by the level of fuel in the reactor, not by control rods that penetrate the vessel.

(e) Safety control system

APDA 146 remarked that a reaction could be quenched by adding boron, but a fluid system might be vulnerable, especially during a seismic event. They advocated a hydraulically actuated solid poison control material, and remarked that it poses no new problems. In the present proposal, the storage region is the primary safety system. If that is considered not to be sufficient, a solid control-rod system could be included.

(f) Sodium reactivity coefficient

APDA 146 was concerned about the reactivity coefficient of sodium. That question has been extensively investigated at EBR-II, as well as in France, Russia, and Japan.

5. Problem areas related to maintenance

APDA 146 remarked upon the difference to other homogeneous reactors, in which fuel is also coolant. Because fuel is not coolant in the design proposed in APDA 146 [2], and in the present proposal, and because of the small amount of fuel circulating outside the core, maintenance problems are no different from those in any other sodium-cooled reactor. Eliminating a transfer crane and coffin simplifies maintenance.

Appendix B – from Nuclear Science Abstracts

This is abstract 1869, for **Conceptual Design of a 300 MWe Paste-Fueled Fast Breeder Power Reactor**, Atomic Power Development Associates, Inc., Detroit, (October 1961) [2] that appeared in **Nuclear Science Abstracts 19**, 1 (January 15, 1965) [3].

The conceptual design of a 300-MW(e) fast breeder reactor power plant that utilizes a paste-fuel system consisting of small, spherical particles settled in sodium is described. Both the core and blanket material in this reactor are mobile, moving continuously through the reactor at a low velocity. The core and blanket are shell-and-tube structures with paste flow on the shell side. Sodium flowing through the tubes transports the heat out of the reactor to a secondary sodium system. Steam, produced in a sodium-water steam generator, drives a conventional turbine. The basic reactor design, performance and cost data are given. A major portion of the report is devoted to a discussion of the paste-fuel system, which is a unique feature of the reactor concept. The design of the core and blanket structure is discussed, and a detailed analysis of the design is given. Included is a description of a fuel-handling system that provides for circulating the paste, filling and draining the core and blanket, supplying fresh fuel to the reactor, and bleeding off fuel for reprocessing. Processes for fabricating and processing the fuel particles are described, and the nuclear characteristics of a paste-fuel system are considered, with particular reference to the conceptual design. Novel concepts that were used in the design for the operating and safety control systems, the reactor vessel, the primary heat transport system, and the shielding are also covered. These innovations were incorporated into the design on the basis that they are desirable to preserve the full advantages of the mobile-fueled system.

<https://www.osti.gov/biblio/4690257-conceptual-design-mwe-paste-fueled-fast-breeder-power-reactor>.

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