

Reactor Design Compilation

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1 Introduction

To begin, take note of [?] and [?]. These articles are not specific designs, instead, they give a general history of US MSR technology up to approximately 1980. [?], in particular, is a personal account of the author's experience in the growing field, and offers interesting insight.

This report seeks to collect various MSR designs and reprocessing techniques, and from them, compile a general list of MSR features. The intent is to capture the expected varieties of fluid-fueled MSRs such that models and simulations can accommodate a broad range of designs. The features given in this review include characteristics such as:

- Single fluid or two fluid salt
- Single or multi-region core
- neutron energy spectrum
- moderator type
- salt type (relates to single or two-fluid)
- Intensity of processing

The processing in an MSR can also vary. After the general reactor designs have been compiled, processing options will be as well.

2 Molten Salt Reactor Experiment (MSRE)

This reactor is given as the first MSR design. Technically, the Aircraft Reactor Experiment is its predecessor, however, given its unsuitability as a commercial reactor (and the focus of this report on such reactors) it is not included in detail here. The MSRE has general characteristics, described thusly: [?]

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Below, a test using tikz:

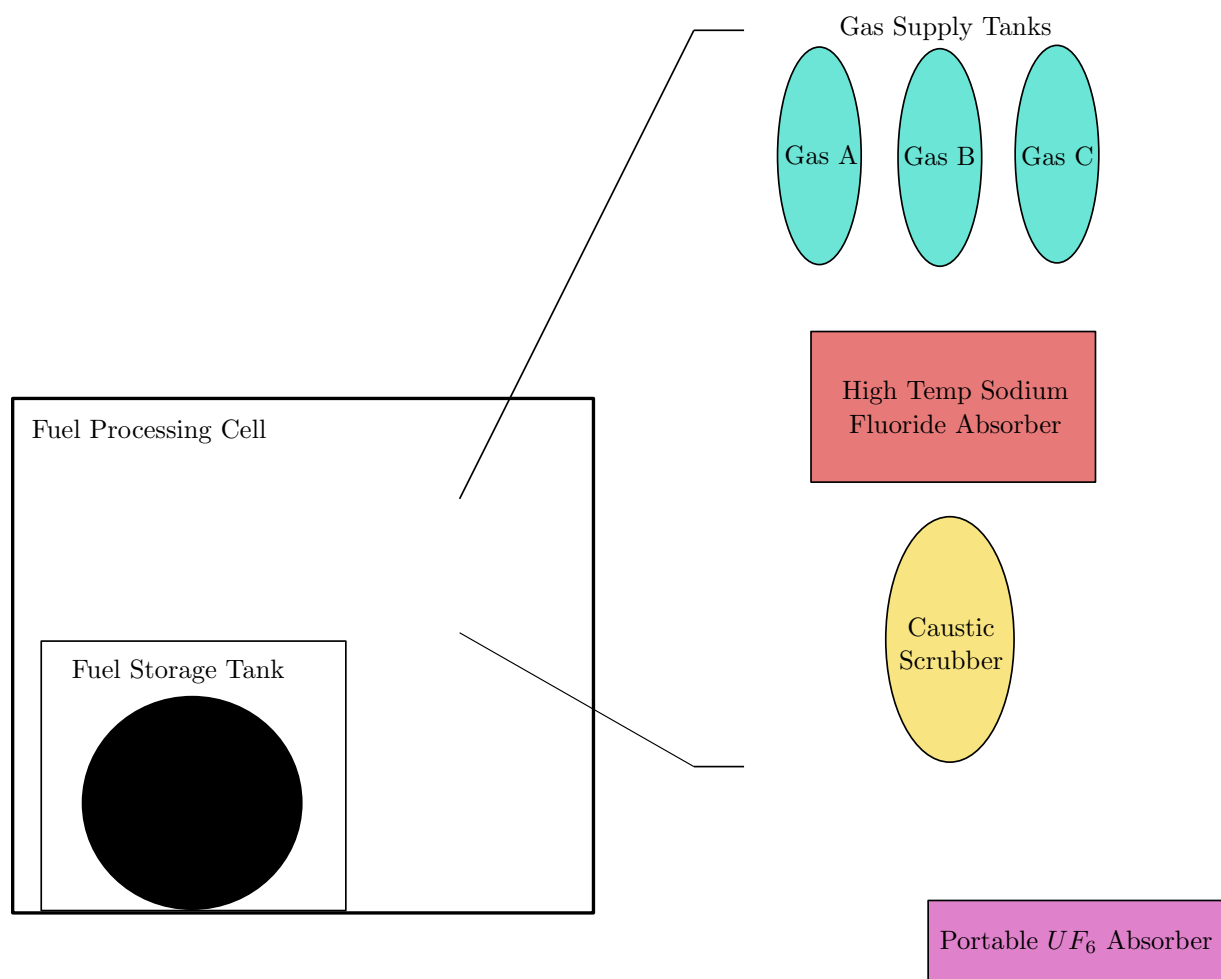


Figure 1: I tried so hard

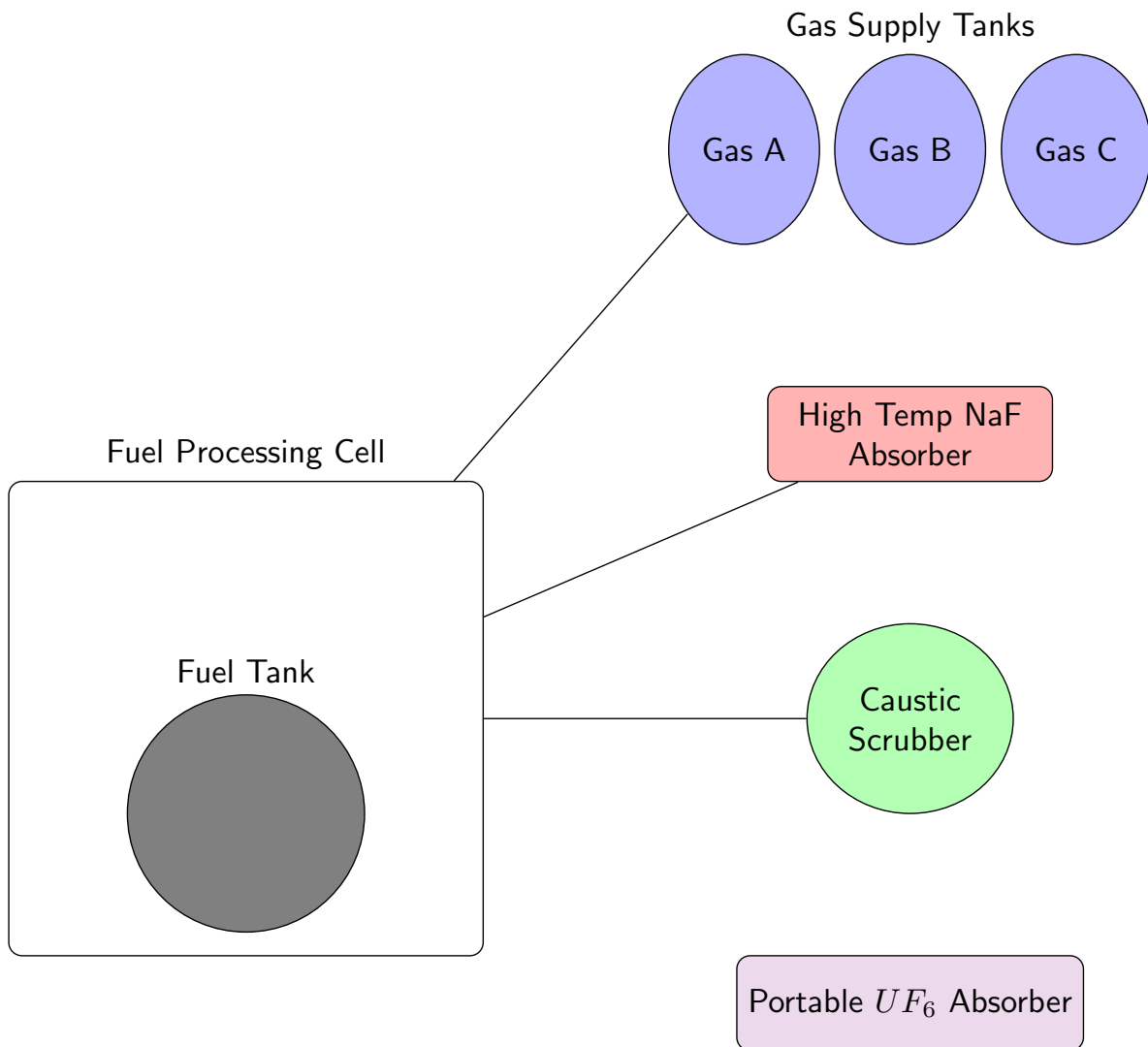


Figure 2: And got so far

- 10 MW
- Single-region
- Graphite moderator
- Fuel salt is a mix of lithium, beryllium, and zirconium fluoride salts, using either uranium or uranium and thorium. Specifics of the composition are given in Table 2.1 of [?].
- Total core volume is 90 cubic feet. 20 cubic feet is fuel, 70 cubic feet is graphite.
- Graphite matrix is set in a rectangular grid, with 6 holes taken out to hold control rods.

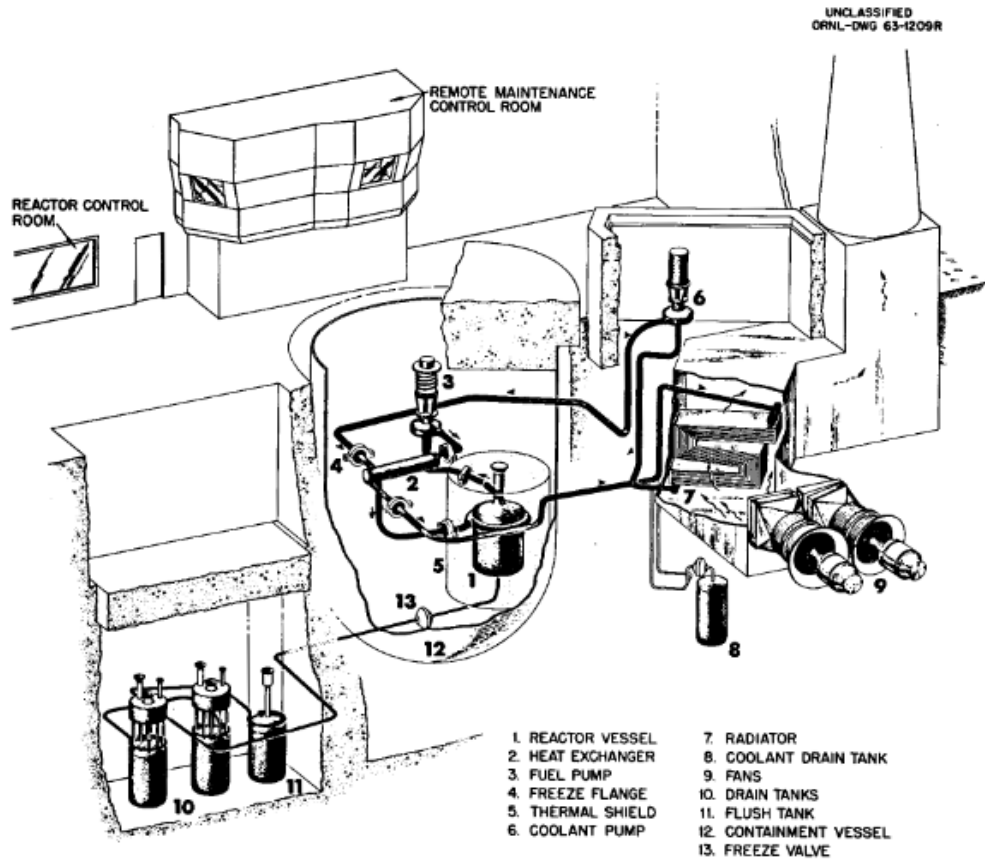


Fig. 2.1. MSRE Flow Diagram.

Figure 3: An image of the reactor building setup, from [?] directly

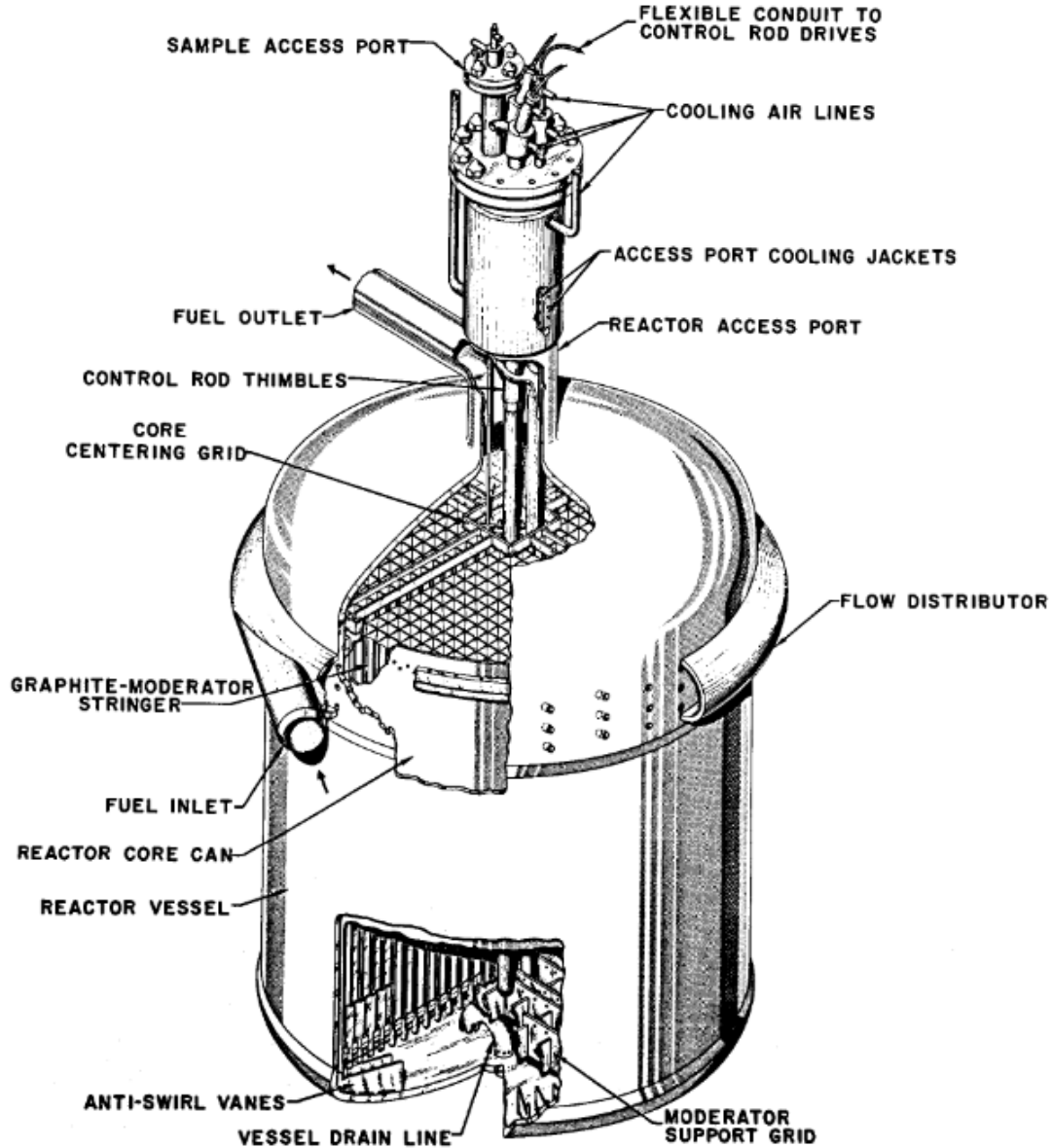


Fig. 2.2. Reactor Vessel.

Figure 4: An image of the reactor core, from [?] directly

There is not "online" reprocessing in this design, exactly. When the fuel salts have become contaminated or otherwise undesirable, they are removed from the reactor, which is then flushed with a "flush salt". This flush salt is simply the fuel salt mixture without any of the fissile isotopes added.

After chemical treatment, what can be saved from the salt is reused, the rest is disposed of.

3 Molten Salt Breeder Reactor (MSBR)

The MSBR builds on the MSRE, adding a conversion ratio high enough to classify the MSBR as a true breeder reactor. It features a higher power in its design specifications, at the cost of a low graphite lifetime.

Additionally, it has a lesser fuel vol% than the MSRE, and two fewer control rods.

- 1000 MWe, with a thermal plant efficiency of 44%
- Average core power density 22kW/liter, with a plant factor of 80%. This gives:
 - A four year graphite lifetime
 - A fuel yield of 3.3%
 - A compounded fuel doubling time of 21 yr
- Reactor vessel is approximately 22ft in diameter and 20 ft high.
- Core is 14.3ft in diameter and 13ft high
- Salt to graphite ratio in the core is 13%
- Graphite moderator
- Fuel salt is $LiF - BeF_2 - ThF_4 - UF_4$, using ^{233}U as the fissile isotope. The concentrations in mole%, from table 1 of [?], is given as 71.6 – 16.0 – 12.0 – 0.4, respectively.
- Graphite matrix is a rectangular grid with 4 control rod slots in the center.

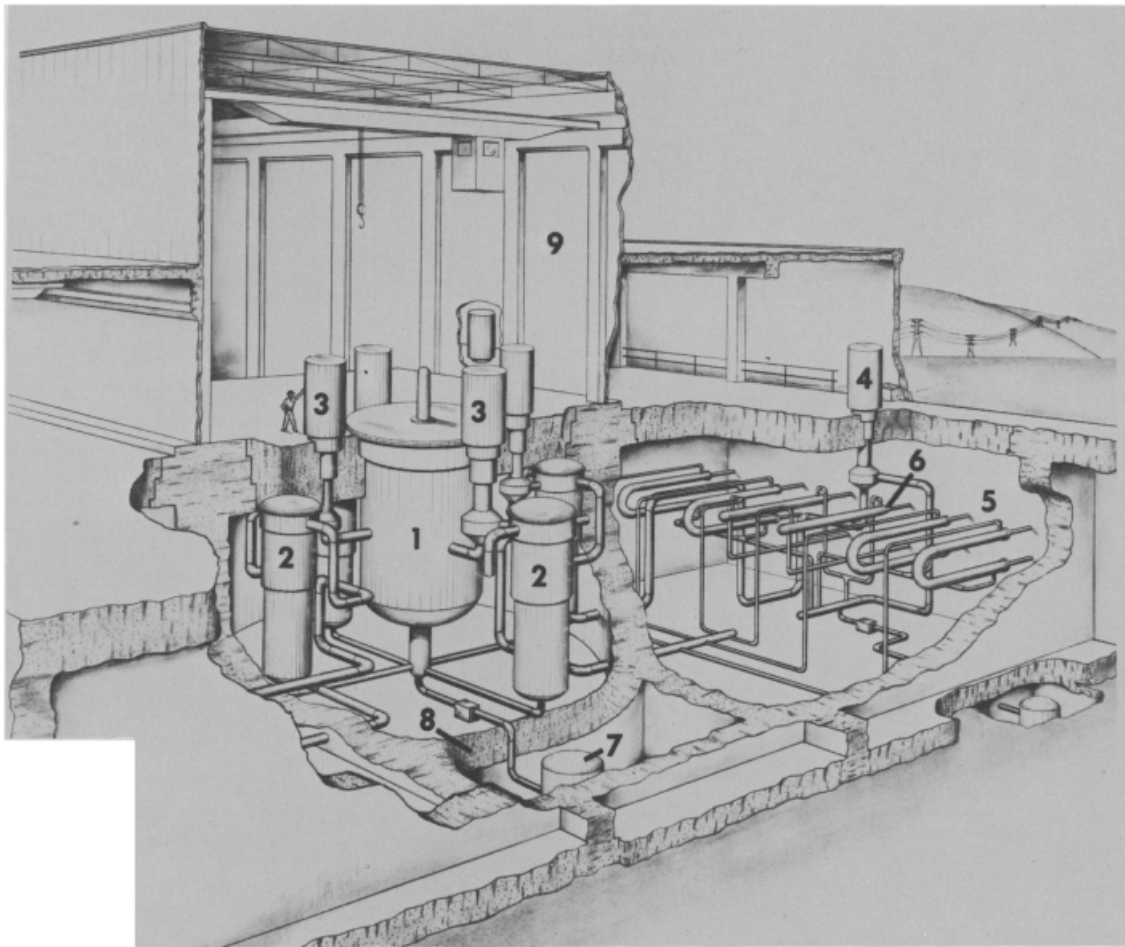


Fig. 3. Cutaway perspective of MSBR reactor and steam cells. (1) Reactor, (2) Primary heat exchangers, (3) Fuel-salt pumps, (4) Coolant-salt pumps, (5) Steam generators, (6) Steam reheaters, (7) Fuel-salt drain tank, (8) Containment structure, (9) Confinement building.

Figure 5: An image of the reactor and steam systems, from [?]

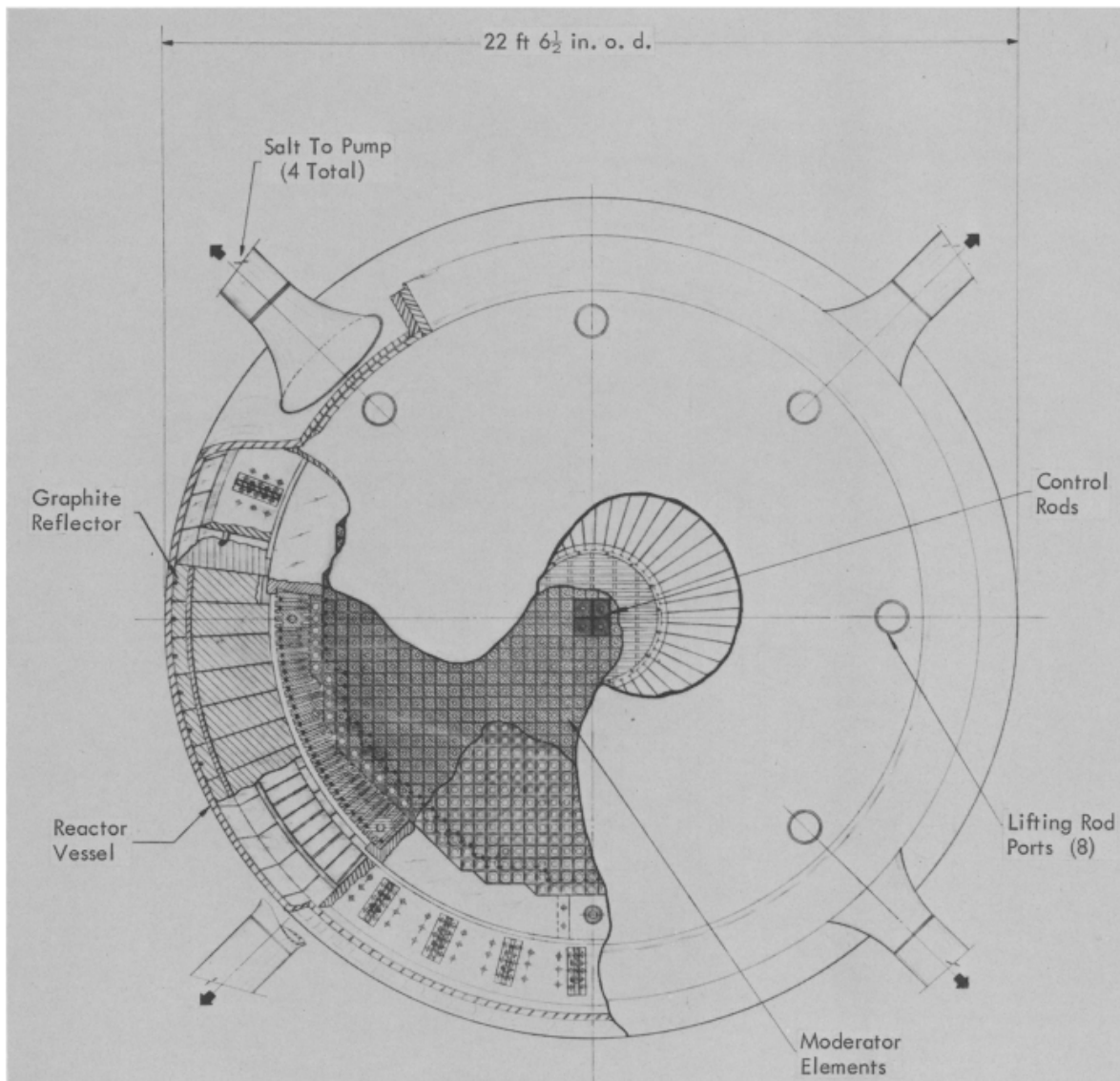


Fig. 5. Top cut-away view of reactor vessel for MSBR 1000 MW(e) station.

Figure 6: A bird's eye view of the reactor core, from [?]

The chemical processing is more involved than the MSRE, and includes:

- An off-gas system to remove gaseous fission products, using helium spargers.
- A continuous chemical processing loop to:
 - Remove fission products
 - Recover bred ^{233}U
 - Add more fertile material, as needed.

4 Molten Salt Demonstration Reactor (MSDR)

A reactor concept from ORNL, hoping to build on the MSRE and show the commercial capabilities of an MSR. The intention is to show the feasibility of a breeder MSR, however, the MSDR's conversion ratio isn't

high enough to technically be a breeder. Instead, it is a converter [?]. One difference of note between the MSDR and the MSBR is that the MSDR maintains a low enough power density that the graphite moderator is expected to last 30 years. This is in stark contrast to the MSBR, which operates at a higher power density, and only anticipates a 4 year graphite lifetime.

- 350 MWe
- Peak power density 114 W/cc
- Reactor vessel is 26ft tall and 26ft in diameter
- Graphite is used as the reflector in a square matrix, with graphite taking up 10% of core volume
- FLiBe salt, initially using ^{235}U , that uses thorium to breed ^{233}U
- solid graphite slabs for reflector, arranged in an axial/ radial matrix. Six slots in the matrix for control rods.

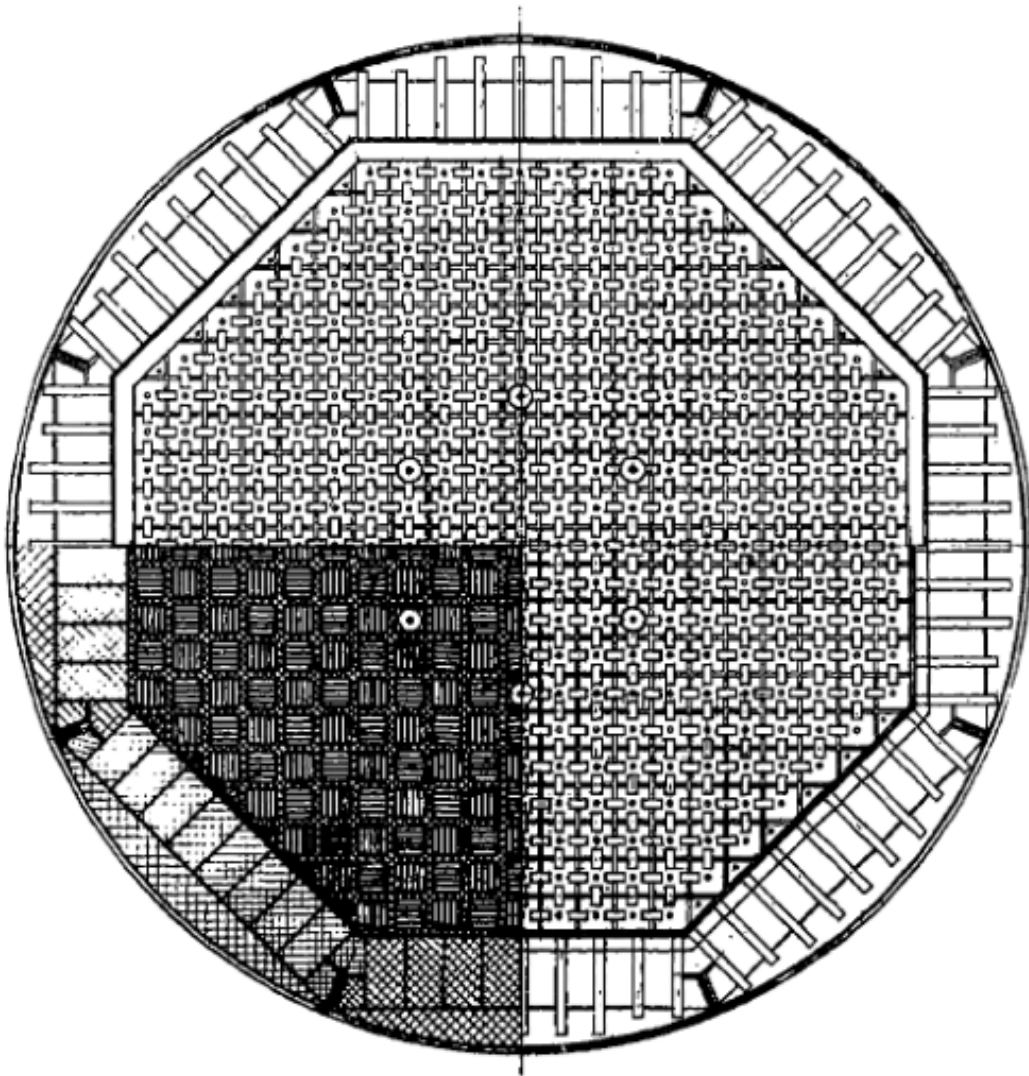


Fig. 6. Reactor Core and Reflector Plan.

Figure 7: The layout of the reactor core, from [?]

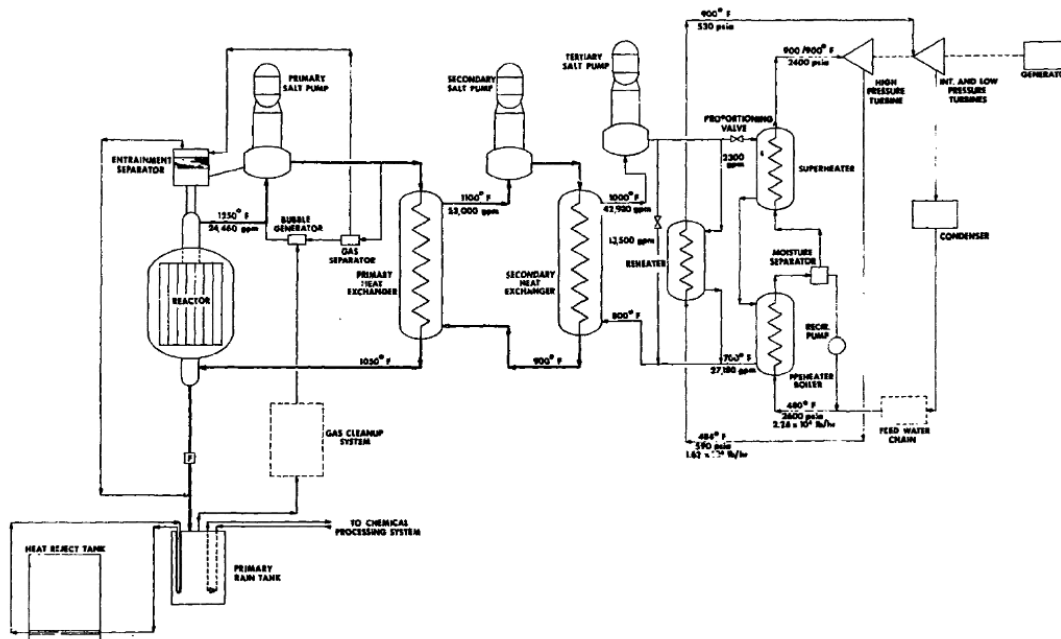


Fig. 1. Simplified Flowsheet for 300-MW(e) Molten-Salt Demonstration Reactor.

Figure 8: Layout of the reactor, steam generation, and (most) of the salt processing, from [?]

The processing used in this reactor is minimal, and is intentionally limited to what was used in the MSRE. All salt processing is as follows:

- A Hitec salt loop oxidizes tritium in the fuel salt into tritiated water for removal
 - This salt loop goes to the heat exchanger for steam generation
- Xenon and other noble gases are removed via helium sparging
 1. Initially, this gas spends 6 hrs in a drain tank
 2. Then, it is filtered for solids
 3. Approximately half of the filtered gas returns to the helium bubble generator, the other half spends 90 days in a charcoal clean-up system
- Other fission products are not removed from the salt in a short time scale. Instead, the salt is replaced every 8 years. Fissile materials are taken from "spent" salt, where possible.

5 Denatured Molten Salt Reactor (DMSR)

This reactor is heavily based on the MSBR. In fact, the design is mostly identical, except the DMSR does not remove fission products during the 30 year lifetime of design. It does however, include helium sparging and some limited chemical processing to maintain salt quality. This particular design is prompted by guidance given in 1976 by what is now the DOE, along with reports that concluded a breeder reactor without denatured fuel would not be able to be deployed worldwide, due to insufficient proliferation resistance. [?]

The basic qualities of this reactor are as follows:

- 1000 MWe power generation, with a low enough power density to give the graphite moderator a 30 year lifetime.

- Low power density also reduces neutron capture in ^{233}Pa , to bolster nonproliferation
- Uses 20% enriched ^{235}U to reach initial criticality.
- Like the MSBR, uses $\text{LiF} - \text{BeF}_2 - \text{ThF}_4 - \text{UF}_4$ salt (with the above change in fissile isotope)
- This reactor vessel is 10m in both height diameter, with the following core specifications:
 - The core is 8.3m in height and diameter.
 - * The outer 95% of the core volume, core B, has a salt volume of 12.94%
 - * The inner 5% of the core, core A, has a salt volume of 20%
- Table 9 and Table 10 in [?] give isotope concentrations and neutron utilization, as calculated for a few points in the reactor lifetime.

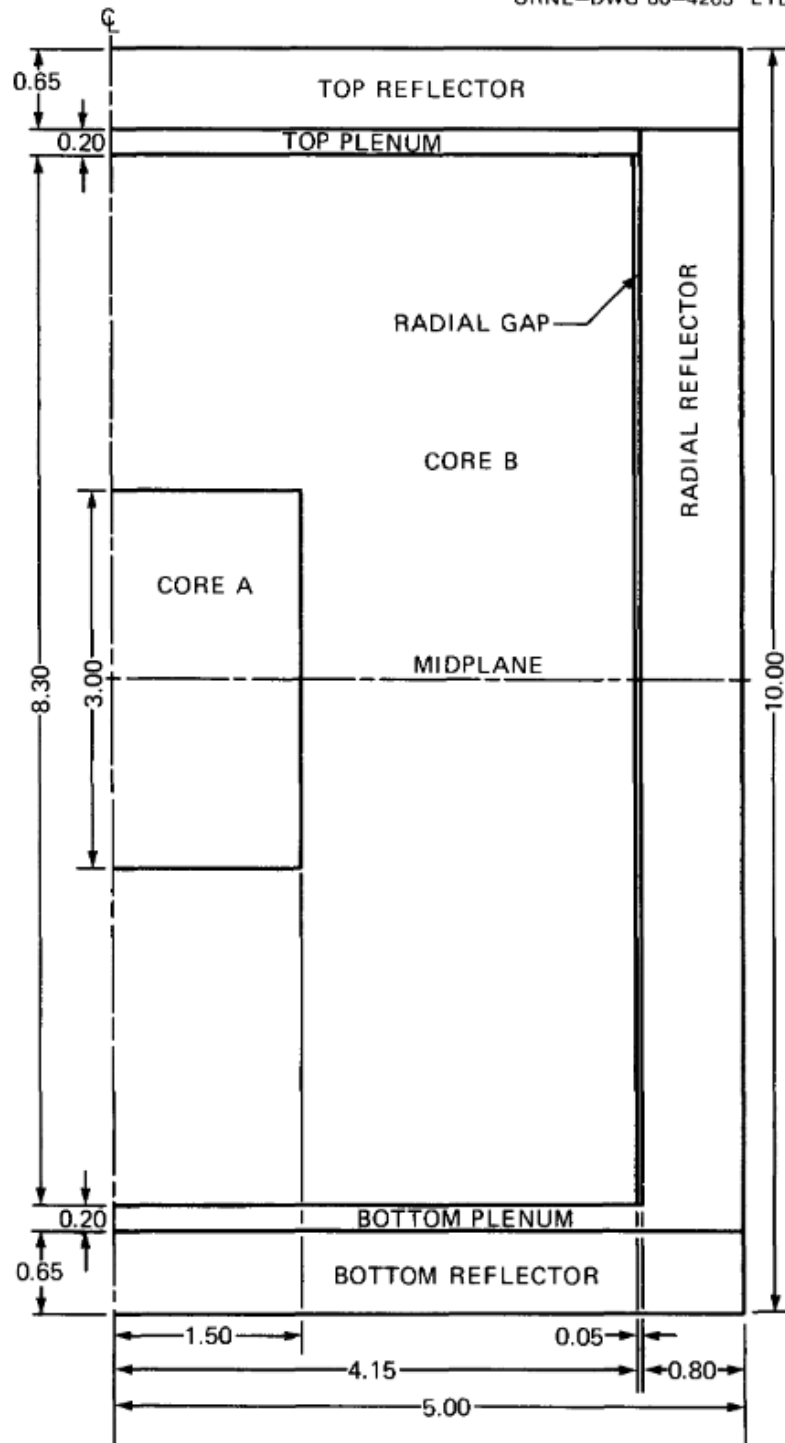


Fig. 2. DMSR core model for neutronic studies - cylindrical geometry (all dimensions in meters).

Figure 9: A cut-away view of the core, from [?]

6 Integral Molten Salt Reactor (IMSR)

The IMSR400 is a small modular reactor (SMR) patented by Terrestrial Energy Inc. The "core-unit" consists of the core, and integrated pumps and heat exchangers. The core-unit has a lifetime of 7 years, but is made to be easily replaced, giving the designed plant an expected lifetime of 30 years. Some specifics of this reactor, such as the fuel-coolant mixture, is proprietary, and explicit detail is not given. What information is publicly available is as follows [?]:

- 400 MWe, with an average core power density of $11\text{--}15 \frac{\text{MW}}{\text{m}^3}$
- Core is 4m in height, and 3.4m in diameter.
- The length of each fuel cycle is 84 months, i.e., the 7-year lifetime of the core-unit
- The moderator is graphite, and the shutdown rods are made of gadolinium oxide, and it does not have control rods
- At the time of discharge, the average burnup is 26-29 MWd/kg
- The salt mixture is a blend of fluoride salts, including sodium fluoride, beryllium fluoride, and lithium fluoride. At startup, the fuel has an enrichment of 2-3%, and an enrichment of 5-19% when used fissile material is replaced

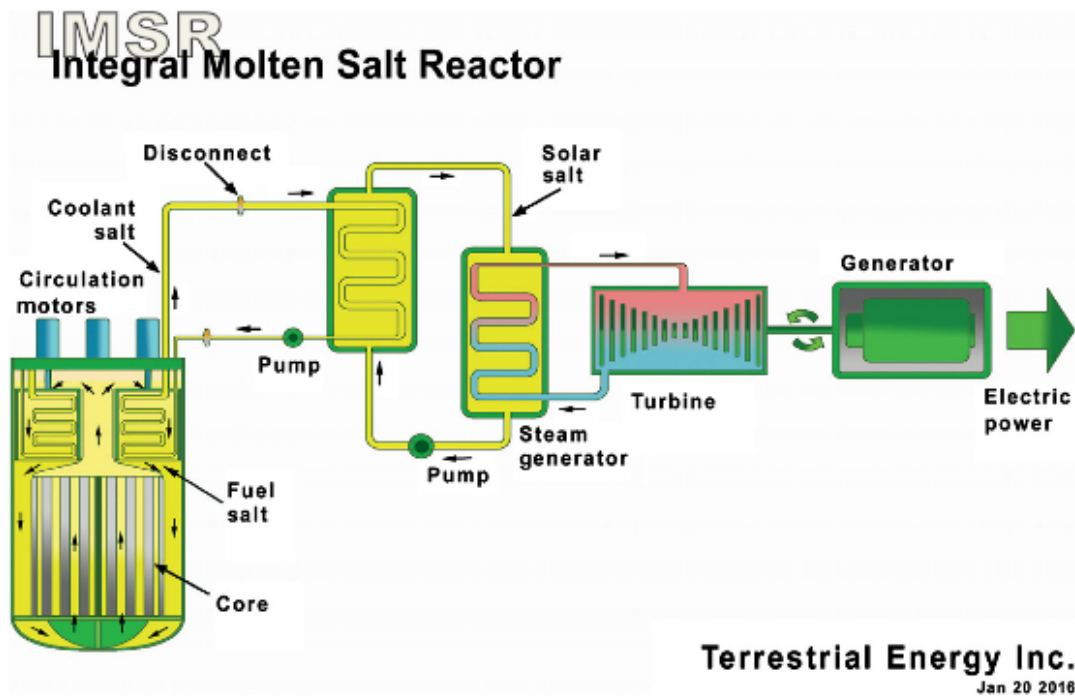


Figure 18.2 IMSR400 main heat transport paths for power generation.

Figure 10: A simplified view of the core-unit, and its attachment to the power generation loops, from [?]

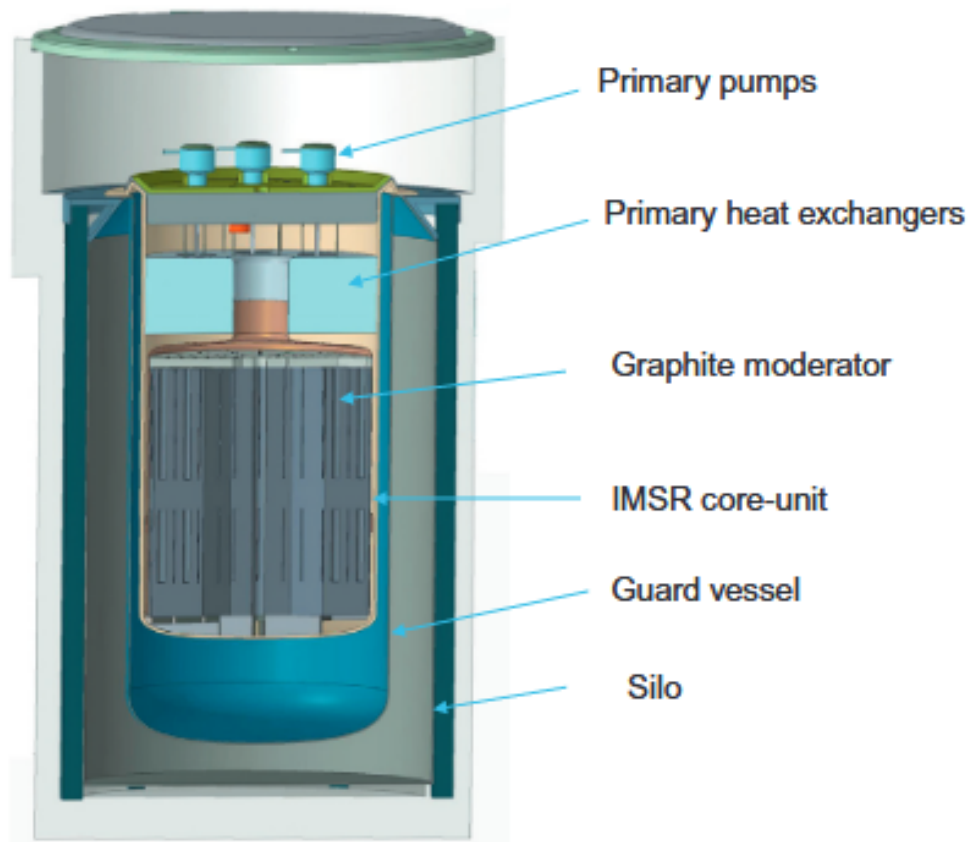


Figure 18.3 Core-unit and guard vessel in one of the two reactor silos.

Figure 11: The core, from [?]

7 Molten Salt Fast Reactor (MSFR)

Of the reactors given in this review, this is one of the few fast reactors (the other being Terrapower's MCFR, given below). Because such a reactor does not use a moderator, it circumvents some of the material constraints associated with degradation of the graphite moderator. It also has a much higher breeding ratio. This report uses a conceptual reference reactor with these characteristics [?]:

- A power of 3000 MWth
- Three loops: the fuel, intermediate, and power conversion loops
- Within the fuel circuit, there is a total salt volume of 18 cubic meters
 - The fuel salt is lithium fluoride and actinide fluoride, with the mol% of the actinide fluorides is assumed to be a fixed 22.5 mol%
- Within the core, there is a fertile isotope blanket region, composed of a $LiF - ThF_4$ blend that has a concentration of ThF_4 of 22.5 mol%
- The blanket serves as the radial reflectors, to protect the reactor vessel. On the top and bottom, there are reflectors made of nickel-based alloys. This particular report also assumes this alloy will absorb 99% of incoming neutrons.

- The design initially used a very simple cylindrical geometry for the core, but by the time the report was written, the study moved on to more realistic, and complicated geometries.
 - The first geometry is referred to as Geometry I. The radial core walls are curved, along with the top reflector. The bottom reflector is flat
 - The second Geometry, Geometry II, features symmetrically curved walls within the core. Both this and Geometry I are given in ?? below.
- Helium sparging is assumed, but because its impact and the thermal-hydraulic properties was deemed negligible, it is neglected in calculations

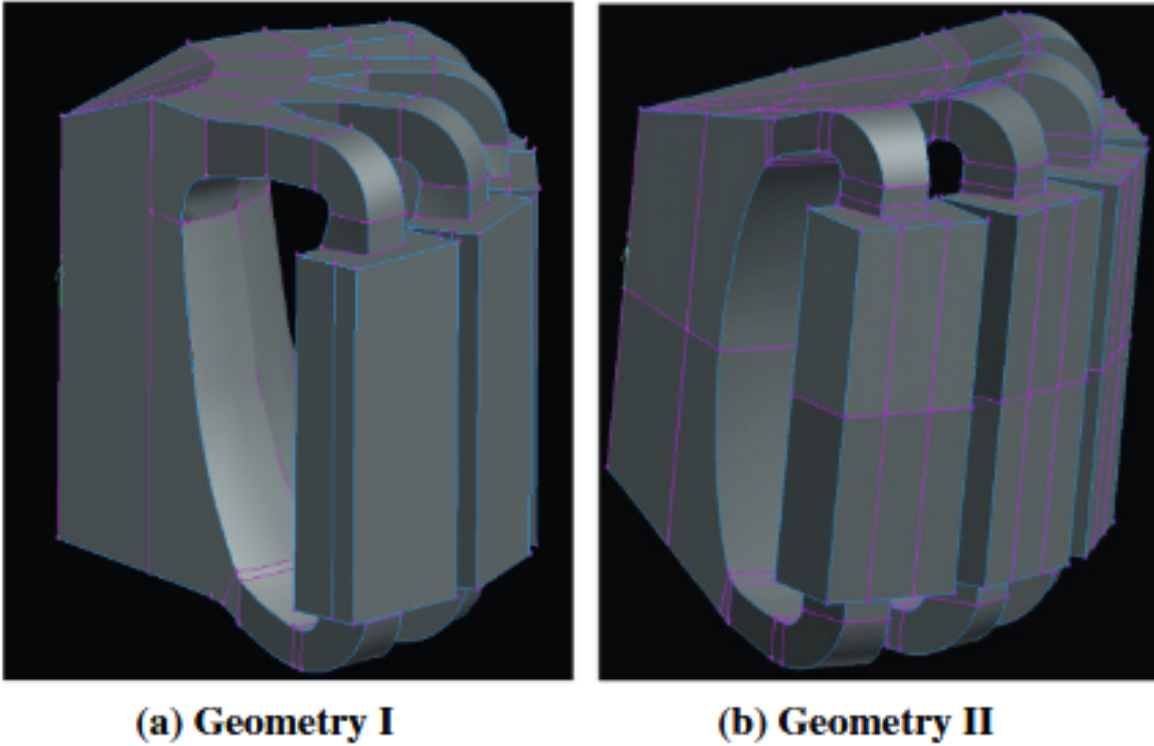


Fig. 2. MSFR core geometries used in the CFD thermal-hydraulics studies.

Figure 12: Geometries I and II, from [?]

In a separate report, [?] , a reactor with the same nominal power, and actinide mol%. While [?] is focused on the thermal-hydraulic facets of an MSFR, [?] provides more in-depth information about the sort of fuel salt composition used in its reference model, and includes information on the reprocessing within the reference MSFR.

- This report gives the fissile salt explicitly: $LiF - ThF_4 - {}^{233}UF_4$ in with mol% concentrations of 77.5% – 20% – 2.5%
- The fertile blanket is 50 cm thick
- The initial blanket salt is identical to the above report - $LiF - ThF_4$ in mol% concentrations of 77.5% – 22.5%

8 Transatomic

The Transatomic reactor has two important differences from other thermal-spectrum MSRs in this review. It changes the fuel salt mixture, and forgoes a graphite moderator for something with a better lifespan under the conditions of the reactor [?].

- The fuel salt is a $LiF - UF_4$ mixture, with a uranium concentration of 27.5%
- Unlike the other MSR designs reviewed, the Transatomic reactor uses a zirconium hydride moderator with corrosion resistant cladding
 - Table 1 of [?] gives dimensional parameters for the moderator rods in the core
- Transatomic has proposed three fueling scenarios, but only the first has been the focus of ORNL studies:
 1. 5% start-up enrichment, followed by a 5% online feed
 2. 5% start-up enrichment, followed by an online feed of spent fuel from light water reactors
 3. 10% start-up enrichment, followed by an online feed of 19.9%
- Burnup can be as high as 200 MWd/MTU, with the intention of limiting waste products
 - After analysis of core models, with simulation of the chemical processing included with use of ChemTriton, the report concludes that after 15 years of operation, the reactor has bred enough plutonium to reach a burnup of 91.9 GWd/MTU by year 29.1 of operation

9 Terrapower

website here

Much of the current information about Terrapower's designs are in patents, and, therefore, not given in exact detail [?]. However, it can be said that:

- The core has two regions, one fissile, one a fertile blanket. The patent does not specify how exactly these regions are arranged, and also gives a homogenous mixture of the two materials as a possibility
- ^{239}Pu is given as a possible isotope present in the fissile region, and ^{238}U as the fertile isotope in the fertile blanket