NRSEA

Liquid vs Solid Fuel Molten Salt Reactor Trade-off Study

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List of Acronyms and Abbreviations

AOO Anticipated Operational Occurrence
BDBE Beyond Design Basis Event
C&S Containment and Surveillance
DBA Design Basis Accident
DBE Design Basis Event
DEGB Double-Ended Guillotine Break
DOE Department of Energy
DRACS Direct Reactor Auxiliary Cooling System
ECCS Emergency Core Cooling System
FERC Federal Energy Regulatory Commission
FHR Fluoride-salt-cooled High-temperature Reactor, *Mk-1 Pebble Bed Reactor in this report*
FLiBe LiF-BeF2
FP Fission Product
GCC Greater than Class C Waste
IAEA International Atomic Energy Agency
LOHS Loss of Heat Sink
LOCA Loss of Coolant Accident
MoPSC Missouri Public Service Commission
MSR Molten Salt Reactor, *Liquid-Fluoride Thorium Reactor in this report*
NDA Non-Disclosure Agreement
NPP Nuclear Power Plant
NRC Nuclear Regulatory Commission
NRSEA Nuclear Reactor Solutions for Empowering America
RIA Reactivity Insertion Accident
SNF Spent Nuclear Fuel
SNM Special Nuclear Material
TRISO Tri-structural Isotropic

Executive Summary

NRSEA has been hired by Ameren to evaluate two advanced reactor designs to inform the selection of a reactor for their St. Clair, Missouri site. The two advanced reactors studied are a pebble-bed fluoride-cooled high-temperature reactor (FHR) and a two-loop breeder molten salt reactor (MSR). A fundamental difference between these two reactors is their fuel type. The FHR uses solid fuel in the form of TRISO particles within fuel pebbles, and the MSR uses liquid fuel incorporated with the molten salt coolant. The effects of key differences on the economics and safety of the reactors has been evaluated, leading to the recommendation of the FHR.

The FHR was determined to be a more economically viable option. Although the fuel is costly (up to $10,000/kgU for fuel fabrication [1], especially when compared to the essentially zero-cost liquid fuel for the MSR, the MSR requires a chemical processing plant which increases the capital costs as well as operation & maintenance costs. Regular intensive inspection and maintenance are required for both reactors, so these increased costs are presumably marginal. However the results of a technology readiness level assessment show that the research and development required for the MSR to reach market are greater than that of the FHR, and these technology gaps present considerable challenges. Liquid-fuel chemical processing has not yet been fully developed or prototyped, and this is a critical element of the design. Challenges with corrosion and tritium plague both designs, but the liquid fuel exacerbates these issues in the MSR.

Both the FHR and MSR concepts make use of intrinsic passive safety systems and offer increased safety and reliability over traditional LWRs. In a design-basis loss of external power, the FHR has buoyancy-controlled moderation and magnetic-latch control rods. The MSR’s core could drain into a subcritical geometry. Both designs have robust safety systems as detailed in Volume II, and NRSEA is confident in recommending either reactor design due to the integrity of these systems. However, the added complexity of the additional molten salt loops in the MSR makes the FHR a preferred technology when comparing the designs’ safety and reliability. More molten salt loops (including loops which contain uranium and thorium) means greater mobility of fission products and fuel, allowing for more channels for release. The solid-fueled FHR is simpler and, thus, seems to offer less pathways for release.

When considering waste management for the two designs, the different fuel type plays an important role. Used solid fuel from the FHR can be treated in a similar manner as

that of conventional LWRs. Fission products are largely contained within the spent fuel pebbles, so wet storage for a year followed by dry cask storage is a straightforward plan for safe storage. Waste liquid fuel from the MSR would likely be a smaller and less-active volume than FHR or LWR waste streams due to on-line reprocessing of the fuel salt. However, treatment of liquid fuel (freezing, vitrification, etc.) has never been demonstrated commercially, and there is no precedent end-of-life plan. The FLiBe could be stripped of its radioactive species and then disposed of, but this presents a technological and regulatory risk.

As a result of the comparison of the economics, safety & reliability, and waste management & proliferation concerns for the two reactors, NRSEA recommends that Ameren build an FHR for their St. Clair site. It is challenging to predict progress in R&D and estimate the cost or time of the licensing process, but the FHR design has been found to be lower-risk while offering a safe and economically viable option.

Introduction

Nuclear Reactor Solutions for Empowering America (NRSEA) is an engineering consulting group seeking to facilitate the development and implementation of advanced nuclear reactor technologies in the United States. NRSEA firmly believes that nuclear energy holds a critical position in meeting current and future energy demands in a sustainable manner. As a part of their mission to direct energy resources to their best end, NRSEA evaluates advanced reactor technologies and advises business and electrical utilities on the reactor most suited to their needs. Their commitment to sustainability, clean energy, and safety informs this evaluation process from start to finish. There is an abundance of ideas when it comes to advanced reactor design. NRSEA is working to identify the most economically and technologically viable designs by their risk-informed analyses.

Ameren Corporation is a Missouri and Illinois electricity and gas utility. Ameren employs roughly 8,800 individuals and serves 2.4 million electric customers and 900,000 natural gas customers [2]. Ameren operates four coal-fired facilities which account for 52% of the utility’s 10,300 MW capacity. Missouri’s dependency on coal is substantial. In 2018, Missouri was the second highest consumer of coal of all the states with a consumption of 709.8 trillion BTU, just behind Texas, a much larger state [3]. Ameren’s goal is to reduce carbon emissions from their 2005 levels by 80% by the year 2050. This aim is broken into into goals of 35% reduction by 2030 and 50% reduction by 2040. Nuclear energy offers a promising option to provide clean energy to Missouri and help Ameren achieve this objective. Ameren has hired NRSEA to evaluate what advanced reactor would be best suited for a power plant located in St. Clair, Missouri.

The trade-off study presented in this report is the result of the study of two advanced reactors considered for Ameren's new power plant. The report includes technical overview of the two designs (a fluoride-salt-cooled high-temperature reactor and a liquid-fluoride thorium reactor), as well as a comparison of their economic viability, their safety and reliability, and the waste management and proliferation concerns associated with each. An overview of the relevant regulation and responses to requests for additional information (RAIs) from the project's pre-application are also included in the report.

Design Overview & General Design Criteria

The following provides an overview of the two technologies compared in this report. Beyond this section, the Mk1 Pebble Bed Reactor is called the FHR and the Liquid-Fluoride Thorium Reactor (LFTR) is called the MSR.

A. Fluoride-Salt-Cooled High-Temperature Reactor (FHR)

The Mk1 Pebble Bed Reactor (Mk1 PB-FHR) (see Fig. 1) is a small, modular 236 MWth pebble-bed fluoride-cooled high-temperature reactor that offers many advantages over standard light water reactors (LWRs). A distinctive feature of the Mk1 PB-FHR is its core, consisting of many discrete, spherical fuel elements known as pebbles. These pebbles, roughly the size of a golf ball, are made of compacted TRISO particles (see Fig. 2). TRISO (tri-structural isotropic) particles are tiny uranium spheres coated in multiple layers of carbon that are highly resistant to radiation damage, corrosion, oxidation, and high temperatures and are widely considered to be one of the most robust and safe forms of nuclear fuel [4]. This type of fuel is costly and is currently only produced in small batches. TRISO fuel fabrication costs range from $1,650 to $10,000 per kg U [1]. The pebbles are cooled by a fluoride-based molten salt known as FLiBe, a mixture of LiF and BeF_2 that possesses a high boiling temperature, as well as similar thermophysical properties to that of water. Because of the low atomic weight of its constituent elements, FLiBe is a relatively effective neutron moderator, although not as effective as hydrogen. A disadvantage to using FLiBe is that natural lithium contains roughly 7.5% Li-6, which is a strong neutron absorber and leads to the production of tritium. Therefore, the lithium must be enriched, making it expensive to produce.

By using TRISO particles and FLiBe, the reactor can be operated at very high temperatures while remaining at atmospheric pressure, increasing thermal efficiency and eliminating risks and costs associated with pressurized systems. Other advantages of the Mk1 PB-FHR include online refueling, passive safety features, and increased proliferation resistance.

The Mk1 PB-FHR is designed to produce up to 100 MWe of baseload electricity by itself. This can be increased to 242 MWe during peak hours using co-firing in an air-Brayton combined cycle, an extremely efficient thermal cycle combining aspects of both the traditional Rankine and Brayton cycles [1].

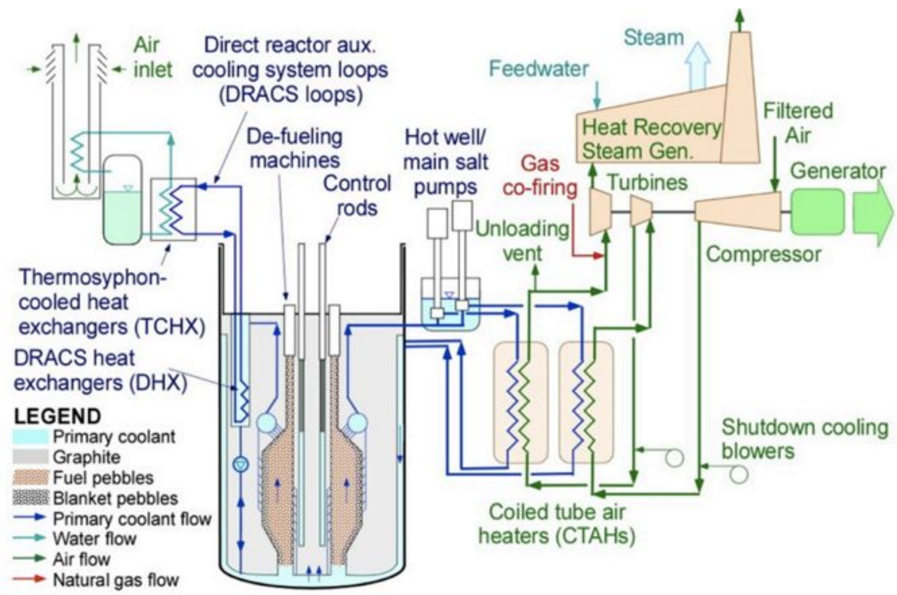


Fig. 1: The Mk1 PB-FHR using an air-Brayton combined cycle [1].

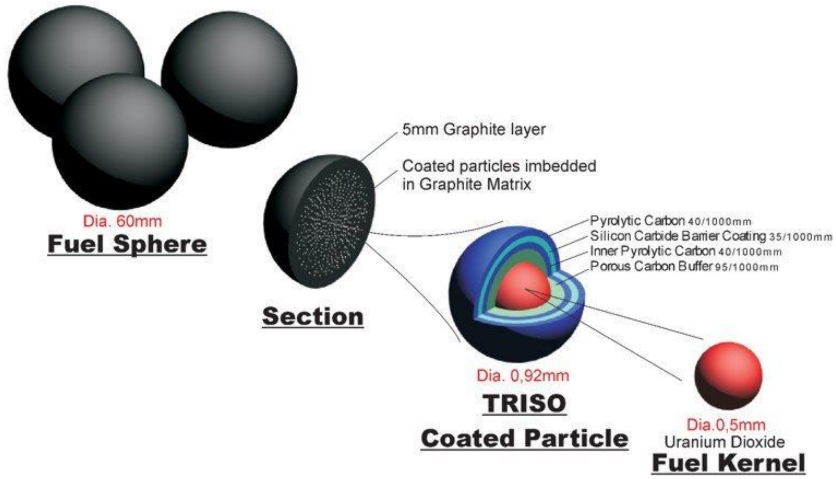


Fig. 2: TRISO particle fuel pebbles [5].

B. Liquid-Fluoride Thorium Reactor (MSR)

The other reactor design NRSEA is considering is the Liquid-Fluoride Thorium Reactor currently being developed by Flibe Energy. The LFTR is a 600 MWth Two-Fluid Molten Salt Breeder Reactor [5]. It has a liquid core made of FLiBe with uranium dissolved inside it. Fuel is bred from a thorium-salt fuel blanket contained in a separate flow loop, as seen in Fig. 2, allowing U-233 to bred from thorium in the following reaction:

$$\overset{\text{neutron}}{\mathrm{n}} + {}^{232}_{90}\mathrm{Th} \longrightarrow {}^{233}_{90}\mathrm{Th} \xrightarrow{\beta^-} {}^{233}_{91}\mathrm{Pa} \xrightarrow{\beta^-} \overset{\text{fuel}}{{}^{233}_{92}\mathrm{U}}$$

.

After being bred, the U-233 is chemically separated from the salt mixture and inserted into the primary fuel loop to be used as fuel. Breeder reactors, like this, are advantageous because their minimized fuel costs. A diagram of the plant can be seen in Fig. 4. The primary coolant loop passes its heat to a secondary, intermediate salt loop which is connected to a tertiary loop containing the turbines.

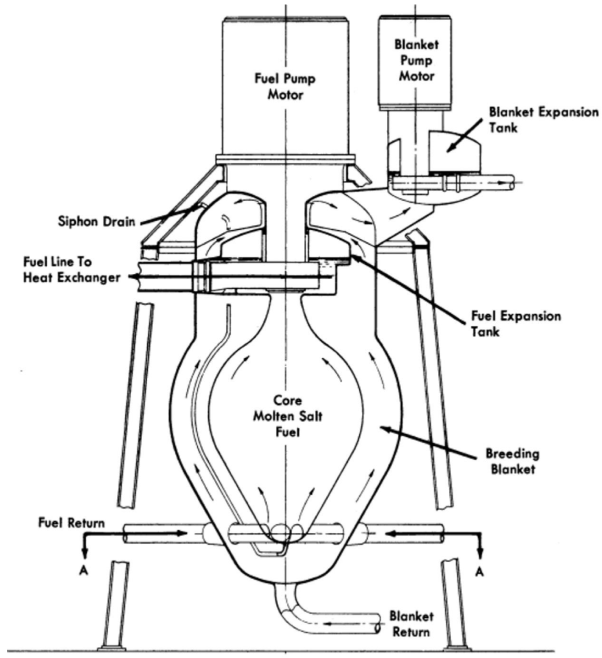


Fig. 3: A diagram of the core layout for a two-fluid MSR [7]

By using a liquid core instead of a solid core, the LFTR is able to take advantage of many interesting design features, such as the ability to refuel while at power (online refueling), the continuous removal of fission products from the fuel salt, reactivity control by changing the fuel-salt concentration, and enhanced safety features, including both active and passive systems.

The reference LFTR can produce up to 250 MWe using a supercritical gas cycle similar to that of the Mk1 PB-FHR. However, it is designed to be scalable for modular use [6].

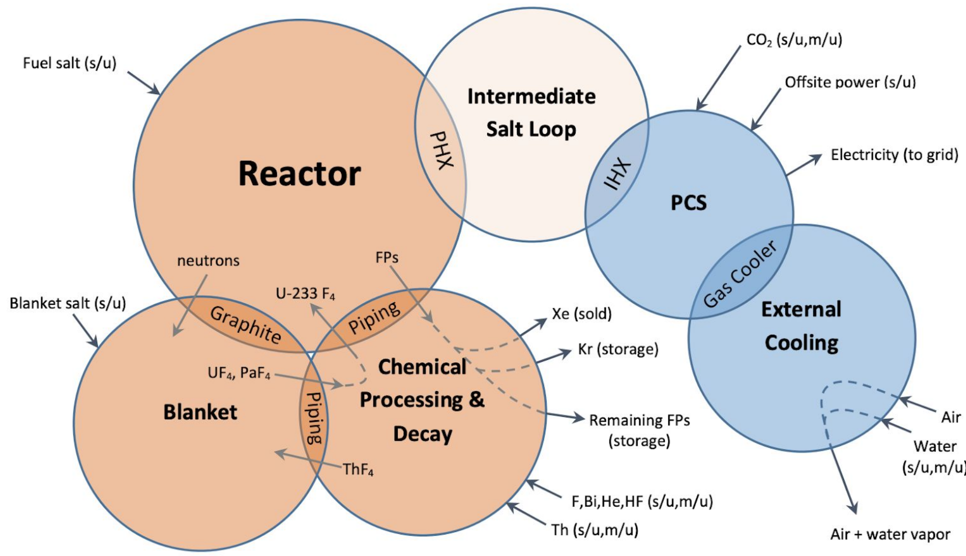


Fig. 4: The general plant layout for the MSR [6].

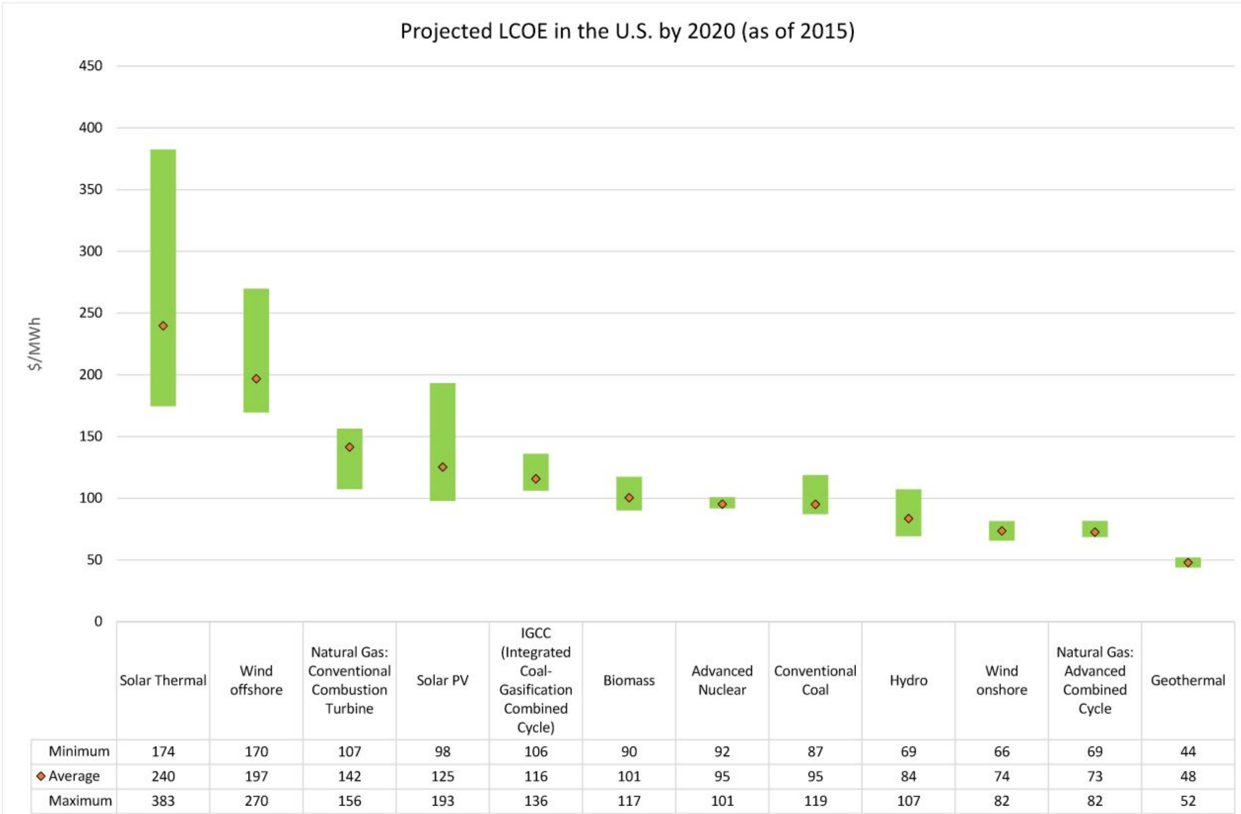
Volume I: Economics of Design

Ameren is seeking the most cost efficient nuclear technology to deliver safe and reliable power to its customers. The cost of developing, implementing, maintaining, and operating the selected reactor all factor into the energy prices that consumers must pay, and minimizing these costs will bolster support for the project while ensuring investors receive the best returns on upfront capital expenditures. To this end, the economics volume of this study consist of analyses of development cost, construction cost, and operational costs. Also included in this section is an overview of the current market in the client location.

A. Market

When considering the economics of the construction of a new power plant, it is useful to begin with a comparison of conventional power technologies for perspective on the real impact of the differences between the two reactor concepts considered. To this end, a brief summary of the current energy market in our client location and examples are listed below. From this perspective, the comparison of the FHR and MSR will follow.

Table 1: LCOEs for different energy sources. [8]



	Solar Thermal	Wind offshore	Natural Gas: Conventional Combustion Turbine	Solar PV	IGCC (Integrated Coal-Gasification Combined Cycle)	Biomass	Advanced Nuclear	Conventional Coal	Hydro	Wind onshore	Natural Gas: Advanced Combined Cycle	Geothermal
Minimum	174	170	107	98	106	90	92	87	69	66	69	44
Average	240	197	142	125	116	101	95	95	84	74	73	48
Maximum	383	270	156	193	136	117	101	119	107	82	82	52

As indicated in table 1, the current energy market is skewed towards natural gas and coal. The LCOE of fossil resources is kept artificially lower by a combination of government subsidies and current fuel availability. A significant advantage of fossil fuels is that they can be used to provide both base load power and be stepped up to load follow throughout the usage cycle. Modern plants are mostly impervious to environmental conditions, unlike wind or solar energy. While the LCOE for the fossil resources is low, the externalities neglected in this analysis are significant. Although the monetary cost of pollution to human and environmental health from one plant is difficult to quantify, it is estimated that at current emissions levels and with projected population growth, the cost of global warming in the US alone could reach over a hundred billion dollars annually by 2090 [9] .

The continued improvement of solar photovoltaic (PV) technology has steadily brought down the price of solar electricity over the last decade, and this trend is expected to continue. As newer and more efficient solar panels are developed, along with improvements in plant design and implementation, the LCOE of solar power will further decrease. While solar has proved to be an attractive alternative for load-following power, it still can not meet base-load power requirements without significant advances in battery or other energy storage technologies. Even with these advances, for areas with large population densities, solar will not be able to provide steady, year-round base-load power. For this reason, a direct comparison between solar and nuclear power is not particularly relevant. A more fruitful approach would be to consider the benefit of using solar and nuclear power together to replace fossil fuels.

The economics of constructing an advanced nuclear power plant must be weighed against the long-term externalities of fossil and renewable resources. While the upfront capital expenditure for any nuclear technology is significantly larger than any other form of electricity generation, the LCOE over the life span of the reactor is competitive with fossil resources. Moreover, these purely economic analyses neglect the long-term costs of environmental destruction and climate change that accompany conventional power generation. When factoring in the costs to human and environmental health, fossil fuels end up being far more expensive than nuclear energy [9].

B. Development

When considering the R&D costs still required to bring these concepts into commercial reality, it is helpful to base the comparison in Technology Readiness Level (TRL) assessments. TRL assessments, also referred to as TRAs, are an evaluation system developed by NASA in the 1970s to quantify the readiness of components and systems for rockets and shuttles. The scores range from laboratory proof-of-concept at the lowest level to fully implemented and field proven at the highest level. The scheme has since been adapted and adopted by a wide range of government and non-governmental agencies. The results of one of such studies, evaluating a number of generation IV reactor concepts, are reflected in table 2. From the chart below, it is clear that the FHR is farther along in the development process than any MSR concept. The overall design for the FHR is simpler than that of the MSR, and, as such, the number of components still needing development is reduced.

The categories and rankings represented below are taken from a study performed by Idaho National Lab in 2015.

Table 2: Technology readiness level assessment for FHR and MSR [10]

Category	**FHR**	**MSR**
Fuel Element (fuel, cladding, assembly)	6	5

Reactivity Control	4	4
Heat Transport	4	3
Power Conversion	7	7
Safety Systems	3	4
Control Instrumentation	4	6
Fuel Cycle	N/A	5
Waste Management	6	5
Safeguards	3	3
Licensing	2	2
Overall	3	3

Categories with scores 4 and below indicate that a specific component has been shown to work in a laboratory setting (4), or has met some basic observation or proof-of-concept (1-3). TRL 5 and 6 refer to technologies demonstrated in simulated or real environmental conditions, respectively. TRL 7 refers to systems that have been proven in full scale prototypes. TRL 8 and 9, which are not yet applicable to these concepts refer to fully operational test reactors and reactors that have performed a full service life.

These figures are taken from an assessment performed several years ago, and as such, may not reflect recent developments or progress on the design for either concept. It should also be kept in mind that an identical score for any category might not represent identical costs required for R&D. The FHR concept, with its simpler design, may require less resources to fully develop and implement components, such as reactivity control or safeguards. Categories that have received scores of 5 or 6 could also advance to 7 with the construction of a prototype test reactor, without much additional development.

There are some areas of overlap between the two concepts in terms of required research and development, specifically for systems directly exposed to the molten salt. The MSR, especially the two fluid design, presents more challenges in this regard. While the core containment vessel of the FHR must only resist corrosion from one side, for the MSR a barrier must be developed that can withstand salt exposure from both sides without negatively impacting the neutron economy. This barrier must be able to withstand corrosion and thermal stresses on both sides, while resisting radiation damage, activation of alloying elements, and mechanical stresses under accident scenarios. While many materials are under development for this purpose, no suitable material has yet been produced.

Additional challenges include control instrumentation and reactivity control, fuel and waste management, and overall plant design. Advanced reactors seek to have more automated control systems, which will require both infrastructure and coding to accomplish. The layout of plants will require test reactor construction to monitor a range of variables such as waste heat generation, flow rates and pump efficiencies, reactivity control and responsiveness, and more.

Waste management presents a major area of concern for both concepts, and is considered in depth in Volume III of this report. In terms of economics, however, the MSR concept will require on-site chemical processing, which has not yet been fully developed or prototyped. This represents a major area of research and development not applicable to the FHR.

Another large cost impediment to implementing either reactor is the licensing process, which neither concept has finished. Kairos Power is currently engaged in pre-application discussions for licensing of its FHR concept, but is still years away from beginning, much less completing the licensing process. As for the MSR concept, Terrestrial Energy is currently engaged in pre-application discussions for its Integral MSR (IMSR), but it is in the absolute earliest stages and will be facing a rigorous path of licensing a novel design [11].

C. Construction and Capital Costs

The cost of construction for a nuclear power plant is affected by several parameters, most significantly the construction time, over which interest is accrued. Nuclear power plants often exceed estimates for both cost and schedule due to unexpected difficulties during construction. A major contributor to this is the amount of training and troubleshooting required to build the first reactor of a specific design. Once that reactor is finished, however, the same workforce can be utilized to build the same reactor repeatedly at reduced cost and time per iteration. With both of the designs considered, the plants will consist of multiple “small” reactor units rather than a single large reactor unit. The cost of the plant can therefore be reduced, as the first reactor built will incur most of the overruns on budget and time, although at a fifth of the scale for each. Once the first reactor is completed, workers can take advantage of their experience to construct the rest of the reactor units in line with budget and schedule. In this way, the overall construction cost and time can be significantly reduced with either the FHR or MSR concept.

When comparing the technical differences between the concepts with respect to construction costs, it can be assumed that construction of the MSR concept will be more exhaustive. As both the coolant and fuel are molten salt, the infrastructure in place to handle molten salts must be essentially doubled. Also, the MSR will require on-site chemical processing facilities which involves complex design and construction. For these main reasons, the MSR construction costs will exceed that of the FHR. The FHR concept however includes gas co-firing, which will narrow the cost differences somewhat. The significance of these increased expenditures, according to most studies surveyed, is eventually offset by fuel price and utilization, as will be discussed later in this volume. On the whole, for both reactor concepts, the overnight construction costs can be reduced significantly over a conventional reactor, given advances in technology, regulatory requirements, and the design improvements.

The following table has been reproduced from a report produced by MIT evaluating the future of advanced reactor technologies. It presents a comparison of projected advanced reactor capital costs for an “Nth-of-a-kind” reactor built in the United States. These means that the estimate is for reactors which are not the first to be built of their type. The table includes a contingency item to account for the level of design maturity and uncertainty in reactor development. Direct costs include equipment costs (for the reactor and turbine plant), installation labor and electrical costs, and labor costs for preparation of the site. Indirect costs include construction services, design costs, engineering services such as scheduling and management, field services including drafting and administration, and owner’s costs including project fees, training, and startup costs. This value was estimated as a percentage of the direct costs since there is limited experience in advanced reactor construction. In this report, both designs were considered “pre-conceptual”, so their contingency is 30%. These estimates are based on an assumed 60 months of construction time with an 8% interest rate.

Table 3: Comparison of reactor capital costs to two significant figures. [12]

Cost ($/kWe)	**FHR**	**MSR**
Machine Size	12 x 242 MWth	2275 MWth
Direct Cost	2,300	2,500

Indirect Cost	1,300	1,700
Contingency	1,100	1,200
Total Overnight Cost	4,700	5,400
Interest During Construction	700	700
Total Capital Invested	5,400	6,100

These projected capital investments are not precise due to the assumptions made and the level of design detail available, but they do offer interesting information about the costs associated with the reactor designs. The direct cost and, thus, total capital for the MSR is higher. The MSR understandably has higher capital costs due to the addition of the chemical processing facility, but a more accurate analysis will show the true difference in these costs.

D. Operation and Maintenance

The FHR's TRISO fuel is intrinsically more expensive than the MSR's FLiBe fuel. Production of the FHR fuel requires a multi-stage assembly process, quality assurance of individual fuel particles and then pebbles, and SNM transport both to the production facility and then to the NPP itself. With the MSR, fuel can be produced from mined thorium on-site, reducing the production and transportation costs. In addition, the fuel utilization in the MSR is significantly higher than in the FHR. With a liquid fueled reactor with constant FP filtration, any unspent U233 remaining in the fuel salt will be recirculated through the core until it fissions. With the FHR's solid pebbles fuel, even if the pebbles are fed through the core multiple times, there will be an unavoidable fraction of unused U remaining in the pebbles. Thus, from a fuel cost and utilization standpoint, the MSR will perform better than the FHR.

When considering the non-fuel operation and maintenance costs, several factors stand out. For the MSR, on-site chemical processing will incur costs for both operation and maintenance. The increased number of molten salt loops in the design will also increase maintenance costs over the FHR. However, as regular intensive inspection and maintenance is standard for all nuclear reactors, these differences are most likely negligible. Excluding the MSR's chemical processing, it can be assumed that the increased maintenance costs are marginal, if not negligible.

The chemical processing will involve careful monitoring and control, and will consume a significant quantity of resources for normal operation. The enrichment of lithium, chemical separation of fission products, and conversion of thorium from ore to usable breed material will require energy and produce additional chemical and low level nuclear waste. Aside from supplying these raw materials, which factor into fuel costs, the additional chemical waste from the COLEX lithium enrichment process will need to be disposed of. The COLEX process, which separates Lithium 6 from Lithium 7, uses mercury during the separation, which must be dealt with. The fission product separation will also produce a steady stream of spent fuel waste that is not in standard form, which will require additional processing to convert to a storable format.

E. Staff

For both reactor concepts considered, the labor staff during both construction and operation is expected to be similar. Considering the skilled workforce necessary to run the plant, it can be assumed that the number of operators will be identical. The only staffing differences between the two reactor concepts is the increased workforce required to operate the chemical plant for the MSR. However, as this is a necessary fuel production step, a more fair comparison would include the staff required for production of the TRISO fuel for the FHR. However, this cost is included in the fuel price, rather than the operational and labor costs. In either reactor concept, the labor force will require the same level of training to run the reactors.

For either facility, training requirements will be in accord with 10 CFR 50.120, “Training and qualification of nuclear power plant personnel”. This section describes the necessity for a systematic approach to training and periodic evaluations and revisions. A training program will be put into place 18 months prior to fuel load. The systematic approach to training will include five elements: a systematic analysis of jobs, determination of the learning objective, training design and implementation, evaluation of the trainees, and evaluation & revision of the training itself. Training will be specific to each of the reactor technologies, but these differences should have no impact on cost since the staff size for each NPP is similar.

Volume II: Safety and Reliability

A. Safety Systems

The nuclear industry as a whole subscribes to the design philosophy of defense-in-depth to ensure the safety and health of the public from the hazards associated with nuclear materials. Defense-in-depth emphasizes the creation of multiple independent, diverse, and redundant layers of defence to help prevent and mitigate accidents that may result in the release of radioactive materials. This is based on the idea that no single safety system, no matter how robust, is exclusively relied upon.

Both the FHR and MSR concepts take great advantage of intrinsic passive safety systems, both in their physical design and in the theory of operation, which significantly increases the safety and reliability beyond that of any nuclear reactor in service, and beyond most other power generation technologies. By design, these reactors are both walk-away safe for an indefinite period of time and are resistant to any imaginable damage scenario.

The FHR's main intrinsic safety feature is the TRISO fuel, designed to exhibit incredible accident tolerance under extreme conditions, as shown by extensive simulation and isolated testing[13]. The self-contained fuel particles reduce the likelihood of runaway reactions and physically eliminate the possibility of a "meltdown" scenario.

Beyond the safety of the fuel, the safety features of the reactor do not rely on external power or human intervention but solely on intrinsic features of thermodynamics and fluid dynamics. First, there is the direct reactor auxiliary cooling system, more commonly referred to as DRACS. Replacing the electricity-dependent emergency core cooling systems of previous reactors, the DRACS system consists of 3 modular coolant loops, each capable of removing 1% of nominal power (2.36 MW). They are entirely passive; they function by natural circulation. The function of the DRACS system is to maintain safe temperatures in the reactor's structural materials, as they are significantly more vulnerable than the fuel and thus more likely to fail [1]. Secondly, the primary control rods are buoyancy controlled, meaning that as the core temperature increases, the control rods will sink further into the core, moderating the reaction. There are also active safety measures. The buoyancy controlled rods can be manually deployed by the operator, as can the secondary control blades which can immediately stop the reaction. Built into all of these systems are several layers of redundancy. For example, should all of the control rods and half of the control blades fail, the remaining half of control blades can safely bring the reaction to a halt on their own.

The MSR concept has perhaps the most impervious passive safety systems of any reactor. Intrinsically, the "meltdown" scenario is impossible, as the fuel is already molten. Furthermore, the fuel salt has a negative temperature coefficient; as the salt gets hotter, the reactivity is reduced. By carefully managing the fuel ratio in the salt, the core can be kept in a condition where the reaction would stop itself by heating up before it could damage any systems. While these systems alone are enough to render the reactor walk-away safe, the MSR still has the ultimate passive safety feature: the freeze plug. Simply put, the core sits above an empty storage tank, separated only by a plug made of salt that is kept frozen using external power. Should the core temperature increase above a critical threshold or external power be lost to the plant, the freeze plug melts, and the fuel dumps into the storage tank. This tank is specifically designed to have a subcritical geometry, meaning the reaction can not continue in the tank. No other reactor concept matches the MSR in terms of engineered passive safety.

Table 4: Emergency Shutdown Systems

Method	FHR	MSR
Active	• Secondary control blades can be inserted for SCRAM • Buoyant rods can be manually inserted if passive insertion fails • Reactor can be defueled with or without blades inserted	• Removing fuel from fuel salt loop gradually stops chain reaction • Control rod insertion immediately stops reaction
Passive	• Buoyancy controlled moderation - Temperature increase above neutral buoyancy temp causes control rods to insert passively • Decay heat removal system uses natural convection	• Negative temperature coefficient- reactivity decreases as temperature increases • Freeze plug melts above threshold temperature, draining fuel into drain tank with subcritical geometry • Cooling systems for blanket and drain tank use natural circulation

B. Anticipated Occupational Occurrences

Throughout a reactor’s lifetime, certain potentially negative events are anticipated to occur. Known as anticipated occupational occurrences (AOOs), these events include things such as loss of offsite power, recirculation pump failure, and the tripping of the turbine generator set. Because AOOs are anticipated to occur at some point, the NRC requires reactors to be designed with sufficient margins to assure acceptable fuel design limits not be exceeded.

I. Turbine Trip

Both plant designs use an air-Brayton combined cycle in which superheated gas spins a turbine to generate electricity. During normal operation, this turbine acts as a heat sink, removing energy from the system and cooling the secondary and primary loops. However, like all turbines and pumps, it is designed to only operate in a certain range of conditions, such as inlet/outlet temperatures, pressures, and flow rates. When operated outside these ranges, the turbine experiences greater amounts of stress and can potentially fail. Because of this, power plants use what are known as turbine trips to automatically shut the turbine down and prevent it from damaging itself. When this occurs, the plant loses a significant amount of its ability to dissipate heat. Even when shutdown, reactors produce a significant amount of heat through the decay of radioactive fission products. Thus, plants must be designed to cope with the loss of their turbine. Both the FHR and MSR have passive decay heat removal systems that meet this requirement.

The turbine can also be tripped by an overly rapid change in speed. The generator to which the turbine is connected provides significant resistance, controlling the speed at which the turbine is spinning. If this resistance suddenly changes, the turbine will rapidly begin to accelerate, causing it to trip and shutdown.

One of the most dangerous failure points in a power plant is a turbine overspeed failure. Operating turbines have an enormous amount of energy (thermal, mechanical, chemical, etc.) coursing through them. If the rotational speed of the turbine is allowed to exceed its safe operating limits, it can pull itself apart and explode.

By law, the trip mechanisms on large turbines must be tested periodically to ensure they work.

II. Loss of Offsite Power

Under all circumstances, it is vital for reactor operators to maintain control over the instrumentation and control systems of the power plant. The IAEA defines these systems to include the following [14]:

i. Reactor protection systems
ii. Reactivity control systems and their monitoring
iii. Reactor cooling, emergency power, and containment isolation and monitoring
iv. Control and monitoring
v. Accident monitoring instrumentation

As dictated by the defense-in-depth design philosophy, there are multiple independent and diverse sources of electricity for the plant. During normal operations, the plant generator itself is able to provide all the power necessary to run these vital systems. In the event of a plant shutdown, it is capable of drawing power from the grid. If that is impossible, emergency diesel generators are located onsite, and if that fails, the final layer of defense is an array of batteries which are capable of powering vital instrumentation and control systems for a short period of time.

The FHR and MSR rely heavily on passive safety systems that do not rely on electricity to function. Both are designed to SCRAM upon loss of offsite power and have passive decay heat removal systems that utilize natural circulation to remove excess heat. Additionally, both the FHR and MSR use abnormal fuel and coolants that should perform much better under accident conditions than the traditional zirconium-cladded fuel rods and water cooling.

C. Design Basis Events

Design basis events (DBEs) are events that, while unlikely, are deemed significant enough for a nuclear power plant that it’s systems, structures, and components must be designed to manage and withstand the event [15].DBEs can involve outside events such as natural disasters or acts of sabotage, or a combination of events that could individually be classified as AOOs. Events such as large earthquakes, hurricanes, floods, or attack from hostile actors could constitute a DBE.

1. Earthquake
   NPPs must be adequately designed to withstand seismic events larger than the historical largest event in the area of construction. Large earthquakes can cause pipes and support structures to be damaged and may result in failure of large subsystems. Both the FHR and MSR concepts are designed with seismic isolation systems to mitigate the effects of shaking. In the event of the loss of any main systems, the plants must be able to withstand the damage without releasing radiation. Earthquakes are likely to cause loss of external power, loss of coolant, and/or loss of heat sink. The response to each of these events is detailed in table 5.

2. Flood
   Like earthquakes, plants must be designed to withstand flooding above the historical maximum level recorded in the area. Electrical systems must be

sufficiently insulated such that total submersion of the core and heat removal systems leave the plant unaffected. In the event of a flood, plants must be able to maintain normal operation or safely shut down.

3. Explosion
   The containment vessels of the reactor core must be sufficiently strong to withstand explosions from within or outside of the plant. Typically, reactor pressure vessels (RPVs) for LWRs are more than sufficient for this purpose, but as there are no pressurized elements in the design for either concept, the outer containment vessels must be built to withstand such attacks.

Disasters such as these can cause damage and lead to design basis accidents. Many of these are specific to a particular reactor design, but the end result is often the reactor left without the ability to cool itself normally and the potential release of contamination.

I. Loss of Coolant Accident

Loss of coolant accidents (LOCAs) occur when a pipe rupture prevents coolant from reaching the reactor core and can potentially result in core damage if not managed effectively. LOCAs come in many different sizes, from small leaks in which coolant is still able to reach the core to a full double-ended guillotine break (DEGB) in the primary coolant loop. A DEGB has, in the past, often been used to describe the maximum credible accident, and is typically used as a baseline in the safety analysis of a reactor and the sizing of its emergency core cooling system (ECCS) [16].

Both the FHR and MSR are designed to handle this sort of accident. Upon the break occurring, a SCRAM would be triggered, killing the fission reaction and depowering the reactor. This stops most of the heat production, although the heat produced by the decay of fission products is still significant. Throughout this process, tremendous amounts of thermal strain are put on components as they rapidly increase and decrease in temperature. The FHR handles this with its highly resilient fuel which is able to withstand large temperature transients without failing. This allows more time for the DRACS systems to take over. In the MSR, the core would be drained into the drain tanks which have passive cooling systems in place to remove excess heat produced by fission product decay.

II. Loss of Heat Sink Accident

Loss of heat sink (LOHS) accidents occur when a break happens in the heat exchanger and can lead to secondary loop contamination and core melt. In the FHR, the first response is to SCRAM the reactor. However, if both manual and passive insertion fails, the FHR coolant is able to act as a temporary heat sink and will eventually equilibrate to a temperature close to the original fuel temperature, well below the boiling temperature of FLiBe [1]. In the MSR, because the coolant is also the fuel, the potential for contamination is much greater. Because of this, an intermediate salt loop is used between the primary loop and the gas loop. This prevents contamination of core components such as the turbines. Additionally, as the core heats up, the freeze plugs would melt, draining the core into a subcritical geometry which is passively cooled.

III. Loss of Flow Accident

A loss of flow accident (LOFA) occurs when flow in the primary coolant loop is lost. There are many possible causes for this, such as pump failure, loss of power, pipe blockage, and valve closure. The danger of a LOFA is that it can damage fuel and structural integrity and eventually lead to core failure [17].

One of the advantages and disadvantages to using molten salts as a coolant is that they only remain a liquid when at high temperatures. While this helps trap fission products in the event of a leak, salt solidification in the primary loop poses a significant risk, specifically at the exit of the heat exchanger and before it enters the reactor, when the salt is at its coldest.

In LWRs, the risks posed by LOFAs is mitigated by the ECCS system. In the FHR and MSR, this risk is addressed by having multiple, redundant reactivity control systems in addition to passive cooling systems.

IV. Reactivity Insertion Accident

A reactivity insertion accident (RIA) involves an unintended increase in reactivity, resulting in a rapid increase in fission rate, power, and temperature, and can result in core damage. An example of an RIA is the accidental ejection of a control rod from the reactor core. RIAs are typically mitigated by having a negative temperature coefficient of reactivity - a combination of several parameters that determines the behavior of reactivity as a function of temperature. Both the FHR and MSR have a strong, negative coefficient of reactivity. As power increases and temperatures rise, reactivity decreases and will eventually make the core subcritical.

Table 5: Overview of DBE performance

Accident Type	FHR	MSR
Loss of Coolant Accident (LOCA)	SCRAM, passive decay heat removal system	SCRAM, core drain, or cut fuel injection and burn out
Loss of Heat Sink Accident (LOHS)	SCRAM or remove fuel	SCRAM or reduce fuel:salt ratio
Loss of Flow Accident (LOFC)	SCRAM or remove fuel	SCRAM or core drain
Reactivity Insertion Accident (RIA)	SCRAM, negative reactivity feedback	SCRAM, core drain, large negative reactivity feedback

D. Beyond Design Basis Events

Beyond design basis events (BDBEs) are accident scenarios in which the sequence of events, while possible, is deemed too unlikely to be considered a DBE and are therefore beyond the scope of the design. A BDBE would include freak accidents like earthquakes or other natural disasters far larger than any event recorded in the area. The combined damage caused by a BDBE could render the plant inoperable, but not necessarily irreparable. Designing a plant to withstand such events would be prohibitively expensive, and as such the main goal is to mitigate impact in these extremely unlikely scenarios. As with AOO and DBE performance, both the FHR and MSR have highly reliable safety systems that can prevent the release of materials in any accident scenario.

E. Environmental and Health Risks

With respect to human and environmental health, the safety of the proposed reactor designs is unparalleled during standard operation. The FHR's TRISO fuel is designed to completely contain the waste products, mitigating fission product release concerns under all scenarios. The MSR's liquid fuel will constantly be contained within the plant, and release concerns are mitigated by constantly filtering out fission products. There is only ever a small fraction of fission product at any time in the molten salt. This gives the MSR a very small source term. Any activation of materials will be monitored and controlled as would be in any nuclear power plant, and are furthermore reduced by using advanced alloys in components that are less prone to transmutation reactions.

F. Reliability

There are several scenarios in which a molten salt reactor, whether cooled or fueled, may need to be shut down and drained of salt for maintenance. This is because salt solidification within some components may damage or render them inoperable. Because of this, it is reasonable to assume that shut downs for maintenance may be longer than experienced in traditional reactors. However, due to the ability of both reactors to have constant online refueling, overall up-time for these reactors should be the same as or better than conventional LWRs, which require lengthy shutdowns for refueling.

Volume III: Waste Management and Proliferation

The impact of regulations regarding waste management and non-proliferation can be very different depending on the type of fuel used in the reactor. FHRs use graphite coated TRISO particles filled with solid fissile material. MSRs, on the other hand, use FLiBe as both the coolant and the solvent for the fissile material, meaning the fission products are dissolved in the liquid coolant. In a general sense, solid fuel can be treated and protected with a very similar strategy to the one already used for conventional LWRs; liquid fuel introduces additional economic and regulatory uncertainties.

A. Waste Management

I. High Level Waste

Under current Department of Energy rules and following the decision by the U.S. Court of Appeals to suspend the payment of the nuclear waste collection fee, spent nuclear fuel should pose no extra liability to Ameren [18]. The operators would still be responsible for on-site storage until the DoE is ready to accept and dispose of the SNF. Due to legislative uncertainties, this could take decades, and, therefore, it is in Ameren's interest to have a comprehensive plan for safe storage of SNF up to decommissioning.

Compared to LWR spent uranium oxide, it is believed that fuel pebbles from FHRs would have superior performance if they were to be disposed of in a geological repository [19]. Fission products are self-contained inside the pebbles, making it suitable to undergo all conventional waste treatment processes. Therefore, a safe and well-understood strategy would be wet storage for a year followed by dry cask storage [20].

For liquid fuel, there are additional advantages and complications. Due to on-line reprocessing, most actinides can be reused in the reactor, decreasing the volume of the waste stream by 95% compared with LWRs [21]. The separated waste contains only unusable fission products and is therefore also less active. For all purposes, this report will continue to classify it as SNF. The waste can be easily frozen, vitrified, or treated otherwise in preparation for interim storage. However, all these processes have never been demonstrated in a commercial scale in the United States. In addition, there is no clear path for handling the coolant at the end of the plant's lifetime. One possibility is to transfer the liquid to an operating plant, which depends on the availability of such recipient as well as a well-understood, safe, and non-destructive transportation technology [21]. Another possibility is to strip the FLiBe of its radioactive species and dispose of it with the other fission products. If Ameren ultimately selects the MSR design, this is the recommended course of action.

II. Low Level Waste

Both designs would generate very similar low level wastes during operation which could be sent to Clive Disposal Facility in Utah as Ameren has done for the past several years for the Callaway plant. This includes activated experimental equipment and contaminated clothes. These are usually transported by land much like regular cargo due to their low activity. Missouri charges a fee of $120 dollars per container of low level nuclear waste exiting the state [22]. Additional fees may incur from other states depending on the route taken to Utah, although these are very small compared to transportation costs. At the facility, the low level waste is stored in shielded containers, underground.

Upon decommissioning, one would expect there to be low level activated components generated at an MSR plant due to its attached chemical processing plant (pipes, filters, containers). These may be greater than class A waste, the limit accepted at Clive, and would therefore have to be sent to the same facility Ameren has in mind for its other activated structural components. A good candidate is Waste Control and Storage Services in Texas (WCS). In spite of these aspects, either reactor would be smaller than an LWR, so the disposal of low level waste should pose no extra difficulty compared to Ameren's decommissioning plans for Callaway.

III. GCC and Other Wastes

Greater than Class C (GCC) and orphan wastes can be safely mixed with spent pebbles (FHRs) or fission products from the normal operation waste stream (MSRs), down blended, and disposed. This procedure successfully avoids regulatory scrutiny. It is in Ameren's interest to bypass complicated and unclear regulations for such wastes by simply treating them as high level waste. This should be tolerable given the reduced complexity (FHRs) or volume (MSRs) of the High Level waste streams.

B. Proliferation Concerns

Compared to LWRs, both advanced reactor designs are thought to have superior performance with respect to safeguarding [22][23]. In FHRs, the self-contained character of the spent fuel makes it very difficult for extraction of actinides from the pebbles. During normal operation, none of the stages of chemical processing in an MSR provide attractive opportunities for diversion.

There are, however, minor concerns associated with each design. TRISO particles can be directly diverted or intentionally infused with fertile material that may later be recovered [24]. Both practices are deterred by current IAEA requirements (NP-T-2.9 Section 5.3.1) which must be observed by Ameren [25], including:

- Surveillance systems directed at the access hatches to fuel storage.
- Access for installation and maintenance of flow monitors.
- In the fresh fuel area, adequate space for managing seals as well as an extra 2 square meters for installment of IAEA NDA accountancy instruments.

Alternatively, the main proliferation concern surrounding MSRs comes from the separation capabilities of the chemical processing plant. Protactinium can be effortlessly separated from the coolant through chemical processes and then allowed to decay into fissile U-233 [26]. This would require, however, a generalized effort from the plant management and employees. For a private site in the United States, this is not a major concern. Current IAEA safeguards make use of material balance to account for nuclear material, which is meaningless in the context of a breeder reactor like the MSR. Existing documentation on breeders [25] only acknowledges the need for additional regulatory guidelines, which is a major source of regulatory uncertainty for this design. If the NRC determines that the MSR design is as proliferation resistant as other advanced reactors and that current regulations are sufficient, much bureaucracy can be skipped. On the other hand, the IAEA recommends thorough and invasive monitoring of the chemical processing plant [25], which, if adopted by the NRC, could result in significant additional costs. Invasive monitoring equipment such as internal flow monitors could be substituted by containment and surveillance (C&S) techniques such as cameras, designation of material areas and protected areas and increased security.

In observance of 10 CFR Part 73, either reactor would need a clear physical protection plan with designation of defense areas based on defense in depth [27]. These include:

- Protected Area: The immediate perimeter of the facility as well as the adjacent bank of the surrounding river. This is the visible site boundary and includes fences, security personnel, and controlled access.
- Exclusion Area: This is part of the same requirement, albeit not for proliferation prevention. An exclusion area is usually the protection area with additional 400 to 500 meters ranging outwards, within which the utility is required to have full control in case of an accident. Preparations should be in place in order for any road to be closed and person to be evacuated if necessary.
- Vital area: The control room, the reactor core building, and the spent fuel storage units. These require increased C&S capabilities at all times.
- Material access area: All fuel storage units and, in the case of the MSR, all parts of the chemical plant from which nuclear material is recoverable. No one is allowed inside a material area by themselves (two-person rule).

Regulatory Considerations

Ameren is a rate-regulated gas and electric utility. In Missouri, Ameren operates an electric generation, transmission, and distribution business as well as a natural gas distribution business. As a regulated utility, Ameren is subject to specific state and federal energy regulations. Their current and future nuclear facilities are subject to regulation by the NRC. An overview of the applicable details of these regulatory entities is described below, along with regulation-relevant explanations of the siting and public engagement for the plant.

A. Regulatory Framework

Ameren must comply with regulations set by the Federal Energy Regulatory Commission (FERC). Ameren’s cost-based rates for wholesale energy transmission and distribution for interstate commerce are regulated by the FERC. Certain acquisitions, mergers, and consolidations, and issuance of short-term debt securities must be approved by the FERC. To ensure the reliability of the electric power system, the FERC provides oversight for business and reliability standards (including cybersecurity) which are then enforced by the regional reliability corporation, SERC Reliability Corporation, the central and southeastern regional group of the North American Electric Reliability Corporation (NERC).

The Missouri Public Service Commission (MoPSC) is responsible for the regulation of Ameren Missouri's electric operating revenues. Ameren Missouri's electric rates may be adjusted if certain criteria are met. MoPSC is also responsible for the organization of trust funds for decommissioning. They require cost study updates every three years for the decommissioning of Callaway Energy Center, and the same will be required of the new facility.

The Code of Federal Regulations (10 CFR 50) provides the process for domestic licensing of production facilities and includes the standards for licenses and construction permits. Ameren will be applying for a Class 103 license since its reactor will be for commercial/industrial use. NRC Regulatory Guide 1.232 outlines the Advanced Reactor Design Criteria in Appendix A which have been thoroughly considered in the evaluation of the two reactor designs. These criteria are the overall requirements, multiple barriers, reactivity control, fluid systems, reactor containment, and fuel and radioactivity control. Significant differences between the FHR and MSR designs pertaining to these topics have been described in Volumes I-III of this report. Existing regulatory guides are primarily focused on light water reactors, so the licensing of either of the advanced reactors should conform to the regulatory guide for an acceptable design approach.

B. Siting

NRSEA is not responsible for the full evaluation of the site for the proposed nuclear facility but is in communication with Ameren to make sure that the recommended design is suitable for Ameren's selected location. The plant will be located in St. Clair, Missouri, in a lower-population area, south of Interstate 44. St. Clair is a fitting site for the power plant because of its lower likelihood of earthquakes and isolation from high population and high traffic areas. The New Madrid Fault is located in the southeastern part of Missouri, along the eastern part of the bootheel. St. Clair's foundation contains considerable bedrock, making it less likely to experience the effects of a severe earthquake [28]. St. Clair is approximately 40 miles from St. Louis County, allowing it to have sufficient distance from major traffic and Lambert International Airport while still serving Ameren's territory. According to the Advanced Reactor Siting Policy Considerations from Oak Ridge National Laboratory, exclusion areas and low population zones can be reduced due to the inherent safety of advanced reactors [29]. Considering the comparison of the two reactor designs, the area's probability for flooding, earthquakes, and severe storms and tornadoes affects both designs, and both are equally suited to handle these disasters when properly design, according to the safety systems described in Volume II.

C. Public Engagement

NRSEA will serve as a technical advisor for Ameren's public engagement appearances. NRSEA's analyses of both reactor technologies allow them to speak knowledgeably about the technical specifications and safety systems of the reactor designs. Although NRSEA is not responsible for the completion of the licensing process, this trade-off study includes a licensing-minded approach. The comparison of the two designs keeps in mind the regulations described above with an end goal of licensing a commercial reactor. NRSEA's position gives credibility to Ameren and helps check Ameren's corporate interests with sound technical consultation.

D. Regulatory Risk Management

The free-rider effect could be a point of concern for these designs. Kairos Power, a startup commercial reactor vendor is currently conducting pre-application discussion for their FHR technology. Pending this advancement, the barrier to the FHR approval will be passed. Terrestrial Energy, another startup, has been engaged in pre-licensing activities for their IMSR (Integral Molten Salt Reactor) design since February. In fact, the IMSR has been selected for joint technical review by the NRC and the Canadian Nuclear Safety Commission (CNSC) as announced in a press release on December 4th, 2019 [11]. The IMSR is not exactly the same as the MSR evaluated in this report, but it is a liquid-fueled reactor which is an important novel feature for licensing. Depending on the timeline of Ameren's project, the risk of being a first-mover may have passed. However, the timeline of licensing the first MSR seems to be behind that of the FHR.

Recommendation & Conclusion

NRSEA recommends that Ameren selects an FHR for its advanced nuclear power plant in St. Clair, Missouri. This study has found that an FHR is preferred due to its simpler design with fewer salt loops, lower-risk waste management plans, and higher level of technological readiness. With solid fuel and fewer salt loops, the mobility of fission products and radioactive species are more limited in the FHR. Additionally, SNF from the FHR can be treated in a manner similar to that of conventional LWRs because the fuel is solid and fission products are largely contained within the fuel pebbles. Although there may be a smaller volume of waste from an MSR thanks to on-line reprocessing of the fuel salt, there is no precedent end-of-life plan. This presents considerable technological and regulatory challenges. The TRISO fuel pebbles for the FHR are more expensive than the liquid MSR fuel, but this cost has been determined to be non-prohibitive given the other advantages and simplicity of the design (for example, the lack of chemical processing facility).

The MSR is still a viable option. Its safety systems reviewed in Volume II are thoroughly diverse and redundant. Passive emergency shutdown features such as the negative temperature reactivity coefficient in addition to active systems like control rods render the design remarkably safe. The freeze plug and core drain response allow the MSR to safely shutdown following a variety of BDBEs. However, there are still considerable unknowns to handle the challenges of liquid fuel, and these challenges would also likely extend the licensing process.

Responses to RAIs

1. The NRC has a long-standing practice of conducting its licensing activities openly and providing the public with opportunities to participate in the agency's decision-making process. As laid out in 10 CFR 2.309, the NRC has a legal requirement to conduct hearings and review all petitions submitted by the public. In observation meetings, the NRC conducts discussions between applicants, the NRC representatives, vendors, and other public interest and non-government groups. As a vendor, please clarify and provide details on NRSEA's plan to be involved in public meetings.

NRSEA is not a vendor, so they are not directly responsible for holding public meetings. They will, however, serve as technical advisors at these public meetings and throughout the licensing process. Further explanation of NRSEA's advisory role in public engagement can be found in the "Regulatory Considerations" section, part C.

2. Please provide a more detailed description of how low-level nuclear waste will be transported to its final destination and how it will be stored, as required by NUREG-0902. No specific method of transport or description of the particular waste storage facility was mentioned. Additionally, how does the chemical processing plant, and byproducts, factor into the definition of low-level waste?

The questions raised by this RAI are very important, so the answers have been added to the main body of the PDSAR as the section "Low Level Waste" in Volume III. Please refer to it for clarifications.

3. Tritium is an activation product continuously formed in FHRs. It is known that tritium poses serious health concerns to human beings if released into the environment. Thus, it is critical to control and manage the tritium generated within the FHR. Describe your tritium control strategy for the FHR. What measures are taken to guarantee surrounding air and water quality are not impacted?

Since FLiBe will be used as the coolant in the FHR, isotopically separated 7Li will be used to minimize neutron absorption and tritium production. Due to beryllium in the FLiBe, the remaining 6Li (which has a large neutron cross section which maximizes tritium generation) will partly burn out [30]. However, neutrons interacting with beryllium can generate 6Li, so the tritium production is still an important concern. Tritium will be primarily contained inside the TRISO particles. An additional layer of aluminum coating on the interior of the graphite pebbles prevents most of the diffusing tritium from reaching the coolant. Utilizing specialized graphite such as ISO-88 in the pebble coatings and in the structural materials can further increase the tritium absorption within the core. Understanding of these absorption pathways and interactions with salt are currently being researched, including computer simulations of hydrogen diffusion through the various containing layers.

Tritium control is also closely linked to corrosion control. LiF can be converted to 3HF, a corrosive, under neutron irradiation. Manipulation of the cover gas can allow for isotopic exchange of 1H for 3H, affecting the rate of tritium transport. This may also shift the salt’s redox potential.

An estimation for the Mk-1 FHR being studied in the comparison suggests that ~0.03% of tritium which is produced by the FHR could escape while still staying below the rates of tritium emission in existing PWRs [1].Tritium release will be mitigated by all of the safeguards provided above, and the surrounding air and water quality will be checked periodically to ensure safe and acceptable amounts of release. From the design comparison in this trade-off study, tritium control seems to be less of a challenge in the solid-fueled FHR when compared to the MSR due to the nature of the fuel. Solid fuel contained within the reactor core minimizes the movement of diffusing species. Additionally, the fuel salt of MSRs can create “hot spots”, or areas of fast heat generation, in places where the salt penetrates the carbon.

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