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Fission Battery Initiative

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Markets and Economic Requirements for Fission Batteries

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SUMMARY

Fission batteries (FBs) are nuclear reactors defined by five attributes that enable large-scale deployment, as mentioned and defined in the FB R&D plan [1]: (1) economic, (2) standardized, (3) modular, (4) unattended, and (5) reliable. FBs are not defined by reactor technology or power level. Technical and market considerations suggest most FBs will produce 20 to 30 MW_t. Two workshops were held in January 2021 to better define markets and economic challenges for FBs.

Three major markets were identified. The largest market is the industrial and commercial heat market. There are about 4,000 industrial users (excluding utilities) that require more than 1 megawatt (MW) of heat. The number of customers versus size of heat demand was determined. In a low-carbon world, there is potential for many additional customers—including expanded biofuels production and district heating. The second market is non-grid electricity, which includes cogeneration plants that produce heat and electricity for a single customer. The third market is the maritime market with ~100,000 ships worldwide.

In the United States, natural gas is the low-cost energy option today and will remain so unless constraints or taxes impact its use. If restrictions on greenhouse gas emissions exist, the FB competition includes natural gas with carbon capture, biofuels, hydrogen, and grid electricity. Natural gas with carbon capture is not economically viable on a small scale. Biofuels may be expensive but may be the economically preferred option for locations with small energy demands of a few megawatts. Hydrogen is a potential competitor with many of the characteristics of natural gas. Grid electricity is not a competitive source of heat.

For FBs to be economically competitive, the price of delivered heat must be $ 20–50/MWh ($6–15/million BTU). The economically competitive range for non-grid electricity is estimated at $70–100/MWh. These electricity prices are competitive with the retail prices of electricity in many parts of the United States. FBs are not expected to be competitive selling wholesale electricity to the grid. To achieve the aforementioned cost targets for heat and electricity markets, FB designers must (1) maximize the power output within the constraints of a FB (e.g., truck transportability and passive decay-heat removal), (2) drastically reduce or eliminate onsite staff needs, (3) adopt core designs with low fuel costs (e.g., enrichment and fabrication), and (4) develop a system design that is efficiently manufactured in factories.

The business case depends upon more than just being a replacement for natural gas. The largest incentives for adopting FBs are the potential for creating new markets and new sources of revenue. An example is the paper and pulp industry that burns biomass wastes to provide heat and electricity to make paper. An external heat source could meet the demand for heat and electricity by the paper process and enable converting waste biomass into liquid biofuels rather than burning to provide heat. Other markets, such as data centers, are driven by special energy requirements such as extreme reliability. Most customers are not in the energy business but need heat and electricity to produce a product; for example, manufactured goods, education, retail sales (shopping malls), marine transport, or some other product. As a consequence, there will be large incentives to lease rather than own FBs. Leasing avoids the regulatory challenges that

remain with the owner of the FB. Leasing also creates large incentives for FB standardization of sizes and transportability to maintain the value of the FB at the end of the lease—similar to the leasing of jet engines and aircraft.

The economic constraints combined with technical constraints suggest competitive FBs will likely have outputs exceeding 10 MW_t. There appear to be little incentives for very long-lived reactor cores because such machines require significantly larger inventories of fuel. Replacement requirements and the option to provide technology updates may favor shorter lifetimes (~5 years). Based on this assessment, there is potential for FBs to be economically viable and play a major role in global decarbonization in three markets: heat, non-grid electricity, and maritime applications. Three future research thrusts were defined.

Definition of commercial requirements. FB users are not in the business of selling energy. Their goal is to have an economic reliable source of heat and/or electricity. The lessor must address licensing with the Nuclear Regulatory Commission and other siting issues. The different ownership model will impose functional requirements on the FB, but these are poorly understood. This includes the interface between the nuclear system and the customer system. An understanding of these requirements that considers business, institutional, and technical constraints is required.

Requirements for maritime applications. There is a very large maritime FB market for container ships and other ships. This market has different requirements than land-based applications: (1) the FB will be installed and removed in a shipyard without the size and weight constraints associated with other FB applications, (2) there are weight distribution requirements associated with ship stability—minimizing the risk of ship rollover in storms, (3) ships at sea roll, thus imposing added requirements relative to land-based plants, (4) accident scenarios include sinking of the ship which may create separate design constraints, and (5) ships must meet international maritime requirements. In this context, the FB model is fundamentally different than the historical model of a nuclear-powered commercial ship where the nuclear power plant was tightly integrated into the ship design. In this case, the FB is a package replacement to be completed when the ship is in dry dock for maintenance. Requirements for the development of FBs for maritime applications are needed.

Practical maximum power output of an FB. Economics favors larger FB systems. However, large FB systems would need bank-vault type security (reactor in vault) to minimize security costs. Unlike money, valuable art, gold, and fissile materials in storage, FBs generate decay heat when shut down, which can destroy the reactor by overheating it. The FB bank vault must be able to remove decay heat while maintaining the bank vault security features. This constraint, not size or weight, may limit the maximum FB power output that defines potential markets.

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ACRONYMS

CCS	Carbon Capture and Storage
FB	Fission Battery
MW	Megawatt
MWh	Megawatt-hour
MW_t	Megawatt thermal
R&D	Research and Development

Fission Battery Initiative - Markets and Economic Requirements for Fission Batteries Workshop Report

1. INTRODUCTION

Reaching the goal of a low-carbon energy system requires replacing natural gas and oil for industrial and commercial users. Small users with energy demands under a megawatt (MW) can potentially use electricity or biofuels. However, large users have options ranging from modular nuclear reactors to fossil fuels with carbon capture and sequestration—options that are uneconomic at smaller scales. Some energy users, such as ships, cannot be continuously connected to the electricity grid. The fission battery (FB) initiative [1] envisions developing technologies that enable nuclear reactor systems to function as batteries to address this need. FBs will be integrated into a variety of applications, as "plug and play" nuclear systems, providing affordable and reliable energy in the form of electricity and/or heat, functioning without operations and maintenance staff.

The FB initiative is focused on conducting fundamental research and development (R&D) to address the challenges related to the five FB attributes: economic, standardized, modular, unattended, and reliable. R&D progress through the technology readiness levels provides the evidence needed to inform and/or develop new regulatory guidelines, policies, and technical measures. These advancements aim to achieve domestic and international regulatory acceptance to support successful deployment and operation of FBs.

Idaho National Laboratory and the National University Consortium identified five scoping areas and organized a workshop series to drive discussion on technological innovation and development required to achieve FB attributes. These scoping areas are:

1. Market and economic requirements for FBs and other nuclear systems
2. Technology innovation for FBs
3. Transportation and siting for FBs
4. International safeguards and security of FBs
5. Safety and licensing of FBs.

This report focuses on the findings collected under the workshop topic of market and economic requirements for FBs. Two workshops were held in January 2021 and a detailed workshop proceedings document was published [2]. The current report summarizes results of the workshops.

1.1 Markets and Economic Requirement Workshop Series Purpose

The purpose of the two workshop sessions on market and economic requirements was to identify cost targets for FBs within addressable markets based on competitive analysis. To fulfill this purpose, the workshop organizers invited speakers with expertise in grid and off-grid electricity systems, heat, and cogeneration for industrial facilities (including paper mills and biorefineries), maritime shipping, hydrogen production, and related topics. The speakers showed current and projected costs of energy in these various contexts using information for fossil and renewable sources. To achieve market viability, FBs must have comparable costs to these competitors.

The workshop sessions also identified opportunities for FBs to create new markets, increase revenue, and provide valuable services in specific deployment scenarios. For example, FBs could enable greater sales of biomass products at pulp mills by reducing reliance on biomass for energy and could enhance energy resilience for data centers or other critical use cases. The workshop highlighted the importance of standardization (particularly for mass manufacturing and leasing), fast installation, unattended operation through autonomous control, and high reliability. The workshop confirmed the need for focused R&D on these intended FB attributes so that eventual designs will be commercially viable.

1.2 Summary of Workshop

This subsection draws on the executive summary from the proceedings [2] of the two workshops on FB economics and markets. The workshops were a first effort to understand these aspects of FBs; thus, the conclusions must be considered preliminary results. The proceedings appendixes include the presentations to enable the reader to review the source material to draw their own conclusions independent of the report authors.

1.2.1 Fission Battery Definition

FBs are not defined by technology (water, sodium salt, and helium) or size (micro, small, modular, large, etc.) but rather by a set of attributes.

- *Economic* – Cost competitive with other distributed energy sources (electricity and heat) used for a particular application in a particular domain. This will enable flexible deployment across many applications, integration with other energy sources, and use as a distributed energy resources.
- *Standardized* – Developed in standardized sizes, power outputs, and manufacturing processes that enable universal use and factory production, thereby enabling low-cost and reliable systems with faster qualification and lower uncertainty for deployment.
- *Modular* – Readily and easily installed for application-specific use and removal after use. After use, FBs can be recycled by recharging with fresh fuel or responsibly dispositioned.
- *Unattended* – Operated securely and safely in an unattended manner to provide demand-driven power.
- *Reliable* – Equipped with systems and technologies that have a high level of reliability to support the mission life and enable deployment for all required applications. They must be robust, resilient, fault tolerant, and durable to achieve fail-safe operation.

Market, technical, and other constraints as discussed below imply power outputs of a few tens of MWs.

1.2.2 Markets

Three major markets were identified. The largest market is the industrial and commercial heat market. The industrial heat demand by itself is more than twice the total electricity output of the United States. There are about 4,000 industrial users (excluding power plants) that require more than 1 MW of heat. The number of customers versus size of heat demand is shown in Figure 1. Facility rank refers to their ordering from highest to lowest heat demand.

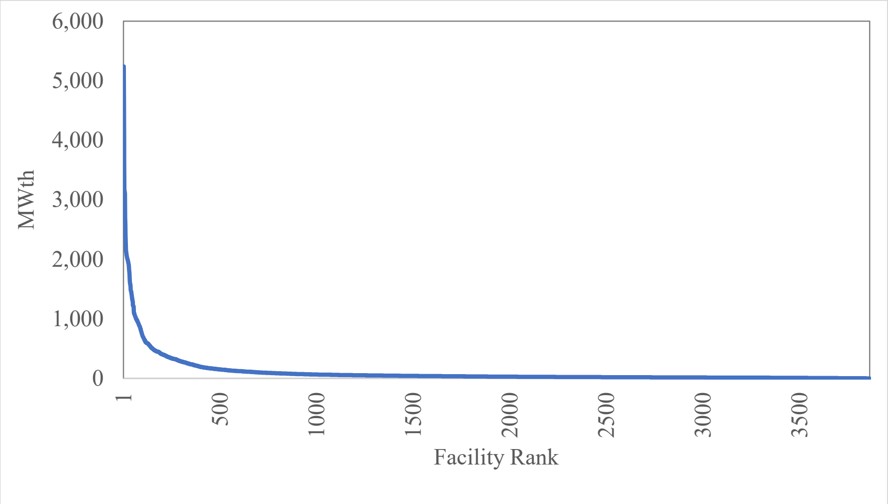


Figure 1. Industrial Market by Number of Industrial Customers Vs. Heat Demand.

Figure 2 shows the number of customers versus heat demand up to 250 MW_t (excluding the largest 335 facilities in the full figure shown above). At 250 MW_t, the industrial facility would require 10 FBs if each had heat output of 25 MW_t, for example.

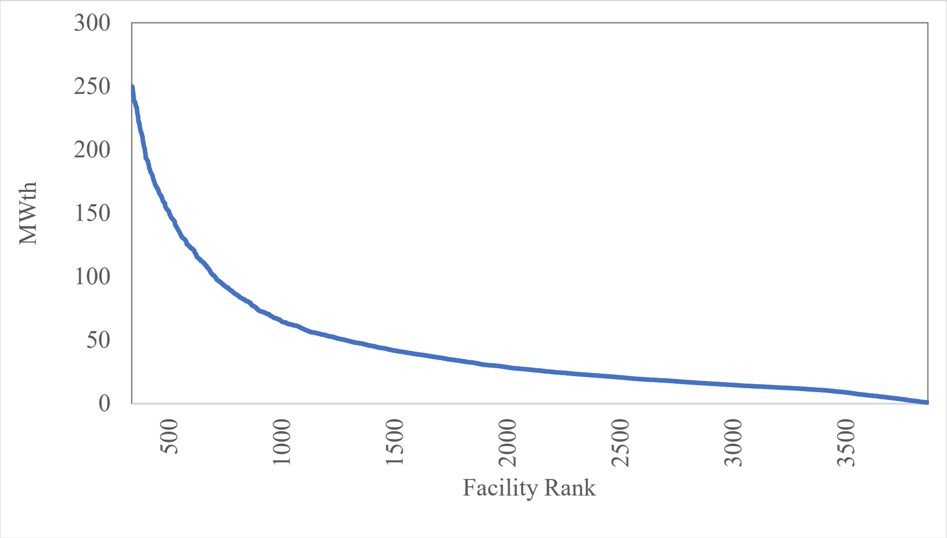


Figure 2. Industrial Market by Number of Industrial Customers Vs. Heat Demand up to 250 MW_t.

A low-carbon world will require transformation of energy markets. The largest potential future market identified is biofuels production [3]—drop-in replacements for gasoline, diesel, and jet fuel. Alternative hydrocarbon fuel sources could be implemented much more readily than wide-scale replacement of combustion systems. Biomass concentrates carbon from the atmosphere, but the conversion processes from biomass to liquid fuels are energy intensive. Biomass can be the feedstock and the energy source for biofuels production. If external sources of heat and electricity are available (rather than burning biomass itself), the hydrocarbon fuel output per ton of biomass can be doubled. This market has three segments: conversion of starch or sugar into ethanol (the primary current method), conversion of cellulosic materials into hydrocarbon fuels, and conversion of biomass wastes that are currently burnt for energy, such as from paper and pulp plants, into biofuels. Total heat and electricity input could be 10% of total U.S. energy consumption. The first and third market segments could use FBs. The expected size and energy consumption of cellulosic biofuels plants are much larger and thus may not be a market for FBs.

The second FB market is for non-grid electricity with three segments. The first segment includes isolated communities, mining facilities, and military bases. The second segment is facilities with special electricity requirements such as data centers with extreme reliability requirements. The third segment is customers where self-generation is less expensive than grid electricity. The retail price of electricity is significantly higher than the wholesale price of electricity because of electricity transmission and distribution costs. This market includes cogeneration plants that produce heat and electricity for a single customer.

The third market is the worldwide maritime market with ~100,000 ships plus offshore platforms and some port facilities. This market's distinctive characteristic is that ships can travel to a port facility to change out FBs. This removes many of the restrictions on the weight and size of the FB. However, maritime applications impose other requirements. Power for propulsion can be provided as electricity or coupling the power system to the propeller(s) with a transmission. The maritime market is split into many segments, among which container ships may be the most attractive first market. Thirty ports handle most of the world's container freight; thus, relatively few port facilities would need to include nuclear-powered ships in their operations. Container ships spend a large fraction of time at sea relative to most ships and thus a larger fraction of their cost is associated with fuel—factors that favor FBs.

1.2.3 The Competition

The economic requirements of FBs are determined by the competition. In the United States, natural gas is currently the low-cost thermal energy option and will remain so unless constraints or taxes inhibit its use. Natural gas with carbon capture and sequestration is not economically viable on a small scale, (a few tens of MWs). It is not just the cost of carbon capture but the pipelines and sequestration of the carbon dioxide that add to the significant expense. Fossil fuel utilization with carbon capture and storage (CCS) is most economically viable for large cogeneration facilities producing heat—most likely as steam delivered to multiple customers in an industrial park. Figure 3 projects natural gas prices with different carbon taxes that can also be viewed as the range of costs for large-scale CCS. Current large-scale CCS costs are between \$50 and \$100 per ton of carbon dioxide. For FBs to be economically competitive, the price of delivered heat must be \$20–50/MWh (\$6–15/million BTU). These prices are significantly higher than the current price of natural gas in most of the United States, but similar to the prices of natural gas in much of the rest of the world.

Biofuels have the potential to be competitive with FBs—depending partly upon the external energy sources used to convert biomass into liquid and gaseous fuels. Potential low-carbon energy sources for biofuel plants are fossil fuels with CCS, nuclear heat, and hydrogen.

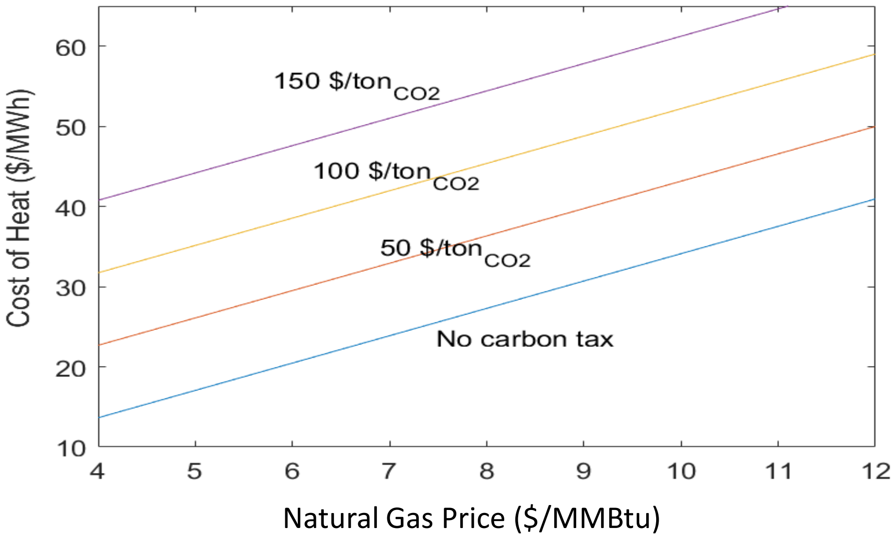


Figure 3. Cost of Heat Vs. Natural Gas Prices for Different Carbon Taxes.

Hydrogen as a heat source is potentially competitive in some parts of the U.S. as a low-carbon replacement for natural gas, assuming a carbon tax on natural gas or a requirement for CCS. There are two major routes to widespread hydrogen adoption. The first is steam methane reforming of natural gas with carbon dioxide sequestration. This is potentially competitive in locations with cheap natural gas and suitable geological features. In steam methane reforming, natural gas is used as a feedstock and an energy source. The process produces hydrogen and relatively pure carbon dioxide. Separately, the natural gas used as an energy source requires removing the carbon dioxide from the stack gas. In effect, there is carbon dioxide steam with low CCS costs and a second stream with higher CCS costs. There are also process variants that produce only relatively pure carbon dioxide streams. This feature enables lower cost hydrogen production in some locations. However, hydrogen is more expense to transport than natural gas. The geographical variations of hydrogen prices will be larger than for natural gas. The other large-scale option is nuclear hydrogen production with the potential for location-independent economic hydrogen production. The economics of nuclear hydrogen production favor very large hydrogen production facilities—similar in size to global refineries. This is dictated by both the economics of nuclear power and economics of hydrogen production.

The economically competitive range for non-grid electricity is estimated at $70–100/MWh. These electricity prices are competitive with the retail prices of electricity in many parts of the United States for the customer as shown in Table 1. Retail prices include generation, transmission, and distribution. FBs are not expected to be competitive selling wholesale electricity to the grid.

Grid electricity as a source of heat is likely to be uneconomic for customers with heat demands of a few tens of MWs. The laws of thermodynamics imply several units of heat are required to make one unit of electricity—but under most circumstances, one unit of electricity with resistance heating makes one unit of heat. Heat is cheap and electricity (work) is more expensive. Because FBs produce heat, they have a competitive advantage in delivering heat to the customer relative to production of electricity. Electric heat is likely to be competitive for users with small energy demands.

Table 1. Retail Electricity Prices by Region for Different Sectors ($/MWh).

Region	Residential	Commercial	Industrial	Transportation	All Sectors
New England	210	163	131	92	178
Middle Atlantic	158	122	66	112	123
East North Central	134	102	69	71	101
West North Central	119	97	73	87	97
South Atlantic	119	94	65	79	100
East South Central	114	107	58	--	94
West South Central	112	82	54	66	84
Mountain	118	96	63	93	94
Pacific Contiguous	156	144	97	90	138
Pacific Noncontiguous	283	245	235	--	255
U.S. Total	**130**	**107**	**68**	**97**	**105**

The above analysis is based on energy as a commodity. However, there is a difference between the value of energy to a customer and its price. The value may be much higher than the commercial price of heat or electricity. The two examples below can clarify this.

First, the largest incentives for adopting FBs are creation of new markets and new sources of revenue. As an example, the paper and pulp industry burns biomass wastes to provide heat and electricity to make paper. An external heat source could enable these plants to produce paper (old business) and use the internally generated biomass wastes as a feedstock for biofuels production—rather than burning the wastes to produce heat.

A second example is data centers with special energy requirements including extreme reliability and significant cooling demands; the latter of which may be provided through (heat-driven) sorption chilling technologies. The costs and risks of downtime results in decisions to choose more expensive energy sources if more reliable. In these cases, the value of reliable electricity is more important than the cost of commodity electricity.

1.2.4 Business Models

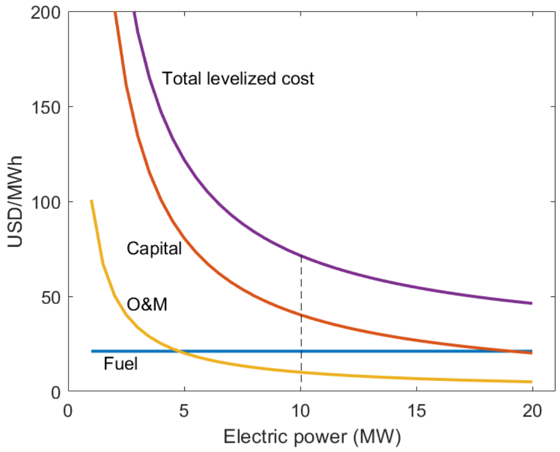
Most FB customers are not in the energy business but need heat and electricity to produce a product—such as manufactured goods, education, retail sales (shopping malls), and marine transport. They are not in the business of producing electricity for sale, instead requiring a business arrangement that mitigates risks of energy availability and price. Moreover, businesses do not want to be dependent upon other businesses for energy—the holdup problem where the energy supplier can raise prices. They want competitive suppliers—like the competitive market for fossil fuels. This creates incentives to lease FBs to supply energy with multiple suppliers. Another, possibly stronger factor is the administrative and legal burden of nuclear operations. If responsibility for licensing, compliance, and interfacing with the Nuclear Regulatory Commission were carried by the leasing company, nuclear energy could become available to a much broader range of businesses. Leases are simple relative to other commercial agreements. As a consequence, they are widely used to lease everything from trucks and train cars to jet engines and aircraft, although operational responsibility is an important consideration.

The leasing model imposes requirements on FBs. FBs must be transportable for delivery and return to the lessor. FBs must also be standardized—partly for economics of mass production, but also to maintain the value of the FB. If the FB is customized for a particular customer, at the end of the lease, it cannot be quickly refurbished and sent to the next customer or repossessed for failure to pay leasing fees. Equally important, if there is a problem with a customized FB, there will not be a replacement available at the factory.

Business decisions that consider risk will often lead to different conclusions than simple economic models. For example, a simple engineering economic model may show the most economical solution to provide heat would be a large nuclear reactor or a fossil fuel plant with CCS cogeneration that produces heat and electricity for multiple customers. The problem is the interests of the cogeneration plant owners and the different heat users do not align over time. Industrial customers are concerned that once they site their plant in an industrial park with a large cogeneration plant, they will be hostage to the owner of the cogeneration plant. This creates incentives to assert control over their own energy sources. Consequently, most large cogeneration plants with multiple customers have been built in the former Soviet Union with centrally planned economics. These types of considerations also create markets for FBs.

1.2.5 Implications for FB Design

A series of engineering assessments [4] were undertaken to help define technical constraints based on the above economic constraints. To achieve the aforementioned cost targets for heat and electricity markets, FB designers must (1) maximize the power output within the constraints of a FB (e.g., truck transportability and passive decay-heat removal), (2) drastically reduce the size of onsite staff, (3) adopt core designs requiring low fuel enrichment and fabrication costs, and (4) develop a system design that is efficiently manufactured in a factory. The other major conclusion is within the design envelope, the FB size should be maximized in size to be economically viable as shown in Figure 4. FBs under 5 MW_t are unlikely to be economic.



Zero scaling
(fixed fabrication cost, $)

Linear scaling
(fixed unit fabrication cost, $/kW)

Figure 4. FB Cost Vs. Size of FB for Different Sets of Assumptions.

1.2.6 Conclusions

The workshop and proceedings are a first assessment of the markets, economics, and business models for FBs. This is a work in progress. FBs are defined by attributes—not reactor technology or power levels. The attributes will limit power output to less than 100 MW_t—and most likely between 20 to 30

MW_t except for maritime and other such applications unconstrained by transport weight and size limits. The market size (1) is sufficient to support large-scale FB manufacturing similar to that of large jet engines and (2) may ultimately be 10 to 20% of total U.S. energy use. Most potential customers are not in the business of selling energy, but rather are energy consumers producing some other product, such as manufactured goods, education, data processing, sales (shopping centers), or marine transport.

For FBs to be economically competitive, the price of delivered heat must be \$20–50/MWh (\$6–15/million BTU). The economically competitive range for non-grid electricity is estimated at \$70–100/MWh. The competition in a low-carbon world for energy demands of a few tens of MWs includes hydrogen (and its derivatives such as ammonia) and biofuels. Grid electricity may be competitive at much smaller energy demands and fossil fuels with CCS competitive at much larger energy demands.

The likely business model is leasing FBs—similar to the model for leasing jet engines and aircraft. Presumably, the lessor would obtain and manage the reactor license with the Nuclear Regulatory Commission. The customer wants multiple suppliers to ensure competitive prices—similar to multiple suppliers of fossil fuels. This requires transportability and standardized FBs to enable switching FB suppliers and retain the value of used FBs after refurbishment for the next lessee. Manufacturing cost considerations imply very small FBs under a few MWs are unlikely to be competitive.

2. MARKETS AND ECONOMICS CHALLENGES AND GAPS

There are a series of challenges and gaps in knowledge that need to be addressed to enable rapid development and commercialization of FBs.

2.1 Definition of Commercial Requirements

The historical market for nuclear reactors has been the production of energy in the form of electricity by utilities for sale to the public. The facilities are very large, but the output of a FB is relatively small. The user’s goal is to have an economic reliable source of heat and/or electricity to produce goods (manufacturing and data centers) or services (transportation, education, sales, etc.). That implies a different ownership and operational model where in most cases the local customer will not own the FB. FBs are likely to be leased where the lessor must address licensing with the Nuclear Regulatory Commission, maintenance, and other issues. The different ownership model will impose functional requirements on the FB, but these are poorly understood. This includes the interface between the nuclear system and the customer system including not only the physical interface, but who is responsible for activities such as different types of maintenance. The requirements on equipment are different if (like today) the existence of a large onsite maintenance and operations organization versus calling the lessor if a problem is identified. An understanding of these requirements that involves business, institutional, and technical constraints is required.

2.2 Practical Maximum Output of a Fission Battery

Economics favors larger FB systems. However, there is a requirement for bank-vault type security (reactor in vault) to minimize security costs. Unlike money, valuable art, gold, and fissile materials in storage, FBs generate decay heat when shut down that can destroy the reactor by overheating it. The FB bank vault must be able to remove this decay heat while maintaining the security features of the bank vault. This constraint, not size or weight, may limit maximum FB power output that defines potential markets. This limit may be different for different types of reactors (water, sodium, helium, or salt cooled) and partly determine what types of reactors are commercially viable as FBs.

When a reactor shuts down, the decay of short-lived fission products generates heat. The decay heat decreases rapidly over the first day (Figure 5). At shutdown the decay heat is about 6% of full power. Within a day, the decay heat has decreased to about 0.5% of full power. If the heat is not removed from the reactor core, the reactor temperature will increase and may result in fuel damage or melting of fuel. Loss of decay-heat removal was the cause of the Three Mile Island and Fukushima accidents. The radioactivity decreases at about the same rate as decay heat; thus, the accident source term decreases rapidly in the first day.

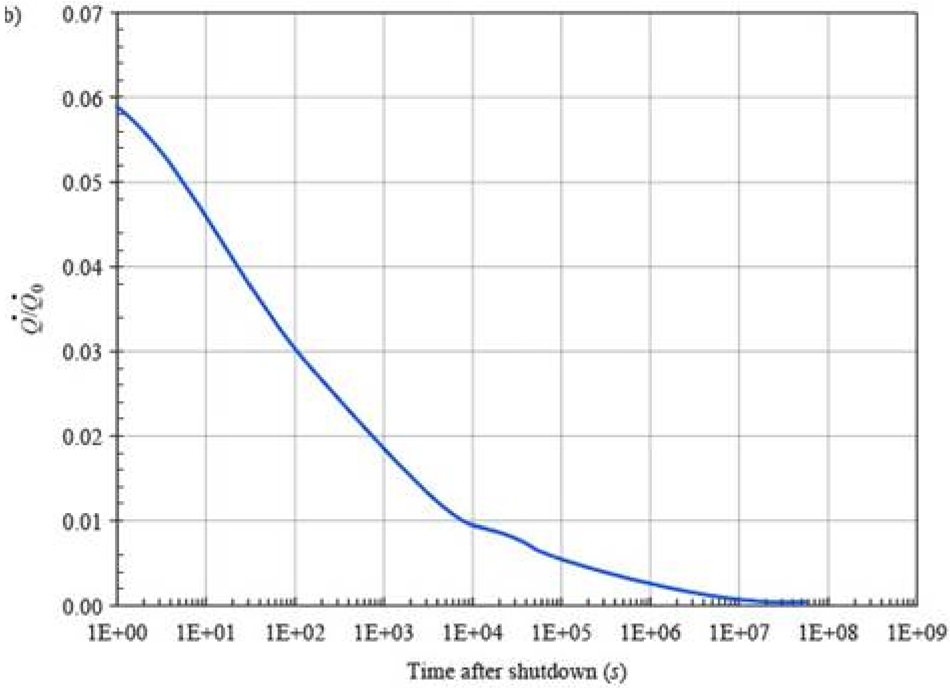


Figure 5. Decay-Heat Release Vs. Time.

There are many ways to remove decay heat and ensure reactor safety. FBs present no fundamental differences from other reactors in terms of decay-heat removal during normal conditions. However, there are special challenges for decay-heat removal because of the following characteristics: (1) unattended operations with no local security forces and (2) transportability. FB security with the constraint of unattended operation can be addressed by placing the reactor in a silo or other vault-like structure—the same security strategy used for protecting money, jewelry, valuable paintings, nuclear weapons, and intercontinental ballistic missiles. However, vaults/silos are barriers to removal of decay heat. During normal operations, when the reactor shuts down, the decay heat can be dumped to the atmosphere by heat exchangers outside the vault/silo; but such decay-heat removal systems can be destroyed by external events from tornadoes to assaults. Decay-heat removal systems can be protected with large physical structures and security forces, but those solutions are incompatible with FB economic and unattended operations goals.

These FB constraints suggest a FB generic area of research is the silo/vault that addresses security, emergency decay-heat removal, and easy unit replacement. In terms of decay heat, FBs can be characterized by two parameters: (1) maximum power output that determines decay heat with time and (2) maximum allowable reactor-vessel temperature under accident conditions. One can separate the details of FB characteristics, (reactor design, coolant choice, and fuel choice), from vault/silo designs and technologies with the goal of developing the silo/vault technologies to enable maximum FB power output. The peak allowable FB accident vessel temperature limit for any FB is chosen to ensure public safety, although the reactor may be damaged when reaching this temperature and could become unusable as a power-generating system. The division between vault/silo and FB is also the division between minimized field construction and the mass-produced FB.

A FB emergency decay-heat removal system could (1) use the mass of the silo/vault to absorb short-lived decay heat during the first day and (2) include features to conduct decay heat to the environment over longer periods of time. The system must contain vessel insulation that limits heat losses during normal operation but allows heat transfer from reactor vessel to vault/silo if the vessel overheats—a trigger mechanism. This implies one can consider emergency decay-heat removal as a generic technology coupled to the vault/silo system—further coupled to a conductive metallic vessel generating decay heat with some peak vessel temperature limit. This defines a generic FB research agenda for emergency decay-heat cooling systems and raises the following questions:

- Can security and emergency decay-heat removal with vault/silo technologies be separated from the reactor technologies? If so, we can develop a generic set of technologies and address common challenges for vault/silo security and emergency decay-heat removal systems.
- What is the maximum allowable FB power level versus peak allowable accident vessel temperature? Different reactor types will have different peak vessel temperatures. The design space that would be applicable to all FBs must be mapped out.
- How can the heat capacity of the silo and soil be used to provide short-term heat capacity to adsorb the high initial decay heat generation by the reactor? What is the option space?
- What are the options, capabilities, and costs for the transfer of that decay heat to the atmosphere and/or surface for long-term decay heat removal?
- Are there other design cliffs in addition to decay heat that limit FB power output or divide FBs into classes? For example, if power output is limited, the FB shielding may be sufficient for transport. However, if power output is high, will long-term neutron activation of the reactor vessel require added radiation shielding for transport?
- Are silo mockups with electric heaters required for full-scale confirmatory proof of concepts? Should such silos also be used to test security features under realistic conditions? These are non-nuclear tests and thus relatively inexpensive.

The above strategy divides the FB decay heat challenge into two components: (1) at the reactor site (discussed within this challenge) and (2) transport (discussed in the FB transportation challenge). That division exists because (1) after reactor shutdown, the decay heat, reactor radiation levels, and radioactive source term decrease rapidly with time, and (2) transport includes a different set of functional safety requirements. There are a set of interface questions between FB site operations and transport. There is also the option to hold the FB at the site for a period of time to allow decay heat and radiation levels to decrease before off-site transport—either in dry cask storage or the transport cask before movement off site.

2.3 Definition of Maritime Fission Battery Requirements

The worldwide maritime market comprises ~100,000 ships plus offshore platforms and some port facilities. The total carbon dioxide emissions are about 2.5% of global emissions with 45% of those emissions from about 3,000 ships.

The maritime market is split into many segments. Container ships may be the most attractive first market for FBs. There are about 5,000 container ships currently in service. They are the largest energy users among vessel categories because of their size and their large fraction of time at sea. As a result, a large fraction of their cost is associated with fuel. Figure 6 shows fuel usage by ship type in millions of tons of heavy fuel oil equivalent today and projected into the future. Thirty ports handle most of the world’s container freight; thus, relatively few port facilities would need to include nuclear-powered ships in their operations to create a large market for FBs.

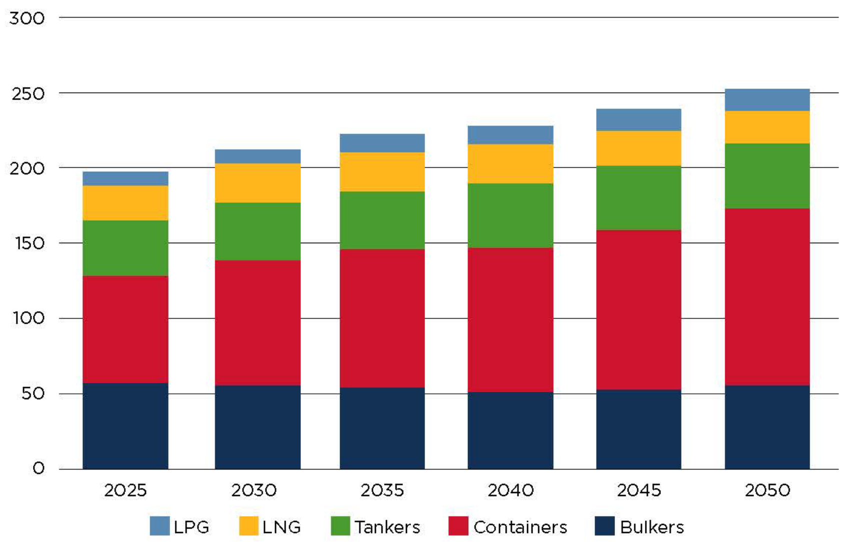


Figure 6. Fuel Consumption (Millions of Tons of Heavy Oil Equivalent) by Ship Type [5].

Historically, nuclear-powered ships had the reactor built into the ship. FBs are a radical rethinking of the nuclear ship design. In one context, FB requirements are relaxed—shipyards can lift very large and heavy packages. However, there are other unique maritime requirements: (1) there are weight distribution requirements associated with ship stability—minimizing the risk of ship rollover in storms, (2) accident scenarios include ship collisions and sinking of the ship that may create separate design constraints, and (3) ships must meet international maritime requirements. The requirements and constraints for FBs are needed to determine if there unique technology gaps for this application.

3. PRIORITY RESEARCH DIRECTIONS

There are two types of research priorities. The first is better definition of requirements imposed by the customer—whether it be the customer leasing a battery or the ship owner. These requirements, in turn, define technical necessities that reveal technology development gaps. The second priority is to understand the technical limits of FBs—specifically the maximum reasonable power output that defines what an FB can and cannot do. It may also define licensing strategies since power output is coupled to the radioactive source term that drives many types of accident analysis. Some of those technical limits may drive the choice of reactor technology.

4. RESEARCH THRUST AREAS

4.1 Thrust Area 1: Definition of Commercial Requirements

The FB user is not in the business of selling energy. Instead, the user's goal is to have an economic reliable source of heat and/or electricity. The lessor must address licensing with the Nuclear Regulatory Commission and other siting issues. The different ownership model will impose functional requirements on the FB, but these are not well understood at present. This includes the interface between nuclear and customer systems. An understanding of these business, institutional, and technical constraints is required.

4.2 Thrust Area 2: Practical Maximum Output of a Fission Battery

Economics favors larger systems. However, bank-vault type security (reactor in vault) is needed to minimize security costs. Unlike money, valuable art, gold, and fissile materials in storage, a FB generates decay heat when shut down that can destroy the reactor by overheating it. The FB vault must have a method to remove this decay heat while maintaining the security features of the bank vault. This constraint, rather than size or weight, may limit maximum FB power output that defines potential markets. This limit may also define licensing strategies because fission product inventory (accident source term) is the starting point of any safety analysis. Reactors with small fission product inventories have different licensing constraints.

4.3 Thrust Area 3: Requirements for Maritime Applications

The maritime FB market for container vessels and other ships is very large and has different requirements from land-based applications. First, the FB would be installed and removed in a shipyard without the size and weight constraints associated with other FB applications. Second, additional weight distribution requirements associated with ship stability must be met to minimize the risk of ship rollover in storms. Third, the ship will roll in high seas, which may present major challenges to some types of liquid-cooled reactors but not a constraint for other types of reactors. Fourth, accident scenarios include sinking of the ship that may create separate design constraints. Last, ships must meet international maritime requirements. In this context, the FB model is fundamentally different from the historical model of a nuclear-powered commercial ship where the nuclear power plant was tightly integrated into the ship design. In this case, the FB is a package replacement to be completed when the ship is in dry dock for maintenance. The requirements for design are needed.

5. OUTCOMES AND IMPACTS

FBs are defined to meet the requirements of a specific market—heat and electricity demand for smaller energy users in a low-carbon world. The market defines the economic and technical requirements that, in turn, provide the basis for defining required technologies and technology gaps. The market and economics workshops provided a first set of requirements.

The work defined three areas that require additional examination. The first is a better definition of FB requirements where the likely business model is leasing. This is very different from the traditional utility nuclear plant model. The second area is determining the maximum credible power output of a FB that meets the top-level requirements. This defines what is and what is not a FB and what are the markets for FBs. The third area is defining the technical requirements for maritime applications.

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