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Changing the World's Energy Future

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INTRODUCTION

Microreactors may be able to be cost competitive in niche markets, but they are likely to be much more expensive than small modular reactors or large reactors in terms of levelized cost. The vision of microreactors being catered to larger markets relies heavily on their ability to be mass produced and cut costs. Since commercial nuclear reactors have not been mass produced before it is challenging to estimate what kind of manufacturing facilities will be needed, what they will cost, and how factory considerations influence the unit cost of microreactors. This summary attempts to imagine the various possible production layouts of microreactors and identify the different possible manufacturing facilities (factories) that might be required. Regulatory and economic considerations for these layouts and factories are then listed.

BACKGROUND

The success of microreactors will depend on the ability to scale production and cut costs. Microreactor production facilities, or factories, are therefore critical for this endeavor. Nuclear microreactor factory considerations will primarily depend on the manufacturing specifications of microreactors, such as material requirements, production rate, machinery, safety and quality control requirements, and licensing requirements. While ideally, all activities related to microreactor production should be performed at an offsite factory, significant technological and regulatory barriers lie before such a production line is achieved. Therefore, a microreactor factory will likely evolve from current factories that produce safety-critical components, like reactor vessels, to a more general factory where fuel loading and testing can be performed in addition to fabrication and assembly. Given the very early stage of the microreactor concept with uncertainties in their market sizes, demands, costs, and regulations, it is challenging to determine these specifications and therefore to envision what a microreactor factory might look like. A detailed international market analysis conducted by Shropshire et al. (2021) found that build rates in hundreds of reactor units in the 2040s and thousands in the 2050s are needed to attain market penetration if developers are able to cross the technological and regulatory barriers and develop safe microreactors. Microreactors are likely to be regulated similarly to current nuclear power plants and the NRC is currently actively investigating mechanisms to streamline the licensing of microreactors, including accommodations for design standardization, manufacturing licenses, and environmental reviews (NRC, 2021). The NRC is also developing 10 CFR Part 53, which is a technology-inclusive regulatory framework for advanced reactors, some of which, may set technological precedence to microreactors and thereby ease microreactor licensing.

SPECIFICATIONS AND ECONOMIC AND REGULATORY CONSIDERATIONS OF A NUCLEAR MICROREACTOR FACTORY

In order to understand the various possible specifications of microreactor factories, this section outlines potential production and operation layouts of microreactors starting from the layouts of current, large reactors and SMRs in development. These layouts (shown in Figures 1 to 5) describe the activities performed offsite at factories and onsite, including fuel fabrication, reactor fabrication (in case it is manufactured in a factory), plant construction, fuel placement in the core, start-up testing, operation, refueling, maintenance, and temporary spent fuel storage. The layouts ignore activities that are common amongst all of them, regardless of the reactor type or size (e.g., assembly, site preparation, and long-term storage of the spent fuel or reactor). Note that these layouts are highly simplified to meet the goal of understanding the different types of factories that might be involved in producing microreactors. In practice, it is very likely that microreactor developers will be working with numerous different vendors and suppliers that fabricate different parts of the reactor, fuel, etc. It is assumed that the activities at the factories shown in these layouts will include procurement from these suppliers for various materials and components. Additionally, the type of layout a developer might follow also depends on their business model, supply chain, and economic and regulatory environments at the time of development.

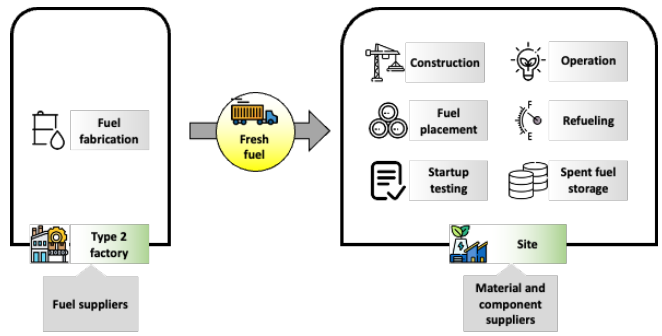
Figures 1 to 4 illustrate the various possible layouts that might be employed in microreactor production and operation. Each figure includes the various factories, transportation types, and offsite and onsite activities corresponding to each layout. Note that, as shown in the figures, the eventual goal for microreactors is to move most activities offsite. The factories where microreactors will be produced may fall into one of the following four categories:

Type 1: A factory where everything but the microreactor fuel can be fabricated and assembled. That is, this facility will not have any nuclear material present and will be similar to the current (safety-significant) reactor component fabrication facilities that are not NRC licensed but Nuclear Quality Asssurance-1 (NQA-1) certified. Although the figures show that Type 1 factories include reactor fabrication, in practice, it is more likely that several of the reactor components will be procured from other manufacturers and suppliers (e.g., off-the-shelf components) and a part of the fabrication, assembly, and inspection will be performed at the Type 1 factory, depending on the economic and regulatory constraints and business model of the developer. Since microreactors have never been licensed before, it is also possible that a Type 1 factory might require a manufacturing or construction license per 10 CFR Part 52 or the upcoming Part 53, since the whole reactor is being "constructed" at this facility. However, in the absence of fuel or any other nuclear material, the definition of reactor construction (in the sense of current, large reactors) vs. fabrication (in the sense of microreactors, which are orders of magnitude smaller) is still a gray area. Therefore, to avoid the potential regulatory burden, developers might choose to limit fabrication activities at the Type 1 factory to safety components and assemble the microreactor at the site.

Type 2: This is a fuel fabrication facility, which can be licensed under 10 CFR Part 70 as a "fuel cycle facility." The fuel used by existing reactors is currently fabricated at such facilities. However, many microreactors are being developed to use fuel types (e.g., tristructural isotropic [TRISO] fuel using HALEU) that do not have existing large-scale fabrication facilities. Therefore, new fuel fabrication facilities will have to be developed and licensed by the NRC as the demand for fuel increases. Depending on the amount and types of radioactive material stored and handled at the site, fuel facilities can be categorized into Category I (most stringent, with highly enriched uranium [HEU] fuel), Category II (less stringent with HALEU fuel with >10% enrichment), and Category III (least stringent with low-enriched uranium [LEU] and other fuel with enrichment <10%) facilities.

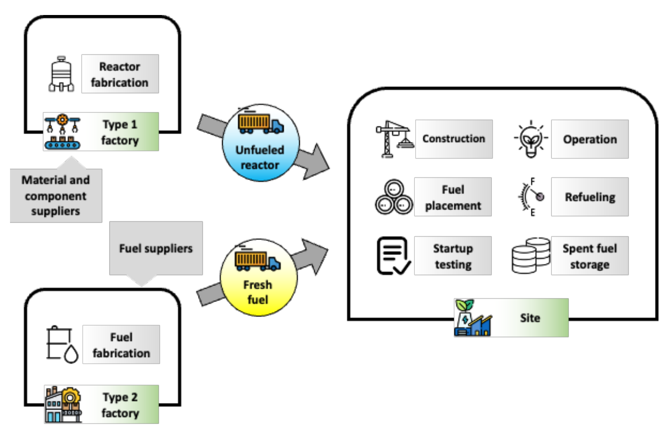
Type 3: A microreactor production facility that can include fuel-related activities (fuel loading, reloading, etc.) except for start-up testing, which involves achieving criticality in the reactor. This facility can be built and operated with a manufacturing license per 10 CFR Part 52 or the upcoming Part 53. Microreactors produced in this facility can significantly reduce activities at the site except for start-up testing that involves achieving criticality. However, subcritical testing can be performed in this factory, and only essential, critical testing can be performed at the site. Centralizing many activities in this factory can enable leveraging the advantages of mass production, such as economy by numbers, better quality control, etc., and reduce the unit cost of microreactors. Production at a Type 3 factory takes microreactors closer to the "plug-and-play" concept.

Type 4: This is an "all encompassing" microreactor production facility that can include both non-fuel-related and fuel-related activities and also start-up testing, which involves achieving criticality. This factory is needed for "plug-and-play" microreactors that will be shipped to the site and "plugged" into the grid to produce power. However, the Type 4 factory will also be the most difficult to license, and under current regulations, will require a construction and operating license (COL). Therefore, in addition to requiring a COL for the site (which is required for any scenario), production in a Type 4 facility will require a COL for the microreactor factory as well. Given the large capital investment likely required for a facility with a COL, this facility would be suitable only if there is a large demand for "plug-and-play" microreactors.



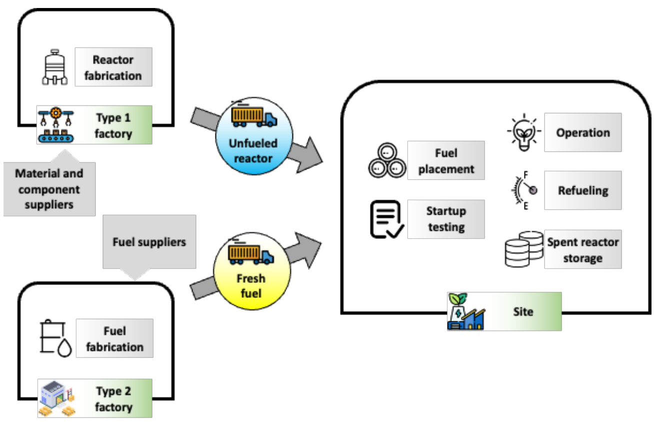
Description	Regulatory considerations	Economic considerations
Representative of current, large reactors, where most of the activities, including construction, testing, refueling, and temporary storage, are all performed onsite.	Most current regulations are intended for this scenario, where the nuclear power plant requires a design certification, and the site requires a COL based on 10 CFR Part 50 or 52.	This is the current state of practice of the nuclear industry and involves the least amount of standardization or modularization and is therefore the most expensive. Each plant is custom, and stick built.
Fuel is fabricated in a fuel fabrication facility and is shipped to site, where it is loaded into the reactor core.	The fuel fabrication facility is licensed per 10 CFR Part 70.	

Fig. 1. Layout of current, large reactors.



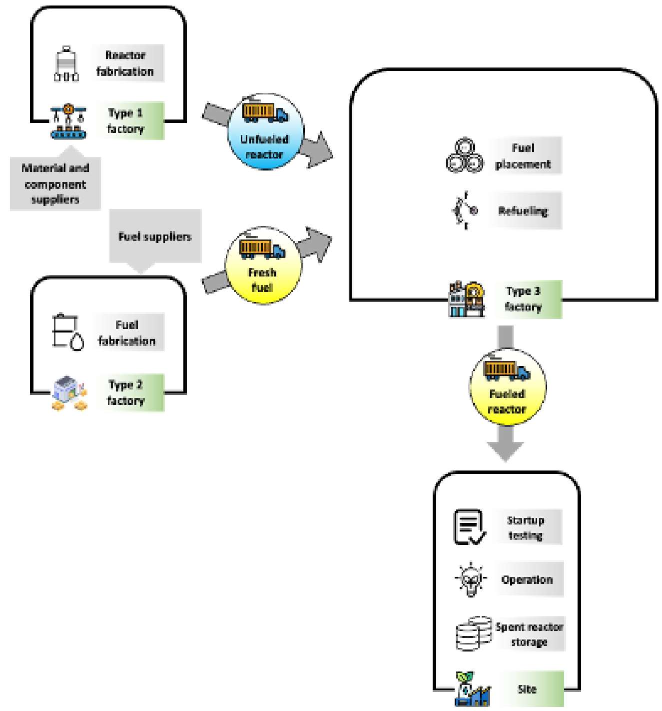
Description	Regulatory considerations	Economic considerations
Representative of SMRs like NuScale, where the reactor itself is manufactured in a factory, while the rest of the plant is constructed onsite. **The reactor is shipped to the factory unfueled.** **Fuel is fabricated in a fuel fabrication facility and is shipped to site, where it is loaded into the reactor core.**	This layout is still very similar to the current state of practice, where the nuclear power plant requires a design certification, and the site requires a COL based on 10 CFR Part 50 or 52. The reactor is manufactured in a Type 1 factory, which does not involve any nuclear material. While the NRC might require a manufacturing license (10 CFR Part 52 Subpart F) for this factory, it could be argued that the reactor is just another safety-critical component and can be manufactured in an NQA-1-certified facility without an NRC license. The Type 2 factory will be licensed as a fuel facility under 10 CFR Part 70.	This layout, proposed by many SMR reactor vendors, is intended to improve economics through factory manufacturing of the reactor. However, such modularity is limited to the reactor itself, and the rest of the plant is still constructed onsite. Factory fabrication of the reactor is expected to reduce the capital costs of SMRs, especially for the NOAK plant.

Fig. 2. SMR (e.g., NuScale) layout.



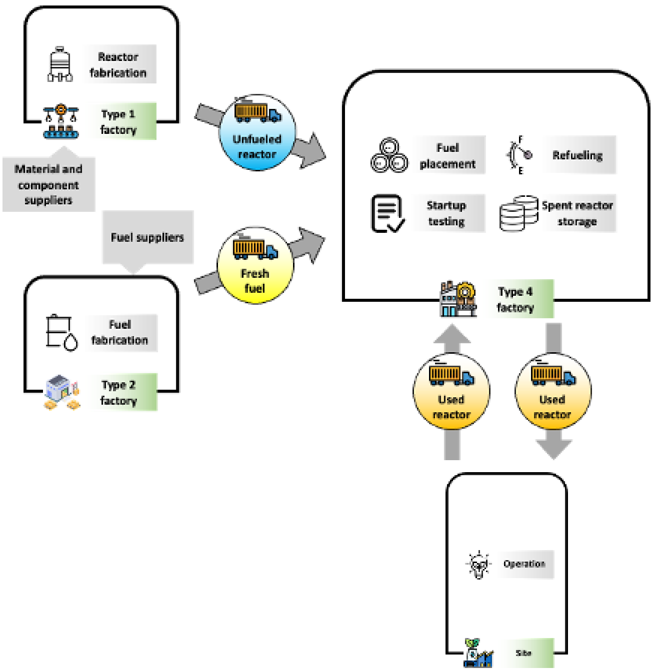
Description	Regulatory considerations	Economic considerations
Illustrates the most feasible layout for microreactors under the current regulatory atmosphere. This layout is very similar to that of SMRs (in the previous figure), except for much less construction at the site in the case of microreactors. **Similar to SMRs, the fuel and reactor are fabricated in separate facilities and are shipped to site, where everything is assembled and operated.** **The microreactors that follow this layout are likely to be stationary and operated at a single site through their lifetime.**	Since this layout is not far from the current state of practice (and is similar to SMRs, which are currently under development), it is likely to have the least regulatory risk amongst all the possibilities for microreactors. Therefore, it is hypothesized that the first generation of microreactors will be manufactured and operated this way. The Type 1 and 2 factories and the site are licensed similarly to those in the SMR layout. The transportation of fresh fuel and the unfueled reactor can also be performed within the current regulatory environment.	The fixed costs of microreactors produced and operated according to this layout may include the cost of the Type 1 and 2 factories unless existing factories are used, which is very much feasible. As a large number of microreactors are produced with this layout, a major cost driver might be the fact that many start-up activities are performed onsite for each microreactor. This adds significant labor costs. Although most feasible in the current regulatory environment, this layout does not take full advantage of the large-scale factory production and testing of microreactors and is therefore still likely to have a high NOAK cost.

Fig. 3. Microreactors, Gen I layout.



Description	Regulatory considerations	Economic considerations
In the second generation of microreactors, most activities (except start-up testing) will likely be performed offsite at a Type 3 factory. **The reactor and fuel are produced at Type 1 and 2 factories as in the previous layouts and are shipped to a Type 3 factory for assembly.** **This layout is more suitable for a "movable" microreactor that may be operated at multiple sites in its lifetime.**	The Type 1 and 2 factories and the site are licensed similarly to those in the SMR layout and the Gen I microreactor layout. The Type 3 factory can be operated with a manufacturing license under the upcoming 10 CFR Part 53, which allows certain fuel-related activities but still does not allow start-up testing. Note that since Part 53 is still under development, there is uncertainty as to what activities can be included in this factory. Transportation of the fresh fueled reactor is similar to the transportation of fresh fuel. Transportation of the spent reactor might require custom Type B packages, which can be expensive.	Moving most activities to an NRC-licensed Type 3 factory will add fixed costs but reduces the labor costs incurred at each site. Shipping requirements of a spent reactor will require a custom Type B packaging, which can be expensive. The additional fixed costs in this layout will likely be alleviated by the cost advantages of mass production and ease of licensing of the factory and multiple sites. Due to the additional fixed costs, this layout may be more economical than the Gen I layout when a large number of microreactors are produced.

Fig. 4. Microreactors, Gen II layout.



Description	Regulatory considerations	Economic considerations
This is representative of the "plug-and-play" microreactors, such as those envisioned in the Fission Battery Initiative (Agarwal et al. 2021). **All activities except operation are performed offsite, and the microreactor may be shipped to multiple sites before refueling. Minimal site preparation is required.** **Unlike the Gen II microreactor layout, even start-up testing is performed in an offsite factory.** **Since start-up testing is performed offsite and the reactor has reached criticality once, the reactor shipment to the site is considered a "used" reactor.**	The Type 1 and 2 factories and the site are licensed similarly to those in the SMR layout and the Gen I microreactor layout. Since the Type 4 factory also includes start-up testing and hence involves the reactor reaching criticality, it cannot be licensed under a manufacturing license. Under the current regulatory requirements, a facility involving a reactor reaching criticality will require a COL. Therefore, in this layout, both the Type 4 factory and site will require a COL. The transportation of the reactor to and from the site requires Type B packaging.	The fixed costs of a Type 4 factory with COL will be larger than those of a Type 3 factory with a manufacturing license since COL has a lot more requirements. Additionally, when the reactor is transported to and from the site, it will be in a used state and transportation is therefore more expensive. These costs can be alleviated with large-scale production and ease of licensing of the microreactor factories and multiple sites.

Fig. 5. Microreactors, Gen III, 'plug-and-play' layout.

Some additional considerations for these layouts are below:

- Under current regulations, all microreactor sites will need a COL, like currently existing large reactors and SMRs. Obtaining a COL can be a lengthy and expensive process and is therefore an economical barrier to scaling up deployment. However, the NRC is investigating streamlining microreactor licensing (NRC 2021a), including standardization and environmental reviews.
- As more activities (especially fuel and testing related) are performed in a factory, the regulatory requirements increase and so will the initial capital investment for constructing and licensing the factory. However, centralizing activities in a factory also achieves an economy by numbers and reduces the unit cost of microreactors. Therefore, it is a business decision to manage economics and regulatory risks.
- As microreactors move towards Gen II, Gen III, and "plug-and-play" systems, transportation solutions are needed for transporting non-operating microreactors with fresh fuel (yet to achieve criticality) and used fuel (achieved criticality in the past). The transportation of microreactors with fresh fuel has lower regulatory requirements than with used fuel due to the corresponding radionuclide inventories and consequent risk to the public. However, there is regulatory precedence for the transportation of fresh fuel (transportation of current fresh fuel) and spent fuel (spent fuel transportation in Type B casks), and technological advancements will be needed to ensure the safe, reliable, and economical transportation of microreactors.

FUTURE WORK

The different production layouts and factories identified in this summary paper describe the distinct paths forward for factory fabrication of microreactors and the economic and regulatory requirements for these factories. Based on the regulatory requirements and the various activities performed in these factories, it will be possible to perform a rough-order-of-magnitude (ROM) estimation of the capital costs of these factories. These ROM factory costs can then be levelized and used in the capital cost estimation of microreactors. Such a cost estimation will be performed in future work. The economic and regulatory requirements identified in this summary also provide an insight into the regulatory effort involved in taking microreactors from a first generation (custom built at site) product to a 'plug-and-play', fission-battery (Agarwal et al. 2021) type product.

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