

## Material-Constrained Deployment Modeling of Compact Tokamak Fusion Power Plants Using the Nuclear Fuel Cycle Simulator Cyclus

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### 1. Introduction

The growing interest in nuclear fusion as a firm, low-carbon energy source has intensified efforts to move from experimental facilities to commercial deployment. Multiple reactor architectures are under development worldwide, supported by both public programs and private ventures. Public-sector initiatives such as the UK's Spherical Tokamak for Energy Production (STEP) programme [1] aim to establish the basis for grid-connected fusion, while private companies including Commonwealth Fusion Systems (CFS) are advancing high-field compact tokamak concepts [2].

As fusion systems progress toward commercialization, the discussion increasingly extends beyond plasma performance to practical questions of construction, manufacturing, and fleet-level deployment. Techno-economic analyses of compact tokamak concepts, including ARC-class designs [3], suggest that first-of-a-kind (FOAK) plants will be capital intensive, with costs in the tens of thousands of dollars per kilowatt for early units [4], and that cost reductions will depend strongly on production learning and multi-unit deployment.

A key assumption in such projections is that supply chains for critical materials can scale with reactor construction. Fusion power plants require large quantities of specialized materials for structural components, magnet systems, and breeder blankets. For blanket concepts employing lithium-bearing salts and neutron multiplier materials, deployment at scale implies material production rates that may exceed current industrial capacity, potentially constraining deployment.

Although material challenges are frequently acknowledged, their quantitative impact on deployment timelines remains unclear. In particular, the extent to which production limits influence FOAK realization time and subsequent fleet growth remains unclear.

In this study, we develop a material-constrained deployment model for a compact tokamak fusion power plant using the nuclear fuel cycle simulator Cyclus [5]. The configuration is adapted from the ARC conceptual design [3]. We model material production rates, fabrication capacities, and construction events in a time-dependent framework to evaluate how supply bottlenecks govern FOAK deployment time and nth-of-a-kind (NOAK) fleet expansion.

### 2. Material Basis and Deployment Constraints

This study adopts the ARC-class conceptual design [3] as the reference for a compact tokamak configuration. The reference plant is designed for a thermal output of 525 MW, corresponding to an electrical output of 190 MW, and utilizes an enriched-lithium-based FLiBe blanket for tritium breeding and primary heat removal. The design also requires approximately 5,730 km of REBCO tape for the high-field superconducting magnet system. A schematic of the ARC reactor configuration, adapted from the reference design [3], is shown in Fig. 1.

The ARC design relies on a substantial quantity of REBCO tape, indicating that superconducting material supply may represent an additional constraint for large-scale deployment. However, in the present study, REBCO supply is not explicitly included as a limiting factor in the FOAK or NOAK deployment modeling. Instead, its potential impact is assessed separately by comparing the cumulative REBCO demand implied by the deployment results with projected supply growth scenarios.

The principal material inventories considered in this study are summarized in Table 1, which combines initial construction requirements with long-cycle replacement materials. Initial deployment is dominated by the FLiBe blanket ( $\approx 958$  t), corresponding to a beryllium demand of roughly 90 t for first loading. In contrast, long-cycle replacement of beryllium occurs on the order of 3.82 t every  $\sim 9$  years, while TiH<sub>2</sub> shielding materials are replaced on similar multi-year intervals. Other structural and replacement materials are not explicitly treated as limiting factors in the present analysis [6,7].

We note that establishing nuclear-grade supply chains is non-trivial for a range of materials, including structural components such as vanadium, due to quality control requirements and the need to scale production processes. In this context, the FLiBe supply chain can be viewed as a representative limiting case, as it combines multiple challenges including beryllium resource constraints and the availability of enriched lithium. By focusing on FLiBe, this study captures key supply-chain limitations that are likely to be encountered across other nuclear-grade materials, while representing a conservative limiting case for deployment.

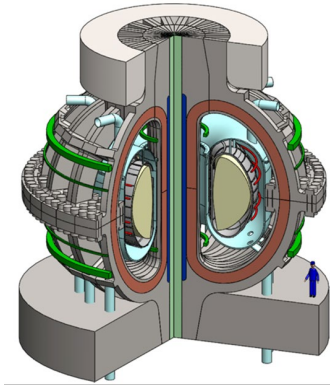


Fig. 1. ARC reactor schematic with demountable superconducting coils (adapted from [3]).

Table 1. Principal material inventories

Material	Weight [tons]	Replacement Period
Tungsten	3.72	6-12 month
Vanadium*	58.3	6-12 month
Beryllium	3.82	5-9 years
TiH <sub>2</sub>	380.18	5-9 years
FLiBe	958	Steady
SS316	5,300	Steady
Copper	358	Steady
Vanadium**	71.4	Steady

V\* is related to vacuum vessels. V\*\* is related to blanket tanks.

### 3. FOAK Deployment Analysis

The time required to realize a first-of-a-kind (FOAK) unit is governed by the rate at which critical materials can be secured for initial construction. In the reference configuration, initial deployment is dominated by the FLiBe blanket inventory of approximately 958 t, about 10 wt% of which is beryllium. This corresponds to a first-loading beryllium requirement of roughly 90 t per reactor.

Global beryllium production in 2024 is approximately 360 t yr<sup>-1</sup>, with about half produced in the United States [8]. Reported growth rates are on the order of 3–4% annually [9]. While the long-cycle replacement requirement of about 3.82 t every nine years is small relative to global production, the initial loading demand for a single FOAK unit represents a noticeable share of annual supply.

The availability of enriched lithium further influences FLiBe production. Public information on large-scale enrichment capacity remains limited. Historical methods such as COLEX have been applied to lithium enrichment, though environmental and regulatory factors constrain their wider use [10,11]. Consequently, both beryllium supply and FLiBe fabrication capacity must be considered when estimating FOAK realization time.

In this study, the FOAK construction time is expressed as a function of beryllium supply rate and FLiBe fabrication capacity. The effective production rate is taken as the minimum of these two constraints, and the realization time is estimated by dividing the required blanket inventory by this rate. This analytic estimate is then compared directly with time-dependent Cyclus simulations under equivalent supply conditions.

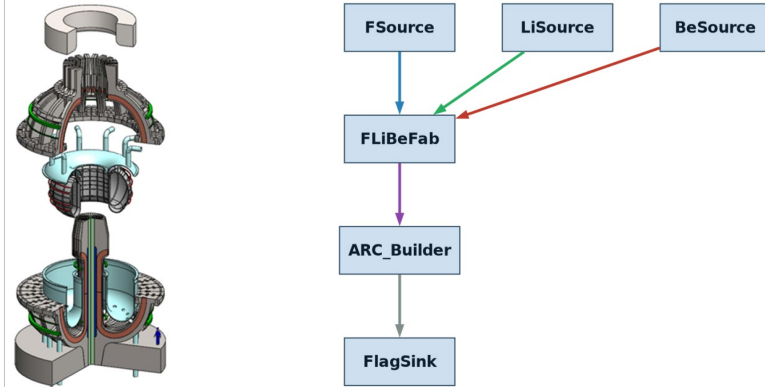


Fig. 2. Simplified Cyclus representation of the FLiBe supply chain and ARC construction workflow.

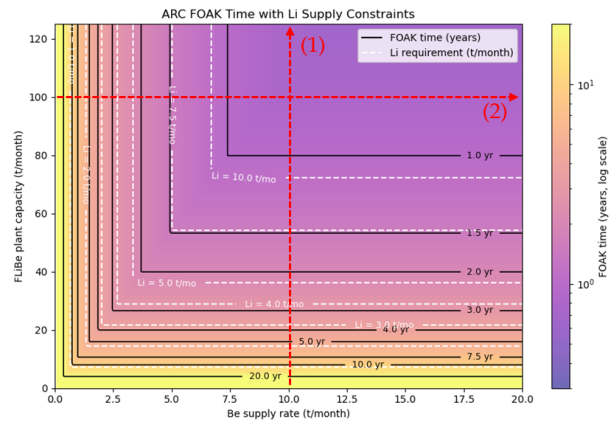


Fig. 3. FOAK realization time under beryllium supply and FLiBe fabrication constraints.

The material flow structure implemented in Cyclus is depicted in Fig. 2. Fluorine, enriched lithium, and beryllium are supplied to a centralized FLiBe fabrication facility, which delivers salt to the ARC construction unit. This framework captures the supply and fabrication limits governing FOAK realization.

Figure 3 shows the resulting FOAK realization time over a wide range of beryllium supply rates and FLiBe fabrication capacities. The contour map highlights two distinct regimes. At low beryllium supply, deployment is upstream-limited, and increasing fabrication capacity has little impact on construction time. At higher beryllium availability, the system transitions to a fabrication-limited regime, where FOAK time decreases primarily with plant production capacity.

To further clarify this behavior, Figs. 4 and 5 present one-dimensional slices of the parameter space. In Fig. 4, beryllium supply is fixed at 10 t month<sup>-1</sup> while FLiBe production capacity is varied. FOAK time decreases rapidly with increasing fabrication rate before approaching a lower bound set by beryllium availability. In Fig. 5, the fabrication capacity is fixed at 100 t month<sup>-1</sup> and beryllium supply is varied. In this case, FOAK time is strongly sensitive to supply at low rates but becomes insensitive once fabrication capacity becomes the limiting factor.

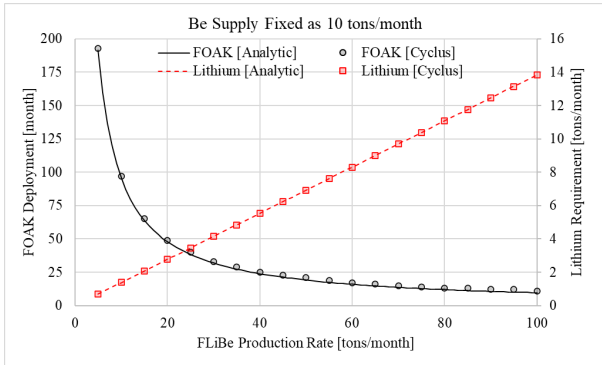


Fig. 4. FOAK time for fixed beryllium supply (10 t month<sup>-1</sup>), corresponding to line (1) in Fig. 3.

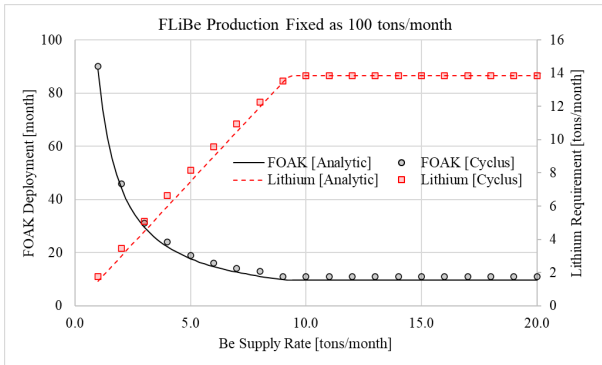


Fig. 5. FOAK time for fixed FLiBe fabrication capacity (100 t month<sup>-1</sup>), corresponding to line (2) in Fig. 3.

Across all cases, the analytic estimates agree closely with the Cyclus results. This confirms that FOAK realization is largely governed by the interplay between upstream material supply and downstream fabrication capacity, and that the simplified representation captures the dominant deployment dynamics.

#### 4. NOAK Fleet Deployment Under Supply Growth

Beyond FOAK realization, long-term deployment depends on how beryllium supply evolves over time. Since the fraction of global production allocated to fusion remains uncertain, we examine fleet expansion under assumed compound annual growth rates (CAGR) of supply.

First, a baseline CAGR of 4% is adopted and the initial monthly beryllium supply is varied. Figure 6 shows the resulting fleet electric capacity over a 50-year horizon. Larger initial supply accelerates early deployment, while lower values delay successive construction due to the time required to accumulate the initial FLiBe inventory.

Second, the initial supply is fixed at 2 t month<sup>-1</sup> and CAGR is varied from 0% to 10%, with the upper bound motivated by uranium supply expansion [12]. As shown in Fig. 7, higher CAGR leads to sustained increases in fleet growth, with the deployment trajectory exhibiting a strong dependence on supply expansion rate.

Under the present configuration, fleet expansion is primarily governed by the assumed growth in beryllium supply. As a result, higher supply rates and CAGR values directly translate into accelerated deployment overtime.

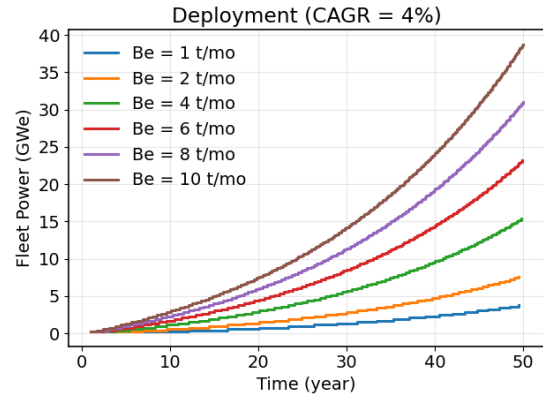


Fig. 6. Fleet electric capacity with 4% CAGR in beryllium supply. Initial monthly beryllium allocation to FLiBe production is varied from 1 to 10 t month<sup>-1</sup>.

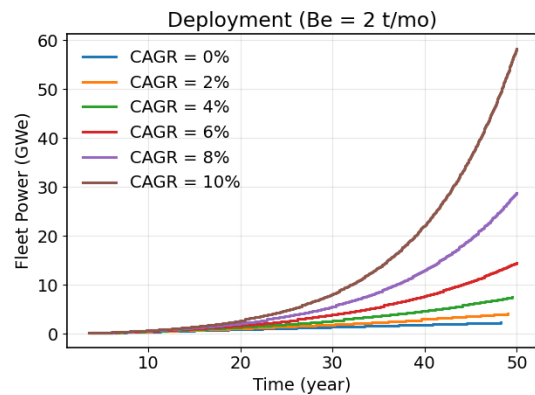


Fig. 7. Fleet electric capacity with initial beryllium supply of 2 t month<sup>-1</sup> and CAGR varied from 0% to 10%.

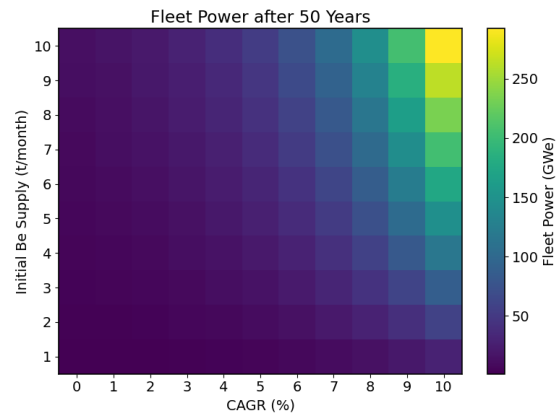


Fig. 8. Fleet electric capacity after 50 years as a function of initial beryllium supply (t month<sup>-1</sup>) and CAGR (%).

To summarize the combined effect of initial supply and growth rate, Fig. 8 shows fleet electric capacity after 50 years as a function of initial beryllium allocation and CAGR. Both parameters increase long-term deployment, with higher values leading to larger fleet capacity.

Figure 9 shows one-dimensional slices of this behavior. At a fixed CAGR of 5%, fleet capacity increases nearly linearly with initial beryllium supply. In contrast, at a fixed supply of 5 t month<sup>-1</sup>, fleet capacity shows a stronger sensitivity to CAGR, reflecting the cumulative effect of supply growth.

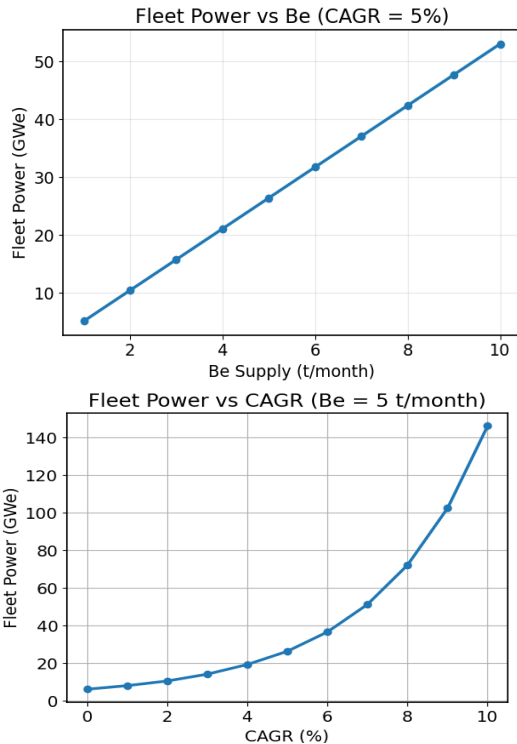


Fig. 9. Fleet capacity after 50 years vs. (top) initial beryllium supply (CAGR = 5%) and (bottom) CAGR (Be = 5 t month<sup>-1</sup>).

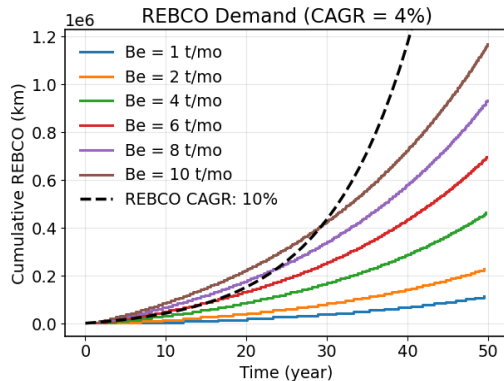


Fig. 10. Cumulative REBCO demand for ARC-class deployment (Be CAGR = 4%) compared with a representative supply curve.

Using the deployment results obtained under a 4% CAGR in beryllium supply, the corresponding cumulative REBCO demand can be estimated. As shown in Fig. 10, this demand increases rapidly with time and may exceed supply based on an initial production of 2,400 km yr<sup>-1</sup> and a 10% CAGR. This suggests that REBCO availability could become an additional constraint, particularly during the early stages of deployment.

### 5. Conclusions

In this study, we investigated a material-constrained deployment model for compact tokamak fusion power plants using the Cyclus nuclear fuel cycle simulator. An ARC-based reference design was used to represent the FLiBe supply chain with explicit beryllium supply and

fabrication constraints, allowing evaluation of both FOAK realization time and NOAK fleet expansion.

For FOAK deployment, realization time is determined by the tighter of beryllium availability and FLiBe fabrication capacity. For longer-term deployment, fleet growth is strongly influenced by beryllium supply and its growth rate, with higher initial supply and CAGR leading to accelerated expansion.

In addition, superconducting material demand suggests that REBCO availability may be an additional constraint. Based on the projected deployment trajectories, cumulative REBCO demand can exceed plausible supply levels during early deployment, suggesting limitations beyond the FLiBe supply chain.

These results indicate that large-scale fusion deployment depends not only on material availability but also on the growth of supporting supply chains. Future work will incorporate potential competition for critical materials across different fusion concepts.

### ACKNOWLEDGMENTS

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### DECLARATION OF COMPETING INTEREST

Ben Lindley has an ownership interest in and is a technical advisor of Realta Fusion.

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