INL/RPT-23-74316
Revision 1

First-Principles Cost Estimation of a Sodium Fast Reactor Nuclear Plant

January | 2024

Milestone M3CT-23IN1207065 | Task Report 278111

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Integrated Energy Systems

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SUMMARY

A multi-tiered cost analysis is performed to estimate full costs of a nuclear power plant (NPP) based on sodium-cooled fast reactor (SFR) technology. To address the lack of fully transparent cost estimations from past undertakings for NPPs, we have developed a detailed and first-principles-based cost estimate for a generalized SFR NPP. Our intent is to achieve a high degree of transparency with our cost assumptions and develop a cost model that is flexible and easily extendable to variations in NPP design and other nuclear reactor types. Furthermore, we strive to achieve a clear organization of costs and complete identification of key cost drivers based on first principles. To this end, the cost results of our analysis as given in Table 24 and Table 25 are organized and categorized into a code of accounts (COA) under development at Idaho National Laboratory (INL). Varying degrees of first-principles methods are employed, such as design for manufacture and assembly® (DFMA®), to elucidate costs in all process levels of the plant equipment, buildings and site structures, personnel, and other miscellaneous but significant cost elements. These approaches have been successfully applied in past cost analysis projects and are designed to enable rapid and flexible cost estimation. Application of these techniques for evaluating NPP costs is similar in concept to the full, detailed estimation of construction and fabrication costs determined in a later stage of NPP development. Note that our approach tries to avoid use of other past analysis results and data such as those from the legacy Energy Economic Data Base (EEDB) Program, as these resources are based on historical NPP costs and thus may not be indicative of new reactor technologies or construction and fabrication/manufacturing techniques. However, we provide a comparison of our SFR NPP cost results in Table 90 against those included in the EEDB for a representative pressurized water reactor (PWR).

While our ultimate intention is to provide costs for the full COA, the primary objective of this analysis is to tabulate SFR NPP total overnight cost (TOC) which consists of costs from Accounts 10 through 50 in the COA. A fully detailed cost accounting of an entire NPP is an enormous undertaking, especially since it relies on an accurate estimation of the design and cost nuances affected by extensive nuclear regulatory requirements. Consequently, in various instances we make simplifications in our assumptions and methods that future efforts can selectively improve to produce a more detailed and accurate cost estimate, capturing the remaining accounts we do not cover. For these other cost accounts (Accounts 60 through 90), we provide an approximation which require further development. We further include estimates for costs of larger reactor and plant sizes to highlight cost scaling and potential sources of cost reduction. An examination of nuclear versus non-nuclear costs are presented in Table 92 to demonstrate the level of cost escalation that results for the premium practices required for satisfying the regulatory requirements of nuclear design and construction. Finally, we estimate and compare first-of-a-kind (FOAK) and N^{th}-of-a-kind (NOAK) SFR NPP costs which are displayed in Figure 5.

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ACRONYMS

AACE	Association for the Advancement of Cost Engineering
ACI	American Concrete Institute
ACS	Auxiliary Cooling System
AHTR	Advanced High-Temperature Reactor
ALMR	Advanced Liquid-Metal Reactor
ANL	Argonne National Laboratory
APY	Annual Percentage Yield
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
B_4C	Boron Carbide
BDI	Boothroyd Dewhurst, Inc. (Purveyors of DFMA®)
BE	Better Experience
BFW	Boiler Feedwater
BCC	Base Capital Cost
BOAK	Between First-of-a-Kind & Nth-of-a-Kind
BOC	Beginning of Cycle
BOP	Balance of Plant
CapEx	Capital Expenditure
CC	Consumable Material Cost
CEPCI	Chemical Engineering Plant Cost Index
CF	Cash Flow
CIP	Cast-in-Place
CM	Construction Management
COA	Code of Accounts
COL	Combined Operating License
CPI	Consumer Price Index
CPI-U	CPI for All Urban Consumers
CRD	Control Rod Driveline
CS	Carbon Steel
CT	Cask Transporter
CW	Cooling Water
CWT	Cooling Water Tower
DCC	Direct Capital Cost

DFM-CC	Design for Manufacture Concurrent Costing (software commercially developed by BDI)
DFMA®	Design for Manufacture & Assembly®
DOE	United States Department of Energy
EBR	Experimental Breeder Reactor
EEDB	Energy Economic Database
EIS	Environmental Impact Statement
EMWG	Economic Modeling Working Group
ER	Environmental Report
FFTF	Fast Flux Test Facility
FHC	Fuel Handling Cell
FOAK	First-of-a-Kind
FSTB	Fuel Storage & Transfer Building
FTC	Fuel Transporter Cask
FTE	Full-Time Equivalent
G&A	General & Administrative
GE	General Electric
GEH	GE-Hitachi Nuclear Energy
GEM	Gas Expansion Module
GIF	Generation IV International Forum
HAA	Head Access Area
HALEU	High-Assay Low-Enriched Uranium
HCFM	High-Chromium Ferritic-Martensitic
HP	High Pressure
HTGR	High-Temperature Gas-Cooled Reactor
I&C	Instrumentation & Controls
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IDC	Interest During Construction
IES	Integrated Energy Systems
IHX	Intermediate Heat Exchanger
INL	Idaho National Laboratory
IRP	Integrated Resource Plan
IVSR	In-Vessel Storage Rack
IVTM	In-Vessel Transfer Machine
LCOE	Levelized Cost of Electricity

LEU	Low-Enriched Uranium
LMFR	Liquid Metal-Cooled Fast Reactor
LMTD	Log-Mean Temperature Difference
LP	Low Pressure
LWR	Light-Water Reactor
MAWP	Maximum Allowable Working Pressure
MAWT	Maximum Allowable Working Temperature
ME	Median Experience
MIG	Metal Inert Gas
MOC	Materials of Construction
MOX	Mixed Oxide
MR	Machine Rate
NEA	Nuclear Energy Agency
NI	Nuclear Island
NOAK	N^{th}-of-a-Kind
NPP	Nuclear Power Plant
NRC	United States Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
O&M	Operations & Maintenance
O&P	Overhead & Profit
ONE	US-DOE Office of Nuclear Energy
OpEx	Operating Expenditure
ORNL	Oak Ridge National Laboratory
PFD	Process Flow Diagram
PM	Project Management
PPI	Producer Price Index
PRISM	Power Reactor Innovative Small Module
PSC	Public Service Commission
PWHT	Post Weld Heat Treatment
PWR	Pressurized Water Reactor
R&D	Research & Development
RCCS	Reactor Cavity Cooling System
RE	Reactor Enclosure
ROM	Rough-Order-of-Magnitude
RSMeans	Robert Snow Means (purveyor of RSMeans construction cost data now owned by Gordian)

RVACS	Reactor Vessel Auxiliary Cooling System
SA	Strategic Analysis, Inc. or Surface Area
SAR	Safety Action Report
SFR	Sodium Fast Reactor
SG	Steam Generator
SMR	Small Modular Reactor
SS	Stainless Steel
SWU	Separative Work Unit
TCIC	Total Capital Investment Cost
TIG	Tungsten Inert Gas
TOC	Total Overnight Cost
TRU	Transuranic Waste
UIS	Upper Internals Structure
UOM	Units of Measure

First-Principles Cost Estimation of a Sodium Fast Reactor Nuclear Plant

1. INTRODUCTION

Rising atmospheric CO_2 concentrations and projections of their impact on the global climate is driving decarbonization of many industrial sectors that historically have relied mostly or entirely on fossil fuels for energy. As of 2021, electricity and thermal energy generation in the United States (US) accounted for approximately 63% of its total annual CO_2 emissions.[1] Unlike current conventional fossil-fuel-derived electrical and thermal energy, various net-zero or near-net-zero carbon-based energy technologies, such as solar and nuclear, offer large reduction in CO_2 emissions across all sectors. In particular, nuclear power plants (NPPs) are well suited to provide carbon-free electricity and thermal energy since these are relatively constant and stable energy sources offering high availabilities over large areas. However, many challenges currently limit expanding the deployment of nuclear solutions for energy such as technological, high costs, and long timeframes relative to the state-of-the-art fossil-fuel-based energy infrastructure currently in widespread use.

Average electricity costs from traditional reactor designs based on low-temperature water-cooling processes have historically been ~2023 US $0.06/kWh–2023 US $0.07/kWh with construction costs exacerbated by cost overruns and construction delays.[2] This is significantly higher than many other net zero-carbon energy technologies such as solar which can generate electricity at costs of around 2023 US $0.035/kWh and 2023 US $0.045/kWh for solar coupled with batteries as an electrical energy storage solution (without accounting for seasonal storage and system-wide costs).[3,4] To enhance the cost competitiveness of nuclear energy relative to other clean energy technologies, new and alternative strategies are required for the design and construction of these processes.

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1 U.S. Energy Information Administration, (EIA). Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA). *Homepage - U.S. Energy Information Administration (EIA).* [Online] April 2022. [Cited: February 19, 2023.] https://www.eia.gov/tools/faqs/faq.php?id=75&t=11#:~:text=What%20are%20U.S.%20energy%2Drelated,million%20metric%20tons%20in%202021.&text=Emissions%20from%20combustion%20of%20waste,types%20of%20geothermal%20power%20plants.

2 Association, World Nuclear. Nuclear Power Economics | Nuclear Energy Costs - World Nuclear Association. *World Nuclear Association.* [Online] August 2022. [Cited: February 20, 2023.] https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx.

3 U.S. Energy Information Administration, (EIA). U.S. Energy Information Administration - EIA - Independent Statistics and Analysis. *Homepage - U.S. Energy Information Administration (EIA).* [Online] March 31, 2022. [Cited: February 20, 2023.] https://www.eia.gov/outlooks/aeo/electricity_generation.php.

4 Bolinger, Mark, et al. Utility-Scale Solar, 2022 Edition. *Electricity Markets and Policy Group.* [Online] Berkeley Lab, September 2022. [Cited: February 20, 2023.] https://emp.lbl.gov/sites/default/files/utility_scale_solar_2022_edition_slides.pdf.

Small modular reactors (SMRs) allow for the standardization of system components, particularly the reactor design and fuel conformation, which presents the opportunity to capitalize on cost reduction from high-volume manufacturing.[5] Traditional nuclear plant design and construction has relied on site-built, in-field, and one-off construction and assembly approaches which requires a significant orchestration in simultaneous parallel efforts, often leading to very long project completion times and high probability of schedule overruns.[6] Alternatively, maximizing a factory and serial-build paradigm where practical allows for these components to become more readily manufacturable and "off-the-shelf", not only reducing their costs but also the installation and commissioning times.[7] Furthermore, standardization allows cost reductions related to refueling and storage of nuclear waste by a combination of designing for rapid and easier refueling, a common approach with streamlined approval for waste storage, and advanced reactors that consume or minimize radioactive waste.

SMRs also provide flexibility in power scaling as small numbers of these relatively low power reactors (nominally 300 MW_e and lower) can be combined in a "just-in-time" fashion to boost the system's energy capacity.[8] A scale-up attribute like this would be necessary to allow for flexible coupling of nuclear energy with various industrial processes that undergo their own constant and gradual expansion. This also offers substantial economic advantage since a more discrete capitalization of plant construction could be covered by actual realized revenue from simultaneously operating plants.

Sodium-cooled fast reactors (SFR) are a demonstrated nuclear technology with electrical power outputs of 10–864 MW_e and are expected to become mainstream nuclear reactor designs in the near-term.[9] Our cost analysis effort provides a detailed and first-principles-based cost estimation of a generalized SFR NPP. We estimate the costs of complete NPPs based on multiple parallel SM-SFRs having a nominal electrical power output of 165 MW_e. Since cost-optimal configurations of NPPs depend on many factors, we develop flexible cost models that can be extended to variations in reactor size, power block definition, reactor quantity and plant size, and various site configurations. Reactor and other critical nuclear grade equipment costs are modeled using first-principles cost estimation techniques such as design for manufacture and assembly® (DFMA®).

5 Nuclear Energy Agency (NEA). *Small Modular Reactors: Challenges and Opportunities.* s.l. : Organization for Economic Cooperation and Development, 2021. NEA No. 7560.

6 *Sources of Cost Overrun in Nuclear Power Plant Construction Call for a New Approach to Engineering Design.* Philip Eash-Gates, Magdalena M. Klemun, Goksin Kavlak, James McNerney, Jacopo Buongiorno, Jessika E. Trancik. s.l. : Elsevier, 2020, Joule, Vol. 4, pp. 2348-2373.

7 Office of Nuclear Energy. Benefits of Small Modular Reactors (SMRs) | Department of Energy. *Office of Nuclear Energy | Department of Energy.* [Online] U.S. Department of Energy, 2023. [Cited: February 23, 2023.] https://www.energy.gov/ne/benefits-small-modular-reactors-smrs.

8 Mark Sullivan, Alex Pasternack. Small Nuclear Reactors: What to Know About the New Technology. *Fast Company | Business News, Innovation, Technology, Work Life and Design.* [Online] Fast Company & Inc., August 10, 2022. [Cited: February 23, 2023.] https://www.fastcompany.com/90777719/new-nuclear-reactors-finally-get-regulators-nod-but-they-still-have-a-lot-of-proving-to-do.

9 Accessed July 27, 2023, from https://world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors.aspx.

Other direct costs for plant items such as buildings are modeled using geometry and materials-driven commercial construction cost calculation methods which use labor-time and equipment cost correlations derived from empirical data. Indirect costs are developed as percentages of direct costs based on commercial construction data, while supplemental costs, such as the initial nuclear fuel loaded within the reactor, are modeled based on first-principles methods and built up from individual materials and processing step costs. Annualized costs are determined from division-level staffing estimates and typical nuclear financing procedures. The combination of individual cost models into a total financial analysis of the NPP can be a powerful tool in understanding the importance and significance of changes to any one variable. Finally, the cost results of our analysis of an NPP with 1 to 10 reactors are organized and categorized into a nuclear code of accounts (COA) data structure developed by Idaho National Laboratory (INL).[10]

2. BASE CASE DESIGN OF SODIUM-COOLED FAST REACTOR NUCLEAR POWER PLANT

The basis of design for a representative SFR NPP is defined from non-proprietary information and data available for use in the public domain. The design basis is meant to be general and not aligned with any single design or commercial effort. Nonetheless, the generic SFR design draws heavily from design specifications for the MOD-A PRISM SFR developed by GE-Hitachi (GEH) as a demonstration scale reactor in the 1980–2016 timeframe before being halted in 2022.[11] We note that this base reactor design is not necessarily an optimized commercial reactor, but rather a reference design point that has significant detail published in the public sphere that we use to establish a cost estimate for a general reactor design.

Other significant influences on the generic design are the other variants of PRISM, the Natrium SFR, and, to a lesser extent, the pressurized water reactor12 (PWR12) light water reactor (LWR) (with costing based on the Energy Economic Data Base [EEDB]). We use the substantial design details available in the public domain to inform our conceptualization of a representative SFR. We select the smallest reactor size and style as our base case to anchor our cost estimation and project the cost at different reactor and facility sizes by applying cost scaling relationships.

2.1 Process Configuration & Definition

The baseline SFR NPP design configuration consists of three main levels of modularization: (1) reactor module; (2) power block; and (3) plant. Table 1 lists the main reference design parameters and equipment contained within each process level used in defining our base case. Figure 1 provides a simplified process flow diagram (PFD) of the base configuration devised for the power block of the general SFR NPP showing the main equipment contained within this block while Figure 2 gives a basic PFD for the base reactor module. The following subsections describe in more detail each process level configuration and the equipment contained within.

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10 A. Abou-Jaoude, *et al.* Expansion of Cost Algorithm and Technoeconomic Assessment Capabilities. Systems Analysis & Integration Campaign, *Idaho National Laboratory* **June 2022**, *INL/RPT-22-67852*.

11 GE-Hitachi. Attachment 2-Demonstration Sodium-Cooled Fast Reactor GE-PRISM. **2016**. *https://art.inl.gov/ART Document Library/Advanced Demonstration and Test Reactor Options Study/Attachment_2_GE_Hitachi_SFR_DR.pdf*, Brian S. Triplett, Eric P. Loewen, & Brett J. Dooies. PRISM: A Competitive Small Modular Sodium-Cooled Reactor. *Nuclear Technology* **2010**, *178(2)*, 186-200. *https://doi.org/10.13182/NT178-186*, U.S. NRC PSER for the PRISM Liquid-Metal Reactor. *NUREG-1368 Final Report* **1994**. *https://www.nrc.gov/docs/ML0634/ML063410561.pdf*, GE-Advanced Nuclear Technology. PRISM-Preliminary Safety Information Document. *US DOE* **1987**, *Vol. 1–6*, Ch. 1–17 & Appendix A–G.

Table 1. List of primary equipment and basic design data considered within our cost analysis of a sodium-cooled fast reactor nuclear power plant.

Design Parameter	UOM	Base Case Value
Reactor Module		
Type	-	Coolant Pool
Coolant	-	High-Purity Sodium Metal
Nuclear Fuel		
Type	-	Low-Enriched Uranium Metal Alloy
Quantity	kg	15,722
Enrichment	wt% of U	19.75
Thermal Output Power, Net	MW_t	471
Eq. Electrical Output Power, Net	MW_e	165
Equipment		
Core	no.	1
Intermediate Heat Exchanger	no.	2
Primary Coolant Pump	no.	4
Operating Conditions		
Temperature		
Hot Pool	°F	930
Cold Pool	°F	662
Pressure	PSIG	0–3
Power Block		
Working Fluid	-	High-Pressure Steam
Working Fluid Supply Pressure	PSIG	1,785
Electrical Output Power, Net	MW_e	165–622
Power Conversion Efficiency, Net	%	35–37
Equipment		
Reactor Module	no.	1–3
Steam Generator	no.	1–3
Intermediate Sodium Pumps	no.	2–6
Miscellaneous Steam Equipment	no.	Various
Steam Turbine Generator	no.	1
Cooling Water Tower	no.	1
Plant		
Electrical Output Power, Net	MW_e	165–3,108
Equipment		
Reactor Module	no.	1–10
Power Block	no.	1–5

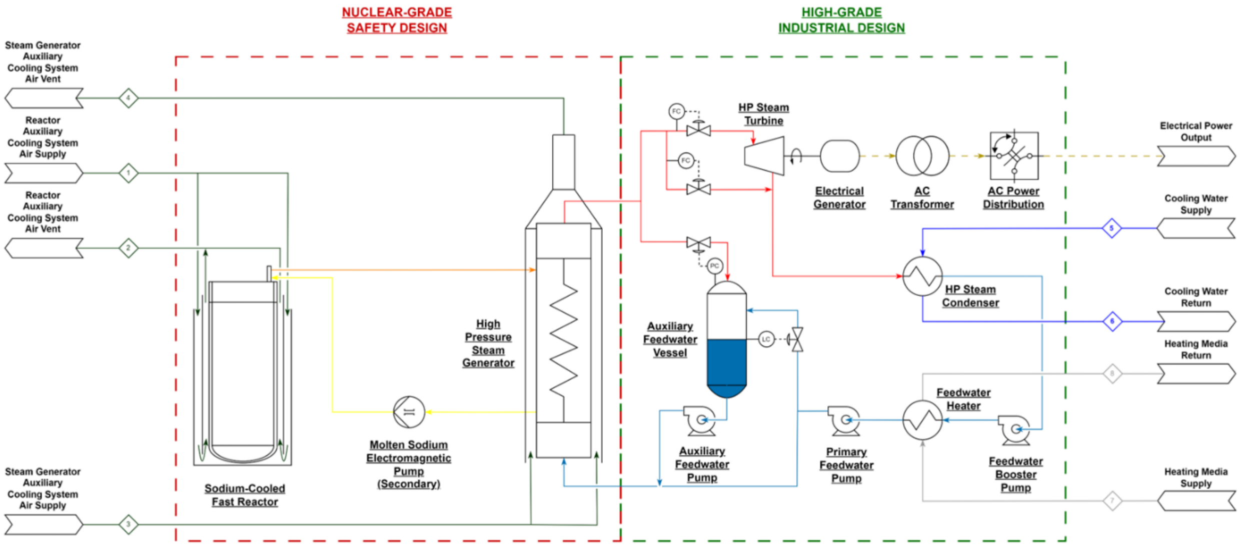

Figure 1. Simplified process flow diagram of a typical power block for a sodium-cooled fast reactor nuclear power plant depicting the closed reactor, intermediate heat management fluid, working fluid, and power conversion subsystems.

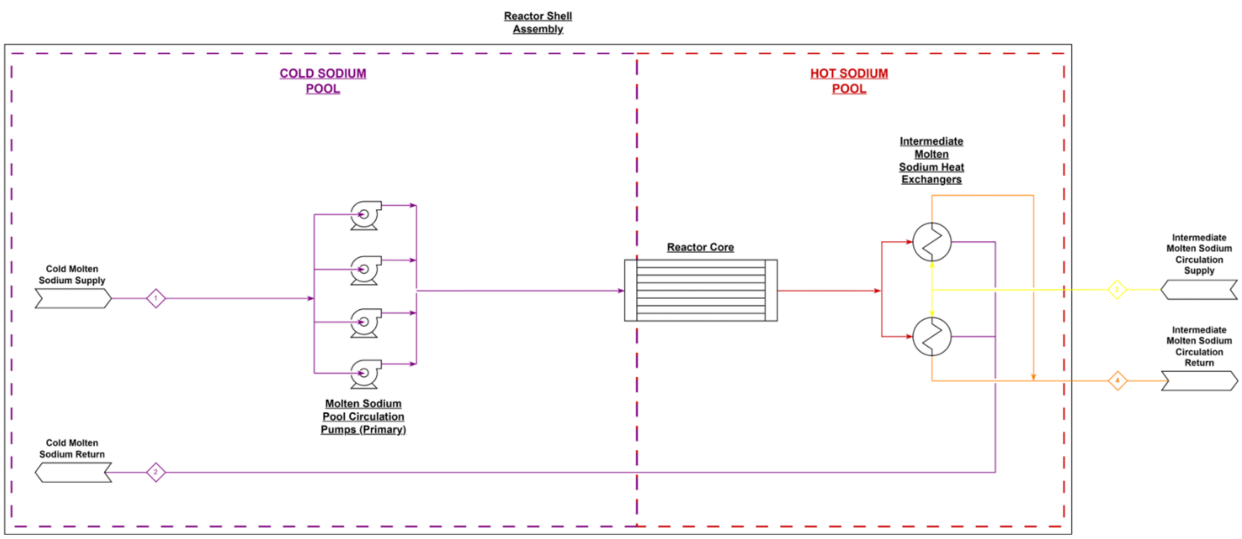

Figure 2. Simplified process flow diagram of a typical pool-type sodium-cooled fast reactor depicting the internal equipment contained and operated within the reactor shell assembly including the primary sodium pumps, reactor core, and intermediate sodium exchangers. Two sodium pools (cold and hot) are stratified across the core each containing the primary sodium pumps (cold pool) and the intermediate heat exchangers (hot pool).

2.1.1 Reactor Modules

We assume and use a pool-type SFR design for reactor modules which are completely sealed and fully contain the internal primary liquid sodium coolant that manages the heat evolving from the reactor core. The sodium coolant is stratified into two separated pools, hot and cold, with the hot pool sitting in the upper and inner region of the reactor and the cold pool situated toward the bottom and against the walls of the reactor vessel. Cold sodium coolant is pumped through the core using multiple submerged primary sodium pumps (Table 2) each having a mechanical shaft driven by induction motors sitting on the outside of the top closure head of the reactor shell assembly. The reactor core is positioned in the bottom half of the reactor with this mechanically supported by beams that sit against the inside of the bottom head of the reactor vessel. After flowing through and leaving the core, heated primary sodium enters the upper portion of the reactor and is pulled through to the side intermediate heat exchangers (IHXs) (Table 3) to indirectly contact and exchange heat with the intermediate sodium coolant loop pumped into the reactor vessel by means of the IHX tubeside.

Table 2. Primary sodium pump design parameters.

Parameter	UOM	Base Case Value
Quantity	no./reactor	4
Type	-	Centrifugal
Configuration	-	Vertical, End Suction
Design Conditions		
Flow	US GPM	11,384
Pressure		
Suction/Inlet	PSIG	0
Discharge/Outlet	PSIG	120
Temperature		
Suction/Inlet	°F	715
Discharge/Outlet	°F	715
Power	kW_e	1,300
Overall Efficiency, Net	%	70
Materials of Construction	-	316 SS
Service Life	years	Undefined
Weight	kg	5,525

Table 3. Intermediate heat exchanger design parameters.

Parameter	UOM	Base Case Value
Quantity	no./reactor	2
Type	-	Shell & Tube
Orientation	-	Vertical
Cold Side Design		
Exchanger Side		Tube
Fluid Service	-	Intermediate Sodium
Flow	kg/hr	4,127,691
Pressure		
Inlet	PSIG	110
Effluent	PSIG	91
Temperature		
Inlet	°F	574
Effluent	°F	864
Materials of Construction	-	316 Stainless Steel (SS)

Parameter	UOM	Base Case Value
Hot Side Design		
Exchanger Side		Shell
Fluid Service	-	Primary Sodium
Flow	kg/hr	4,513,245
Pressure		
Inlet	PSIG	15
Effluent	PSIG	11
Temperature		
Inlet	°F	930
Effluent	°F	662
Materials of Construction	-	316 Stainless Steel (SS)
Thermal Duty	MW_t	238
Service Life	years	60
Weight	kg	22,100

The reactor shell assembly is composed of three primary components (Table 4). All sodium is normally fully contained within the reactor vessel which is a cylindrical pressure vessel with bottom elliptical head. The containment vessel sits around and full encases the reactor vessel acting as the final containment for coolant leak accidents/events from the reactor vessel and to provide further radiological isolation. Both the reactor and containment vessels are attached to and mechanically supported by the top, flat closure head which also directly supports much of the internal equipment such as the primary sodium pumps and intermediate heat exchangers.

Table 4. Sodium-cooled fast reactor module shell assembly design parameters.

Reactor Shell Assembly Component	UOM	Base Case Value
Vessel		
Design Conditions		
MAWP	PSIG	20
MAWT	°F	900
Service Life	years	60
Body		
Geometry	-	Cylindrical, Circular
Dimensions		
Width/Diameter (Outer)	ft	18.83
Length/Height (T/T)	ft	54.19
Thickness	in	2
Materials of Construction	-	316 Stainless Steel (SS)
Bottom Head		
Geometry	-	2:1 Elliptical
Dimensions		
Width/Diameter (Outer)	ft	18.83
Length/Height (Outer)	ft	4.71
Thickness	in	2
Materials of Construction	-	316 SS
Weight	kg	133,685
Containment Vessel		
Design Conditions		
MAWP	PSIG	20
MAWT	°F	800
Service Life	years	60
Body		
Geometry	-	Cylindrical, Circular
Dimensions		
Width/Diameter (Outer)	ft	19.83
Length/Height (T/T)	ft	54.59
Thickness	in	1
Materials of Construction	-	316 SS
Bottom Head		
Geometry	-	2:1 Elliptical
Dimensions		
Width/Diameter (Outer)	ft	19.83
Length/Height (Outer)	ft	4.96
Thickness	in	1
Materials of Construction	-	316 SS
Weight	kg	73,177
Top Closure Head		
Design Conditions		
MAWP	PSIG	20
MAWT	°F	300
Service Life	years	60
Body		
Geometry	-	Cylindrical, Circular, Flat
Dimensions		
Width/Diameter (Outer)	ft	20.83
Length/Height (T/T)	ft	-
Thickness	in	12
Materials of Construction	-	316 SS
Weight	kg	37,015

2.1.2 Power Blocks

The next highest modular level within the process configuration are power blocks. Power blocks contain multiple reactor modules and multiple steam generators which supply a single steam-to-electrical power turbine generator for producing electricity. A single steam generator is assumed to be paired with one reactor module where the dual-loop intermediate sodium coolant carries heat away from the reactor to the steam generator to produce high-pressure (HP) steam (Table 5). Two intermediate sodium coolant pumps are used to supply the two IHXs within each reactor module (Table 6). HP steam generated within each steam generator is collected within steam drums before being routed to the electrical power generator turbine (Table 7). Electrical power generation is carried out in a multi-staged turbine where the primary power is produced in the first, HP stage followed by a second lower-pressure (LP) stage (Table 8).

Table 5. Steam generator design parameters.

Parameter	UOM	Base Case Value
Quantity	no./reactor	1
—	no./power block	1–3
Type	—	Helical Coil Shell & Tube
Orientation	—	Vertical
Cold Side Design		
Exchanger Side		Tube
Fluid Service	-	Boiler Feedwater/High Pressure Steam
Flow	kg/hr	730,283
Pressure		
Inlet	PSIG	2,015
Effluent	PSIG	1,786
Temperature		
Inlet	°F	380
Effluent	°F	830
Materials of Construction	—	Low Alloy Steel (2 ¼ Cr, 1 Mo)
Hot Side Design		
Exchanger Side		Shell
Fluid Service	-	Intermediate Sodium
Flow	kg/hr	825,538
Pressure		
Inlet	PSIG	90
Effluent	PSIG	13
Temperature		
Inlet	°F	860
Effluent	°F	578
Materials of Construction	—	Low Alloy Steel (2 ¼ Cr, 1 Mo)
Thermal Duty	MW_t	479
Service Life	years	60
Weight	kg	464,760

Table 6. Intermediate sodium pump design parameters.

Parameter	UOM	Base Case Value
Quantity	no./reactor	2
—	no./power block	2–6
Type	—	Centrifugal
Configuration	—	Horizontal, End Suction
Design Conditions		
Flow	US GPM	20,823
Pressure		
Suction/Inlet	PSIG	13
Discharge/Outlet	PSIG	133
Temperature		
Suction/Inlet	°F	625
Discharge/Outlet	°F	625
Power	kW_e	2,000
Overall Efficiency, Net	%	70
Materials of Construction	—	316 SS
Service Life	years	60
Weight	kg	10,000

Table 7. Steam generator steam drum design parameters.

Parameter	UOM	Base Case Value
Quantity	no./steam generator	1
—	no./power block	1–3
Orientation	—	Vertical
Design Conditions		
MAWP	PSIG	Undefined
MAWT	°F	925
Service Life	years	60
Body		
Geometry	—	Cylindrical, Circular
Dimensions		
Width/Diameter (Outer)	ft	12.00
Length/Height (T/T)	ft	34.00
Thickness	in	5
Materials of Construction	—	A516 GR70 Carbon Steel (CS)
Heads		
Geometry	—	2:1 Elliptical
Dimensions		
Width/Diameter (Outer)	ft	12.00
Length/Height (Outer)	ft	3.21
Thickness	in	5
Materials of Construction	—	A516 GR70 (CS)
Weight	kg	136,356

Table 8. Steam-to-electrical power turbine generator design parameters.

Parameter	UOM	Base Case Value
Quantity	no./power block	1
Type	—	Axial
Number of Stages	—	2
Configuration		
High-Pressure	no.	1
Low-Pressure	no.	2
Generator	no.	1
Steam Inlet Conditions		
Temperature	°F	541
Pressure	PSIG	942
Power, Output (Net)	MW_e	165
Overall Efficiency, Net	%	35–37
Materials of Construction	—	SS
Service Life	years	60
Weight	kg	252,782

A condenser is sequentially connected to the steam effluent from the steam turbine to fully condense all steam leaving the turbine so this can be reconditioned and transported back to the steam generator for reheating and repressurization (Table 9).

Table 9. Steam turbine condenser design parameters.

Parameter	UOM	Base Case Value
Quantity	no./turbine	1
	no./power block	1
Type	—	Shell & Tube
Thermal Duty	MW_t	306
Materials of Construction	—	CS
Service Life	years	60
Weight	kg	2,665,199

Other steam and boiler feedwater management equipment such as deaertors, blowdown and flash drums, boiler feedwater and steam condensate pumps, and boiler feedwater preheaters are also situated within the power block level and associated with a single turbine generator. Also, in the power block level are the required cooling subsystems which are assumed to be comprised of cooling water towers (CWTs), CW circulation pumps, and other miscellaneous equipment required for maintaining the CW quality (Table 10).

Table 10. Cooling water system design parameters.

Parameter	UOM	Base Case Value
Quantity	no./power block	1
Type	—	Forced Convection, Cross-Flow
Thermal Duty	MW_t	306
Service Life	years	60

2.1.3 Plant Level

At the plant level, multiple power blocks are integrated in parallel and are supported by plant-level components such as the controls building, electrical power switchyard, wastewater treatment facility, and other buildings and site structures (Table 11). The configuration and layout of the site of our base design case follows the conventional arrangement required for all NPPs, where nuclear safety grade site elements are segregated and isolated form non-nuclear elements and situated on a "nuclear island" (NI) construct. To estimate total site requirements, particularly building and area sizing and layout, we rely on data included and detailed in the reference media we use to develop our base SFR design case.[12] This data consists of detailed footprints, site structure and area arrangements, and boundary definitions from which we are able to ascertain dimensions for certain buildings, surface spaces such as roadways, parking lots, and other open areas, and their separation distances. The plant basis for this available site layout and dimensioning is for a nine-reactor, three-power block plant having a net power generation of 1,485 MW_e (see Appendix A). Total land space is also estimated from this information which allows us to establish the land requirements for the entire site including the required regulatory safety buffer area. For this plant basis, a total plant acreage is estimated to be about five acres for the facility proper excluding additional space devoted to outside battery limit separation and buffering.

We further use this information to determine the proportion of site structures that fall within the NI boundary relative to those that are outside, helping us determine the concentration of nuclear grade construction required for plant site structures. Furthermore, we use this point design data and other design specifications pertaining to the plant equipment and personnel that we establish and assume, to estimate building dimensions and spacing for other plant sizes.

Table 11. Plant-level components including sitewide buildings and structures.

Description of Site Structures & Buildings	Design Grade
Security Building & Gatehouse	Non-Nuclear
Reactor Service Buildings	Nuclear Safety
Radwaste Building	Nuclear Safety
Fuel Service Building	Nuclear Safety
Control Building	Nuclear Safety
Administration Building	Non-Nuclear
Operation & Maintenance (O&M) Center	Non-Nuclear
Storage Buildings	Non-Nuclear
Maintenance Shop	Non-Nuclear
Foundations for Outside Equipment & Tanks	Non-Nuclear
Balance of Plant Service Building	Non-Nuclear
Wastewater Treatment Building	Non-Nuclear
Emergency & Start-Up Power Systems	Non-Nuclear
Warehouse	Non-Nuclear
Railroad Tracks (Tunnel)	Nuclear Safety
Roads & Paved Areas	Non-Nuclear
Reactor Receiving & Assembly Building	Nuclear Safety
Training Center	Non-Nuclear
Special Materials Unloading Facility	Nuclear Safety
Dry Cast Storage Area	Nuclear Safety
Crane Operating Area	Nuclear Safety
Fencing	Nuclear Safety & Non-Nuclear
Switchyard	Non-Nuclear

[12] GE-Advanced Nuclear Technology. PRISM-Preliminary Safety Information Document. *US DOE-DE-ACO3-89SF17445* **1987**–**1993**, *6*(App. G), G.4.14-11. *https://www.nrc.gov/docs/ML0828/ML082880400.pdf*.

2.2 Reactor Fuel Configuration & Definition

Fast-neutron reactors (or simply fast reactors) require a fuel that is relatively rich in fissile material. The two most common fast reactor fuels are: (1) oxide fuel in the form of uranium oxide (UO_2) or mixed oxide (MOX); and (2) metal fuel in the form of U-Zr or U-Pu-Zr. SFR's have been extensively studied in the past and there has been considerable testing conducted on metal-alloy fuels. This study assumes the use of metal alloy fuel for compatibility with the sodium coolant, desirable thermomechanical properties, and relative ease of fabrication.[13,14] In particular, U-Zr is selected since it utilizes unirradiated uranium which allows for direct contact handling during fuel fabrication and has near-term applicability as opposed to recycled plutonium or uranium.

The beginning-of-cycle (BOC) core inventory of U-Pu-Zr fuel for a 471 MW_t SFR was used from similar SFR systems designed previously.[15] However, unlike these past systems, modern concepts are expected to rely exclusively on high-assay low-enriched uranium (HALEU) while excluding plutonium and transuranic waste (TRU) in their inventory. Hence, the Pu-based fuel composition and core configuration in PRISM MOD-A must be revised to utilize HALEU. According to a recent study of reactor neutronics, a reactor concept with significant leakage requires 45% less fissile mass if using ^{239}Pu compared to ^{235}U.[16] Other fissile isotopes, such as ^{241}Pu, are assumed to be similar to ^{235}U such that a 1:1 replacement of ^{241}Pu for ^{235}U is possible. Based on these approximations, we estimate the required increase in fissile fuel loading to achieve this criticality utilizing HALEU instead of the fuel composition typically proposed for most historic SFR designs which contains transuranics.

The BOC core fuel inventory for our base size SFR is determined to be 15,722 kg of total fuel. Using the isotope breakdowns for the non-HALEU fuel reported in the past design data that we use to establish our current plant design basis, we estimate that replacing the specified ^{239}Pu and ^{241}Pu with ^{235}U at the minimum replacement ratios of 1.45:1 and 1:1, respectively, to ensure criticality within an HALEU fuel, a total of 1,744 kg ^{235}U corresponding to ~11.59 wt% ^{235}U is required in the core. Since this overall core composition is below our assumed maximum enrichment amount of 19.75% for the HALEU we propose to model in our base SFR, it should be possible from a neutronic standpoint to reduce the number of fuel assemblies by about 41%. However, to simplify our work (i.e., to avoid performing detailed and rigorous thermal hydraulic evaluations) and ensure we produce a conservative estimate, the same amount of fuel and fuel assemblies are kept within the core of our model reactor.

Following past core designs and configurations for SFRs, we assume two types of fuel assemblies are included within the core. The main driver fuel assemblies contain the fully enriched HALEU fuel having an enrichment of 19.75 wt% ^{235}U while the other blanket fuel assemblies are filled with depleted uranium obtained as a by-product from the uranium enrichment process. Both the U-Pu-Zr fuel case and the adjusted U-Zr fuel case are given in Table 12. The U-Zr fuel case is used for all cost estimation in this report, while the U-Pu-Zr is included for reference only. Note that the reactor core design and refueling strategy assumed in this study differ from that assumed in the PRISM MOD-A configuration developed by GE-Hitachi (GEH), leading to a different initial core inventory.[17] Thermal calculations to validate the BOC core inventory for this reactor design is out of scope for this study. Therefore, the assumed core inventory mass is used for general cost estimation only.

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13 Dubberley, A. E.; Boardman, C. E.; Yoshida, K.; Wu, T. S-PRISM Oxide and Metal Fuel Cord Designs. *Proc. 8th Int. Conf. Nuclear Engineering (ICONE-8)*, Baltimore, Maryland, **April 2– 6, 2000**.

14 Dubberley, A. E.; Wu, T.; Kubo, S. S-PRISM High Burnup Metal-Fuel Core Design. *Proc. Int. Conf. Advancement of Nuclear Power Plants (ICAPP '03)*, Cordoba, Spain, **May 4–7, 2003**.

15 GE-Advanced Nuclear Technology. PRISM-Preliminary Safety Information Document. *US DOE* **1987**, *Vol. 1*, Ch. 1–4.

16 Heidet, F.; Hill, R. N. Reactor Neutronics: Impact of Fissile Material. Nuclear Science and Engineering **2017**, *187 (2)*, 202–211. *https://doi.org/10.1080/00295639.2017.1312933*.

17 GE-Hitachi. Attachment 2-Demonstration Sodium-Cooled Fast Reactor GE-PRISM. **2016**. *https://art.inl.gov/ART Document Library/Advanced Demonstration and Test Reactor Options Study/Attachment_2_GE_Hitachi_SFR_DR.pdf*

Table 12. Beginning-of-cycle core loading for PRISM MOD-A versus our hypothetical high-assay low-enriched uranium fuel utilized in our devised base design sodium-cooled fast reactor.

Beginning-of-Cycle Inventory	UOM	U-Pu-Zr Fuel	U-Zr Fuel
Thermal Power	MW_t	471	471
	—	—	—
Core Inventory			
Fissile Pu	kg	1,268	0
Total Pu	kg	1,634	0
Fissile U	kg	22	1,744
Total U	kg	14,088	15,722
Total HM	kg	15,722	15,722
Driver Fuel			
Material	—	U-Pu-10%Zr	U-10%Zr
Enrichment	%	20.95%[a]	19.75%[b]
Fissile Pu	kg	947	0
Total Pu	kg	1,294	0
Fissile U	kg	6[c]	1,730
Total U	kg	3,227	8,760
Total HM	kg	4,521	8,760
Fuel Life	month	60	60
Refueling Interval	month	20	20
Refueling Fraction	—	0.333	0.333
Number of Fuel Assemblies	#	54	54
Blanket Fuel			
Material	—	Dep. U-10%Zr	Dep. U-10%Zr
Enrichment	%	0.2%	0.2%
Fissile U	kg	16	14
Total U (Depleted)	kg	10,862	6,962
Blanket Life	month	100	100
Refueling Interval	month	100	100
Refueling Fraction	—	1.000	1.000
Number of Blanket Assemblies	#	45	45

[a]Total fissile in total heavy metals (HMs).
[b]Total ^{235}U in total uranium.
[c]Assumes natural uranium.

3. COST ASSIGNMENT & ORGANIZATION BY NUCLEAR CODE OF ACCOUNTS

We include and categorize costs for each element of the total plant cost based on the nuclear COA recently devised by INL.[18] This COA contains many levels of depth to account for, categorize, and detail costs. As shown in Table 13, we primarily focus and report costs on the top-two account levels, although some costs are estimated at deeper subaccount levels. Code descriptions are drawn directly from INL with only minor adjustment for clarity.

Table 13. Top-two levels of the nuclear code of accounts used in this project for categorizing and organizing cost bases and results developed by Idaho National Laboratory.

Account	Title	Description
10	**Capitalized Pre-Construction Costs**	**Purchase of new land for the reactor site & land needed for any co-located facilities such as dedicated fuel cycle facilities. Costs for acquisition of land rights should be included. This category does not include siting costs such as geo-technical work (Account 211) or the preparation of environmental documentation (Account 16).**
11	Land & Land Rights	Costs associated with obtaining all site related permits for subsequent construction of the permanent plant.
12	Site Permits	Costs associated with obtaining plant licenses for construction & operation of the plant.
13	Plant Licensing	Costs associated with obtaining all permits for construction & operation of the plant.
14	Plant Permits	Costs associated with plant studies performed for the site or plant in support of construction & operation of the plant.
15	Plant Studies	Costs associated with production of major reports such as an environmental impact statement or the safety analysis report.
16	Plant Reports	Costs that are incurred by owner prior to start of construction & may include public awareness programs, site remediation work for plant licensing, etc.
17	Other Pre-Construction Costs	Assessment of additional cost necessary to achieve the desired confidence level for the pre-construction costs not to be exceeded.
18	Community Outreach & Education	—
19	Contingency on Pre-Construction Costs	—
20	**Capitalized Direct Costs**	**—**
21	Structures & Improvements	Covers costs for civil work and civil structures, mostly buildings, exclusive of those for the cooling towers.
22	Reactor System	Most dependent on the reactor technology being considered, because the subaccount descriptions & costs depend heavily on the coolant used & whether the subsystems are factory-produced or constructed onsite. For today's light-water reactors (LWRs), the entire nuclear steam supply system (NSSS) can be purchased as a unit from a reactor vendor. The reactor manufacturer may have its own COA structure for all the NSSS components. The sublist under this account attempts to be as general as possible. The initial & reload fuel cores are not included here.
23	Energy Conversion System	Assumes that electricity is the primary product. The categories below apply mostly to a steam-driven turbine; however, similar categories would exist for gas-driven turbines. This account includes all process equipment & systems associated with the plant output. For other plants, appropriate coding is required to separate the plant into logical & significant plant systems.
24	Electrical Equipment	Accounts 21 through 23 all have interfaces with the power plant electrical service system & its associated equipment. This equipment is located both inside & outside the main reactor/BOP buildings. (Note: The IAEA account system normally puts all I&C costs in this account. The EMWG decided to retain I&C costs within the accounts that require I&C equipment, mainly Account 227 & 236.)
25	Heat Rejection System	Heat rejection equipment such as circulating water pumps, piping, valves, & cooling towers, which may be required even if the plant does not produce electricity. (This is Account 26 in the original EEDB [ORNL, 1988].)
26	Miscellaneous Equipment	Covers items not in the categories above. (This is Account 25 in the original EEDB.)
27	Special Materials	Non-fuel items such as heavy water, other special coolants, & salts needed before start-up.

[18] A. Abou-Jaoude, *et al.* Expansion of Cost Algorithm and Technoeconomic Assessment Capabilities. Systems Analysis & Integration Campaign, *Idaho National Laboratory* **June 2022**, *INL/RPT-22-67852*.

Account	Title	Description
28	Simulator	Development of new simulators for training operators.
29	Contingency on Direct Costs	Assessment of additional cost that might be necessary to achieve the desired confidence level for the direct costs not to be exceeded. Contingency is usually applied at an aggregated level, although its determination may include applying contingencies to individual high-cost-impact items in the estimate. There are both deterministic & probabilistic methods for calculating its value. Deterministic methods require assessment of the maturity & complexity of the various aspects of the project & cost weighting of the base estimate. The probabilistic approach relies on statistical methods to determine uncertainty ranges for the key cost parameters affecting the base plus owner's costs. Contingency must have a statistical level of confidence associated with it (e.g., an 80% chance that a total cost will not overrun the base plus contingency sum).
30	**Capitalized Indirect Services Costs**	—
31	Factory & Field Indirect Costs	Cost of construction equipment rental or purchase, temporary buildings, shops, laydown areas, parking areas, tools, supplies, consumables, utilities, temporary construction, warehousing, & other support services. Account 31 also includes: - Temporary construction facilities, such as site offices, warehouses, shops, trailers, portable offices, portable restroom facilities, temporary worker housing, & tents. - Tools & heavy equipment used by craft workers & rented equipment such as cranes, bulldozers, graders, and welders. Typically, equipment with values of less than $1,000 are categorized as tools. - Transport vehicles rented or allocated to the project, such as fuel trucks, flatbed trucks, large trucks, cement mixers, tanker trucks, official automobiles, buses, vans, & light trucks. - Expendable supplies, consumables, & safety equipment. - Cost of utilities, office furnishings, office equipment, office supplies, radio communications, mail service, phone service, & construction insurance. - Construction support services, temporary installations, warehousing, material handling, site cleanup, water delivery, road & parking area maintenance, weather protection & repairs, snow clearing, & maintenance of tools & equipment.
32	Factory & Construction Supervision	Covers direct supervision of construction (craft-performed) activities by the construction contractors or direct-hire craft labor by the A/E contractor. The costs of the craft laborers themselves are covered in the labor-hours component of the direct cost in Accounts 21 through 28 or in Account 31. Covers work done at the site in what are usually temporary or rented facilities. It includes non-manual supervisory staff, such as field engineers & superintendents. Other non-manual field staff are included with Account 38, PM/CM Services Onsite.
33	Commissioning & Start-Up Costs	Costs incurred by the A/E, reactor vendor, other equipment vendors, & owner or owner's representative for start-up of the plant including: - Start-up procedure development - Trial test run services - Commissioning materials, consumables, tools, & equipment
34	Demonstration Test Run	Services necessary to operate the plant to demonstrate plant performance values & durations, including operations labor, consumables, spares, & supplies.
35	Design Services Offsite	Covers engineering, design, & layout work conducted at the A/E home office and the equipment/reactor vendor's home office. Often pre-construction design is included here. These guidelines use the IAEA format for a standard plant (& equipment) design/construction/start-up only & not the FOAK design & certification effort. (FOAK work is in the one-time deployment phase of the project & not included in the standard plant direct costs.) Design of the initial full size (FOAK) reactor, which will encompass multiple designs at several levels (pre-conceptual, conceptual, preliminary, etc.), will be a category of its own under FOAK cost. Also includes site-related engineering & engineering effort (project engineering) required during construction of particular systems, which recur for all plants, & quality assurance costs related to design.
36	PM/CM Services Offsite	Covers the costs for project management & management support on the above activities (Account 31) taking place at the reactor vendor, equipment supplier, & A/E home offices.
37	Design Services Onsite	Same items as in Account 35, except that they are conducted at the plant site office or onsite temporary facilities instead of at an offsite office. Also includes additional services such as purchasing & clerical services.
38	PM/CM Services Onsite	Covers costs for project management & construction management support on the above activities taking place at the plant site. Includes staff for quality assurance, office administration, procurement, contract administration, human resources, labor relations, project control, & medical & safety-related activities. Costs for craft supervisory personnel are included in Account 32.

Account	Title	Description
39	Contingency on Indirect Services Cost	Assessment of additional cost necessary to achieve the desired confidence level for the support service costs not to be exceeded.
40	**Capitalized Owner's Costs**	—
41	Staff Recruitment & Training	Costs to recruit & train plant operators before plant start-up or commissioning activities (Account 33), or demonstration tests (Account 34).
42	Staff Housing	Relocation costs, camps, or permanent housing provided to permanent plant operations & maintenance staff.
43	Staff Salary-Related Costs	Taxes, insurance, fringes, benefits, and any other salary-related costs.
44	Other Owner's Costs	—
49	Contingency on Owner's Costs	Assessment of additional costs necessary to achieve the desired confidence level for the capitalized owner's costs not to be exceeded.
50	**Capitalized Supplementary Costs**	—
51	Shipping & Transportation Costs	Shipping and transportation costs for major equipment or bulk shipments with freight forwarding.
52	Spare Parts	Spare parts furnished by system suppliers for the first year of commercial operation. It excludes spare parts required for plant commissioning, start-up, or the demonstration run.
53	Taxes	Taxes associated with the permanent plant, such as property tax, to be capitalized with the plant.
54	Insurance	Insurance costs associated with the permanent plant to be capitalized with the plant.
55	Initial Fuel Core Load	Covers fuel purchased by the utility before commissioning, which is assumed to be part of the Total Capitalized Investment Cost (TCIC). In the U.S., the initial core is not usually included in the design/construction (overnight) cost sum to which interest during construction (IDC; see below) is added. Because the first core, however, will likely have to be financed along with the design/construction/start-up costs, its cost is included in overnight costs as part of capital at risk before revenues. A new account added to the modified IAEA account system.
58	Decommissioning	Cost to decommission, decontaminate, and dismantle the plant at the end of commercial operation, if it is capitalized with the plant.
59	Contingency on Supplementary Costs	Assessment of additional cost necessary to achieve a desired confidence level for the capitalized supplementary costs not to be exceeded. The contingency for the initial core load should not be applied to this item, because the contingency is already embedded in the fuel cycle costs from the fuel cycle model.
60	**Capitalized Financial Costs**	—
61	Escalation	Typically excluded for a fixed year, constant dollar cost estimate, although it could be included in a business plan, a financing proposal, or regulatory-related documents.
62	Fees	Fees or royalties that are to be capitalized with the plant.
63	Interest	IDC is applied to the sum of all up-front costs (i.e., Accounts 10 through 50 base costs), including respective contingencies. These costs are incurred before commercial operation and are assumed to be financed by a construction loan. The IDC represents the cost of the construction loan (e.g., its interest).
69	Contingency on Financial Costs	Assessment of additional cost necessary to achieve the desired confidence level for capitalized financial costs not to be exceeded, including schedule uncertainties.
70	**Annualized O&M Costs**	—
71	O&M Staff	Salary costs of O&M staff.
72	Management Staff	Salary costs of operations management staff.
73	Salary-Related Costs	Taxes, insurance, fringes, benefits, and any other annual salary-related costs.
74	Operating Chemicals & Lubricants	—
75	Spare Parts	Cost of any operational spare parts, excluding capital plant upgrades or major equipment that will be capitalized or amortized over some period or quantity of product.
76	Utilities, Supplies, & Consumables	Cost of water, gas, electricity, tools, machinery, maintenance equipment, office supplies and similar items purchased annually.
77	Capital Plant Upgrades	Upgrades to maintain or improve plant capacity, meet future regulatory requirements or plant life extensions.
78A	Taxes & Insurance	Property taxes and insurance costs, excluding salary related.
78B	Outage Costs	—
79	Contingency on Annualized O&M Costs	Assessment of additional cost necessary to achieve the desired confidence level for the annualized O&M costs not to be exceeded.
80	**Annualized Fuel Cost**	—
81	Refueling Operations	Incremental costs associated with refueling operations.
84	Additional Nuclear Fuel	Annualized costs associated with the fuel cycle.
86	Fuel Reprocessing Charges	Storage and reprocessing charges for spent fuel.
87	Special Nuclear Materials	Heavy water, sodium, lead, helium or other energy transfer mediums that are required on an annual basis. Includes costs associated with disposal or treatment if necessary.

Account	Title	Description
89	Contingency on Annualized Fuel Costs	Assessment of additional cost necessary to achieve the desired confidence level for the annualized fuel costs not to be exceeded.
90	**Annualized Financial Costs**	—
91	Escalation	Excluded from estimated costs for Generation IV nuclear energy systems, although it could be included in a business plan, a financing proposal, or regulatory-related documents.
92	Fees	Cost of fees incurred for annual fees such as licensed reactor process, nuclear operating license fees, and similar.
93	Cost of Money	Value of money utilized for operating costs. May be financed externally or retained earnings.
99	Contingency on Annualized Financial Costs	Assessment of additional costs necessary to achieve the desired confidence level for the annualized financial costs not to be exceeded, including schedule uncertainties.

4. GENERAL COST ESTIMATION APPROACH, METHODS, ASSUMPTIONS, & KEY PARAMETERS

To effectively estimate the costs for advanced NPPs, we employ a range of methods that span low-detail/high-level techniques to the use of bottom-up, process-based, and first-principles approaches that require and generate a high amount of system design, performance, and cost detail. Selection of the cost estimation method for an individual part within the NPP depends on the magnitude of its cost contribution, availability and accessibility of reliable and accurate cost estimates, and the level of accuracy that needs to be captured in the final estimate. In general, we attempt to utilize more detailed first-principles and bottom-up approaches to produce the most accurate estimates, using lesser methods where costs could be more reliably obtained by alternative means (e.g., vendor cost quoting, etc.) or the cost was inconsequential. This approach is consistent with our goal of producing a high-fidelity, full-scale plant cost model that allows for future extension and use in exploring alternative cost estimation cases.

We provide a high-level summary of the cost estimation and scaling approach and some key assumptions taken for every main account included in the COA in Table 14. Table 14 serves as a quick guide for immediate identification of the calculation approach employed within each high-level account and comparison of estimation methods across accounts. Specific details for the calculation method, assumptions, parameters, and results for each account are provided in each corresponding separate subsection that follows which we also reference in many instances within this Table 14.

Table 14. High-level cost estimation approach for each account in the second level of the nuclear code of accounts developed by Idaho National Laboratory and used for categorizing and organizing cost bases and results. All cost values given are on a 2023US$ basis.

Account	Title	High-Level Cost Estimation Approach/Assumptions
10	**Capitalized Pre-Construction Costs**	
11	Land & Land Rights	$22,000 per acre, 500 acres including recommended buffer
12	Site Permits	1.25% of land (11) and improvements (21)
13	Plant Licensing	$78.45/kW$_e$ per 2016 Georgia Integrated Resource Plan
14	Plant Permits	$12,679,167
15	Plant Studies	$12,679,167
16	Plant Reports	$10,079,938 per estimates based on 1996 NRC report for environmental report (ER), environmental impact statement (EIS), and safety action report (SAR)
17	Other Pre-Construction Costs	$12,679,167
18	Community Outreach & Education	Not included in analysis
19	Contingency on Pre-Construction Costs	20%
20	**Capitalized Direct Costs**	
21	Structures & Improvements	See Table 15 and Section 5.3.1
22	Reactor System	See Table 15 and Section 5.3.2
23	Energy Conversion System	See Table 52 and Section 5.3.3
24	Electrical Equipment	See Table 54 for details. Costs based on:

Account	Title	High-Level Cost Estimation Approach/Assumptions
		$C_{SFR} = C_{PWR12-BE} \left(\frac{MWe_{SFR}}{1{,}144}\right)^{0.8}$
25	Heat Rejection System	Structures cost based on: $C_{SFR} = C_{PWR12-BE} \left(\frac{MWe_{SFR}}{1{,}144}\right)^{0.8}$ Cooling water tower (CWT) and condenser costs based on Section 4.2
26	Miscellaneous Equipment	Scaled with MW_e and staffing at a mix of exponents. See Table 56
27	Special Materials	No other special materials utilized within plant
28	Simulator	Simplified build-up of hardware costs (Table 57)
29	Contingency on Direct Costs	20%
30	**Capitalized Indirect Services Costs**	
31	Factory & Field Indirect Costs	10% general contractor (GC) overhead (OH), 15% GC profit, both applied to direct cost
32	Factory & Construction Supervision	Captured in Accounts 20 and 31
33	Commissioning & Start-Up Costs	$C_{SFR}\ [\$M] = 36.795 \left(\frac{MWe_{SFR}}{1{,}144}\right)^{0.5}$
34	Demonstration Test Run	Not included
35	Design Services Offsite	RSMeans % for structural, mechanical, & electrical applied individually for each building in Account 21
36	PM/CM Services Offsite	$C_{SFR}\ [\$M] = 38.747 \left(\frac{MWe_{SFR}}{1{,}144}\right)^{0.5}$
37	Design Services Onsite	Included in Account 35
38	PM/CM Services Onsite	3.9% of direct costs
39	Contingency on Indirect Services Cost	20%
40	**Capitalized Owner's Costs**	
41	Staff Recruitment & Training	Plant staffing levels used to estimate recruiting and training
42	Staff Housing	$40k relocation fee for 50% of staff hired
43	Staff Salary-Related Costs	Build-up based on estimated expenses, sums to 57–59% of staff salary
44	Other Owner's Costs	None
49	Contingency on Owner's Costs	20%
50	**Capitalized Supplementary Costs**	
51	Shipping & Transportation Costs	Build-up based on 50/50 split between rail and truck transport
52	Spare Parts	1.5% of Accounts 22–25, 0.5% of Accounts 26–28
53	Taxes	Assume after-tax profit of 8%, electricity sales price of $50/$MWh_e$, 21% Federal and 6% state tax rates
54	Insurance	1% per year of total investment cost approximated by Accounts 10–30
55	Initial Fuel Core Load	Build-up based on estimated U core mass with costs for mining, conversion, 2-stage enrichment, and fabrication. Pelletization also estimated.
58	Decommissioning	$Cost[2007US\$M] = 197 + 0.024(P[MW_t] - 1200)$ Further adjusted to 2023US$
59	Contingency on Supplementary Costs	20%
60	**Capitalized Financial Costs**	
61	Escalation	None
62	Fees	No royalties, annual operating fees included in Account 92
63	Interest	Present value of interest on a 5% (5.12% APY) discount rate for a 5.7–year construction loan. Full overnight cost borrowed in equal quarterly tranches.
69	Contingency on Financial Costs	20%

Account	Title	High-Level Cost Estimation Approach/Assumptions
70	**Annualized O&M Costs**	
71	O&M Staff	Headcount scaled from GE Super-PRISM staffing estimate to align with operator requirements specified in 10 CFR 50.54 (based on number of reactors and job function)
72	Management Staff	Headcount scaled from GE Super-PRISM staffing estimate to align with operator requirements specified in 10 CFR 50.54 (based on number of reactors and job function)
73	Salary-Related Costs	Based on headcount and average salaries for each operations, maintenance, technical, and administrative staffing function. Average benefits estimated at $29.55/hour for all labor functions
74	Operating Chemicals & Lubricants	Not included in analysis
75	Spare Parts	2% of Accounts 22–26
76	Utilities, Supplies, & Consumables	Not included in analysis
77	Capital Plant Upgrades	Annualized cost of upgrade expenses: $\text{Annual Capital Plant Upgrade}[2023US\$/kW] = \begin{cases} 1.23 \cdot (17 + 1.25 \cdot \text{Age}), \text{up to 50 years of life} \\ 1.23 \cdot 70, beyond\ 50\ years\ of\ life \end{cases}$ For facility life of 60 years and discount rate of 5%
78A	Taxes & Insurance	Not included in analysis
78B	Outage Costs	Not included in analysis
79	Contingency on Annualized O&M Costs	20%
80	**Annualized Fuel Cost**	
81	Refueling Operations	Approximate build-up based on detailed enumeration of activities and estimated labor costs
84	Additional Nuclear Fuel	Based on refueling cycle provided in Table 12
86	Fuel Reprocessing Charges	None
87	Special Nuclear Materials	None
89	Contingency on Annualized Fuel Costs	20%
90	**Annualized Financial Costs**	
91	Escalation	None
92	Fees	$5,492,000 per reactor as specified in Federal regulations
93	Cost of Money	Set to zero per Idaho National Laboratory guidance
99	Contingency on Annualized Financial Costs	20%

4.1 First-Principles Methods

Our first-principles approaches rely on methodologies and datasets that have not been previously applied and reported by others conducting similar cost estimations for NPPs. While each approach has its own benefits and shortcomings, we choose these methods due to our successful experience in applying them to cost estimates of other energy-based systems produced at high rates of manufacturing.

4.1.1 Design for Manufacture & Assembly® (DFMA®)

The primary first-principles method that we apply to estimate component costs within the SFR NPP is rooted in design for manufacture and assembly® (DMFA®). DFMA® is a process-based cost estimation methodology that mimics actual fabrication, manufacturing, assembly, integration, and construction activities and operations used to create, build, and make parts, entire pieces of equipment, subsystems and full systems of equipment, entire process plants, and plant complexes. It is a systematic means for the design and evaluation of cost-optimized components, systems, and processes allowing for the identification of low-cost manufacturing methods and component designs to be used to accurately project cost of component production. These techniques are powerful, flexible, and able to incorporate historical cost data and manufacturing acumen accumulated in various manufacturing industries. Our application of DFMA® focuses on factory-built and shop fabricated plant equipment and equipment parts, specifically non-standard and critical SFR NPP components such as reactor modules, steam generators, heat management equipment, and various site structures. Application of DFMA® to these items enables highly detailed and accurate cost estimates of a complete SFR NPP. Furthermore, this methodology is well suited to modeling operations having the lowest production cost, namely, rapid/high-rate serial production from highly standardized and controlled production processes, which is quite advantageous for estimating costs of SFR NPPs that typically employ a high degree of modularity.

Varying levels of DFMA® are applied within our SFR NPP cost estimation to different plant components depending on their level of significance and according to Table 15. Detailed DFMA® estimates are made for more specialized and custom components that are expected to have significant cost contributions to the overall NPP cost and for which direct costs could not be reliably obtained through alternative means, such as vendor cost quoting or use of general and standardized cost correlations. To determine the purchase capital cost over a specific range of annual system manufacturing rates for these items, we estimate the full material costs of every major part including waste/scrap material from manufacturing, their corresponding fabrication costs (e.g., fabrication machine amortization and operation), and other miscellaneous business costs all adjusted by either quoted or assumed discounting rates and relationships. Direct material costs are determined from the exact type and mass of materials used to build up the component with material prices generally obtained through recent (2023) material vendor cost quotes based on the material specifications (e.g., ASTM A240 TP316 Stainless Steel [SS]) and dimensions (e.g., thickness) for each part. Fabrication costs are estimated by devising an approximate list of the primary fabrication/manufacturing process steps needed to achieve the required features of each part and determining the time and expenses for personnel, machinery and tools, consumed materials and parts, and other commercial aspects such as taxes, insurance, other miscellaneous employment expenses, and corporate markup for profit needed to generate those features and the complete part. Labor costs include an estimate of competitive wages based on region and skill, experience, and education-level of the personnel required to work through the process and with the machinery for producing every part and fully assembled equipment components. Additional employment costs such as recruitment and training, fringe benefits, taxes, and insurance are further added to capture the correct level of extra expense typically associated with employing skilled workers. Corporate markup costs capture expenses for business overhead, general and administrative (G&A), scrap, R&D, and profit.

We further breakdown the manufacturing process into location-specific operations where we assume the use of two specific sites: (1) the NPP site which we also refer to as the field-site; and (2) offsite manufacturing facilities/shops where either entire assemblies are fabricated or large parts for individual equipment components are manufactured. Offsite manufacturing facilities are employed as much as possible in our analysis to utilize the demonstrated cost savings of automated and rapid production of parts and equipment in a highly controlled production environment. Parts or partial fabrications for each piece of equipment are projected to be built to sizes as large as practical for transportation via roadway or railway freight to the NPP field-site. Once onsite, equipment would either be installed directly if coming from the offsite fabrication facility in a fully assembled form or be fully assembled and integrated into its final form followed by onsite installation. Therefore, costs for onsite equipment assembly and integration are distinguished from costs for final onsite installation.

For all reactor-based equipment including the steam generator, we estimate the amount of materials required for every part and their corresponding manufacturing processes from detailed dimensions that we establish in our basis of design described in Section 2. Essential manufacturing aspects for both the reactor and steam generator such as welding, integrity examination and testing, and certification are included at a sufficient level of detail since these can have a significant cost impact. Additional fabrication requirements to build the reactor and steam generator internals are further defined to estimate the costs associated with constructing and assembling these parts as well to make a complete reactor module and steam generator. We use the past design documents published for the reference SFR we devise our design basis from to also establish dimension differences for larger reactor modules and steam generators. For the reactor module, we use the diameter specifications provided for the larger PRISM MOD-B SFR described in this documentation but assume that its length remains the same as that of the PRISM MOD-A reactor since this is not explicitly defined within the documents or drawings. The dimensions of every part identified within the reactor module are then scaled according to these assumptions and we estimate the material and associated manufacturing requirements for this larger reactor size using the same first-principles DFMA® method described in this section. For the steam generator, we assume that the aspect ratio between the shell length and diameter remains the same for different sizes and scale up the dimensions of every part for this equipment item using this assumption. We employ a 5/10th scaling relationship between the shell diameter and thermal output power (i.e., this comes from a linear scaling between the approximate area and the thermal power of the steam generator) to scale the diameter and then employ the constant aspect ratio assumption to reset the length. Similarly, costs for larger steam generators are estimated using the method described in this section where we enumerate the materials and manufacturing requirements for the larger size and calculate their corresponding costs. No cost reductions are imposed through either reduced material costs owing to larger material purchase volumes or higher manufacturing utilizations for these items. All cost reductions realized for larger reactor-based equipment are from non-linear scaling of equipment and part dimensions that lead to a smaller quantity of materials and manufacturing time required on a power normalized basis.

Table 15. Cost estimation methodology utilized for each main sodium-cooled fast reactor plant equipment component.

No.	Component	Process Level	Cost Estimation Methodology
1	Reactor	Reactor Module	Detailed DFMA®
2	Intermediate Heat Exchanger	Reactor Module	Detailed DFMA®
3	Primary Sodium Pump	Reactor Module	General Cost Correlation
4	Reactor Core	Reactor Module	Detailed DFMA®
5	Steam Generator	Power Block	Detailed DFMA®
6	Steam Drum	Power Block	General Cost Correlation
7	Steam Turbine	Power Block	General Cost Correlation
8	Turbine Steam Condenser	Power Block	General Cost Correlation
9	Boiler Feedwater Deaerator	Power Block	General Cost Correlation
10	Boiler Blowdown & Flash Drums	Power Block	General Cost Correlation
11	Cooling Water Tower	Power Block	General Cost Correlation
12	Boiler Feedwater & Steam Condensate Pumps	Power Block	General Cost Correlation
13	Boiler Feedwater Preheaters	Power Block	General Cost Correlation
14	Electrical Equipment	All	Analogous Cost
15	Site Buildings & Structures	All	Intermediate DFMA®

To simplify the application of DFMA® to estimating costs of the SFR NPP cases we evaluate, empirical cost functions for common manufacturing processes are derived from cost data based on process times (e.g., seconds/part), machine cost rates ($/hr), and the cost of materials consumed in each process step (e.g., $/kg, $/ft^2, $/ft, $/piece, etc,). Cost data from the Boothroyd Dewhurst, Inc. (BDI) DFM Concurrent Costing® (DFM-CC®) software v3.0.0.115 (2017)[19] are used to establish our correlations for estimating required process times and consumable material quantities and costs. Table 16

[19] www.dfma.com

summarizes these cost correlations and associated machine rates that we devise. Process costs are determined by multiplying the process time by the applicable machine rate and adding any costs for consumables. Where available, machine rates from the DFM-CC® software are used directly and adjusted to a 2023 value basis. Machine rates not included in DFM-CC® are calculated from:

1. Representative capital equipment price quotes from various manufacturing equipment vendors.
2. Equipment lifetime typically taken as 15 years.
3. Discount rate normally around 8%.
4. Installation costs which can be up to as much as 40% of machinery capital costs.
5. Estimated yearly facility miscellaneous and spare part expenses, commonly approximated as 5% and 2% of machinery capital costs, respectively.
6. Utilities such as electricity (e.g., \$0.08/kWh_e).
7. Labor rates which we usually set at \$51/hr inclusive of miscellaneous employment costs such as fringe benefits.

Machine rate is further assessed at a constant utilization value assuming 85% equipment utilization. We base this assumption on expected capacity utilizations of common processes conducted in general vendor equipment manufacturing facilities relying on job-pooling (i.e., application of machinery to a range of separate projects including non-NPP equipment to ensure a high operating efficiency to achieve a lower \$/hr cost rate).

Table 16. Manufacturing process operation cost correlations used in estimating costs of sodium-cooled fast reactor nuclear power plants.

Machining Operation	Cost Correlation	Machine Rate (MR)
-	2023 US \$	2023 US \$/hr
Plasma Cutting SS	$MR\left[\frac{\$}{s}\right]\cdot\left((1800[s]+r[no.]\cdot\left(\frac{L[in]}{0.988\left[\frac{in^{2.494}}{s}\right]\cdot t[in]^{-1.494}}+607.3[s]\right)\right)$	63.98
Plasma Cutting CS/Cr-Mo	$MR\left[\frac{\$}{s}\right]\cdot\left(1800[s]+r[no.]\cdot\left(\frac{L[in]}{0.728\left[\frac{in^{2.032}}{s}\right]\cdot t[in]^{-1.032}}+607.3[s]\right)\right)$	63.98
Hand Deburring	$MR\left[\frac{\$}{s}\right]\cdot\left(r[no.]\cdot\left(1.071\left[\frac{s}{in}\right]\cdot L[in]\right)\right)$	51.00
Drilling	$MR\left[\frac{\$}{s}\right]\cdot(300[s]+120[s]\cdot r[no.])$	51.00
Face Milling	$MR\left[\frac{\$}{s}\right]\cdot\left(300[s]+r[no.]\cdot\left(341.198\left[\frac{s}{in^{1.042}}\right]\cdot V_{removed}^{0.3474}[in^{1.042}]\right)\right)$	69.92
Hand Bead Blasting	$MR\left[\frac{\$}{s}\right]\cdot\left(300[s]+r[no.]\cdot\left(0.0387\left[\frac{s}{in^2}\right]\cdot SA[in^2]\right)\right) + 0.0035\left[\frac{lb}{in^2}\right]\cdot SA[in^2]\cdot CC_{bead}\left[\frac{\$}{lb}\right]$	58.40
Manual MIG/TIG Single-Sided Butt Weld	$MR\left[\frac{\$}{s}\right]\cdot\left(300[s]+r[no.]\cdot\left(\frac{L[in]}{0.0373\left[\frac{in^{1.682}}{s}\right]\cdot t[in]^{-0.682}}+900[s]\right)\right) + r[no.]\cdot CC_{Weld}\left[\frac{\$}{lb}\right]\cdot 0.0760\left[\frac{lb}{in^2}\right]\cdot t[in]\cdot L[in]$	151.16

Machining Operation	Cost Correlation	Machine Rate (MR)
-	2023 US $	2023 US $/hr
Manual MIG/TIG Single-Sided Seal	$MR\left[\frac{\$}{s}\right]\cdot\left(300[s]+r[no.]\cdot\left(\frac{L[in]}{0.0746\left[\frac{in^{1.682}}{s}\right]\cdot t[in]^{-0.682}}+900[s]\right)\right)$ $+r[no.]\cdot CC_{Weld}\left[\frac{\$}{lb}\right]\cdot 0.0380\left[\frac{lb}{in^2}\right]\cdot t[in]\cdot L[in]$	151.16
Manual MIG/TIG Fillet Weld	$MR\left[\frac{\$}{s}\right]\cdot\left(300[s]+r[no.]\cdot\left(\frac{L[in]}{0.00854\left[\frac{in^{2.524}}{s}\right]\cdot t_{fillet}[in]^{-1.524}}+900[s]\right)\right)$ $+r[no.]\cdot CC_{Weld}\left[\frac{\$}{lb}\right]\cdot 0.245\left[\frac{lb}{in^3}\right]\cdot t_{fillet}[in]^2\cdot L[in]$	151.16
Manual MIG/TIG Double-Sided Butt Weld	$MR\left[\frac{\$}{s}\right]\cdot\left(300[s]+r[no.]\cdot\left(\frac{L[in]}{0.0186\left[\frac{in^{1.705}}{s}\right]\cdot t[in]^{-0.705}}+900[s]\right)\right)$ $+r[no.]\cdot CC_{Weld}\left[\frac{\$}{lb}\right]\cdot 0.160\left[\frac{lb}{in^{1.9999}}\right]\cdot t[in]^{0.9998}\cdot L[in]^{1.0001}$	151.16
Robotic MIG Fillet Weld	$MR\left[\frac{\$}{s}\right]\cdot\left(300[s]+r[no.]\cdot\left(\frac{L[in]}{0.0144\left[\frac{in^{2.576}}{s}\right]\cdot t_{fillet}[in]^{-1.576}}+900[s]\right)\right)$ $+r[no.]\cdot CC_{Weld}\left[\frac{\$}{lb}\right]\cdot 0.245\left[\frac{lb}{in^{2.993}}\right]\cdot t_{fillet}[in]^{1.996}\cdot L[in]^{0.997}$	24.69
Robotic MIG Double-Sided Butt Weld	$MR\left[\frac{\$}{s}\right]\cdot\left(300[s]+r[no.]\cdot\left(\frac{L[in]}{0.0315\left[\frac{in^{1.724}}{s}\right]\cdot t[in]^{-0.724}}+900[s]\right)\right)$ $+r[no.]\cdot CC_{Weld}\left[\frac{\$}{lb}\right]\cdot 0.160\left[\frac{lb}{in^{1.99988}}\right]\cdot t[in]^{0.9995}\cdot L[in]^{1.0003}$	24.69
X-ray Weld Inspection	$MR\left[\frac{\$}{s}\right]\cdot\left(1500[s]+r[no.]\cdot\left(3.782\left[\frac{s}{in^2}\right]\cdot SA[in^2]+750[s]\right)\right)$ $+CC\left[\frac{\$}{in^2}\right]\cdot SA[in^2]$	77.17
Roll Bending	$MR\left[\frac{\$}{s}\right]\cdot\left(1800[s]+r[no.]\cdot\left(210\left[\frac{s}{in}\right]\cdot t[in]\right)+900[s]\right)$	831.76
Cr-Mo PWHT (Thickness <1 in.)	$MR\left[\frac{\$}{s}\right]\cdot 17{,}850[s]\cdot r[no.]$	118.16
Cr-Mo PWHT (Thickness ≥ 5 in.)	$MR\left[\frac{\$}{s}\right]\cdot\left(r[no.]\cdot\left(900\left[\frac{s}{in}\right]\cdot t[in]+36{,}000\right)\right)$	118.16
Generic Part Handling	$MR\left[\frac{\$}{s}\right]\cdot\left(r[no.]\cdot\left(0.0497\left[\frac{s}{in^3}\right]\cdot V[in^3]+16.01\right)\right)$	Depends on Machining Operation

CC = Consumable Material Cost; L = Relevant Process Length; MR = Machine Rate; r = Number of Process Repetitions; SA = Surface Area; t = Thickness; t_{Fillet} = Fillet Weld Base Dimension; V = Part Volume; $V_{Removed}$ = Volume of Material Removed

4.1.2 Nuclear vs. Non-Nuclear Design & Construction

Apart from the reactor module, steam generator, and site structures related to fuel and radwaste handling and processing, which are nuclear/radioactive-related, the remaining elements of the NPP have direct fabrication and construction analogs to standard industrial, non-nuclear engineering sectors. Concrete buildings, steam boilers, electric generators, and electrical substations are all present in conventional electrical production plants. The costing methodology described above draws heavily from fabrication processes and business practices in the general industrial fabrication and construction markets. To achieve our goal of analysis transparency, we seek to clearly define the analysis main assumptions and to clearly differentiate between non-nuclear and nuclear practice.

Regardless of non-nuclear or nuclear design and construction, the NPP must be functional. Consequently, we do not include material/alloy selection, component sizing, or component design in this discussion of differences; these are treated as being the same for both non-nuclear and nuclear construction. Instead, we try to quantify cost differences due to greater material certification requirements, material tracking and handling, labor rates for workers with higher certifications, additional quality control/assurance, physical security at the site, financing costs, and various other miscellaneous aspects that differ between nuclear and non-nuclear applications.

4.1.2.1 Non-Nuclear Design & Construction

Estimates for material and manufacturing costs for all reactor-based equipment including the steam generator are calculated from the detailed dimensions and material specifications established for our basis of design for all sizes as described in previous sections. These costs represent the base non-nuclear grade cost estimates to which we apply markups and contingencies as described in the next section to account for additional nuclear requirements.

Values from RSMeans[20] are used to estimate the cost for building non-nuclear grade site structures. RSMeans is a leading construction cost estimating software company that maintains a construction cost database of over 85,000 unit prices and 25,000 building assemblies. “Unit prices” represent the cost of individual construction parts or actions whereas “building assemblies” are a set of combined parts and actions. Where possible, building assembly costs are used as this allows rapid cost estimation with transparency of the specific steps and assumptions involved in constructing the assembly. Some customization is performed to base assemblies to better account for expected conditions. For example, the following steps detail a standard assembly for an 8″-thick concrete floor, but with a modification in Step 5 for pumping the concrete rather than using a direct chute:

1. Cast-in-Place (CIP) concrete forms, slab on grade, edge, wood, 7″ to 12″ high, 4 used, includes erecting, bracing, stripping and cleaning.
2. Expansion joint, premolded, bituminous fiber, 1/2″ × 6″
3. Welded wire fabric, plain, sheets, 6 × 6 - W4 × W4 (4 × 4) 58 lb./C.S.F., American Society for Testing and Materials (ASTM) A185, including labor for accessories, excluding material for accessories.
4. Structural concrete, ready mix, heavyweight, 4,500 psi, includes local aggregate, sand, Portland cement (Type I) and water, delivered, excludes all additives and treatments.
5. Structural concrete, placing, elevated slab, pumped, less than 6″ thick, includes leveling (strike off) and consolidation, excludes material.
6. Concrete finishing, specified Random Access Floors American Concrete Institute (ACI) Classes 1, 2, 3, and 4, for Composite Overall Floor Flatness and Levelness to FF35/FL25, bull float, machine float and steel trowel (walk-behind), excluding placing, striking off and consolidating.
7. Concrete finishing, floor, hardener, dry shake on fresh concrete, metallic, heavy service, 1.0 psf.
8. Concrete surface treatment, curing, sprayed membrane compound.

[20] From Gordian’s RSMeans Data Online Copyright Gordian. 30 Patewood Dr. Suite 350, Greenville, SC, 29615; All rights reserved.

9. Concrete finishing, floor, granolithic topping on fresh or cured concrete, machine trowel finish, 1″ thick, 1:1:1-1/2 mix.
10. Vapor retarders, building paper, polyethylene vapor barrier, standard, 6 mil thick, 9′ × 400′ roll.
11. Fine grading, finish grading, small area, to be paved with grader.
12. Fill, gravel fill, compacted, under floor slabs, 4″ deep.

The materials, labor, and equipment costs are estimated for each line item independently and summed to achieve a materials and installation cost for a square foot unit of concrete floor. In some cases, RSMeans did not have preconfigured assembly costs and fully customized assemblies are created from individual items. For example, the assembly cost for epoxy coating applied to concrete in the nuclear reactor building is cost modeled as the summation of four-unit steps in RSMeans: sandblasting, epoxy primer spraying, epoxy coating spraying, and a cost percentage adder for an intricate structure.

While the RSMeans database provides estimates of material costs, those costs are "bare" and do not include related and necessary expenses. Consequently, the material and installation/labor markups from Table 17 are applied to the bare material costs to calculate the total direct cost.

4.1.2.2 Nuclear Safety Grade Design & Construction

Capturing the difference between non-nuclear and nuclear grade equipment is done through the application of overall cost escalation factors applied to our estimates of non-nuclear component costs. Separate factors to increase both material and manufacturing/construction costs of every SFR plant item that is designated as a nuclear design grade are added individually to each of these cost aspects for every component. We detail and summarize the individual parameter values that we use for both non-nuclear and nuclear rated items in Table 17 to highlight differences and cost escalation for nuclear relative to non-nuclear grade applications. The differences between these two sets of markup factors are broadly categorized as: (1) material and labor differences; and (2) business-related differences.

The two most impactful differences relate to nuclear material and labor costs. As noted in past work by others[21], the cost of materials and labor used in the nuclear industry are substantially higher than those used in non-nuclear, standard industries. These higher costs do not result because of rework, project delays, or project management issues which do occur and are addressed separately, but rather, higher costs are inherent to the nuclear industry due to the regulatory quality assurance and quality control, and inspection and testing requirements. While our first-principles approach to cost estimation has tried to define and call out added inspection actions (such as x-ray inspection of welds), there are other unenumerated costs which are difficult to estimate using process-based approaches. Consequently, these real costs are addressed using these material and labor cost multipliers.

A nuclear-industry material cost adder of 50% is applied to the base material cost for all direct costs modeled in Accounts 21 to 28 associated with nuclear components. This multiplier is the average material multiplier in Stewart[22] which examine seven structural commodities, eleven piping commodities, and eleven electrical commodities. While the multiplier is not the same for each commodity (i.e., structural ranges from 1 to 2.1, piping ranges from 1 to 2.35, and electrical ranges from 1.23 to 2), the average of each group, and the overall, is very close to 1.5. Therefore, application of a single overall multiplier is deemed both reasonable and practical, as it simplifies computation.

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21 Delene, J. G.; Hudson II, C. R. Cost Estimate Guidelines for Advanced Nuclear Power Technologies. *Oak Ridge National Laboratory Technical Report* **May 1993**, *ORNL/TM-10071/R3*. *https://doi.org/10.2172/10176857*;.

22 Stewart, W. R.; Capital Cost Evaluation of Advanced Reactor Designs Under Uncertainty and Risk. *University of Texas at Austin, Ph.D. Thesis* **2022**. *https://hdl.handle.net/1721.1/144869*.

Likewise, Stewart also assessed the difference between nuclear and non-nuclear industry labor rates. The canonical example cited is a nuclear quality assured welder who is presumably of higher experience and skill level and thus commands an 81% higher salary.[23] Variation among the three commodity sets is higher than seen in materials. Six of the seven structural commodities are ~1.2×, whereas the seventh, structural steel, is ~4.2×. All eleven of the piping commodities have a labor multiplier of ~2.6x, and all eight of the electrical commodities have a labor multiplier of ~2.15×. We select a single multiplier of 1.3× to be applied to all labor rates associated with nuclear fabrication and construction used in Accounts 21 to 28. A 1.3× multiplier is chosen as it is the approximate numerical average over the data for all commodities. While this is a blunt approach given the labor multiplier variation, it has the advantage of simplicity and allows for future refinement.

Table 17 also includes other parameters used in the analysis that differ between non-nuclear and nuclear projects. The basis for value selection is indicated for each. In many instances, these additional parameters reflect indirect business-related impacts of nuclear projects such as higher risk, longer timeframes, and more "friction" in conducting business operations due to nuclear-related bureaucracy. These added costs are difficult to quantify and are thus generally captured in the analysis by selecting the high end of the percentage range suggested by RSMeans data.[24] Contingency costs appear in multiple Accounts of the COA and thus are comprehensively listed in Table 17 for completeness and clarity even though they often have the same value for both non-nuclear and nuclear projects. Other values (such as sales tax, bonds, and profit) also have the same values for both cases but are listed to affirmatively state our assumptions since future analyses may explore the cost impact of changes to these parameters.

Table 17. Summary of assumed parameters for non-nuclear and nuclear grade plant construction projects.

Cost Category	Parameter	Non-Nuclear Grade	Basis	Nuclear Grade	Basis
Construction	Construction Period (years)	4.7	Est. of 1 year less than nuclear reactor average	5.7	Worldwide average of 29 new reactors connected to grid between 2011–2015[25]
	Indirect Cost Multiplier	1.0	Baseline value	1.0	No change from non-nuclear
Pre-Construction	Contingency	20%	20% is consistent with an AACE Class 2 estimate and GenIV EMWG/EPRI practice	20%	20% is consistent with an AACE Class 2 estimate and GenIV EMWG/EPRI practice
Direct	Material Markup Multipliers				
	Subcontractor Overhead and Profit	10%	Representative value from RSMeans	15%	5% added for specialty work
	Materials Markup	0%	Materials for non-nuclear construction are the baseline	50%	Average over range of material categories in Stewart
	Waste	3%	Engineering judgment	3%	Engineering judgment
	State Sales Tax	5.1%	50-State average	5.1%	50-State average
	Local Sales Tax	1.5%	50-State average	1.5%	50-State average
	Installation/Labor Markup Multipliers				
	Subcontractor Overhead and Profit	10%	Representative value from RSMeans	15%	5% added to reflect specialty work.
	Labor Remote Location Markup	10%	Representative value from RSMeans	10%	Representative value from RSMeans
	Labor Markup	0%	Labor rates for non-nuclear construction are the baseline	130%	Average over range of labor categories in Stewart
	Waste	3%	Engineering judgment	3%	Engineering judgment

23 Welder Annual Salary ($36,884 Avg | Jan 2022) - ZipRecruiter n.d. https://www.ziprecruiter.com/Salaries/Welder-Salary (accessed February 7, 2022); Nuclear Welder Annual Salary ($66,978 Avg | Jan 2022) - ZipRecruiter n.d. https://www.ziprecruiter.com/Salaries/Nuclear-Welder-Salary (accessed February 7, 2022) (both taken from Stewart, W. R. Capital Cost Evaluation of Advanced Reactor Designs Under Uncertainty and Risk. *University of Texas at Austin, Ph.D. Thesis* **2022**. *https://hdl.handle.net/1721.1/144869*).

24 From Gordian's RSMeans Data Online Copyright Gordian. 30 Patewood Dr. Suite 350, Greenville, SC, 29615; All rights reserved.

25 See Table 8 from https://www.iaea.org/publications/15211/nuclear-power-reactors-in-the-world.

Cost Category	Parameter	Non-Nuclear Grade	Basis	Nuclear Grade	Basis
	Security electronic scan at entry/exit	0%	N/A	4%	Representative value from RSMeans
	Contingency on Account 20	20%	20% is consistent with an AACE Class 2 estimate and Gen4 EMWG/EPRI practice	20%	20% is consistent with an AACE Class 2 estimate and Gen4 EMWG/EPRI practice
Indirect	Factory and Field Indirect Costs				
	General Contractor Overhead & Requirement	10%	Midpoint of RSMeans range	15%	High end of RSMeans range
	General Contractor Profit	10%	Representative value from RSMeans	10%	Representative value from RSMeans
	Bond	0.12%	Representative value from RSMeans	0.12%	Representative value from RSMeans
	Design Services Offsite				
	Design Fee Multiplier	1.0	Multiplier on calculated fee based on RSMeans data applied to multiple categories, with effective value of 42–44% for both nuclear & non-nuclear	1.0	Same as non-nuclear
	Project Management/Construction Management Services Offsite				
	General Contractor Main Office Overhead	3.9%	Representative value from RSMeans for large projects	3.9%	Representative value from RSMeans for large projects
	Contingency on Account 30	20%	20% is consistent with an AACE Class 2 estimate and Gen4 EMWG/EPRI practice	20%	20% is consistent with an AACE Class 2 estimate and Gen4 EMWG/EPRI practice
Capitalized Owner's	Contingency	20%	20% is consistent with an AACE Class 2 estimate and Gen4 EMWG/EPRI practice	20%	20% is consistent with an AACE Class 2 estimate and Gen4 EMWG/EPRI practice
Capitalized Supplementary	Contingency	20%	20% is consistent with an AACE Class 2 estimate and Gen4 EMWG/EPRI practice	20%	20% is consistent with an AACE Class 2 estimate and Gen4 EMWG/EPRI practice
Capitalized Financial	Contingency	20%	20% is consistent with an AACE Class 2 estimate and Gen4 EMWG/EPRI practice	20%	20% is consistent with an AACE Class 2 estimate and Gen4 EMWG/EPRI practice
Annualized O&M	Contingency	20%	20% is consistent with an AACE Class 2 estimate and Gen4 EMWG/EPRI practice	20%	20% is consistent with an AACE Class 2 estimate and Gen4 EMWG/EPRI practice
Annualized Fuel	Contingency	20%	20% is consistent with an AACE Class 2 estimate and Gen4 EMWG/EPRI practice	20%	20% is consistent with an AACE Class 2 estimate and Gen4 EMWG/EPRI practice
Annualized Financial	Contingency	20%	20% is consistent with an AACE Class 2 estimate and Gen4 EMWG/EPRI practice	20%	20% is consistent with an AACE Class 2 estimate and Gen4 EMWG/EPRI practice

4.1.3 First-of-a-Kind (FOAK) vs. Nth-of-a-Kind (NOAK) Design & Construction

First-of-a-Kind (FOAK) refers to a development scenario where the very first system manufactured suffers from heightened inefficiency, uncertainty, and longer durations associated with a first-time activity or process. Nth-of-a-Kind (NOAK) refers to a production scenario where the system has been under production for considerable time, having achieved sufficiently high production efficiency and rate such that processes are generally optimized, with minimal waste, downtime, and uncertainty in unit operations. As expected, NOAK costs are typically much less than FOAK costs.

The baseline analysis presented here is neither FOAK nor NOAK as it seeks to apply a ground-up cost methodology tied to manufacturing rates (i.e., one system per year). Due to this and in terms of the NPP technology maturity relative to FOAK and NOAK, we classify our base case as between an FOAK and NOAK, or BOAK. Consequently, costs for our BOAK baseline case will fall between those for the baseline FOAK and baseline NOAK. To simulate FOAK and NOAK scenarios within the flexible modeling framework we develop, certain input parameters consistent with each scenario are changed. Table 18 specifies these parameters along with a comparison to the non-nuclear and nuclear grade baseline BOAK scenario parameter values and those we use for the nuclear baseline FOAK and NOAK. In general, the FOAK and NOAK values are based on the nuclear grade BOAK parameter values downgraded for FOAK and improved for NOAK, although some parameter values remain unchanged.

Table 18. Summary of markup and contingency assumptions applied for estimating first-of-a-kind (FOAK), Nth-of-a-kind (NOAK), and between an FOAK and NOAK (BOAK) nuclear power plant cost scenarios including a comparison to those assumed for non-nuclear BOAK design and construction.

Cost Category	Parameter	Non-Nuclear Grade Between First-of-a-Kind (FOAK) & Nth-of-a-Kind (NOAK) or BOAK	Nuclear Grade BOAK	Nuclear Grade FOAK	Basis	Nuclear Grade NOAK	Basis
Construction Duration	Construction Duration (years)	4.7	5.7	8.7	5.7 years baseline nuclear BOAK is extended by 3 years due to unforeseen delays associated with FOAK	3.3	3.3 years is postulated for NOAK by the Generation IV International Forum (GIF) Economic Modeling Working Group (EMWG) for small modular reactors (SMRs)
	Indirect Cost Multiplier	1.0	1.0	1.53	Increase in Account 30 Indirect costs proportional to lengthened construction (8.7 y/5.7y)	0.59	Decrease in Account 30 Indirect costs proportional to shortened construction (3.3 y/5.7y) assuming costs are driven by full-time equivalent (FTE) staff
Pre-Construction	Contingency	20%	20%	27%	20% baseline nuclear BOAK plus 5% for FOAK low confidence estimates plus 2% additional re-work	10%	20% baseline nuclear BOAK minus 10% for NOAK high confidence estimates
Direct							
	Subcontract or Overhead and Profit	10%	15%	20%	10% RSMeans average plus 5% for nuclear BOAK plus 5% for inefficiency of FOAK	10%	10% RSMeans average plus 5% for nuclear BOAK minus 5% for NOAK streamlined operations
	Materials Markup	0%	50%	55%	50% adder for nuclear BOAK plus 5% for inefficiency of FOAK	40%	50% adder for nuclear BOAK minus 10% for NOAK streamlined operations
	Waste	3%	3%	5%	3% average plus 2% for inefficiency of FOAK	2%	3% average minus 1% for NOAK streamlined operations
	State Sales Tax	5.1%	5.1%	5.1%	50-State average of State Sales Taxes	5.1%	50-State average of State Sales Taxes
	Local Sales Tax	1.5%	1.5%	1.5%	50-State average of State average Local Tax Rate	1.5%	50-State average of State average Local Tax Rate
	Installation/ Labor Markup Multipliers						
	Subcontract or Overhead and Profit	10%	15%	20%	10% RSMeans average plus 5% for nuclear BOAK plus 5% for inefficiency of FOAK	10%	10% RSMeans average plus 5% for nuclear BOAK minus 5% for NOAK streamlined operations
	Labor Remote Location Markup	10%	10%	10%	Representative value from RSMeans	8%	10% Representative value minus 2% for increased labor pool consistent with NOAK high-rate production

Cost Category	Parameter	Non-Nuclear Grade Between First-of-a-Kind (FOAK) & N^th-of-a-Kind (NOAK) or BOAK	Nuclear Grade BOAK	Nuclear Grade FOAK	Basis	Nuclear Grade NOAK	Basis
	Labor Markup	0%	130%	130%	130% is average over range of nuclear labor categories in Stewart et. al	110%	130% minus 20% for increased labor pool consistent with NOAK high-rate production
	Waste	3%	3%	5%	3% average plus 2% for inefficiency of FOAK	2%	3% average minus 1% for NOAK streamlined operations
	Security electronic scan at entry/exit	0%	4%	4%	Representative value from RSMeans	4%	Representative value from RSMeans
	Contingency	20%	20%	27%	20% baseline nuclear BOAK plus 5% for FOAK low confidence estimates plus 2% for addiitional re-work	10%	20% baseline nuclear BOAK minus 10% for NOAK high confidence estimates
Indirect	Factory and Field Indirect Costs						
	General Contractor Overhead	10%	15%	20%	15% baseline nuclear BOAK plus 5% for inefficiency of FOAK	10%	15% baseline nuclear BOAK minus 5% for NOAK streamlined operations
	General Contractor Profit	10%	10%	12%	10% baseline nuclear BOAK plus 2% risk premium	9%	10% baseline nuclear BOAK minus 1% for increased competition consistent with NOAK high-rate production
	Bond	0.12%	0.12%	0.12%	Representative value from RSMeans	0.12%	Representative value from RSMeans
	Design Fee Multiplier	1.0	1.0	1.0	Varies. RSMeans data applied to multiple categories, with effective value of 42–46%	0.33	Cut in third to represent streamlined NOAK design and construction largely limited to site-specific adjustments
	Program Management/ Contract Management Services Offsite						
	General Contractor Main Office Overhead	3.9%	3.9%	4.9%	3.9% baseline nuclear BOAK plus 1% for inefficiency of FOAK	3.4%	3.9% baseline nuclear BOAK minus 0.5% for NOAK streamlined operations
	Contingency	20%	20%	27%	20% baseline nuclear BOAK plus 5% for FOAK low confidence estimates plus 2% additional re-work	10%	20% baseline nuclear BOAK minus 10% for NOAK high confidence estimates
Capitalized Owner's	Contingency	20%	20%	27%	20% baseline nuclear BOAK plus 5% for FOAK low confidence estimates plus 2% additional re-work	10%	20% baseline nuclear BOAK minus 10% for NOAK high confidence estimates
Capitalized Supplementary	Contingency	20%	20%	27%	20% baseline nuclear BOAK plus 5% for FOAK low confidence estimates plus 2% additional re-work	10%	20% baseline nuclear BOAK minus 10% for NOAK high confidence estimates
Capitalized Financial	Contingency	20%	20%	27%	20% baseline nuclear BOAK plus 5% for FOAK low confidence estimates plus 2% additional re-work	10%	20% baseline nuclear BOAK minus 10% for NOAK high confidence estimates

Cost Category	Parameter	Non-Nuclear Grade Between First-of-a-Kind (FOAK) & Nth-of-a-Kind (NOAK) or BOAK	Nuclear Grade BOAK	Nuclear Grade FOAK	Basis	Nuclear Grade NOAK	Basis
Annualized O&M	Contingency	20%	20%	27%	20% baseline nuclear BOAK plus 5% for FOAK low confidence estimates plus 2% additional re-work	10%	20% baseline nuclear BOAK minus 10% for NOAK high confidence estimates
Annualized Fuel	Contingency	20%	20%	27%	20% baseline nuclear BOAK plus 5% for FOAK low confidence estimates plus 2% additional re-work	10%	20% baseline nuclear BOAK minus 10% for NOAK high confidence estimates
Annualized Financial	Contingency	20%	20%	27%	20% baseline nuclear BOAK plus 5% for FOAK low confidence estimates plus 2% additional re-work	10%	20% baseline nuclear BOAK minus 10% for NOAK high confidence estimates

Central to the analysis, but not highlighted in Table 18, is the impact of production rate on direct cost. In theory, the DFMA® cost analysis methodology captures the production rate cost impacts of each component primarily by better utilization of production equipment. However, the simplified DFMA® calculations employed within the NPP cost analysis assumes job sharing of factory-fabrication tasks (i.e., equipment fabrication machinery is used on other projects besides the NPP) and thus can achieve high equipment utilization (85% of a single shift) regardless of NPP fabrication time. This simplifying assumption significantly reduces the manufacturing cost impact between NOAK and FOAK. Additionally, a mild discounting factor is applied for some equipment that is estimated based on non-DFMA® approaches. Overall, a more detailed analysis than what we devote here is required to fully quantify the cost impact of manufacturing rate on fabrication costs.

4.2 Cost Correlations for General Equipment

Plant equipment items that are non-SFR specific and used ubiquitously throughout the power and other industries are estimated using previously established and trialed cost correlations based on certain overall equipment size parameters. We detail the various cost correlations and equations we use to estimate equipment costs for different classes of equipment used within non-nuclear safety grade designed and constructed sections of the SFR plant. These correlations generally depend on overall sizing metrics and parameters for each equipment type and capture the overall magnitude and trend of costs with these size parameters. Since the costs produced by these correlations are for highly mature and well-established technologies, these most likely represent NOAK technology maturity costs. However, we instead assume that the cost results these produce correspond to our BOAK costing classification and so we use these in combination with costs we estimate for all other NPP components for this costing scenario. To estimate FOAK and NOAK NPP costs, we adjust the cost results from these correlations in the applicable fashion as described in previous sections.

4.2.1 Cooling Water Towers & Condensers

Costs for CWTs and steam cycle turbine condensers are expected to be similar whether for our SFR design case or for other types of nuclear applications. We therefore utilize cost correlations previously reported in literature to determine these costs.[26] Specifically, Equation 4.2.1 expresses the cost correlation that we employ to estimate total installed costs (C_{CW}) for both of these equipment items having a dependence on the overall cooling duty required (Q_{CW}):

$$C_{CW}[2023US\$] = 557.30 \cdot \frac{Q_{CW}[kW]}{2{,}200 \cdot \Delta T_{LMTD}[K]} + 1{,}480.89 \cdot \dot{m}_{CW}[kg/s] + 139.95 \cdot Q_{CW}[kW] \cdot (-0.6936 \cdot ln(\bar{T}_{CW}[K] - T_{WB}[K]) + 2.1898) \quad 4.2.1$$

with ΔT_{LMTD} being the log-mean temperature difference (LMTD) of the steam turbine condenser, $\dot{m}_{CW}$ the total CW mass flow rate, $\bar{T}_{CW}$ the CW temperature, and T_{WB} the wet bulb temperature.

We apply Equation 4.2.1 directly to our base case SFR for a single 471 MW_t/165 MW_e reactor and power block and assume the cost estimated by this correlation applies to this size plant. To capture some expected level of cost reduction due to economies of scale and economies of manufacturing rate, we adjust this correlation to estimate reduced costs owing to both increased equipment size and multiple purchases. Costs for different plant scales that include larger CWTs and condensers, apply an 9/10th power-law cost scaling with cooling duty per the general scaling relationship given in Equation 4.3.1. Costs are further reduced assuming a 5% discount rate for the purchase of multiple identical equipment items as given in Equation 4.3.2.

4.2.2 Heat Exchangers

Installed shell and tube heat exchanger costs (C_{HEX}) for carbon steel (CS) fixed head and U-tube type exchangers are estimated by Equation 4.2.2 which is dependent on the exchanger surface area A_{HEX}, tube length $L_{Tube,HEX}$, and shellside pressure $P_{HEX,Shell}$.[27] Valid variable ranges for this correlation are 6.9 barg < $P_{HEX,Shell}$ < 137.9 barg for pressure, 2.5 m < $L_{HEX,Tube}$ < 6.1 m for tube length, and 13.9 m^2 < A_{HEX} < 1,114.9 m^2 for exchanger area.

$$C_{HEX}[2023US\$] = 4.71 \cdot [0.9803 + 0.00261 \cdot P[barg] + 3.576x10^{-5} \cdot P[barg]^2] \cdot L_{HEX,tube}[m]^{-0.243} \cdot e^{\left(11.147 - 2.332 \cdot ln\left(A_{HEX}[m^2]\right) + 0.5528 \cdot ln\left(A_{HEX}[m^2]\right)^2\right)} \quad 4.2.2$$

A correction factor for different MOC can be applied; however, since we only use this correlation to estimate costs for exchangers requiring CS and low alloy steels, we omit adjustment factors to account for other MOC. Multi-purchase cost reductions according to Equation 4.3.2 are also applied for multiple identical heat exchangers.

4.2.3 Pressure Vessels

Equation 4.2.3 taken from Seider *et al.* expresses the total installed cost (C_{PV}) for vertical cylindrical pressure vessels constructed of CS having a diameter within the range of 0.9 m < D_{PV} < 6.5 m and aspect ratio range of 1 < $(L/D)_{PV}$ < 14 with total weight of the bare shell and heads W_{PV} within 1,900 kg < W_{PV} < 417,305 kg.

$$C_{PV}[2023US\$] = 3.04 \cdot e^{\left(6.775 - 0.14432 \cdot ln(W_{PV}[kg]) + 0.01436 \cdot ln(W_{PV}[kg])^2\right)} + 4{,}836.46 \cdot D_{PV}[m]^{0.7396} \cdot L_{PV}[m]^{0.70684} \quad 4.2.3$$

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26 Roosen, P.; Uhlenbruck, S.; Lucas, K. Pareto Optimization of a Combined Cycle Power System as a Decision Support Tool for Trading Off Investment vs. Operating Costs. *International Journal of Thermal Sciences* **2003**, *42*, 553–560. *https://doi.org/10.1016/S1290-0729(03)00021-8*

27 Seider, W. D.; Seader, J. D.; Lewin, D. R. Product and Process Design Principles: Synthesis, Analysis and Evaluation, 2nd Ed. New York, USA: John Wiley & Sons, Inc., **2004**. *ISBN: 9780471216636*

Costs for other MOC are estimated by multiplying the first term in this equation by material cost escalation factors between base costs for CS and other metallurgies. We further add a cost reduction to capture cost differences for several similar vessels being installed within the plant in parallel using Equation 4.3.2.

4.2.4 Pumps

Costs for general pumps are computed from Equation 4.2.4 which depend on the isentropic pump power $P_{Pump,S}$, and isentropic pump efficiency $\eta_{Pump,S}$ as adapted from Roosen *et al.* 2003.

$$C_{Pump}[2023US\$] = 1{,}406 \cdot P_{Pump,S}[kW]^{0.71} \cdot \left(1 + \frac{2}{1-\eta_{Pump,S}}\right) \qquad 4.2.4$$

Cost savings for many similar pumps are also included by applying Equation 4.3.2 at a discount rate of 5%.

4.2.5 Steam Turbine Generator

We use Equation 4.2.5 also adapted from Roosen *et al.* 2003 to determine costs for typical multi-stage steam driven turbines including the electrical power generator used in various electrical power plants.

$$C_{ST}[2023US\$] = 7{,}376 \cdot P_{ST,S}[kW_S]^{0.7} \cdot \left(1 + \left(\frac{0.05}{1-\eta_{ST,S}}\right)^3\right) \cdot \left(1 + 5 \cdot e^{\left(\frac{T_{Inlet}[K]-866}{10.42}\right)}\right) \qquad 4.2.5$$

$P_{ST,S}$ represents the steam turbine isentropic power, $\eta_{ST,S}$ is the isentropic efficiency, and T_{Inlet} the turbine steam inlet temperature. Similar to our adjustment of the CWT and condenser equipment, we apply this correlation for our base SFR plant size having a single 471 MW_t/165 MW_e reactor and power block and account for cost changes with turbine size differences using Equation 4.3.1 at a size scaling power of $9/10^{th}$ as well as include additional high-quantity purchase impacts on costs from Equation 4.3.2 at a discount rate of 5%.

4.3 Cost Scaling

We scale costs for non-SFR-based plant equipment according to relationships previously used in our past work. To capture physical scale impacts on equipment costs, we utilize a general power-law relationship dependent on key size factors (e.g., power, surface area, mass flow rate, etc.) as given in Equation 4.3.1.

$$C_{Scaled} = C_{Base} \left(\frac{S_{Scaled}}{S_{Base}}\right)^n \qquad 4.3.1$$

where C_{Scaled} and C_{Base} are the costs for the size-scaled and base-size equipment component having key physical size parameters S_{Scaled} and S_{Base}, respectively related through power-law scaling exponent, n.

To capture cost reductions due to discounting that normally is available for multiple purchase quantities, we employ a standard learning-style scaling relationship to adjust single unit costs as defined by Equation 4.3.2.

$$P(N) = P_B \cdot r^{\left(\frac{ln\left(\frac{N}{N_B}\right)}{ln(2)}\right)} \qquad 4.3.2$$

where P(N) represents the forecasted price for purchasing a given quantity N of any identical equipment item with base price P_B and quantity N_B at a specific learning rate r. The learning rate r can be defined as (1 - d) where d is the discount rate and represents a percentage reduction in price for every doubling of purchase quantity.

In some instances, we utilize past cost estimates devised for more typical nuclear technologies such as the pressurized water reactor12 (PWR12) better experience (BE) estimate published in the final report of the EEDB program for plant equipment and components that will be similar enough to allow for analogous cost assignment. We employ Equation 4.3.3 for this scaling which is an assumed power-law relationship that we set approximate scaling orders for each equipment item based on our past work and cost estimation experience with similar equipment items.

$$C_{SFR,i} = C_{PWR12-BE,i} \cdot \left(\frac{P_{SFR}[MW_e]}{P_{PWR12-BE}[MW_e]}\right)^m \qquad 4.3.3$$

In Equation 4.3.3, $C_{SFR,i}$ is the scaled cost for equipment component i that exists in both the SFR and PWR12 plants with a similar enough design to allow for size scale up based on plant size differences. The cost for component i given by $C_{PWR12\text{-}BE,i}$ is taken from the BE case/analysis in the PWR12 plant having a nominal electrical power output capacity of $P_{PWR12\text{-}BE}$ which is 1,144 MW_e. P_{SFR} is the nominal electrical output power of the SFR plant with m being the power-law exponent used to scale between these two plants having values set individually for each piece of equipment that we typically vary between 0.6–1.

4.4 Site Structures & Buildings

Costs for site structures, buildings, and improvements were developed based on geometric parameters given in literature[28,29] and augmented with the authors' judgment. The geometric parameters scale with overall plant power output, power block size, reactor size, physical distances between buildings and many other features having physical meaning for the proposed NPP. The footprint area is the most frequently scaled parameter with other building parameters, such as wall lengths, being derived from the scaled area. Scaled costs are estimated from these newly derived building and site structure sizing parameters through scaling relationships that we devise based on our experience with cost scaling of similar items.

As an example, the basic dimensions of the plant control building are estimated from the literature sources for a facility having nine 165 MW_e reactors. The area of the building is computed from those basic dimensions. The area is then scaled for NPPs with different number of reactors as follows: half the building area nine-reactor reference design is held constant and half scales linearly with the number of reactors (Table 19). With those new projected areas, new wall lengths are calculated, and most exterior and interior features are scaled linearly with the new wall lengths. In some cases, such as stairs, the number remains constant.

Table 19. Scaled size parameters for the plant control building for different size facilities with different sodium-cooled fast reactor sizes and counts.

	Parameter	UOM				
	Plant Nominal Power	MW_e	165	311	1,243	3,108
	Power Block Nominal Power	MW_e	165	311	622	622
	Reactor Nominal Power	MW_e	165	311	311	311
	Power Blocks/Plant	—	1	1	2	5
	Reactors/Plant	—	1	1	4	10
	Reactors/Power Block	—	1	1	2	2
Building Size Parameter	**Primary Scaling Method**[a]					
Story 1 Area	50% Constant + 50% based on reactors	ft^2	22,000	23,948	36,391	61,278
Story 1 Exterior Wall	Calculated from area above	ft	771	797	941	1,168
Story 1 Interior Wall	Calculated from area above	ft	1,217	1,324	2,013	3,389
Story 2 Area	50% Constant + 50% based on reactors	ft^2	5,556	6,047	9,190	15,474
Story 2 Exterior Wall	Calculated from area above	ft	298	311	383	498

28 General Electric Advance Nuclear Technology. (1987). *PRISM™ Preliminary Safety Information Document*. GEFR-00793 UC-87Ta. U.S. Department of Energy.

29 General Electric Nuclear Energy. (1990). *Appendix G, Amendment 12 to the PRISM (ALMR) Preliminary Safety Information Document.* GEFR-00793 UC-87Ta. U.S. Department of Energy.

	Parameter	UOM				
Story 2 Interior Wall	Calculated from area above	ft	283	308	469	789
Exterior Doors (various)	Scaled from exterior wall length	Each	13	14	16	20
Windows	Scaled from exterior wall length	Each	37	39	46	58
Exterior Concrete	Scaled from exterior wall length	ft^2	1,302	1,345	1,589	1,972
Interior Doors (various)	Scaled from internal wall length	Each	48	51	63	84
Total Bathrooms	Scaled from internal wall length	Stalls	7	7	9	13
Flagpoles	Constant	Each	3	3	3	3
Staircases	Constant	Each	4	4	4	4

[a] Scaling is based on the reference PRISM plant design with 9-165 MW_e size reactors.

Not all buildings are scaled with half being constant from the nine-reactor reference design and half scaling linearly with number and size of reactors (abbreviated “50% C + 50% L” in Table 20). Some buildings were related primarily to maintenance functions and are linearly scaled with number and size of reactors. A few improvements were primarily scaled based on lengths from other buildings or based on staff estimates. The methods were applied to each building independently (Table 20).

Table 20. Building/Structure primary scaling method and area for different size facilities with different reactor sizes and counts.

	Parameter	UOM				
	Plant Nominal Power	MW_e	165	311	1,243	3,108
	Power Block Nominal Power	MW_e	165	311	622	622
	Reactor Nominal Power	MW_e	165	311	311	311
	Power Blocks/Plant	—	1	1	2	5
	Reactors/Plant	—	1	1	4	10
	Reactors/Power Block	—	1	1	2	2
Building/Structure	**Primary Scaling Method**[a]					
Nuclear Reactor	Linear	ft^2	17,360	30,653	37,245	50,429
Energy Conversion Building	Linear	ft^2	26,302	46,908	97,213	97,213
Security Building & Gatehouse	Constant	ft^2	300	300	300	300
Reactor Service Buildings	50% C + 50% L	ft^2	2,000	2,177	3,308	5,571
Radwaste Building	50% C + 50% L	ft^2	23,959	26,187	40,417	68,878
Fuel Service Building	50% C + 50% L	ft^2	18,032	19,628	29,827	50,224
Control Building[b]	50% C + 50% L	ft^2	33,111	36,043	54,770	92,226
Operations & Maintenance Center	50% C + 50% L	ft^2	1,333	1,451	2,206	3,714
Storage Buildings	Linear	ft^2	2,000	3,771	15,083	37,707
Pipe Tunnels	Linear	ft^2	900	1,605	3,210	8,025
Electrical Tunnels	Building Lengths	ft^2	1,182	1,387	3,451	8,628
Maintenance Shop	Linear	ft^2	2,000	3,771	15,083	37,707
Outside Equipment & Tank Foundations	Linear	ft^2	4,389	7,828	15,655	15,655
Balance of Plant Service Building	Linear	ft^2	2,000	3,771	15,083	37,707
Wastewater Treatment Building	50% C + 50% L	ft^2	112,722	122,702	186,458	313,971
Emergency & Start-Up Power Systems	Linear	ft^2	533	1,006	4,022	10,055
Warehouse	Linear	ft^2	2,000	3,771	15,083	37,707
Railroad Tracks	Building Lengths	ft^2	10,250	11,157	16,955	28,550
Roads & Paved Areas	Personnel	ft^2	122,641	127,568	202,537	345,089
Reactor Receiving & Assembly Building	Linear	ft^2	711	1,341	5,363	13,407
Special Materials Unloading Facility	50% C + 50% L	ft^2	2,000	2,177	3,308	5,571
Total	—	**ft^2**	**385,725**	**455,200**	**766,577**	**1,268,334**

[a] Scaling is based on the reference PRISM plant design with 9-165 MW_e size reactors.
[b] The control building includes portions of the building for security, administration, and training that are not explicitly broken out.

4.5 Plant Personnel & Staffing

To estimate the required number of personnel, we rely on Nuclear Regulatory Commission (NRC) rules for the required number of operators and apply scaling from estimated headcounts determined in past SFR NPP analyses.[30] We subdivide the operations staff into their primary job assignments and estimate the number of operators from 10 CFR 50.54 which stipulates a minimum of four, five, or eight operators per one, two, or three reactors. While this code may be primarily based on regulation historically applied to LWRs, and the inherent and passive safety built into SFRs may allow for a smaller primary operator workforce, we still assume this regulation to be applicable for our SFR design and estimate the number of core operators from these requirements. Based on the majority opinion of an industry survey[31], six crews, each composed of at least the minimum number of required operators, are needed to provide 24/7/365 operator coverage. An additional eight-operator staff are added for management, supervision, and process control and monitoring based on the judgment of a prior SFR NPP staffing estimate.

Maintenance staff are also closely aligned with the reactors such that staff headcount scales linearly with the quantity of reactors from the prior SFR NPP staffing estimate. The maintenance staff is inclusive of management, supervision, reliability and mechanical engineering, mechanical and electrical crafts, radwaste, quality assurance, planning, grounds, and warehouse personnel.

Administration, technical, and offsite staff are scaled with 50% being constant and 50% scaling with the headcount change of O&M staff. The administration average staff is inclusive of management, environmental control, training, safety including radiological and fire protection, administration services, health services, and security. The technical division is inclusive of management, process engineering, radio and water chemistry, licensing and regulatory assurance, analytical technicians, and health physics. The offsite staff functions are not defined. The staffing estimate (Table 21), is used for estimating parking lots (Account 218Y), furnishings (Account 264), capitalized owner's costs (Accounts 41–43), and annualized O&M costs (Accounts 71–73).

Table 21. Estimate of the required number of plant personnel and staff by function/role for different size facilities with different reactor sizes and counts.

Parameter		UOM				
	Plant Nominal Power	MW_e	165	311	1,243	3,108
	Power Block Nominal Power	MW_e	165	311	622	622
	Reactor Nominal Power	MW_e	165	311	311	311
	Power Blocks/Plant	—	1	1	2	5
	Reactors/Plant	—	1	1	4	10
	Reactors/Power Block	—	1	1	2	2
Staff Division	**Reference Headcount**[a]					
Operations	68	no./plant	32	32	68	158
Maintenance	189	no./plant	48	48	189	473
Administration	115	no./plant	76	76	115	199
Technical	61	no./plant	40	40	60	104
Offsite	60	no./plant	40	40	60	104
Total Staff	**493**	**no./plant**	**236**	**236**	**493**	**1,040**

[a] Estimate taken from Boardman, C. E.; Hui, M.; Carrol, D. G.; Dubberley, A. E. Economic Assessment of S-PRISM Including Development and Generating Costs. *ASME ICONE 9* **2000**. *https://inis.iaea.org/collection/NCLCollectionStore/_Public/33/020/33020128.pdf* based on the Super-PRISM 4-reactor, 1,651 MW_e plant design.

30 Boardman, C. E.; Hui, M.; Carrol, D. G.; Dubberley, A. E. Economic Assessment of S-PRISM Including Development and Generating Costs. *ASME ICONE 9* **2000**. *https://inis.iaea.org/collection/NCLCollectionStore/_Public/33/020/33020128.pdf*

31 Office of Technology Assessment. (1991). *Biological Rhythms: Implications for the Worker.* OTA-BA-463. Case Study: Nuclear Powerplant Control Room Operators (pp. 141–152), U.S. Congress.

Average staff salary estimates (Table 22) are developed from the same SFR NPP literature source that provides plant headcount estimates. The staff salary estimates are used for estimating capitalized owner's costs (Accounts 41–43) and annualized O&M costs (Accounts 71–73).

Table 22. Average annual staff salaries by plant personnel division.

Plant Personnel Division	2023 US $/year
Operations	128,000
Maintenance	101,000
Administrative	80,000
Technical	121,000
Offsites	143,000

Salary-related benefits are estimated with values from the Bureau of Labor Statistics for the Utilities Industry with private ownership (Table 23). While benefits vary with employee salary, on average, salary-related costs add approximately $61,000 per employee (2023US$29.55/h × 2,080h/year) to the salaries provided in Table 22. The benefits are used for estimating capitalized owner's costs (Account 43) and annualized O&M costs (Account 73).

Table 23. Selected employer costs for employee compensation taken from US Bureau of Labor Statistics for March 2023.[32]

Benefit	2023 US $/hour
Paid Leave	6.88
Supplemental Pay	2.59
Insurance	7.27
Retirement and Savings	7.54
Legally-Required Benefits	5.27
Total Benefits	29.55

5. BASELINE COST ESTIMATION RESULTS & DISCUSSION

5.1 Overall Cost Results

An overall summary of the cost results developed in our analysis are provided in this subsection organized by the INL nuclear COA provided in Table 14. Capital cost results for Accounts 10 through 60 are provided in Table 24 while annualized operational and financing costs (Accounts 70 through 90) are provided in Table 25. Cost estimation details of each account are discussed further in the following subsections. We assume an average capacity factor of 93% and a plant lifetime of 60 years for presenting the costs on an energy normalized basis. Finally, electricity generating costs are reported as levelized cost of electricity (LCOE) in Table 26, including the individual contributing levelized annual costs that makeup the LCOE. Unless otherwise noted, all costs reported in this section represent the nuclear BOAK cost scenario.

[32] Bureau of Labor Statistics. (2023). *Employer Costs for Employee Compensation – March 2023*. U.S. Department of Labor. https://www.bls.gov/news.release/pdf/ecec.pdf

Table 24. Capital costs for the between first-of-a-kind and N^th^-of-a-kind (BOAK) cost scenario organized by the Idaho National Laboratory nuclear code of accounts (accts.).

	Parameter	UOM				
	Plant Nominal Power	MW_e	165	311	1,243	3,108
	Power Block Nominal Power	MW_e	165	311	622	622
	Reactor Nominal Power	MW_e	165	311	311	311
	Power Blocks/Plant	—	1	1	2	5
	Reactors/Plant	—	1	1	4	10
	Reactors/Power Block	—	1	1	2	2
Acct.	**Title**					
10	**Capitalized Pre-Construction Costs**					
11	Land & Land Rights	2023 US $/reactor	11,000,000	11,000,000	2,750,000	1,100,000
12	Site Permits	2023 US $/reactor	1,332,867	1,598,891	877,304	737,511
13	Plant Licensing	2023 US $/reactor	12,932,869	24,382,988	24,382,988	24,382,988
14	Plant Permits	2023 US $/reactor	12,679,167	12,679,167	3,169,792	1,267,917
15	Plant Studies	2023 US $/reactor	12,679,167	12,679,167	3,169,792	1,267,917
16	Plant Reports	2023 US $/reactor	1,661,678	3,132,845	3,132,845	3,132,845
17	Other Pre-Construction Costs	2023 US $/reactor	12,679,167	12,679,167	3,169,792	1,267,917
18	Community Outreach & Education	2023 US $/reactor	Not Included	Not Included	Not Included	Not Included
19	Contingency on Pre-Construction Costs	2023 US $/reactor	12,992,983	15,630,445	8,130,502	6,631,419
-	**Subtotal**	**2023 US $/reactor**	**77,957,896**	**93,782,669**	**48,783,015**	**39,788,513**
		2023 US $/kW$_e$	**473**	**302**	**157**	**128**
20	**Capitalized Direct Costs**					
21	Structures & Improvements	2023 US $/reactor	95,629,345	116,911,260	67,434,348	57,900,881
22	Reactor System	2023 US $/reactor	103,339,440	168,954,960	143,122,607	135,181,691
23	Energy Conversion System	2023 US $/reactor	114,790,006	193,175,861	171,185,934	159,966,799
24	Electrical Equipment	2023 US $/reactor	56,420,704	93,718,631	71,057,808	59,181,789
25	Heat Rejection System	2023 US $/reactor	17,362,219	28,452,265	24,546,990	22,560,934
26	Miscellaneous Equipment	2023 US $/reactor	47,811,287	67,299,871	39,391,309	28,341,317
27	Special Materials	2023 US $/reactor	0	0	0	0
28	Simulator	2023 US $/reactor	78,200	78,200	39,100	23,460
29	Contingency on Direct Costs	2023 US $/reactor	87,086,240	133,718,210	103,355,619	92,631,374
-	**Subtotal**	**2023 US $/reactor**	**522,517,443**	**802,309,257**	**620,133,717**	**555,788,246**
		2023 US $/kW$_e$	**3,170**	**2,581**	**1,995**	**1,788**
30	**Capitalized Indirect Services Costs**					
31	Factory & Field Indirect Costs	2023 US $/reactor	131,256,382	201,540,085	155,777,590	139,614,007
32	Factory & Construction Supervision	2023 US $/reactor	0	0	0	0
33	Commissioning & Start-Up Costs	2023 US $/reactor	13,960,144	19,168,403	9,584,202	6,061,581
34	Demonstration Test Run	2023 US $/reactor	0	0	0	0
35	Design Services Offsite	2023 US $/reactor	84,659,197	123,100,443	91,212,053	82,177,509
36	PM/CM Services Offsite	2023 US $/reactor	14,708,518	20,195,981	10,097,990	6,386,530
37	Design Services Onsite	2023 US $/reactor	0	0	0	0
38	PM/CM Services Onsite	2023 US $/reactor	20,378,180	31,290,061	24,185,215	21,675,742
39	Contingency on Indirect Services Cost	2023 US $/reactor	52,992,484	79,058,995	58,171,410	51,183,074
-	**Subtotal**	**2023 US $/reactor**	**317,954,906**	**474,353,968**	**349,028,460**	**307,098,443**
		2023 US $/kW$_e$	**1,929**	**1,526**	**1,123**	**988**
40	**Capitalized Owner's Costs**					
41	Staff Recruitment & Training	2023 US $/reactor	81,563,820	81,563,820	42,335,759	35,703,668
42	Staff Housing	2023 US $/reactor	5,900,000	5,900,000	3,081,250	2,600,000
43	Staff Salary-Related Costs	2023 US $/reactor	42,618,321	42,618,321	22,331,839	18,849,634
44	Other Owner's Costs	2023 US $/reactor	0	0	0	0
49	Contingency on Owner's Costs	2023 US $/reactor	26,016,428	26,016,428	13,549,770	11,430,660
-	**Subtotal**	**2023 US $/reactor**	**156,098,569**	**156,098,569**	**81,298,618**	**68,583,962**
		2023 US $/kW$_e$	**947**	**502**	**262**	**221**
50	**Capitalized Supplementary Costs**					
51	Shipping & Transportation Costs	2023 US $/reactor	1,614,001	1,614,001	8,968,615	22,421,538
52	Spare Parts	2023 US $/reactor	5,096,280	8,185,972	6,683,024	6,084,696
53	Taxes	2023 US $/reactor	1,862,043	3,510,602	3,510,602	3,510,602
54	Insurance	2023 US $/reactor	9,184,302	13,704,459	10,179,452	9,026,752
55	Initial Fuel Core Load	2023 US $/reactor	144,233,628	279,724,434	279,724,434	279,724,434

	Parameter	UOM				
	Plant Nominal Power	MW_e	165	311	1,243	3,108
	Power Block Nominal Power	MW_e	165	311	622	622
	Reactor Nominal Power	MW_e	165	311	311	311
	Power Blocks/Plant	—	1	1	2	5
	Reactors/Plant	—	1	1	4	10
	Reactors/Power Block	—	1	1	2	2
58	Decommissioning	2023 US $/reactor	14,606,673	14,606,673	4,612,595	1,852,156
59	Contingency on Supplementary Costs	2023 US $/reactor	35,319,385	64,269,228	62,735,744	64,524,036
-	**Subtotal**	**2023 US $/reactor**	**211,916,312**	**385,615,371**	**376,414,467**	**387,144,215**
		2023 US $/kW$_e$	**1,286**	**1,241**	**1,211**	**1,246**
60	**Capitalized Financial Costs**					
61	Escalation	2023 US $/reactor	0	0	0	0
62	Fees	2023 US $/reactor	0	0	0	0
63	Interest	2023 US $/reactor	205,693,669	305,741,119	235,947,542	217,199,296
69	Contingency on Financial Costs	2023 US $/reactor	41,138,734	61,148,224	47,189,508	43,439,859
-	**Subtotal**	**2023 US $/reactor**	**246,832,403**	**366,889,343**	**283,137,050**	**260,639,155**
		2023 US $/kW$_e$	**1,497**	**1,180**	**911**	**839**
	Total Direct Capital Cost (Accounts 10 to 20)	**2023 US $/reactor**	**600,475,339**	**896,091,926**	**668,916,731**	**595,576,758**
		2023 US $/kW$_e$	**3,643**	**2,883**	**2,152**	**1,916**
	Base Construction Cost (Accounts 10 to 30)	**2023 US $/reactor**	**918,430,244**	**1,370,445,894**	**1,017,945,191**	**902,675,201**
		2023 US $/kW$_e$	**5,571**	**4,409**	**3,275**	**2,904**
	Total Overnight Cost (Accounts 10 to 50)	**2023 US $/reactor**	**1,286,445,125**	**1,912,159,833**	**1,475,658,276**	**1,358,403,378**
		2023 US $/kW$_e$	**7,804**	**6,152**	**4,748**	**4,371**
	Total Capital Investment Cost (Accounts 10 to 60)	**2023 US $/reactor**	**1,533,277,528**	**2,279,049,176**	**1,758,795,326**	**1,619,042,533**
		2023 US $/kW$_e$	**9,301**	**7,333**	**5,659**	**5,209**

Table 25. Annualized operational and financing costs for the between first-of-a-kind and Nth-of-a-kind (BOAK) cost scenario organized by the Idaho National Laboratory nuclear code of accounts (accts.).

	Parameter	UOM				
	Plant Nominal Power	MW_e	165	311	1,243	3,108
	Power Block Nominal Power	MW_e	165	311	622	622
	Reactor Nominal Power	MW_e	165	311	311	311
	Power Blocks/Plant	—	1	1	2	5
	Reactors/Plant	—	1	1	4	10
	Reactors/Power Block	—	1	1	2	2
	Capacity Factor	%	93%	93%	93%	93%
	Annual Energy Production	MWh$_e$/year	1,343,000	2,532,025	10,128,102	25,320,254
Acct.	**Title**					
70	**Annualized O&M Costs**					
71	O&M Staff	2023 US $/reactor/year	8,944,000	8,944,000	6,948,250	6,799,700
72	Management Staff	2023 US $/reactor/year	16,640,000	16,640,000	6,290,250	4,361,800
73	Salary-Related Costs	2023 US $/reactor/year	14,505,504	14,505,504	7,575,438	6,392,256
74	Operating Chemicals & Lubricants	2023 US $/reactor/year	Not Included	Not Included	Not Included	Not Included
75	Spare Parts	2023 US $/reactor/year	6,794,473	11,032,032	8,986,093	8,104,651
76	Utilities, Supplies, & Consumables	2023 US $/reactor/year	Not Included	Not Included	Not Included	Not Included
77	Capital Plant Upgrades	2023 US $/reactor/year	7,786,050	14,679,432	14,679,432	14,679,432
78A	Taxes & Insurance	2023 US $/reactor/year	Not Included	Not Included	Not Included	Not Included
78B	Outage Costs	2023 US $/reactor/year	Not Included	Not Included	Not Included	Not Included
79	Contingency on Annualized O&M Costs	2023 US $/reactor/year	10,934,005	13,160,194	8,895,893	8,067,568
-	**Subtotal**	**2023 US $/reactor/year**	**65,604,033**	**78,961,161**	**53,375,355**	**48,405,406**
		2023 US $/MWh$_e$	**48.85**	**31.18**	**21.08**	**19.12**
80	**Annualized Fuel Cost**					
81	Refueling Operations	2023 US $/reactor/year	516,961	516,961	516,961	689,281
84	Additional Nuclear Fuel	2023 US $/reactor/year	23,737,084	46,035,558	46,035,558	46,035,558
86	Fuel Reprocessing Charges	2023 US $/reactor/year	0	0	0	0
87	Special Nuclear Materials	2023 US $/reactor/year	0	0	0	0
89	Contingency on Annualized Fuel Costs	2023 US $/reactor/year	4,850,809	9,310,504	9,310,504	9,344,968
-	**Subtotal**	**2023 US $/reactor/year**	**29,104,855**	**55,863,023**	**55,863,023**	**56,069,807**

	Parameter	UOM				
		2023 US $/MWh$_e$	**21.67**	**22.06**	**22.06**	**22.14**
90	**Annualized Financial Costs**					
91	Escalation	2023 US $/reactor/year	0	0	0	0
92	Fees	2023 US $/reactor/year	5,492,000	5,492,000	5,492,000	5,492,000
93	Cost of Money	2023 US $/reactor/year	0	0	0	0
99	Contingency on Annualized Financial Costs	2023 US $/reactor/year	1,098,400	1,098,400	1,098,400	1,098,400
-	**Subtotal**	**2023 US $/reactor/year**	**6,590,400**	**6,590,400**	**6,590,400**	**6,590,400**
		2023 US $/MWh$_e$	**4.91**	**2.60**	**2.60**	**2.60**
-	**Total Annual Operating Costs**	**2023 US $/reactor/year**	**101,299,287**	**141,414,584**	**115,828,778**	**111,065,613**
		2023 US $/MWh$_e$	**75.43**	**55.85**	**45.75**	**43.86**

Table 26. Levelized cost of electricity for the between first-of-a-kind and Nth-of-a-kind (BOAK) cost scenario with constituent cost breakdown.

Parameter	UOM				
Plant Nominal Power	MW$_e$	165	311	1,243	3,108
Power Block Nominal Power	MW$_e$	165	311	622	622
Reactor Nominal Power	MW$_e$	165	311	311	311
Power Blocks/Plant	—	1	1	2	5
Reactors/Plant	—	1	1	4	10
Reactors/Power Block	—	1	1	2	2
Plant Service Life	year	60	60	60	60
Capacity Factor	%	93	93	93	93
Annual Energy Production	MWh$_e$/year	1,344,222	1,344,222	2,688,444	24,195,996
Levelized Annual Capital Cost	2023 US $/MWh$_e$	60.10	47.43	36.66	33.77
Levelized Annual Operations & Maintenance Cost	2023 US $/MWh$_e$	48.85	31.18	21.08	19.12
Levelized Annual Fuel Costs	2023 US $/MWh$_e$	21.67	22.06	22.06	22.14
Levelized Annual Decommissioning Cost	2023 US $/MWh$_e$	0.18	0.10	0.03	0.01
Levelized Unit Electricity Cost	**2023 US $/MWh$_e$**	**130.80**	**100.78**	**79.83**	**75.04**

A graphical depiction of the numerical power normalized total overnight cost (TOC) results given in Table 24 are provided in Figure 3 including the primary account cost breakdown. The leftmost column represents an SFR NPP with a single reactor having a nominal electrical power output of 165 MW$_e$, while the column second from the left is for an SFR NPP with a single 311 MW$_e$ reactor, and all other subsequent columns represent SFR NPPs with multiple 311 MW$_e$ reactors. The power normalized TOC decreases by >15% for a nearly 2x increase in the nominal SFR, power block, and NPP output power due to economies of scale (compare leftmost bar corresponding to the 165 MW$_e$ plant and the second bar associated with the 311 MW$_e$ plant size). This magnitude of decrease is significantly larger than the decrease of only ~7% observed for the same magnitude increase (2x) in the number of 311 MW$_e$ size reactors and the increase in power block size from 311 MW$_e$ to 622 MW$_e$ (compare second and third bars from the left which correspond to the 311 MW$_e$ and 622 MW$_e$ plant sizes, respectively). This cost difference implies that the resulting economies of physical scale impact from increasing reactor and power block size on TOC is greater than that realized from the combination of the economy of manufacturing scale of multiple reactors and economy of physical size for even larger power blocks in this range of plant, power block, and reactor sizes. Marginal decreases in the TOC for even larger plants with more than four-311 MW$_e$ size reactors indicate that the economies of manufacturing scale contribution to TOC reduction slows for plants with greater than this number of reactors.

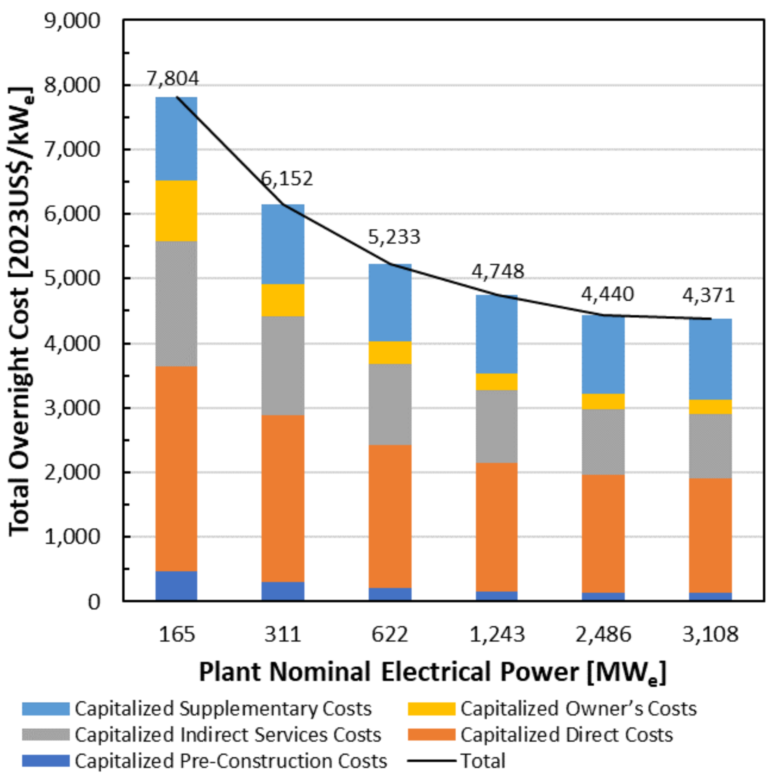

Figure 3. Cost breakdown of the total overnight cost for the between first-of-a-kind and N^{th}-of-a-kind (BOAK) cost scenario of various facility sizes considered in our analysis on a MW_e basis which include a single 471 MW_t/165 MW_e sodium-cooled fast reactor (SFR) (leftmost bar) and an increasing number of 840 MW_t/311 MW_e SFRs (all other bars).

5.2 Account 10: Capitalized Pre-Construction Costs

5.2.1 Account 11: Land & Land Rights

Land and land rights cost is based on an estimate of land acreage and land cost per acre. The land size is estimated with 50% of the area developed for the fenced-in portion of the facility inclusive of all major structures and lagoons and 50% of the area outside of the fenced-in portion for roadways, parking lots, easements, and green space. The calculation for determining the size of fenced-in area is discussed in Account 211. The necessary total land size ranges from 43 to 255 acres, but a minimum threshold of 500 acres is imposed for all facilities for additional buffer with adjacent landowners. This minimum acreage is consistent with guidelines from the Generation IV International Forum (GIF) which recommends a 494 acre site minimum total land space to provide adequate buffer. Average facility footprint[33] for the 59 US nuclear plants is 830 acres/GW_e while our estimates range from 3,030 to 160 acres/GW_e with small plants penalized by the minimum buffer acreage requirement. Consequently, the large buffer minimum has a large impact in incentivizing installations with increased electrical output. Land price is estimated at 2023 US $22,000 per acre based on the recommendation of the GIF. Overall, our projected SFR NPP costs range from 2023 US $83/$kW_e$ to 2023 US $7/$kW_e$ (for all of Account 10, inclusive of contingency).

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33 Accessed on July 19, 2023 from https://www.nei.org/news/2015/land-needs-for-wind-solar-dwarf-nuclear-plants.

5.2.2 Account 12: Site Permits

Site construction permitting fees are estimated as a percentage of land and improvements cost (Accounts 11 and 21). Appropriate values are estimated to range from 0.5% to 2.0% based on RSMeans data with a median value of 1.25% selected for the initial estimation.

5.2.3 Account 13: Plant Licensing

To estimate plant licensing costs, we use a reference case taken from the Combined Operating License (COL) application development work at a nuclear plant proposed for development in Stewart County, Southwest Georgia.[34] This proposed plant is part of a Public Service Commission (PSC) Integrated Resource Plan (IRP) to include an additional 1,600 MW_e of electrical power generated from low-carbon and renewable energy sources including nuclear. The commission approved a total IRP budget for the initial stages of development efforts of 2016US$99 million to cover preliminary site work and license application preparation. We therefore assume this cost amount applies entirely and only to the licensing fees for the NPP and treat the plant's nominal output electrical power as 1,600 MW_e. Furthermore, we ignore any potential NPP technology differences and assume the licensing cost between the actual technology considered for this potential Georgia plant development and our SFR NPP is the same with technology having no impact on the cost for plant licensing. This licensing cost is inflated to a 2023-year basis using the average annual Consumers Price Index (CPI) for All Urban Consumers (CPI-U) and then scaled linearly with plant total output electrical power to estimate the licensing costs for our SFR NPP.

5.2.4 Accounts 14, 15, & 17: Plant Permits, Plant Studies, & Other Pre-Construction Costs

2016US$10 million is assumed for each of Account 14, 15, and 17 with the total across these three accounts being 2016US$30 million based on NPP cost estimating expert judgement. To estimate the corresponding cost amounts for our SFR NPPs we inflate these reference costs to a 2023-year basis using the CPI-U and assume that these remain constant regardless of NPP size, and so do not rescale these across the different plant sizes we utilize in our analysis.

5.2.5 Account 16: Plant Reports

Plant reports include, but are not limited to, reports such as the Environmental Report (ER), Environmental Impact Statement (EIS), and Safety Action Report (SAR). A 1996 NRC report estimated that both the ER and EIS would require approximately 10,000 person-hours[35] for a reference plant size of 1,000 MW_e. At an NRC hourly rate of 2016US$265[36], each report would approximately cost 2016US$2.65 million. Assuming the SAR is approximately the same individual cost, total plant report costs would approximately be 2016US$7.95 million. To estimate the SFR NPP report costs, we therefore use this reference cost adjusted to a 2023 timeframe using the CPI-U and assume this rescales linearly from the reference plant size of 1,000 MW_e to each SFR NPP size we consider in our analysis.

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34 Georgia Public Service Commission - News Release: "Commission Approves Agreement on Georgia Power Integrated Resourced Plan; Increases Renewable Energy Resources; Approves Capitalization of Costs for Early Development of Stewart County Nuclear Power Facility. July 28, 2016. http://www.psc.state.ga.us/GetNewsRecordAttachment.aspx?ID=635

35 Regulatory Analysis for Amendments to Regulations for the Environmental Review for Renewal of Nuclear Power Plant Operating Licenses, Final Report. U.S. Nuclear Regulatory Commission. May, 1996. pp. 3-3. https://play.google.com/books/reader?id=bvE3AQAAMAAJ&printsec=frontcover&output=reader&hl=en&pg=GBS.PR17.

36 U.S. Federal Register: Revision of Fee Schedules; Fee Recovery for Fiscal Year 2016. https://www.federalregister.gov/documents/2016/06/24/2016-14490/revision-of-fee-schedules-fee-recovery-for-fiscal-year-2016.

5.2.6 Account 18: Community Outreach & Education

Since costs associated with community engagement, outreach, and education are highly case dependent varying with factors such as the existence or selection of a plant site and the economic development and income level of the specific location/site, we do not estimate these costs in this effort.

5.2.7 Account 19: Contingency on Capitalized Pre-Construction Costs

The contingency on pre-construction costs is estimated at 20% of Account 11–18 costs.

5.3 Account 20: Capitalized Direct Costs

Capitalized direct costs typically comprise the most significant contribution to full NPP economics. Additionally, many other costs captured in other accounts are often dependent on and estimated relative to the direct costs. Therefore, correctly predicting direct capital costs (DCC) is a crucial requirement for accurately estimating full NPP cost. This account for capitalized direct costs is further subdivided into subaccounts to distinctly enumerate costs for:

- Account 21: Structures and Improvements
- Account 22: Reactor System
- Account 23: Energy Conversion System
- Account 24: Electrical Equipment
- Account 25: Heat Rejection System
- Account 26: Miscellaneous Equipment
- Account 27: Special Materials
- Account 28: Simulator
- Account 29: Contingency

Costs for some categories can be sensitive to the type of nuclear technology. In particular, the reactor and main heat management systems are unique to each nuclear technology and are assessed to comprise the largest DCC subtotal estimated in our analysis, cumulatively contributing 26–41%. On a secondary tier of cost relevance, costs of the energy conversion system tend not to significantly depend on specific reactor types but rather overall power production levels. Our estimations put costs for this system at approximately 18–20% of the total for this account. On a lesser tier of significance, costs for site structures and improvements consist of a blend of contributions that are both unique and non-specific to SFRs. These tend to be based on both reactor specific attributes such as reactor sizing or radioactive waste characteristics, and general equipment design and sizing such as in the balance of plant (BOP) warehouse space where general BOP equipment from various parts of the plant would be stored or staged. We estimate that site structure costs comprise approximately 9–16% of DCC. Other elements that contribute to this account consist of electrical equipment, heat rejection subsystems, and other miscellaneous elements such as plant air systems, communication equipment, simulators, and cost contingencies, which less uniquely correlate with SFR technology and are estimated to cumulatively contribute 40–55% of DCC.

Installation of the main system components of Account 20 is computed using a simplified DFMA®-style methodology. Installation includes siting, onsite integration, and connection of the large components or subcomponents shipped to the plant site from fabrication facilities. In some cases, welding, bolting, or other types of connection methods are required to integrate subcomponents. In other cases, components come fully assembled via truck or rail and only require crane placement, anchoring, and other connections such as piping and electrical to be made. Cost is estimated at the subcomponent level based on an average number of hours (4 to 80 hours per component), average crew size (6–12 workers), average labor rate ($51/hour plus a 15% fieldwork premium), and average crane rate ($371/hour) for the full integration operation. A 30% additional cost adder is placed on the estimated base installation cost to capture non-enumerated expenses.

In the following subsections, we further detail specific cost results and relevant assumptions and key parameters used in deriving costs for each of the primary subaccounts included under Account 20.

5.3.1 Account 21: Structures & Improvements

The site structures account consists of 24 subaccounts that generally define a building function, whether it be a standalone building, multiple buildings, or section(s) of a building(s). The total cost of structures and improvements is estimated at 2023 US $651/kW$_e$ to 2023 US $210/kW$_e$ based on number of installed reactors (Table 27). The structure cost of each building starts with an estimate of the length, width, height, stories, interior rooms, concrete thickness, structural steel spans, and other geometric parameters taken or derived from text-based descriptions and building schematics included in figures having limited dimensions from a nine-reactor facility as discussed in Section 4.4. As necessary, the authors assume geometric values that are otherwise unavailable. RSMeans assembly values, adjusted for markups, are combined with the dimensional parameters to estimate costs for each building. Some building finishes such as bathrooms, epoxy coatings, and doors are added discretely to the cost with adjusted RSMeans values. Additional allowances are applied for other interior finishes, mechanical, electrical, and plumbing based on whether the space more closely matches office or warehouse quality finishes with an area-driven basis. These costs are likewise developed with adjusted RSMeans values. In addition to structures, site specific aspects like fences, barriers, parking lots, roads, railroad tracks, and wastewater lagoons are estimated with adjusted values from RSMeans. The following sections detail the construction assumptions of each structure and site improvement.

Table 27. Summary of structure and improvements capital costs.

	Parameter	UOM				
	Plant Nominal Power	MW$_e$	165	311	1,243	3,108
	Power Block Nominal Power	MW$_e$	165	311	622	622
	Reactor Nominal Power	MW$_e$	165	311	311	311
	Power Blocks/Plant	—	1	1	2	5
	Reactors/Plant	—	1	1	4	10
Account	**Title**					
21	**Structures & Improvements**					
211	Site Preparation & Yard Work	2023 US $/kW$_e$	128	79	38	30
212	Reactor Island Civil Structures	2023 US $/kW$_e$	83	66	63	63
213	Energy Conversion Building	2023 US $/kW$_e$	70	58	52	52
214	Security Building & Gatehouse	2023 US $/kW$_e$	6	3	1	1
215	Reactor Service Buildings	2023 US $/kW$_e$	14	8	3	2
216	Radwaste Building	2023 US $/kW$_e$	87	49	17	11
217	Fuel Service Building	2023 US $/kW$_e$	77	44	15	10
218A	Control Building	2023 US $/kW$_e$	48	27	10	7
218B	Administration Building	2023 US $/kW$_e$	30	17	6	4
218C	Operation & Maintenance (O&M) Center	2023 US $/kW$_e$	3	2	1	0
218E	Storage Buildings	2023 US $/kW$_e$	6	5	4	3
218K	Pipe Tunnels	2023 US $/kW$_e$	5	3	1	1
218L	Electrical Tunnels	2023 US $/kW$_e$	6	4	2	2
218N	Maintenance Shop	2023 US $/kW$_e$	6	5	4	3

	Parameter	UOM				
218Q	Foundations for Outside Equipment & Tanks	2023 US $/kW$_e$	2	2	2	2
218R	Balance of Plant (BOP) Service Building	2023 US $/kW$_e$	6	5	4	3
218S	Wastewater Treatment Building	2023 US $/kW$_e$	8	5	2	1
218T	Emergency & Start-Up Power Systems	2023 US $/kW$_e$	3	2	1	1
218W	Warehouse	2023 US $/kW$_e$	6	5	4	3
218X	Railroad Tracks	2023 US $/kW$_e$	27	16	6	4
218Y	Roads & Paved Areas	2023 US $/kW$_e$	16	9	4	3
218Z	Reactor Receiving & Assembly Building	2023 US $/kW$_e$	3	3	2	2
219A	Training Center	2023 US $/kW$_e$	4	2	1	1
219K	Special Materials Unloading Facility	2023 US $/kW$_e$	8	5	2	1
	Subtotal	**2023 US $/kWe**	**651**	**422**	**244**	**210**

5.3.1.1 Account 211: Site Preparation & Yard Work

The main and developed area of the site is built up from estimated areas of site structures and buildings having associated concrete pads. The building-occupied area is defined as 40% of the fenced-in area with the remainder of the area split between gravel and bare landscaped areas at 50% and 10%, respectively. Additional parking and roadways are included outside of the fenced area. Fencing for the plant includes high-security 10 ft chain link fence, razor wire and taunt line detection. Additional vehicle barrier and microwave detection are included for additional NI fencing. The dry cast storage is a concrete pad with area scaling linearly based on the power plant electrical rating. The switchyard and crane operating areas are 6” and 24” thick compacted gravel surfaces, respectively. The switchyard area scales linearly with plant power. The crane operating area is assumed constant.

Values from RSMeans are used to estimate clearing, grubbing, stripping topsoil, gravel, landscaping, and lighting. Additional building-specific excavation and stormwater allowances are included in the cost estimation for each building.

5.3.1.2 Account 212: Reactor Island Civil Structures

The nuclear reactor building, pipe tunnels to steam generators, and remote shutdown facility are all included in the cost for the reactor island civil structures. A single nuclear reactor building is composed of a deep silo, head containment, seismic isolation, reactor vessel auxiliary cooling system (RVACS), equipment vault, sodium vault, and electrical tunnel. For a 165 MW$_e$ reactor, the deep silo is 28 ft in diameter with a height of 78 ft, 3 ft-thick concrete walls and 5 ft-thick concrete floor. The head containment is 62 ft by 62 ft and 27 ft tall with 2 ft-thick concrete walls and 5 ft-thick concrete floor. The RVACS substructure sits inside the head containment with 2 ft-thick concrete walls and 3 ft-thick concrete floor. The equipment vault is 62 ft by 25 ft and 34 ft tall with three stories and 2 ft-thick walls and 3 ft-thick concrete floors. The sodium vault is 62 ft by 25 ft and 27 ft tall with 2 ft-thick walls and 3 ft-thick concrete floor. The backside electric tunnel is 8 ft wide and 16 ft tall with 2 ft-thick walls and floor. Structural steel is included in the equipment vault and additional steel is included in reinforced concrete.

Reactor diameter scales to 30 ft for a 311 MW$_e$ reactor with a constrained height. Power blocks with two reactors had slight improvements in cost from shared walls. Facilities with more than one power block assume replicated buildings that are linearly scaled.

The pipe tunnel from the nuclear reactor to the steam generator is included in this account as well. For the 165 MW$_e$ reactor, the pipe tunnel is 30 ft wide, 57 ft long, and 14 ft tall. The width of the tunnel is scaled with reactor thermal output power. The concrete floor, walls, and roof are 2 ft thick. There is one pipe tunnel per nuclear reactor. Allowances are included for warehouse-grade finishes.

The remote shutdown facility is considered as a nominal 300 ft^2 portion of the larger combined reactor service, small equipment maintenance, and liquid radioactive waste building. The remote shutdown facility is assigned 3% of the cost of the reactor service building and is included in this account.

5.3.1.3 Account 213: Energy Conversion Building

Costs for the energy conversion building are estimated as a combination of steam generator and turbine building costs. For a 165 MW_e reactor, the steam generator building houses a 35 ft-diameter, 89 ft-deep silo per nuclear reactor. For a scaled reactor size, the height is constrained and the cross-sectional area scales with the thermal output. The superstructure is 36 ft high with two floors and a footprint of 62 ft by 62 ft per nuclear reactor with area scaling by thermal output. The concrete is 2 ft thick for all floors and substructure walls. Superstructure walls are metal paneling rather than concrete. Exterior concrete pads are adjacent to two sides of the building. The steam generator building is formulated as single, double, and triple reactor options. When a site contains more than three reactors, buildings are repeated with linear scaling.

The turbine building for three 165 MW_e reactors is 183 ft by 95 ft. The building is 44 ft tall with three above-ground stories. Substructures are included for a condensate pump well and water pumps. In the main turbine building area, a 5 ft-thick concrete pad is included for a steam turbine pedestal. On the roof, there is a walk-in enclosure covering half the roof. Sub and super structures are included for the water pump and acid storage tank rooms but broken out as a percentage of costs for the turbine building, 10% and 5%, respectively, and attributed to Accounts 251 and 281Q.

Areas for buildings are scaled with thermal output while holding heights constant. For facilities with more than one power block, the buildings are replicated through linear scaling.

5.3.1.4 Account 214: Security Building & Gatehouse

Three security access points are included in each plant. A BOP guardhouse and NI guardhouse are included as portions of the control building and estimated as a combined 5% of the building cost. A construction and outage guardhouse is also estimated with 300 square feet of space with metal panel walls, metal roof, and typical office-grade finishes. The guardhouses that are included in the control building are kept at a constant proportion of the control building to scale with the facility's size for handling additional staff and visitors. The construction and outage guardhouse is kept constant at all facility sizes.

5.3.1.5 Account 215: Reactor Service Buildings

Reactor service buildings consist of a large building used for housing equipment and personnel used for reactor service, remote facility shutdown, small equipment maintenance, and liquid radioactive waste activities. The high bay portion of the building is attributed to the reactor service section that comprises 30% of the total building cost. The high bay is 46 ft tall with 2 ft-thick concrete walls, floor, and roof. The remote shutdown room is housed in the high bay area, but only accounts for about 300 ft^2.

5.3.1.6 Account 216: Radwaste Building

Costs for the radwaste building are estimated from combined costs of two multipurpose buildings. The liquid radioactive waste portion of the combined reactor service, small equipment maintenance, and liquid radioactive waste building contributes 60% of the building cost. This building is constructed with 2 ft-thick concrete floors, walls, and roof with several 2 ft-thick interior walls as well. Its footprint scales from 6,400 to 20,100 ft^2. The other building is the fuel cycle building with area for fuel storage and transfer. Cost of the radioactive waste portion of the building is 43%. This waste portion of the building has a 35 ft-deep basement tied into the reactor tunnel network. The superstructure is three stories with some office/laboratory space on each floor. The floors, walls, and roof are a mix of 2 ft thick and 8" thick concrete depending on the function.

5.3.1.7 Account 217: Fuel Service Building

The fuel service building is a portion of the fuel cycle and radioactive waste combined building with 57% being allocated to the fuel service building. The fuel service building portion has two 35 ft-deep basement sections. The superstructure is 43 ft tall with three stories composed of a mix of 2 ft thick and 8" thick concrete floors, walls, and roof depending on the function of the space. Office space and bathrooms are included on each floor with appropriate finishes.

5.3.1.8 Account 218A: Control Building

For the base plant design case we have devised, we assume the control building is a multipurpose building that contains the operational control center, two guardhouses including the access control area, the administration center, BOP personnel service area, the health physics area, and the training center. The control building cost is estimated at 55% of the total cost of the building. The building is a two-story office building with standard concrete floors, metal panel walls, and a metal roof. The building contains typical office-building finishes. The second floor is about 25% of the footprint of the first floor.

5.3.1.9 Account 218B: Administration Building

The administration building is assumed to be included in the control building as described in account 218A and is estimated as 35% of the cost for the entire control building.

5.3.1.10 Account 218C: Operation and Maintenance (O&M) Center

The operation and maintenance center is part of the multipurpose building described in Account 215 and estimated as 7% of the total building cost. The height of this building is 21 ft with the floor, walls, and roof made from 2 ft thick concrete.

5.3.1.11 Account 218E: Storage Building

The storage building is a 16 ft tall warehouse-style building with a concrete floor, metal sides, and metal roof. There is no interior office space or restrooms.

5.3.1.12 Account 218K: Pipe Tunnels

Plant pipe tunnels are 6 ft wide, 8 ft tall and 100 ft long per power block. Each tunnel is constructed with concrete and situated just below the surface. An allowance for mechanical, electrical, and piping finishes are included, but no additional costs for interior finishing.

5.3.1.13 Account 218L: Electrical Tunnels

Plant electrical tunnels connect the nuclear reactor to the steam generator building in each power block. Each tunnel is 10 ft wide and 14 ft tall. The length ranges from 110 to 170 linear ft depending on the number of reactors in the power block. Tunnels have 2 ft thick concrete floors, walls, and roofs with typical allowances for warehouse-grade finishes.

5.3.1.14 Account 218N: Maintenance Shop

The maintenance shop is estimated as a 16 ft tall warehouse-style building.

5.3.1.15 Account 218Q: Foundations for Outside Equipment & Tanks

Concrete pads are included for most major buildings and are included in their respective building costs. Major outdoor equipment, primarily transformers and tanks, are assumed to be sited near the turbine building. The area allocated for these concrete pads has 8” thick concrete.

5.3.1.16 Account 218R: Balance of Plant Service Building

The BOP service building is estimated as a 16 ft tall warehouse-style enclosed structure.

5.3.1.17 Account 218S: Wastewater Treatment

The wastewater treatment building is a warehouse-style building. Wastewater lagoons are sized for 280,000 to 1,000,000 GPD with a 10-day capacity.

5.3.1.18 Account 218T: Emergency & Start-up Power Systems

A gas turbine building is estimated for the emergency and start-up power systems structures. The height is 30 ft with typical warehouse-style construction.

5.3.1.19 Account 218W: Warehouse

The warehouse is estimated as a 16 ft tall warehouse-style building. The warehouse serves both the BOP side of the facility and nuclear side of the facility. A concrete wall is included as a secure divider to separate portions of the structure, but can be subdivided into two separate structures for each side of the facility. A small portion of the interior is allocated for a few offices and bathrooms which can be on either or both portions of the warehouse.

5.3.1.20 Account 218X: Railroad Tracks

A tunnel with railroad tracks is estimated to connect the nuclear reactor buildings with the multipurpose fuel cycle/storage/transfer and radioactive waste building and refueling enclosure and cask transporter building. The tunnel has a 2 ft thick concrete floor, walls, and roof, and is 20 ft wide and 14 ft high. The tunnel includes warehouse-grade finishes and a steel-tied rail.

5.3.1.21 Account 218Y: Roads & Paved Areas

Parking lots are sized based on the previously devised layout of the proposed facility[37] we use to develop our design basis and scaling estimates from. Total parking spots are estimated to be the same as the estimated number of full-time employees. The parking lot size is scaled based on staffing levels discussed in Account 70. Number of parking spaces range from 236 to 1,040 spaces per plant. Two-lane

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[37] GE-Advanced Nuclear Technology. PRISM-Preliminary Safety Information Document. *US DOE-DE-ACO3-89SF17445* **1987–1993**, *6*(App. G), G.4.14-11. *https://www.nrc.gov/docs/ML0828/ML082880400.pdf*.

asphalt roadways are included for connecting the road to the parking lots, facility entrances at guardhouses, and inside the facility to the cooling tower, warehouse, and switchyard.

5.3.1.22 Account 218Z: Reactor Receiving & Assembly Building

The BOP receiving and assembly building is estimated as a 16 ft tall warehouse-style building.

5.3.1.23 Account 219A: Training Center

The training center is part of a multipurpose building described in Account 218A and estimated as 5% of the total cost for the building. The training portion of the building contains group training rooms.

5.3.1.24 Account 219K: Special Materials Unloading

The special materials unloading building is considered the refueling enclosure and cask transporter building that connect the rail tunnels with grade. A 14 ft high 20 × 60 ft basement is covered by a main 16 ft tall superstructure. The building includes a 2 ft thick concrete floor, walls, and roof with warehouse-grade finishes.

5.3.2 Account 22: Reactor System

The reactor system is the core of the NPP and is therefore the primary account that distinguishes the SFR from all other reactor types. This consists of the reactor module including the nuclear core and all other contained equipment components such as the primary sodium pumps and IHXs, main heat transport system, fuel handling systems, radioactive waste processing subsystems, reactor specific instrumentation and controls including safety systems, and other miscellaneous equipment specific to the reactor such as inert cover gas management systems, coolant treatment systems, auxiliary cooling systems, and reactor-specific insulation. All subcomponents are housed in the nuclear reactor and steam generator buildings defined by Account 212 with the reactor module specifically residing in the below-grade concrete containment silo.

5.3.2.1 Account 221: Reactor Components

In this section, we present our cost results for the reactor shell assembly and accessories including reactor internal and external supports, other non-fuel-based internals, core control devices, and the control rod systems. Table 28 gives a high-level summary of cost results for each component contained within this account. Shipping and transportation costs for the reactor components are tabulated in Account 50.

Table 28. Summary of the material and manufacturing costs for each main reactor component for a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Cost escalations to account for nuclear design and construction requirements are included, but costs for onsite integration and installation are excluded.

Reactor System	Account	Material Cost	Manufacturing Cost	Total Cost
-	-	2023 US $	2023 US $	2023 US $
Reactor Components	**221**			
Reactor Support	221.11	987,829	113,545	1,101,374
Outer Vessel Structure	221.12	7,709,739	312,291	8,022,030
Inner Vessel Structure	221.13	3,569,612	894,603	4,464,215
Reactivity Control System	221.21	—	—	1,084,791
Reflector	221.31	224,281	14,514	238,794
Shield	221.32	3,067,081	174,515	3,241,596

Reactor System	Account	Material Cost	Manufacturing Cost	Total Cost
Moderator	221.33	—	—	—
Total	**-**	**15,558,541**	**1,509,468**	**18,152,800**
2023 US $/kW$_e$	-	**94.38**	**9.16**	**110.12**

Further description of how we estimate costs for each of the main subitems within this set of reactor components account is provided in the following subsections.

Outer Vessel Structure (Reactor Shell Assembly) Material Costs

The reactor shell assembly is the main constituent of the outer vessel structure subaccount (221.12). To estimate material costs for any reactor size, we identify and enumerate the required amount of A240 TP316 (SS) plates of a maximal size provided by material vendors that would have to be shaped and assembled to form each part of the shell construction to suit the final dimensions of the desired reactor size. The shell construction consists of the reactor containment vessel, reactor vessel itself (which holds the sodium coolant), and the top closure head. We then use recent (2023) cost quotes from these vendors to compute the base cost of the amount of SS required inclusive of extra material removed in the process of shaping and sizing each plate segment to fit into the shell. Table 29 provides estimates of the 316 SS required for the shell assembly and the corresponding costs for each part.

Table 29. Estimate of the materials required and their associated costs for a single baseline 471 MW$_t$/165 MW$_e$ sodium-cooled fast reactor shell assembly. Costs not escalated to account for special material design and handling requirements to satisfy nuclear quality.

Reactor Shell Assembly Component	UOM	Value
Reactor Vessel		
Finished Material Mass	kg	133,685
A240 TP316 SS Plates Required	—	22
Quoted Plate Dimensions	ft × ft × in (WxLxt)	10’ × 20’ × 2”
Total Cost	2023 US $	2,206,404
Containment Vessel		
Finished Material Mass	kg	73,176
A240 TP316 SS Plates Required	—	28
Quoted Plate Dimensions	ft × ft × in (WxLxt)	10’ × 20’ × 1”
Total Cost	2023 US $	1,404,076
Top Closure Head		
Finished Material Mass	kg	37,015
A240 TP316 SS Plates Required	—	1
Quoted Plate Dimensions	ft × ft × in (WxLxt)	21’ × 21’ x 12”
Total Cost	2023 US $	1,305,875
Total Cost	**2023 US $**	**4,916,355**
	2023 US $/kW$_e$	**29.82**

Outer Vessel Structure (Reactor Shell Assembly) Manufacturing Costs

The reactor shell assembly includes the reactor closure head, the reactor vessel, and the containment vessel which are assumed to all consist of 316 SS. The reactor closure head has a variety of ports that allow penetration of vital reactor equipment and instrumentation such as the intermediate heat exchangers, primary sodium pumps, control rods, and various detectors/monitors for measuring temperature, pressure, and radiological levels throughout the reactor module. The reactor closure head has an overhang and flange face that attaches to the top of the reactor vessel and containment vessel. The containment vessel and reactor vessel both include their body and an elliptical bottom head that are welded together to form each vessel. The containment vessel has an additional 316SS ring welded flush to the top inner portion of the body which acts as a top flange for connection to the reactor closure head. The closure head is bolted to the containment vessel through the flange and is seal welded on the interior to the reactor vessel and mechanically butt welded on the outside to the containment vessel. The reactor vessel and containment vessel are indirectly joined through the reactor closure head.

A detailed, bottom-up analysis of the necessary machining and assembly steps is conducted as described in Section 4.1.1 to determine the overall manufacturing cost of the reactor shell assembly. The machining steps, their relevant process parameters, machine rates, material requirements, material unit costs, and total costs are summarized in Table 30 to Table 33. All data presented is for one 471 MW_t/ 165 MW_e reactor. The total manufacturing cost is 2023 US $124,880.

Table 30. Estimate of the manufacturing costs for the closure head of a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Costs not escalated to account for special construction, inspection, and testing requirements to satisfy nuclear quality.

Machining Operation	Process Application	Process Repetitions	Process Length	Process Thickness	Machine Rate	Material Requirements & Costs	Total Cost
-	-	-	m	m	2023 US $/hr	2023 US $/Bolt	2023 US $
Plasma Cutting	Overhang Formation	1	39.420	0.140	63.98	0 / -	411
Deburring	Overhang Formation	1	39.420	-	51.00	0 / -	37
Plasma Cutting	Flange Face Formation	1 1	18.99 17.71	0.410 0.08	63.98	0 / -	932
Deburring	Flange Face Formation	1	36.71	-	51.00	0 / -	35
Plasma Cutting	In-Service Inspection Port Formation	4	0.81	0.23	63.98	0 / -	104
Deburring	In-Service Inspection Port Formation	4	0.81	-	51.00	0 / -	53
Plasma Cutting	Fission Gas Detector Port	1	0.48	0.30	63.98	0 / -	25
Deburring	Fission Gas Detector Port	1	0.48	-	51.00	0 / -	13
Plasma Cutting	Primary Sodium Processing Pipes Port	1	0.40	0.30	63.98	0 / -	22
Deburring	Primary Sodium Processing Pipes Port	1	0.40	-	51.00	0 / -	13

Machining Operation	Process Application	Process Repetitions	Process Length	Process Thickness	Machine Rate	Material Requirements & Costs	Total Cost
Plasma Cutting	Intermediate Heat Exchanger Port	2	8.47	0.30	63.98	0 / -	513
Deburring	Intermediate Heat Exchanger Port	2	8.47	-	51.00	0 / -	36
Plasma Cutting	Source Range Flux Monitor Port	3	0.32	0.30	63.98	0 / -	60
Deburring	Source Range Flux Monitor Port	3	0.32	-	51.00	0 / -	39
Plasma Cutting	Fuel Transfer Port	1	1.45	0.30	63.98	0 / -	53
Deburring	Fuel Transfer Port	1	1.45	-	51.00	0 / -	14
Plasma Cutting	Central Rotatable Plug	1	8.62	0.1	63.98	0 / -	285
		2	8.30	0.1			
		2	7.98	0.1			
Deburring	Central Rotatable Plug	1	41.17	-	51.00	0 / -	37
Drilling	Bolt Hole Drilling	180	—	—	51.00	180 / 3.00	850
Total	—	—	—	—	—	—	**3,532**

Table 31. Estimate of the manufacturing costs for the reactor vessel of a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Costs not escalated to account for special construction, inspection, and testing requirements to satisfy nuclear quality.

Machining Operation	Process Application	Process Repetitions	Process Length	Process Thickness	Machine Rate	Material Requirement	Material Unit Cost	Total Cost
-	-	-	m	m	2023 US $/hr	lb.	2023 US $/lb.	2023 US $
Plasma Cutting	Sheet Layers cut to Correct Length	6	3.05	0.05	63.98	0	—	202
Plasma Cutting	Final Sheet Layer cut to Correct Height	3	6.10	0.05				
Deburring	Cut Sheet Deburring	1	36.58	-	51.00	0	—	124
Roll Bending	Body and Bottom Head Bending and Forming	19	—	0.05	831.76	0	—	6,211
Manual Two-Sided Butt Welding	Body Welding	10	6.10	0.05	151.16	1,763.14	14.70	46,875
		5	5.84	0.05				
		15	3.05	0.05				
		3	1.28	0.05				
Manual Two-Sided Butt Welding	Bottom Head Welding	1	18.03	0.05	151.16	227.61	14.70	6,000

Machining Operation	Process Application	Process Repetitions	Process Length	Process Thickness	Machine Rate	Material Requirement	Material Unit Cost	Total Cost
X-ray Weld Inspection	Body Welds	1	3.55[a]	—	77.17	3.55[a]	56.57[b]	1,557
X-ray Weld Inspection	Bottom Head Weld	1	0.46[a]	—	77.17	0.46[a]	56.57[b]	151
Total	—	—	—	—	—	—	—	**61,118**

[a] Process length and required material units are in m^2.
[b] Material unit cost is in 2023 US $/$m^2$.

Table 32. Estimate of the manufacturing costs for the containment vessel of a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Costs not escalated to account for special construction, inspection, and testing requirements to satisfy nuclear quality.

Machining Operation	Process Application	Process Repetitions	Process Length	Process Thickness	Machine Rate	Material Requirement	Material Unit Cost	Total Cost
-	-	-	m	m	2023 US $/hr	lb.	2023 US $/lb.	2023 US $
Plasma Cutting	Body Sheet Layers Cut to Correct Length	6	3.05	0.03	63.98	0	—	170
Plasma Cutting	Body Final Layer Cut to Correct Height	4	6.10	0.03				
Deburring	Cut Sheet Deburring	1	42.67	-	51.00	0	—	140
Roll Bending	Body and Bottom Head Bending and Forming	25	—	0.03	831.76	0	—	6,827
Manual Two-Sided Butt Welding	Body Welding	15	6.10	0.03	151.16	1,019.98	14.70	30,293
		5	0.70	0.03				
		20	3.05	0.03				
		4	1.43	0.03				
Manual Two-Sided Butt Welding	Bottom Head Welding	1	18.99	0.03	151.16	119.87	14.70	4,415
X-ray Weld Inspection	Body Welds	1	4.11[a]	—	77.17	4.11[a]	56.57[b]	1,951
X-ray Weld Inspection	Bottom Head Weld	1	0.48[a]	—	77.17	0.48[a]	56.57[b]	155
Plasma Cutting	Cutting Face Flange Bar to Length	1	0.15	0.06	63.98	0	—	43
Deburring	Deburring Cut Face Flange	1	0.15	-	51.00	0	—	13
Roll Bending	Top Flange Bar Bending and Forming	1	-	0.06	831.76	0	—	745
Manual Two-Sided Butt Welding	Flange Joint Weld	1	0.15	0.06	151.16	2.40	14.70	112
Manual Two-Sided Butt Welding	Flange to Containment Vessel Weld	1	18.83	0.06	151.16	297.09	14.70	7,602
X-ray Weld Inspection	Flange Joint Weld	1	0.004[a]	-	77.17	0.004[a]	56.57[b]	68

Machining Operation	Process Application	Process Repetitions	Process Length	Process Thickness	Machine Rate	Material Requirement	Material Unit Cost	Total Cost
X-ray Weld Inspection	Flange to Containment Vessel Weld	1	0.48[a]	-	77.17	0.48[a]	56.57[b]	155
Plasma Cutting	In-Service Inspection Port Formation	4	0.81	0.06	63.98	0	—	34
Deburring	In-Service Inspection Port Formation	4	0.81	—	51.00	0	—	53
Bolt Drilling	Securing Bolt Drilling	36	—	—	51.00	36[c]	3.00	173
Total	—	—	—	—	—	—	—	**52,958**

[a] Process length and required material units are in m^2.
[b] Material unit cost is in 2023 US $/$m^2$.
[c] Material units are number of bolts.

Table 33. Estimate of the final assembly costs for the complete shell assembly of a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Costs not escalated to account for special construction, inspection, and testing requirements to satisfy nuclear quality.

Machining Operation	Process Application	Process Repetitions	Process Length	Process Thickness	Machine Rate	Material Requirement	Material Unit Cost	Total Cost
-	-	-	m	m	2023 US $/hr	lb.	2023 US $/lb.	2023 US $
Manual Two-Sided Butt Welding	Closure Head to Vessel Attachment	1	18.03	0.03	151.16	227.61	14.70	6,012
X-ray Weld Inspection	Closure Head to Vessel Attachment	1	0.46[a]	—	77.17	0.46[a]	56.57[b]	151
Bolting	Bolt Top Closure Head to Top Flange	36	—	—	51.00	0	—	65
Manual One-Sided Seal Weld	Containment Vessel to Top Closure Head	1	18.99	0.03	151.16	28.41	14.70	89
X-ray Weld Inspection	Bottom Head Welding	1	0.48[a]	—	77.17	0.48[a]	56.57[b]	155
Total	—	—	—	—	—	—	—	**7,273**

[a] Process length and required material units are in m^2.
[b] Material unit cost is in 2023 US $/$m^2$.

Inner Vessel Structure (Reactor Internals) Material Costs

In this subaccount, we capture costs for all reactor internals including reflectors, shielding, and moderators in addition to basic metallic elements not part of these subgroups. Material costs for the reactor internal structures are also assessed by computing raw material amounts, identifying the required material types, and applying a base cost value for each type of raw material. Reactor internals serve many different roles including mechanical support and anchoring, flow direction, diversion, and distribution, and thermal and radiological shielding, insulation, and isolation. Therefore, diverse materials of widely varying geometries and dimensions are utilized in the reactor internal structures. To capture this wide-ranging variation, we create a comprehensive list of the reactor internals that we ascertain from the design data taken to develop our design basis. We further establish the geometry, dimensions, and MOC for every part as well and using quoted raw material prices estimate material costs from computed material quantities.

Although several materials could be used, we simplify this by assuming only two primary materials: (1) 316 SS used for general mechanical construction, support, and containment as well as fluid flow control; and (2) densified natural enrichment $^{10}B_4C$ shielding material to block and absorb radiation emitted from the core. We use the same costs for 316 SS that we applied in estimating the costs for the reactor shell assembly and other equipment items, which are based on vendor quotes. For B_4C, we use commercial price quotes and our own approximation for the densification costs as defined in Section 5.6.5.2. Our material quantity estimations include excess amounts of materials that are not possible to build into each part, where these excesses would be scrapped and possibly salvaged for reuse in other ways which we do not take credit for. Therefore, our material cost estimations are the total costs expected for purchasing all needed raw material amounts to fully fabricate each part in its functioning form. Table 34 presents the high-level list of the reactor internal components we modeled and their corresponding material costs we estimate.

Table 34. Estimate of the materials required and their associated costs for the internal structures of a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Costs not inflated to account for special material design and handling requirements to satisfy nuclear quality.

Reactor Internal Structures Component	UOM	Value
Liner		
Finished Material Mass	kg	38,802
Materials of Construction	—	316 Stainless Steel (SS)
Total Cost	2023 US $	515,381
Seal Plate		
Finished Material Mass	kg	10,772
Materials of Construction	—	316 SS
Total Cost	2023 US $	143,077
Support Cylinder		
Finished Material Mass	kg	22,328
Materials of Construction	—	316 SS
Total Cost	2023 US $	296,566
Core Barrel		
Finished Material Mass	kg	7,383
Materials of Construction	—	316 SS
Total Cost	2023 US $	98,059
Core Support Plates & Former Ring		
Finished Material Mass	kg	14,667
Materials of Construction	—	316 SS

Reactor Internal Structures Component	UOM	Value
Total Cost	2023 US $	194,808
Fixed Reflector & Shield Cylinders		
Finished Material Mass	kg	23,874
Materials of Construction	—	316 SS
Total Cost	2023 US $	317,105
Core Inlet Plenum		
Finished Material Mass	kg	12,551
Materials of Construction	—	316 SS
Total Cost	2023 US $	166,712
Reactor Internals & Core Support Beams		
Finished Material Mass	kg	1,200
Materials of Construction	—	316 SS
Total Cost	2023 US $	15,936
Upper Internals Baffles & Support Plates		
Finished Material Mass	kg	14,044
Materials of Construction	—	316 SS
Total Cost	2023 US $	186,536
Boron Carbide (B_4C) Cans		
Finished Material Mass	kg	395
Materials of Construction	—	Cans: 316 SS; Packing: Natural Enrichment $^{10}B_4C$
Total Cost	2023 US $	27,609
Inner Central Thermal Liner		
Finished Material Mass	kg	5,065
Materials of Construction	-	316 SS
Total Cost	2023 US $	67,269
Fuel Storage Racks		
Finished Material Mass	kg	2,119
Materials of Construction	—	316 SS
Total Cost	2023 US $	28,143
Primary Pump Piping		
Finished Material Mass	kg	1,075
Materials of Construction	—	316 SS
Total Cost	2023 US $	30,895
Upper Internals Structure Assembly		
Finished Material Mass	kg	18,403
Materials of Construction	—	316 SS
Total Cost	2023 US $	528,801

Reactor Internal Structures Component	UOM	Value
Top Closure Head Shielding & Insulation Plates		
Finished Material Mass	kg	131,693
Materials of Construction	—	316 SS
Total Cost	2023 US $	1,749,203
Total Cost	**2023 US $**	**4,375,114**
	2023 US $/kW$_e$	**26.54**

Inner Vessel Structure (Reactor Internals) Manufacturing Costs

We conduct a detailed cost estimation of the manufacturing and final assembly process for the reactor internals per the general methodology described in Section 4.1.1. Table 35 summarizes the various reactor internal structures, their associated manufacturing costs, and percent contributions to the total manufacturing and final assembly cost estimate.

Table 35. Estimate of the manufacturing and final assembly costs for the internal structures of a single baseline 471 MW$_t$/165 MW$_e$ sodium-cooled fast reactor. Costs not inflated to account for special construction, inspection, and testing requirements to satisfy nuclear quality.

Reactor Internal Structures Component	Manufacturing Cost		Total Cost Breakdown
-	2023 US $	2023 US $/kW$_e$	%
Liner	20,877	0.13	5.84
Seal Plate	4,729	0.03	1.32
Support Cylinder	13,103	0.08	3.66
Core Barrel	5,172	0.03	1.45
Core Top Support Plate	5,534	0.03	1.55
Core Bottom Support Plate	2,639	0.02	0.74
Core Former Ring	1,686	0.01	0.47
Core Former Ring Holdown Brackets	1,290	0.01	0.36
Fixed Reflector Cylinder	5,804	0.04	1.62
Fixed Shield Compartment	38,618	0.23	10.80
Core Inlet Plenum	16,720	0.10	4.67
Reactor Internals & Core Main Support Beams	1,358	0.01	0.38
Upper Internals Baffle Plates	6,364	0.04	1.78
Upper Internals Support Plates	9,320	0.06	2.61
Boron Carbide (B_4C) Cans	25,101	0.15	7.02
Inner Central Thermal Liner	2,264	0.01	0.63
Fuel Storage Rack	24,578	0.15	6.87
Primary Pump Piping	821	0.002	0.23
Upper Internals Structure (UIS) Assembly	38,965	0.24	10.89
Closure Head Shielding & Insulation Plate Assembly	6,067	0.04	1.70
Final Manufacturing Assembly Steps	126,726	0.77	35.42
Total	**357,737**	**2.17**	**100.00**

Reactor Support Structures Costs

Reactor external structures consist of the reactor module top support blocks that rest on the top of the below-ground concrete nuclear silo and that support the hanging reactor module, the flanges that sit in the top closure head to hold the hanging IHX, primary sodium pumps, instrumentation and sensors, and miscellaneous primary sodium processing and cover gas piping that penetrate this head, and the central rotatable plug that provides in service access to the reactor for fuel replacement. We report our cost results for these items for the required materials in Table 36 and the manufacturing and assembly in Table 37.

Table 36. Estimate of the material costs for the support structures of a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Costs not escalated to account for special material design and handling requirements to satisfy nuclear quality.

Reactor Support Structures Component	UOM	Value
Support Blocks		
Finished Material Mass	kg	133,685
Materials of Construction	—	316 SS
Total Cost	2023 US $	274,593
Support Guide Blocks		
Finished Material Mass	kg	177
Materials of Construction	—	316 SS
Total Cost	2023 US $	2,351
Support Flanges		
Finished Material Mass	kg	6,935
Materials of Construction	—	316 SS
Total Cost	2023 US $	92,111
Central Rotatable Plug		
Finished Material Mass	kg	12,823
Materials of Construction	—	316 SS
Total Cost	2023 US $	260,865
Total Cost	**2023 US $**	**629,920**
	2023 US $/kW$_e$	**3.82**

Table 37. Estimate of the manufacturing and final assembly costs for the support structures of a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Costs not escalated to account for special construction, inspection, and testing requirements to satisfy nuclear quality.

Reactor Support Structures Component	Manufacturing Cost		Total Cost Breakdown
-	2023 US $	2023 US $/kW$_e$	%
Central Rotatable Plug (UIS Support) Assembly	4,124	0.025	9.08
IHX Support Flanges	658	0.004	1.45
Primary Pump Support Flanges	337	0.002	0.74
In-Vessel Fuel Transfer Machine Support Flanges	95	0.001	0.21
Fission Gas Detector Support Flanges	83	0.001	0.18
Reactor Support Blocks	14,039	0.085	30.92
Reactor Support Guide Blocks	1,949	0.012	4.29
Final Manufacturing Assembly Steps	24,120	0.146	53.12
Total	**45,405**	**0.275**	**100.00**

Control Rod Drive & Driveline Manufacturing Costs

Control rod drives and drivelines are the primary elements included in the control assembly that deploy the control rods into the reactor core for reactivity control. They provide control during normal start-up, load following, and shutdown operational modes. The control rod drive sits above the reactor closure head and consists of two primary components: (1) stepping motor controlled by the plant control system; and (2) lead screw actuated by the stepping motor, which inserts and withdraws the B_4C absorber rods. Depending on the specific control rod drive design, this will also contain sensors, electronics, magnetic latches that automatically activate and release in response to a reactor scram event due to abnormal temperature elevation, and reactor shielding. Each driveline typically connects to a single absorber rod through another latching mechanism that can detach and reattach as needed to allow for carrying out routine maintenance activities within the reactor such as fuel assembly removal and replacement..

A first-principles analysis of the most important control rod drive components is conducted. Summaries of key control rod drive and driveline parameters are shown in Table 38 and Table 39. The total estimated cost of a single control rod drive is 2023 US $74,319, while that for a single driveline is 2023 US $440, and the total cost per reactor for all control assemblies is 2023 US $523,311.

Table 38. Control rod drive design parameters and cost results of a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor.

Parameter	UOM	Value
Quantity[a]	**no./reactor**	**7**
Enclosure		
Diameter	in.	7.5
Height	in.	171.0
Materials of Construction	—	316 Stainless Steel (SS)
Stepping Motor		
Base Cost[b]	2023 US $	18,911
Contingency (Enhanced Drive Length & Speed)	%	30
Contingency (Nuclear Requirements)	%	50
Cost	2023 US $	36,876
Lead Screw		
Materials of Construction	—	SS
Base Cost[c]	2023 US $	5,000
I/O Electronics for Control		
Base Cost[d]	2023 US $	20,000
Shield Plugs		
Nominal Diameter	in	6
Length	in	24
Materials of Construction[e]	—	SS
Base Cost	2023 US $	43
Contingency (Manufacturing)	%	30
Cost	2023 US $	56
Overall Contingency[f]	**% of assembly cost**	**20**
Total Cost	**2023 US $/drive**	**74,319**
	2023 US $/reactor	

[a] Assumes six control and one shutdown drive. Both drive types are assumed to be identical.
[b] Source of cost: https://www.newport.com/f/ims-lm-high-performance-long-travel-linear-motor-stages.
[c] Source of cost: https://www.helixlinear.com/blog/acme-screws/the-helix-acme-lead-screw-advantage/.

Parameter	UOM	Value

[d] Rough-order-of-magnitude estimate. Includes position indicator rod, position indicator transducer, failsafe electromagnets, and wiring.
[e] T91 used as a surrogate material in analysis. See Section 5.6.5.3.
[f] Covers small items not explicitly accounted for.

Table 39. Driveline design parameters and cost results of a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor.

Parameter	UOM	Value
Quantity[a]	**no./reactor**	**7**
Rod		
Diameter (Nominal)	in.	3
Length	in.	569
Materials of Construction[b]	—	HT9
Material Cost	**2023 US $**	**378.31**
Manufacturing Costs		
Hot Extrusion Cost[c]	2023 US $/in.	0.044
Cold Extrusion Cost[c]	2023 US $/in.	0.113
Contingency	%	30
Cost	2023 US $	116.13
Rod Total Cost	**2023 US $**	**494.44**
Latch		
Materials of Construction[b]	—	HT9
Contingency (Manufacturing)	%	10
Cost[d]	2023 US $	33.29
Overall Contingency[e]	**% of rod total cost**	**20**
Total Cost	**2023 US $/driveline**	**593**
	2023 US $/reactor	**4,153**

[a] Assumes six control and one shutdown driveline. Both types are assumed to be identical.
[b] T91 used as a surrogate material in analysis. See Section 5.6.5.3.
[c] Cost assumes manufacturing rate of one reactor/year. Modest cost reduction projected at higher manufacturing rates. See Section 5.6.5.3.
[d] Includes cost of materials/starting parts.
[e] Covers small items not explicitly accounted for.

5.3.2.2 Account 222: Main Heat Transport System

The main heat transport system of the SFR is the next most important part of the plant that facilitates the extraction and conversion of nuclear energy into thermal energy ultimately delivering this for conversion to electrical power. Components in this account also further distinguish the SFR from other reactor technologies since the operating conditions tend to be in a higher temperature regime requiring exchangers to be designed and sized for handling and supporting the unique properties and behavior of the sodium coolant. This account consists of the initial load of the reactor coolant, reactor IHXs, steam generators, primary and intermediate sodium pumps, reactor coolant piping, reactor cover gas system, and in-system diagnostic instrumentation and meters. Additionally, this also includes the main steam piping from the steam generators to the turbine control and isolation valves (Account 231) and feedwater piping from the feed heating system to the steam generator (Account 234). Table 40 presents the summary of cost results for each component contained within this account.

Table 40. Summary of the material and manufacturing costs for each main heat transport system component for a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Cost escalations to account for nuclear design, handling, construction, inspection, and testing requirements are included, and only costs estimated using general cost correlations include onsite integration and installation expenses.

Reactor System	Account	Material Cost	Manufacturing Cost	Total Cost
-	**-**	**2023 US $**	**2023 US $**	**2023 US $**
Main Heat Transport System	**222**			
Reactor Coolant System	222.12	—	—	34,859,349
Heat Exchangers	222.13	6,440,913	1,108,563	7,549,477
Pressurizer System	222.14	—	—	6,396,847
Total	—	**6,440,913**	**1,108,563**	**48,805,672**
2023 US $/kW$_e$	—	**39.07**	**6.72**	**296.06**

Initial Coolant Load

Sodium coolant quantities contained within the reactor and primary sodium processing equipment are estimated for each plant size based on internal reactor volumes, the approximate level of sodium expected to be maintained within the reactor during normal operation, and an assumed 5% of the reactor sodium inventory to account for sodium held in the primary sodium processing equipment including piping (Table 41). The purchased capital costs of high-purity sodium (>99.9 wt%) are then computed based on a sodium purchase price of $1.96/kg Na which we estimate by inflating a price previously reported[38] on a 1978-year basis using the Producer Price Index (PPI) for all commodities. We do not include an estimate for the potential cost savings of sodium with large purchase volumes and so retain the base pricing for larger plant sizes. Consequently, power levelized sodium costs remain flat/constant across the full scale of plants considered.

Table 41. Estimates of sodium coolant amounts and corresponding costs for different sodium-cooled fast reactor (SFR) and SFR nuclear power plant sizes of the base design.

Parameter	UOM				
Plant Nominal Power	MW_e	165	311	1,243	3,108
Power Block Nominal Power	MW_e	165	311	622	622
Reactor Nominal Power	MW_e	165	311	311	311

[38] Vaaler, L. E. A Survey of Electrochemical Metal Winning Process. *Battelle Columbus Labs. Final Report* **1979**, *ANL/OEPM-79-3. https://www.osti.gov/servlets/purl/6063735*

Parameter	UOM				
Power Blocks/Plant	—	1	1	2	5
Reactors/Plant	—	1	1	4	10
Reactors/Power Block	—	1	1	2	2
Sodium Price	[2023 US $/kg]	1.96	1.96	1.96	1.96
Sodium Coolant Quantities					
Primary Sodium					
Volume	US gallons	95,560	247,552	990,208	2,475,520
Mass	kg	315,704	817,842	3,271,370	8,178,424
Primary Sodium Processing					
Volume	US gallons	4,778	12,378	49,510	123,776
Mass	kg	15,785	40,892	163,568	408,921
Total Sodium					
Volume	US gallons	100,338	259,930	1,039,718	2,599,296
Mass	kg	331,489	858,735	3,434,938	8,587,345
Total Cost	**2023 US $**	**649,554**	**1,682,692**	**6,730,770**	**16,826,924**
	2023 US $/kW$_e$	**3.94**	**5.41**	**5.41**	**5.41**

IHX Material Costs

Similar to the reactor shell assembly, we estimate material amounts and corresponding costs for each IHX by enumerating all materials for every part from appropriately sized raw materials provided by material vendors fabricated to specific material specifications. These raw material forms would then be processed within the fabrication shop to construct each part of the IHX and this in its entirety. Each IHX consists of a kidney-shaped shell with contained tube bundles and heads further described in the following subsection. Using recent (2023) vendor cost quotes for pressure vessel plates and tubes used for fabricating heat exchangers we compute the base cost of the amount of SS required to fabricate each part of the IHX which includes extra material removed in the process of manufacturing each IHX. Table 42 gives estimates for the materials required for each main part of a single IHX housed in a single base design of 471 MW$_t$/165 MW$_e$ and the corresponding costs.

Table 42. Estimate of the materials required and their associated costs for a single base design intermediate exchanger contained within a single baseline 471 MW$_t$/165 MW$_e$ sodium-cooled fast reactor. Costs not inflated to account for nuclear material design and handling requirements.

IHX Component	UOM	Value
Shell Assembly[a]		
Finished Material Mass	kg	16,204
Total Cost	2023 US $	215,234
Tube Bundle Assembly		
Finished Material Mass	kg	2,512
Total Cost	2023 US $	33,358

IHX Component	UOM	Value
Lower Toroidal Head		
Finished Material Mass	kg	873
Total Cost	2023 US $	11,586
Total Cost	**2023 US $**	**260,170**
	2023 US $/kW$_e$	**1.58**

[a] Includes shell, upper plenum/intermediate upper channel head with fixed tubesheet, inlet/outlet downcomer/riser assembly, lower plenum.

IHX Assembly Manufacturing Costs

The IHX consists of the shell assembly, the tube bundle assembly, and the lower toroidal head. The shell assembly is divided into the primary shell, the upper plenum, and the lower plenum. The primary shell has stiffening bands to add mechanical support to the structure and orifices that allow entry of primary sodium into the shellside. The primary sodium leaves the IHX through two sodium outlet nozzles at the bottom of the lower plenum. Intermediate sodium is brought into the IHX through a downcomer that enters via the upper plenum and flows out into the bottom floating toroidal head. The intermediate sodium then enters the tubes and exits through an upper tubesheet which is fixed to the upper plenum. The intermediate sodium leaves the system by flowing through the annular region between a concentric riser enclosing the downcomer. The upper section of the downcomer is insulated from the riser by a thermal sleeve that is welded to the upper plenum and primary shell.

The tube bundle assembly consists of the tubes, baffles/tube support plates, and tie rods. Baffles/Tube support plates have holes for the tubes to pass through and additional primary sodium flow holes to ensure a minimum primary sodium flow. The plates are welded to the primary shell of the shell assembly. Tubes are explosively expanded into the various holes in each tubesheet and then welded on the outside to create hermetic seals[39]. We estimate the expansion process to take 45 seconds and require 0.011 lb of explosive material per tubehole. The explosive is assumed to cost 2023 US $0.28/lb[40]. Additional work is needed to further refine and validate the cost estimates for this process.

The lower toroidal (floating) head consists of its main body and a floating tube sheet which are welded together. The downcomer is welded to the top of the floating tubesheet to allow the passage of intermediate sodium and to support the floating head.

The primary machining operations we identified and modeled for each IHX and their relevant process parameters, machine rates, material requirements, material unit costs, and total costs are summarized in Table 43. Overall costs for the IHX shell assembly, tube bundle assembly, lower toroidal head, and final part assembly are summarized in Table 44. Data presented in both tables is for a single IHX sized for one baseline 471 MW_t reactor.

Table 43. Estimate of the manufacturing costs for the primary fabrication steps modeled for constructing a single base design intermediate heat exchanger (IHX) contained within a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Costs not escalated to account for special construction, inspection, and testing requirements to satisfy nuclear quality.

Manufacturing Operation	Process Application	Process Repetitions	Process Length	Process Thickness	Machine Rate	Material Requirement	Material Unit Cost	Total Cost
-	-	-	m	m	2023 US $/hr	lbs	2023 US $/lb	2023 US $
Roll Bending	Forming Primary Shell Sheets	4	—	0.020	831.76	0	—	1,975[a]
Manual Two-Sided Butt Welding	Primary Shell Plate Welding	1	6.10	0.020	151.16	88.08	14.7	2,810
		1	0.78					
		2	3.05					
		2	2.82					
Manual Fillet Weld	Stiffening Band Attachment Weld to Shell	4	6.88	0.0071	151.16	20.96	14.7	1,154
Roll Bending	Upper Plenum Sheets	2	—	0.030	831.76	0	—	1,317[a]
Plasma Cutting	Upper Tubesheet Tubehole Openings	2,140	0.050	0.15	63.98	0	—	1,859

39 GE-Advanced Nuclear Technology. PRISM-Preliminary Safety Information Document. *US DOE* **1987**, *Vol. 2*, Ch. 5–8, *5.4-13*.

40 Assuming the explosive material is similar to ammonium nitrate (NH_4NO_3). Rough-order-of-magnitude costs for NH_4NO_3 taken from https://scienceofagriculture.org/nitrogen/fertilizer/fertilizer-comparison-02.html.

Manufacturing Operation	Process Application	Process Repetitions	Process Length	Process Thickness	Machine Rate	Material Requirement	Material Unit Cost	Total Cost
Manual Fillet Weld	Tubesheet to Upper Plenum Attachment Weld	2	6.82	0.019	151.16	73.87	14.7	2,876
Roll Bending	Lower Plenum Sheets	2	—	0.030	831.76	0	—	1,317[a]
Manual Two-Sided Butt Welding	Outlet Nozzle Attachment to Lower Plenum Nozzle Port	2	2.61	0.030	151.16	32.99	14.7	1,026
Manual Two-Sided Butt Welding	Upper Plenum to Shell Attachment Weld	1	6.82	0.030	151.16	43.01	14.7	1,276
Manual Two-Sided Butt Welding	Lower Plenum to Shell Attachment Weld	1	7.68	0.030	151.16	48.44	14.7	1,433
Manual Fillet Weld	Lower Thermal Sleeve to Shell/Upper Plenum	4	5.82	0.012	151.16	49.25	14.7	2,294
Drilling	Center Baffles/Tube Support Plate Openings	15,965[b]	—	0.02	51.00	0	—	3,397
Drilling	Inner Side Baffles/Tube Support Plate Openings	8,612[b]	—	0.02	51.00	0	—	1,830
Drilling	Outer Side Baffles/Tube Support Plate Openings	10,364[b]	—	0.02	51.00	0	—	2,202
Roll Bending	Lower Toroidal Head Sheets	2	—	0.010	831.76	0	—	1,014[a]
Plasma Cutting	Floating Tubesheet Tube Openings	2,140	0.05	0.13	51.23	0	—	1,279
Explosive Expansion	Tubing Explosive Expansion in Fixed Tubesheet	2,140	—	—	51.00	23.59	0.28	1,371
Manual One-Sided Seal Weld	Tubing Assembly Seal Weld to Fixed Tubesheet	2,140	0.05	0.08	151.16	481.55	14.7	12,155
Manual Fillet Weld	Baffle Plates to Shell Attachment Welds	6 8 8	3.98 2.48 2.80	0.010	151.16	201.47	14.7	8,701
Explosive Expansion	Tubing Explosive Expansion in Floating Tubesheet	2,140	—	—	51.00	23.59	0.28	1,371
Manual One-Sided Seal Weld	Tubing Assembly Seal Weld to Fixed Tubesheet	2,140	0.05	0.06	151.16	401.76	14.7	10,487

[a] Process times are multiplied by a factor of 5 to account for the complex geometry of the IHX.
[b] Assumed 15 seconds of drilling time per hole given that the baffles are 0.019m thick and the juxtaposition of the holes.
[c] Denotes the total inspected area and material required in m^2.
[d] Material unit costs are in 2023 US $/$m^2$.

Table 44. Manufacturing cost breakdown by major parts included in a single base design intermediate heat exchanger (IHX) contained within a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Costs not escalated to account for special construction, inspection, and testing requirements to satisfy nuclear quality.

IHX Component	Manufacturing Cost	Total Cost Breakdown
-	2023 US $	%
Shell Assembly	29,228	36
Tube Bundle Assembly	10,984	14
Lower Toroidal Head	4,097	5
Final IHX Assembly	35,934	45
Total	**80,255**	**100**

Steam Generator Costs

The steam generator within our base design SFR plant is a helical coil type shell and tube heat exchanger designed for producing high-pressure, superheated steam. In terms of the material requirements, this mostly consists of the shell and helical tube bundle which we treat as constructed out of A387 GR22 (2 1/4 Cr, 1 Mo) for the shell and all other pressure vessel appurtenances, and A213 T22 (2 1/4 Cr, 1 Mo) for the tubes. Due to the high steam pressure, thicknesses of the different parts of each steam generator are large at ~5 in. which substantially increases the material costs and requires more severe manufacturing/fabrication expense as well. As described for the IHX previously, the manufacturing of the steam generator follows a similar process except that the extra processing required for the thicker materials and the helical tube bundle having to be bent as well. Our cost results for the required materials and necessary manufacturing and assembly processes are provided in Table 45 and Table 46, respectively.

Table 45. Estimate of the materials required and their associated costs for a single base design steam generator associated with a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Costs not escalated to account for special material design and handling requirements to satisfy nuclear quality. Excludes costs for auxiliary cooling system installed around the steam generator for passive safety cooling to remove residual decay heat since this is included under Account 223 for the reactor safety systems.

Steam Generator Component	UOM	Value
Shell Assembly		
Finished Material Mass	kg	202,824
Materials of Construction	-	2 ¼ Cr, 1 Mo
Total Cost	2023 US $	1,206,652
Sodium Inlet Distributor Assembly		
Finished Material Mass	kg	5,229
Materials of Construction	-	2 ¼ Cr, 1 Mo
Total Cost	2023 US $	18,885
Tube Bundle Assembly		
Finished Material Mass	kg	193,621
Materials of Construction	-	2 ¼ Cr, 1 Mo
Total Cost	2023 US $	2,321,153
Support Skirt		
Finished Material Mass	kg	22,448
Materials of Construction	-	A36 CS
Total Cost	2023 US $	40,203

Total Cost	**2023 US $**	**3,586,893**
	2023 US $/kW$_e$	**21.76**

Table 46. Estimate of the manufacturing and assembly costs for a single base design steam generator associated with a single baseline 471 MW$_t$/165 MW$_e$ sodium-cooled fast reactor. Costs not escalated to account for special construction, inspection, and testing requirements to satisfy nuclear quality. Excludes costs for manufacturing and assembling the auxiliary cooling system installed around the steam generator for passive safety cooling to remove residual decay heat since this is included under Account 223 for the reactor safety systems.

Steam Generator Component	Manufacturing Cost		Percent of Total Cost
-	2023 US $	2023 US $/kW$_e$	%
Shell Assembly	112,239	0.68	30.91
Sodium Inlet Distributor Assembly	5,074	0.03	1.36
Helical Tube Bundle Assembly	70,031	0.43	19.55
Support Skirt	16,476	0.10	4.55
Final Steam Generator Assembly Steps[a]	158,054	0.96	43.63
Total	**361,874**	**2.20**	**100.00**

[a] ACS final assembly costs not included in cost estimate.

Primary & Intermediate Sodium Pump Costs

Total installed capital costs for the primary and intermediate sodium pumps are calculated using the general equipment cost correlation defined in Section 4.2.4 and are listed in Table 47.

Table 47. Estimate of the total installed capital costs for all primary and intermediate base design sodium pumps required for a single baseline 471 MW$_t$/165 MW$_e$ sodium-cooled fast reactor. Costs not escalated to account for special equipment design, fabrication, inspection, testing, and handling requirements to satisfy nuclear quality.

Sodium Pump Component	UOM	Value
Primary Sodium Pumps		
Quantity	no./reactor module	4
Total Installed Cost	2023 US $	6,324,102
Intermediate Sodium Pumps		
Quantity	no./reactor module	2
Total Installed Cost	2023 US $	4,519,315
Total Installed Cost	**2023 US $**	**10,843,461**
	2023 US $/kW$_e$	**65.78**

5.3.2.3 Account 223: Safety Systems

The SFR safety systems maintain plant operation within a safe range. Components in this account also further distinguish the SFR from other reactor technologies due to the incorporation of inherent passive safety features and functions into their design and operation. This account consists of the residual heat removal and reactor cavity cooling subsystems, safety injection subsystem, contaminant spray subsystem, and combustible gas control subsystem. For this system we focus our cost estimate on the two heat removal subsystems since we have enough detail to capture their respective costs in an accurate fashion. While the design we base our SFR basis on does utilize various safety systems for the monitoring, control, and safe operation of the sodium coolant particularly if this contacts either water or air, we do not explicitly estimate costs for its associated equipment items. Costs for this overall account are summarized in Table 48.

Table 48. Summary of the material and manufacturing costs for each main reactor safety system component for a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Cost escalations to account for nuclear design and construction requirements are included, but costs for onsite integration and installation are excluded.

Reactor System	Account	Material Cost	Manufacturing Cost	Total Cost
-	**-**	**2023 US $**	**2023 US $**	**2023 US $**
Safety Systems	**223**			
Residual Heat Removal System	—	134,340	366,900	501,240
Safety Injection System	—	—	—	—
Containment Spray System	—	—	—	—
Combustible Gas Control System	—	—	—	—
Reactor Cavity Cooling System (RCCS)	—	497,952	486,787	984,739
Total	—	**632,292**	**853,687**	**1,485,979**
2023 US $/$kW_e$	—	**3.84**	**5.18**	**9.01**

Residual Heat Removal System

The residual heat removal system we model within the SFR plant is that installed around and over the steam generator. This residual heat removal system utilizes a combination of natural and forced convection to pull ambient air through the steam generator building and along the shell and heads of the steam generator to extract residual heat which is rejected to atmosphere. We estimate the costs for both materials and manufacturing for this system as given in Table 49.

Table 49. Estimate of the material costs and the total manufacturing and assembly costs for the residual heat removal system based around the steam generator associated with a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Costs not escalated to account for special material design, construction, inspection, testing, and handling requirements to satisfy nuclear quality.

Residual Heat Removal System Component	UOM	Value
Collection Hood		
Finished Material Mass	kg	1,628
Materials of Construction	—	A36 CS
Total Cost	2023 US $	2,917
Shell		
Finished Material Mass	kg	34,506
Materials of Construction	—	A36 CS
Total Cost	2023 US $	61,800
Vent Plenum		
Finished Material Mass	kg	8,548
Materials of Construction	—	A36 CS
Total Cost	2023 US $	15,310
Vent Stack		
Finished Material Mass	kg	3,150
Materials of Construction	—	A36 CS
Total Cost	2023 US $	5,641

Residual Heat Removal System Component	UOM	Value
Total Material Cost	**2023 US $**	**85,666**
	2023 US $/kW$_e$	**0.52**
Total Manufacturing & Assembly Cost	**2023 US $**	**67,691**
	2023 US $/kW$_e$	**0.41**
Total Cost	**2023 US $**	**153,357**
	2023 US $/kW$_e$	**0.93**

Reactor Cavity Cooling System (RCCS)

The RCCS removes excess waste heat generated by the reactor system via the natural convection of air through the RVACS. Ambient air travels through the RVACS stacks and enters the reactor cavity through the RCCS inlet plenum. Air advances down through the cavity pulled by natural convection and traverses back up the collector cylinder drawing heat from the reactor vessel. The air then passes through the outlet plenum and exits the reactor silo and building through a parallel duct contained in the same chimney stack that the cool ambient air entered. We report our cost results for these items for the required materials in Table 50 and the manufacturing and assembly in Table 51.

Table 50. Estimate of the material costs for the reactor cavity cooling system of a single baseline 471 MW$_t$/165 MW$_e$ sodium-cooled fast reactor. Costs not escalated to account for special construction, inspection, and testing requirements to satisfy nuclear quality.

Reactor Cavity Cooling System Component	UOM	Value
Collector Cylinder		
Finished Material Mass	kg	91,867
Materials of Construction	—	A36 CS
Total Cost	2023 US $	164,533
Inlet Plenum		
Finished Material Mass	kg	30,869
Materials of Construction	—	A36 CS
Total Cost	2023 US $	55,285
Outlet Plenum		
Finished Material Mass	kg	10,893
Materials of Construction	—	A36 CS
Total Cost	2023 US $	19,509
Reactor Containment Silo Bottom Insulation		
Finished Material Mass	kg	219
Materials of Construction	—	Ceramic
Total Cost	2023 US $	78,207
Total Cost	**2023 US $**	**317,535**
	2023 US $/kW$_e$	**1.93**

Table 51. Estimate of the manufacturing and final assembly costs for the reactor cavity cooling system of a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Costs not escalated to account for special construction, inspection, and testing requirements to satisfy nuclear quality.

Reactor Cavity Cooling System (RCCS) Component	Manufacturing Cost		Total Cost Breakdown
-	2023 US $	2023 US $/kW$_e$	%
Collector Cylinder	103,241	0.63	53.04
Inlet Plenum	58,315	0.35	29.96
Outlet Plenum	23,028	0.14	11.83
Final RCCS Assembly Steps	10,075	0.06	5.18
Total	**194,658**	**1.18**	**100.00**

5.3.3 Account 23: Energy Conversion System

The energy conversion system converts thermal energy in the steam subsystem into alternating current (AC) electricity suitable for electrical power export. Account 23 consists of the subaccounts shown in Table 52.

Table 52. Definition of energy conversion system cost basis.

Account	Title	Cost Basis
231	Electricity Generator	See Eq. 4.2.5 and Table 53
233	Electricity Generator Hydraulic Systems	21.7% of Elec Gen
234	Feed Heating Systems	17.6% of Elec Gen
235	Other Plant Equipment for Electricity Generation	16.6% of Elec Gen
236	Electrical Generator Instrumentation & Control	5.1% of Elec Gen
237	Electrical Generator Miscellaneous Items	6% of Elec Gen

Since steam is used as the working fluid in both our SFR plant and in most PWR plants, and while SFR temperatures are slightly elevated, there is no significant fundamental difference in the thermodynamics and energy conversion options available to SFR systems compared to PWRs. Consequently, we expect there to be only minor differences in their corresponding costs and use the energy conversion system specifications used in the PRISM MOD-A reference system, but set the baseline costs to those previously computed by others for the PWR12-BE. Total installed capital costs for the multi-stage steam turbine which includes the electrical power generator are determined using the general equipment cost correlation for multi-stage steam turbine generators defined in Section 4.2.5 with the total installed capital cost results provided in Table 53. Steam turbine costs at other sizes are scaled based on electrical power via a power-law relationship. Cost of peripheral subsystems are projected as a percentage of the steam turbine cost based on the corresponding proportions reported for each subaccount in the PWR12-BE data. The energy conversion system, in general, is expected to exhibit increased efficiency and lower $/kW$_e$ as electrical output increases. Guided by PRISM projections, the steam turbine generator efficiency is 35% for ~471kW$_t$ and 37% for >800kW$_t$. Economies of scale are reflected in this power-law scaling.

Table 53. Estimate of the total installed capital costs for the multi-stage steam turbine electrical generator required for a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor and power block. Costs not escalated to account for special material design and construction requirements to satisfy nuclear quality since these components are not designed and constructed to nuclear safety grade standards and so do not require this type of escalation.

Steam Turbine Generator	UOM	Value
Quantity	no./power block	1
Total Installed Cost	2023 US $	69,045,149
	2023 US $/$kW_e$	418.46

5.3.4 Account 24: Electrical Equipment

Electrical equipment consists of Accounts 241–246 (Table 54) corresponding to switchgear, auxiliary buildings, switchboards, protective systems equipment, electrical raceway systems, and power and control cables and wiring, respectively. All of these systems primarily deal with the generated power from the NPP and thus are not directly affected by the nuclear cycle by which the power is generated. Consequently, we base these costs on existing estimates (PWR12-BE) for each cost category, scaled via a power law relationship with an exponent to reflect economies of equipment scale. Since much of the equipment is modular by nature, the scaling may be closer to linear resulting in a reduction in cost compared to the selected 0.8 exponent. Details for each subsystem are shown in Table 54.

Table 54. Summary of the total installed capital costs for each main electrical equipment component for a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Costs not escalated to account for special material design and construction requirements to satisfy nuclear quality since these components are not designed and constructed to nuclear safety grade standards and so do not require this type of escalation.

Account	Title	PWR12-BE Cost Basis	SFR Cost Result[a,b]
-	-	2023 US $/$kW_e$	2023 US $/$kW_e$
241	Switchgear	34.08	50.21
242	Auxiliary Buildings	57.53	84.75
243	Switchboards	5.85	8.61
244	Protective Systems Equipment	12.16	17.91
245	Electrical Raceway Systems	63.63	93.74
246	Power & Control Cables & Wiring	58.78	86.59

[a] See Section 4.2 for details regarding cost estimation and scaling relationships.
[b] Scaling exponent is 0.8. PWR12-BE plant nominal power is 1,144 MW_e.

5.3.5 Account 25: Heat Rejection System

We estimate costs for the heat rejection system using general equipment cost correlations. The primary components included in this account are the CWTs and associated CW handling and management equipment such as the circulation water pumps, makeup water treatment equipment, all piping and valves, blowdown water treatment subsystem, and all of their corresponding structures and buildings. The cost correlation provided in Section 4.2.1 for general CWTs is assumed to include costs of all these items. Account 25 costs are summarized in Table 55.

Table 55. Summary of the total installed capital costs for each main heat rejection system component for a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Costs not escalated to account for special material design and construction requirements to satisfy nuclear quality since these components are not designed and constructed to nuclear safety grade standards and so do not require this type of escalation.

Account	Title	PWER12-BE Cost Basis	SFR Cost Result[a]
-	—	2023 US $/kW$_e$	2023 US $/kW$_e$
251	Structures	12.36	18.21[b]
252	Mechanical Equipment	N/A	86.33

[a] See Section 4.2 for details regarding cost estimation and scaling relationships.
[b] Scaling exponent is 0.8. PWR12-BE plant nominal power is 1,144 MW_e.

5.3.6 Account 26: Miscellaneous Equipment

Costs for Account 264 (Furnishings and Fixtures) are estimated based on plant headcount (as discussed in Account 70) with a fixed allowance for safety, office, and changing room equipment allocated for every person. Additional allowances are made for chemical laboratory equipment to technical staff and instrument and maintenance equipment to O&M staff (Table 56).

Table 56. Summary of the total installed capital costs for each main miscellaneous equipment component for a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Costs not escalated to account for special material design and construction requirements to satisfy nuclear quality since these components are not designed and constructed to nuclear safety grade standards and so do not require this type of escalation.

Account	Title	PWR12-BE Cost Basis	SFR Cost Result[a]
-	-	2023 US $/kW$_e$	2023 US $/kW$_e$
261	Transportation & Lift Equipment	17.10	37.12[b]
262	Air, Water, Plant Fuel Oil, & Steam Systems	81.96	177.88[b]
263	Communications Equipment	18.30	39.72[b]
264	Furnishing & Fixtures	N/A	See note c.
265	Other	N/A	0

[a] See Section 4.2 for details regarding cost estimation and scaling relationships.
[b] Scaling exponent is 0.6. PWR12-BE plant nominal power is 1,144 MW_e.
[c] Scaled with staffing and based on cost buildup that varies between $24k - $36k per staff member.

5.3.7 Account 27: Special Materials

Since we account for the initial coolant load in the main heat transport system cost account (Account 222), there are no additional special materials that we identify to include within this cost account. Therefore, we do not attribute any cost amount to this account and leave this empty in our analysis.

5.3.8 Account 28: Simulator

Simulator costs are estimated as the costs for an approximate replicant of an expected high-powered control station (Table 57). Each control station is assumed to consist of three stationary, desktop-style computers connected to two touch-screen monitors each (six total monitors), three touch activated operator interface boards (i.e., keyboards with integral pointer scroll devices), hardwired telephone, and built-in multi-channel communication device (i.e., two-way radio). Costs for each computer were assumed to be 2023 US $10,000 while the touchscreen monitors are assumed to each cost 2023 US $1,000. An extra 2023 US $10,000 is included to account for the desk-style control station stand upon which the computers and monitors are mounted. This stand also contains the operator keyboards and two communication devices (telephone and radio) as built-in items. A 50% purchase cost markup is added to account for setup and connection of all items within the station and this into the training location for use. Additionally, a 20% cost contingency is applied to account for non-estimated or underestimated items. Finally, we assume a single station is adequate for the training requirements of a facility that has up to three reactors. For 4–9 reactors, two stations are assumed, and three stations for greater than 9 reactors. We explicitly exclude cost estimates for the necessary simulation software and so our results reflect hardware and setup costs only.

Table 57. Estimates of simulator quantities and costs for different sodium-cooled fast reactor (SFR) and SFR nuclear power plant sizes of the base design.

Parameter	UOM				
Plant Nominal Power	MW_e	165	311	1243	3108
Power Block Nominal Power	MW_e	165	311	622	622
Reactor Nominal Power	MW_e	165	311	311	311
Power Blocks/Plant	—	1	1	2	5
Reactors/Plant	—	1	1	4	10
Reactors/Power Block	—	1	1	2	2
Simulator Quantities					
Computers	—	3	3	6	9
Monitors	—	6	6	12	18
Keyboards	—	3	3	6	9
Telephones	—	1	1	2	3
Radios	—	1	1	2	3
Control Station Stand	—	1	1	2	3
Complete Simulator	—	1	1	2	3
Simulator Costs					
Computers	2023 US $	30,000	30,000	60,000	90,000
Monitors	2023 US $	6,000	6,000	12,000	18,000
Control Station Stand	2023 US $	10,000	10,000	20,000	30,000
Complete Simulator	2023 US $	46,000	46,000	92,000	138,000
Setup and Installation[a]	2023 US $	23,000	23,000	46,000	69,000
Contingency[b]	2023 US $	9,200	9,200	18,400	27,600
Total Cost	**2023 US $**	**78,200**	**78,200**	**156,400**	**234,600**
	2023 US $/reactor	**78,200**	**78,200**	**39,100**	**23,460**
	2023 US $/kW$_e$	**0.47**	**0.25**	**0.13**	**0.08**

[a] 50% of complete simulator base cost.
[b] 20% of complete simulator base cost.

5.3.9 Account 29: Contingency on Capitalized Direct Costs

A 20% cost contingency is placed on the cost summation of Accounts 21 to 28 to capture unenumerated costs. This level of contingency is deemed consistent with an Association for the Advancement of Cost Engineering (AACE) Class 2 cost estimate which has an expected accuracy range of -10% to -20% for the low end and +5% to +20% for the high end.[41]

5.4 Account 30: Capitalized Indirect Services Costs

5.4.1 Account 31: Factory & Field Indirect Costs

Factory and field indirect costs are modeled as general contractor (GC) overhead and profit costs. GC overhead is estimated as 15% of direct costs based on the recommended value from RSMeans for projects over $10M. GC profit is estimated at 10% of direct costs, also based on the RSMeans recommended value. Combined, the GC overhead and profit costs are 25% of direct costs. For comparison, the subcontractor overhead and profit applied within Account 21 for structures and improvements is 15%. The differing rates are reasonable given they cover different expenses, with the GC costs going to superintendents, construction offices, storage trailers, temporary sanitary facilities, temporary utilities, security fencing, photographs, cleanup, performance and payment bonds, etc.

As an additional comparison, factory and field indirect costs for the PWR12-BE and median experience cases are 26.4% and 47.6%, respectively. Thus, the 25% value used in this project aligns well with the better experience case. For both cases, temporary construction facilities account for almost half of the cost (42–45%). The long construction duration of nuclear projects can be the main contributor to escalated nuclear-industry indirect costs.

As discussed in Section 4.1.2, substantial nuclear-industry markups are applied to materials (50%) and labor (130%) as part of the direct costs of Accounts 21 and 22. As these direct costs are the basis for estimating indirect costs, the carry-through effect of these markups results in a higher magnitude of indirect costs for nuclear grade facilities. Thus, for non-nuclear grade construction, the same 25% estimate is applicable, but the direct costs this is applied to are lower, resulting in a lower estimate of indirect costs for non-nuclear grade construction.

5.4.2 Account 32: Factory & Construction Supervision

Costs for direct supervision of craft-performed construction is included in the subcontractor direct costs through a 15% markup of materials, labor, and equipment. Costs for general contractor additional supervisory work are included in the estimates made in Account 31. Consequently, no costs appear in Account 32.

5.4.3 Account 33: Commissioning & Start-up

The fundamental process for nuclear power plant commissioning and start-up is driven by safety and regulatory concerns. These costs are not expected to be specific to a particular nuclear technology (i.e., PWR vs. AHTR),[42] and thus are estimated with a power law relationship using a 0.5 exponent from the PWR12-BE case applied to the facility electrical output.

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41 AACE International Recommended Practice No. 18R-97, "Cost Estimate Classification System – as Applied in Engineering, Procurement, and Construction for the Process Industries", AACE International, 2005.

42 Holcomb, D. E.; Peretz, F. J.; Qualls, A. L. Advanced High Temperature Reactor Systems and Economic Analysis. *Oak Ridge National Laboratory Status Report* **September 2011**, *ORNL/TM-2011/364. https://info.ornl.gov/sites/publications/files/Pub32466.pdf*

5.4.4 Account 34: Demonstration Test Run

Costs for a demonstration test run are not included in our estimate.

5.4.5 Account 35: Design Services Offsite

Design service fees for structural, mechanical, electrical, and site development are calculated as percentages of the direct costs in Accounts 21–26, covering sitework, buildings, and equipment. The design service fee percentages are based on recommended values from RSMeans. Applied structural engineering fees range from 2 to 2.25% with complex reinforced concrete structures assessed at 50%. Mechanical engineering fees range from 4.1 to 7% based on complexity. Electrical engineering fees range from 4.1 to 10.1%. Site development fees range from 2.5 to 6%.[43] The fees are applied to the direct cost of each building or structure individually based on complexity and summed to determine the total design services fee. For buildings and improvements in Account 21, the complexity level assessments are shown in Table 58. For equipment in Accounts 22–26, the complexity level assessments are shown in Table 59 with structural fees omitted since these elements are inside of a building that already has been assessed. Design fees were not assessed for Accounts 27 and 28 as the relative amount would be negligible.

Table 58. Assigned construction complexities for structures and improvements in Account 21 as basis for their contribution to the estimated design service fee.

Account	Description	Structural	Mechanical	Electrical	Site
211	Site Preparation & Yard Work	—	—	—	High
212	Reactor Island Civil Structures	High	High	High	—
213	Energy Conversion Building	Intermediate	Intermediate	High	—
214	Security Building & Gatehouse	Intermediate	Intermediate	High	—
215	Reactor Service Buildings	High	High	High	—
216	Radwaste Building	High	High	High	—
217	Fuel Service Building	High	High	High	—
218A	Control Building	Intermediate	Intermediate	High	—
218B	Administration Building	Intermediate	Intermediate	High	—
218C	Operation & Maintenance (O&M) Center	Intermediate	Intermediate	High	—
218E	Storage Buildings	Low	Low	Low	—
218K	Pipe Tunnels	High	High	High	—
218L	Electrical Tunnels	High	High	High	—
218N	Maintenance Shop	Intermediate	Intermediate	High	—
218Q	Foundations for Outside Equipment & Tanks	Low	Low	Low	—
218R	Balance of Plant (BOP) Service Building	Low	Low	Low	—
218S	Wastewater Treatment Building	Low	Low	Low	—
218T	Emergency & Start-Up Power Systems	Intermediate	Intermediate	High	—
218W	Warehouse	Low	Low	Low	—
218X	Railroad Tracks	High	High	High	—
218Y	Roads & Paved Areas	—	—	—	Low
218Z	Reactor Receiving & Assembly Building	Intermediate	Intermediate	High	—
219A	Training Center	Intermediate	Intermediate	High	—
219K	Special Materials Unloading Facility	High	High	High	—

43 From Gordian's RSMeans Data Online Copyright Gordian. 30 Patewood Dr. Suite 350, Greenville, SC, 29615; All rights reserved.

Table 59. Assigned construction complexities for equipment in Accounts 22–26 as basis for their contribution to the estimated design service fee.

Account	Description	Mechanical	Electrical
22	Reactor System	High	High
23	Energy Conversion System	High	Low
24	Electrical Equipment	—	High
25	Heat Rejection System	High	—
26	Miscellaneous Equipment	Low	Low

Design services are estimated based on the total account value, regardless of whether the buildings, reactors, or equipment are duplicated many times within the NPP. In scenarios with duplicated structures, it may be reasonable to discount design services. Additionally, if multiple nuclear power plants are built with the same design, design services may be deeply discounted.

5.4.6 Account 36: Project Management/Construction Management Services Offsite

The costs for project management (PM) and construction management (CM) services offsite at the reactor vendor, equipment supplier and home offices may differ between nuclear and non-nuclear projects due to additional regulatory burdens. However, costs are not expected to be nuclear technology specific (i.e., PWR vs. AHTR).[44] Consequently, Account 36 costs are based on the PWR12-BE estimate and scaled via a power-law relationship based on facility electrical output power with a 0.5 exponent. Further details appear in Table 60.

Table 60. Summary of project management (PM)/construction management (CM) services offsite costs for a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor. Costs not escalated to account for special material design and construction requirements to satisfy nuclear quality since this classification is not applicable to these cost elements.

Account	Title	PWER12-BE Cost Basis	SFR Cost Result[a,b]
-	-	2023 US $/kW$_e$	2023 US $/kW$_e$
36	PM/CM Services Offsite	33.87	89.22

[a] See Section 4.2 for details regarding cost estimation and scaling relationships.
[b] Scaling exponent is 0.5. PWR12-BE plant nominal power is 1,144 MW_e.

5.4.7 Account 37: Design Services Onsite

Costs for onsite design services are included in Account 35 for offsite design services.

5.4.8 Account 38: Project Management/Construction Management Services Onsite

The onsite main office overhead is estimated at 3.9% of direct costs based on RSMeans data for large projects. For small projects, main office overhead can be as high as 35%.

5.4.9 Account 39: Contingency on Capitalized Indirect Services Costs

A 20% contingency is allocated for indirect costs.

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44 Holcomb, D. E.; Peretz, F. J.; Qualls, A. L. Advanced High Temperature Reactor Systems and Economic Analysis. *Oak Ridge National Laboratory Status Report* **September 2011**, *ORNL/TM-2011/364*. *https://info.ornl.gov/sites/publications/files/Pub32466.pdf*

5.5 Account 40: Capitalized Owner's Costs

Capitalized owner's costs are composed of costs related to the pre-hire and training of plant staff during the construction period so that they can participate in final construction acceptance testing and be prepared to safely operate the NPP. The capitalized owner's costs are about 5–9% of TOC and depend heavily on the estimates for plant personnel, salaries, and benefits detailed in Section 4.5.

5.5.1 Account 41: Staff Recruitment & Training

Plant staffing levels estimates are used as a basis to project staff recruiting and training costs. Staff recruitment is expected to take a staggered approach with the focus first on professionals, then operators, and then maintenance personnel as suggested by the International Atomic Energy Agency (IAEA).[45] Additionally, some staff will not complete training and so over hiring is encouraged by the IAEA. For the multiyear recruiting period, an average 1.5 years of salary for 110% of the NPP plant staff is used as the basis for estimating staff costs. Recruiting cost is estimated at 25% of employee annual salary for nationwide recruitment.

5.5.2 Account 42: Staff Housing

A nuclear power plant requires staff with specialized experience and the labor force may not be readily available in the immediate area of the power plant. An average relocation cost of $40,000 per person is estimated for 50% of the staff hired for training.

5.5.3 Account 43: Staff Salary-Related Costs

Staff salary related costs are estimated on an even per-hour basis as discussed in Section 4.5, accounting for legally required benefits, paid leave, supplemental pay, insurance, and retirement. Effectively, the benefits are 57–59% of salary expenses in Account 41.

5.5.4 Account 44: Other Owner's Costs

No additional owner's costs are estimated in this project.

5.5.5 Account 49: Contingency on Capitalized Owner's Costs

A 20% contingency is assigned for Owner's Costs.

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45 International Atomic Energy Agency. (1991). Staffing of Nuclear Power Plants and the Recruitment, Training and Authorization of Operating Personnel. https://inis.iaea.org/collection/NCLCollectionStore/_Public/22/073/22073612.pdf.

5.6 Account 50: Capitalized Supplementary Costs

5.6.1 Account 51: Shipping & Transportation

Shipping and transportation costs are based on the total mass of materials used within the reactor and the mass of the initial nuclear fuel load. Costs for concrete and other structural materials are captured in their respective material price and are not tubulated within this account. The reactor materials are assumed to be shipped by a blend of truck and rail (50/50 split by mass) over a one-way distance of 750 miles for truck and 1,000 miles for rail. Baseline truck ($2.97/mile) and railcar ($0.0918/ton-mile) prices, based on average US costs for a full load, are adjusted for partial loads (50%) and deadheading (of the trucks only). Rail shipping of the initial fuel load is based on baseline railcar costs, adjusted for each reactor's fuel to be divided into 10 rail cars, deadheading, and a 2× multiplier for additional security associated with the shipment of radioactive material. A distance of 1,800 miles is assumed based on the distance from Eunice, NM (the only large-scale Ur fuel enrichment facility in the US) to the East Coast.

5.6.2 Account 52: Spare Parts

An annual cost budget is estimated for maintenance, repair, and operations (MRO) spare parts. Cost is based on a percentage of replacement asset value (RAV) which is approximated by the direct cost included in Accounts 21–28 and projected by the SMRP as generally less than 1.5% with a top quartile range of 0.3% to 1.5%, varying by industry.[46] We apply a 1.5% estimate to Accounts 22–25 as these are mission critical, and 0.5% to the other Accounts. This results in an approximate 1% overall cost on Account 20 direct costs, including contingency. In comparison, the DOE's hydrogen production cost models, H2A[47,48], project 0.5% per year for unplanned replacement capital costs which is treated as a surrogate for spare parts. Thus, the higher percentage used for our NPP analysis is viewed as a directionally conservative estimate.

5.6.3 Account 53: Taxes

Annual taxes are based on the NPP operator achieving an after-tax profit of 8%. For simplicity, plant revenue is based on an electricity sales price of $\$50/MWh_e$. Federal and state tax rates are assumed to be 21% and 6%, respectively.

5.6.4 Account 54: Insurance

NPP insurance is estimated based on 1% per year of the total investment cost which is approximated by Accounts 10–30. This is a simplistic estimate based on commercial facilities and not adjusted for nuclear operations or extra regulatory requirements which presumably would play a factor in rate assessment. The 1% rate is consistent with the combined property tax and insurance annual estimate of 2% used within the H2A cost model for large hydrogen production facilities.

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46 Society for Maintenance & Reliability Professionals (SMRP) Body of Knowledge, "Business Management Metric 1.4 Stocked MRO Inventory Value as a Percent of Replacement Value (RAV)", SMRP, 2011.

47 H2A is a discounted cash flow model developed by the National Renewable Energy Agency (NREL) on behalf of DOE with the goal of fully transparent computation of the levelized cost of hydrogen for a variety of production methods. It, thus, is a comprehensive economic estimate of a type of large chemical/energy production facilities.

48 https://www.nrel.gov/hydrogen/h2a-production-models.html.

5.6.5 Account 55: Initial Reactor Core Load

5.6.5.1 Nuclear Fuel

Nuclear fuel costs are estimated using the fuel cycle cost basis methodology laid out by the DOE Nuclear Technology Research and Development report, "Advanced Fuel Cycle Cost Basis – 2017 Edition.".[49] The SFR fuel cost derived for this report is assumed to be a once-through cost without recycling or reprocessing and corresponds to the initial core fuel load. Additional optimization of fuel costs may be possible by recycling and reprocessing spent Uranium, utilization of recycled Pu, and refinement of the fuel enrichment process.

The following cost modules describe the manufacturing pathway for a conventional SFR:

1. A1 – Natural Uranium Mining and Milling
2. B – Conversion Processes
3. C1 – Enrichment[50]
4. D1–6A – Contact-Handled All-U Metal or U-Metal Alloy Uranium Fuel Fabrication[51]

Note that the C1 and D1 cost module results come from forthcoming reports expected in the later part of 2023. The cost for each module is reported in Table 61. All costs are adjusted to 2023 US $ using the Chemical Engineering Plant Cost Index (CEPCI).[52]

Table 61. Fuel cycle module costs used to estimate the reactor initial core fuel load costs taken from the INL Advanced Fuel Cycle Cost Basis report[53].

Fuel Cycle Module	UOM	Low	Mode	High
A1 - Natural Uranium Mining and Milling	2023 US $/kgU	$48.09	$121.63	$418.62
B - Conversion Processes	2023 US $/kgU	—	$18.39	—
C1 - Enrichment (0.71–5 wt%)	2023 US $/kg-SWU	—	$168.27	—
C1 - Enrichment (10–19.75 wt%)	2023 US $/kg-SWU	—	$251.74	—
D1–6A Contact-Handled All-U Metal or U-Metal Alloy Uranium Fuel Fabrication	2023 US $/kgHM[a]	—	$1,763.51	—
D1–6B Contact-Handled U, Pu Metal Alloy Fuel Fabrication	2023 US $/kgHM[a]	—	$2,510.65	—

[a] HM = Heavy Metal, including U and Pu.

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49 B. W. Dixon, F. Ganda, K. A. Williams, E. Hoffman, & J. K. Hanson, Advanced Fuel Cycle Cost Basis – 2017 Edition. United States. *https://doi.org/10.2172/1423891.*

50 DOE-NE Systems Analysis & Integration Campaign. forthcoming. "Advanced Fuel Cycle Cost Basis Report: Module C3 High-Assay Low-Enriched Uranium (HALEU) Enrichment and Deconversion/Metallization." NTRD-FCO-2017-000265, Idaho National Laboratory.

51 DOE-NE Systems Analysis & Integration Campaign, Advanced Fuel Cycle Cost Basis Report: Module D1–6A Contact-Handled All-U Metal or U-Metal Alloy Uranium Fuel Fabrication, Module D1–6B Contact-Handled U,Pu Metal Alloy Fuel Fabrication. Idaho Falls: Idaho National Laboratory, 2023.

52 https://www.chemengonline.com/pci-home

53 B. W. Dixon, F. Ganda, K. A. Williams, E. Hoffman, & J. K. Hanson, Advanced Fuel Cycle Cost Basis – 2017 Edition. United States. *https://doi.org/10.2172/1423891.*

The all-U fuel is assumed to be enriched to 19.75 wt% ^{235}U, which is near the upper bound of low-enriched uranium (LEU). The enrichment process is modeled as a two-stage cascade. Stage 1 feeds natural uranium at 0.711% ^{235}U which is enriched to a 5% product with tail ends of 0.2%. Stage 2 feeds the 5% ^{235}U product from the first stage which is then enriched to a final 19.75% ^{235}U with a tails outlet of 0.711% that is subsequently recycled back into Stage 1. The Separative Work Units (SWUs) are calculated at 942 SWU/tonne of U feed for Stage 1 and 1,313 SWU/tonne of U feed for Stage 2. The overall process requires 38.3 tonnes of natural Uranium to generate 1 tonne of 19.75% ^{235}U product.

We also evaluate whether any of the fuel cycle modules could reduce in cost as a function of increasing demand or manufacturing scale. In general, modules A1, B, and C1 are not subject to cost reductions from scaling because adequate supply is already available for all expected demand in the coming decade.[54] The mode prices for these modules listed in Table 61 provide a useful estimate for understanding likely fuel prices but will be highly dependent on global uranium demand, general upkeep of existing processing facilities, and development of new processing facilities. On the other hand, modules D1–6A and D1–6B represent relatively new fuel fabrication methodologies and will likely reduce in cost as production scales up and more commercial experience is demonstrated. INL suggests that a capital cost scaling exponent of 0.6–0.7 may be appropriate for remote metallic fuel fabrication based on limited cost studies conducted by Argonne National Laboratory (ANL).[54] We therefore choose a more modest 0.95 scaling factor to keep costs conservatively close to the mode cost of D1–6A and D1–6B provided by INL. The baseline fuel production rate is assumed to be 40,000 kg/year.

The BOC core inventory of HALEU U-Zr fuel used for this study is shown in Table 12. A summary of the calculated fuel cost over a range of fuel demand cases is shown in Table 62. The biggest cost driver is the first enrichment stage followed by the natural uranium mining and milling. This is driven by the large amount of natural uranium required to produce the 19.75% enriched fuel. Fuel cost per kW_e is flat with production rate over the range examined. Given that we estimate it could be possible to reduce the amount of fuel and number of fuel assemblies by approximately 41% and still satisfy the reactor neutronics, the fuel cost could reduce by about this same percentage reaching costs of around only 2023 US \$510–520/kW_e. But to confirm this magnitude of reduction, a significantly more detailed core loading analysis and optimization would have to be performed, which is beyond the scope of this current effort. Such a study should be undertaken in a future effort to understand if cost reductions through reduced fuel amounts are possible.

Table 62. Estimated fuel costs for different numbers of baseline 471 MW_t/165 MW_e sodium-cooled fast reactors.

Annual Reactor Production Rate	reactors/year	1	2	3	6	9	18	30	90
Annual Electrical Power Production Rate	MW_e/year	165	330	495	990	1485	2970	4950	14850
Fuel Demand	kg/year	15,722	26,780	40,169	80,339	120,508	241,017	401,695	1,205,084
A1 - Natural Uranium Mining & Milling	2023 US $M/reactor	41	41	41	41	41	41	41	41
B - Conversion Processes	2023 US $M/reactor	6	6	6	6	6	6	6	6
C1 - Enrichment									
Stage 1	2023 US $M/reactor	58	58	58	58	58	58	58	58
Stage 2	2023 US $M/reactor	13	13	13	13	13	13	13	13
D1–6A Contact-Handled All-U Metal or U-Metal	2023 US $M/reactor	29	28	27	27	26	26	26	26

54 B. W. Dixon, F. Ganda, K. A. Williams, E. Hoffman, & J. K. Hanson, Advanced Fuel Cycle Cost Basis – 2017 Edition. United States. https://doi.org/10.2172/1423891

Annual Reactor Production Rate	reactors/year	1	2	3	6	9	18	30	90
Alloy Uranium Fuel Fabrication									
Total Fresh Fuel Cost	**2023 US $M/reactor**	146	145	145	144	143	143	143	143
	2023 US $/kW$_e$	887	881	878	872	869	869	869	869

Since natural uranium mining is a large cost driver, we also tested the sensitivity of the total fuel cost to natural uranium mining and milling costs (see Table 63 for the low and high case for module A1) while holding all other fuel cycle modules constant.[55] Similar to other commodities such as coal, natural gas, and crude oil, uranium prices fluctuate in response to boom/bust cycles of demand. This sensitivity study establishes realistic bounds for the total fuel cost over the next several decades.

Relative to the baseline fuel cost (2023 US $120M/reactor), the sensitivity to uranium pricing suggests that total fuel cost for all-U metal fuel could span -16% (2023 US $101M/reactor) to +64% (2023 US $197/reactor) in response to fluctuating uranium prices. This represents significant risk to nuclear developers and should be considered in final project economics.

Table 63. Sensitivity study of fuel cost for different numbers of baseline 471 MW$_t$/165 MW$_e$ sodium-cooled fast reactors.

Annual Reactor Production Rate	Reactors/Year	1	2	3	6	9	18	30	90
Annual Electrical Power Production Rate	MW$_e$/year	165	330	495	990	1,485	2,970	4,950	14,850
Fuel Demand	kg/year	15,722	31,444	47,166	94,332	141,498	282,996	471,660	1,414,980
Baseline Fuel Cost	2023 US $M	146	145	145	144	143	143	143	143
	2023 US $/kW$_e$	887	881	878	872	869	869	869	869
Low Side A1 Module Cost	2023 US $M	122	121	120	119	119	119	119	119
	2023 US $/kW$_e$	738	732	729	723	720	720	720	720
High Side A1 Module Cost	2023 US $M	246	245	244	243	243	243	243	243
	2023 US $/kW$_e$	1,489	1,483	1,480	1,474	1,471	1,471	1,471	1,471

5.6.5.2 *Other Loaded Materials: Shielding, Reactivity Control, & Inerting*

Materials required for the radiological shielding and reactivity controls are estimated using an approximate DFMA® approach that relies on the base costs collected/obtained from material suppliers. Similarly, for inert gases used to fill and control internal core fuel assemblies are estimated from a detailed calculation of the volume and pressure required within each element in the core, and commercially advertised costs for a given gas purity. The specific identity of the gas was not defined within the reference case we used, so we assume that standard purity Argon gas is adequate and estimate costs for this within the core.

[55] B. W. Dixon, F. Ganda, K. A. Williams, E. Hoffman, & J. K. Hanson, Advanced Fuel Cycle Cost Basis – 2017 Edition. United States. https://doi.org/10.2172/1423891.

Boron Carbide (B_4C) Raw Material Costs

Natural isotopic blends of B_4C and enriched $^{10}B_4C$ materials are required for use in radiological shielding and control of reactivity occurring at any given time within the reactor. These materials are typically loaded within metallic casings that are placed around the reactor core and within other specific locations inside the reactor to protect contained equipment from severe radiological exposure that can cause radiation induced expansion and fatigue, ultimately leading to failure. Additionally, hollow reactivity control rods are similarly filled with B_4C for dynamical insertion into specific radial positions within the reactor core to absorb and limit the neutron flux thereby reducing and slowing down the rate of nuclear conversion. Recently, INL obtained rough-order-of-magnitude (ROM) pricing from a specific material vendor for powders of both natural and enriched $^{10}B_4C$ (Table 64). We therefore use and apply this pricing in estimating the cost for these materials required in the reactor core.

Table 64. Rough-order-of-magnitude pricing for boron carbide (B_4C) powder obtained by Idaho National Laboratory in May 2023 from a material vendor.

B_4C Enrichment	Commercial Price[a] ($/kg)
Natural	80–100
Enriched, 96 wt% ^{10}B	10,000–11,000

[a] Pricing is for general high-mesh powder.

Boron Carbide (B_4C) Pelletization Costs

B_4C is loaded into metallic pins which are then packed into an assembly casing and bundled into the reactor core. Therefore, these materials have to be manufactured into a final geometric form and size that offers robust functionality and performance, and efficient and low costs for manufacturing and loading into the core. Typically, pellet/tablet form of B_4C is an adequate shape that satisfies these requirements since this offers uniform high packing density and adequate flexibility with pin loading. Since B_4C is specifically produced commercially in bulk powder-form, further processing into pellets is required. While costs for different levels of isotopic enrichments of B_4C powder were obtained recently by INL, costs of processing this powder into pellets could not be obtained. To this end, an estimate of the costs associated with producing pellets from powder was conducted to use for computing the total cost of the reactor core.

To complete a ROM cost estimation for the pelletization of B_4C powder into small diameter tablets/pellets (<2 in.), we identify the approximate production process and use a simplified first-principles approach to estimate:

1. Equipment requirements and associated capital, operating, and maintenance costs.
2. Process times for each major processing step.
3. Consumable chemical and material requirements.
4. Labor amounts and wages.
5. Miscellaneous corporate financial aspects such as interest, taxes, and markup.

3M, one of the primary commercial providers of densified and processed carbide materials, specifically natural and various isotopic enrichments of B_4C, briefly describes their hot, ultra-low vacuum mechanical press densification process.[56] They also provide a few of the key processing parameters needed to estimate performance and costs of this process which are summarized in Table 65.

[56] https://www.3m.com/3M/en_US/p/d/b40070681/, https://multimedia.3m.com/mws/media/950554O/3m-10b-enriched-boron-carbide-data-sheet.pdf.

Table 65. 3M toll pressing parameters.

Parameter	UOM	Value
Die Material	—	Carbon/Graphite
Die Size (Diameter / Height)	inches	34 / 60
Temperature (Maximum)	°C (°F)	2,200 (3,992)
Vacuum (Minimum)	mtorr	40
Force	U.S. tons	400–700

From this data and information, we model a three-step process for pelletizing B_4C powder (Figure 4):

Step 1: B_4C powder densification and sintering to press loose powder into cylindrical rods having a slightly larger diameter than required for the finished pellets. This process occurs in a heated, vacuum press.

Step 2: Further processing of the rods through cutting and milling to generate pellets of the appropriate height/length and refined diameter.

Step 3: Packaging these pellets into standard containers used for transporting finished B_4C pellets to the location where reactor core rod and pin loading occurs and loading these packages into transport vehicles (most likely long-haul trucks) by forklift.

Table 66 provides approximate batch characteristics of each press cycle. The die is assumed to have multiple parallel cylindrical holes in the base that run its length/height arranged in a dense layout to allow for the simultaneous production of multiple dense rods during each press batch/cycle. Final B_4C slugs/pellets are assumed to have an aspect ratio of 1 to approximate the length/height of these pellets.

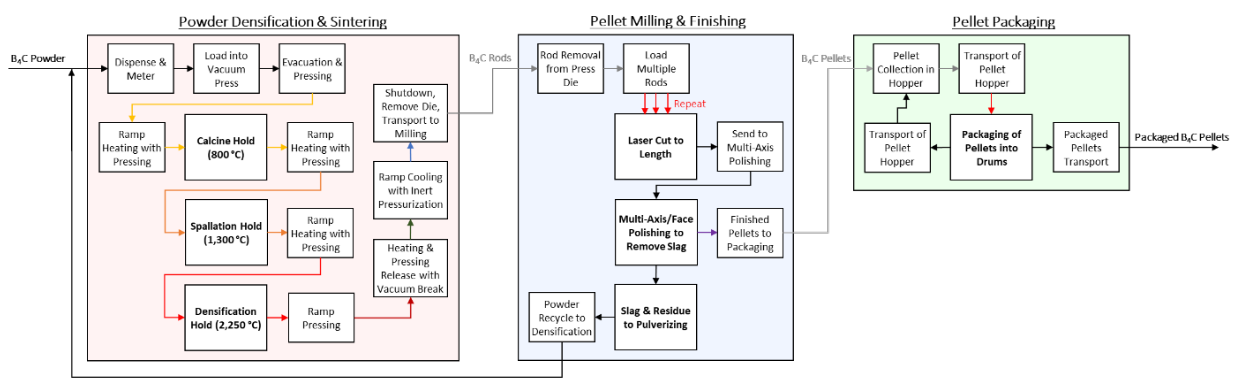

Figure 4. Simplified block flow diagram depicting the processing steps for B_4C pelletization modeled in this work.

Table 66. Estimated boron carbide (B_4C) pelletization batch requirements for a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor core and batch hot vacuum press equipment modeled.

Core Component[a]	-	Control & Shutdown Rods	Shields	Total
B_4C Type	—	Enriched ^{10}B	Natural ^{10}B	-
Required Quantities				
Volume	m^3	0.083	6.440	6.523
Mass	kg	210.2	16,228	16,438

Core Component[a]	-	Control & Shutdown Rods	Shields	Total
Finished Pellet Properties				
Density	g/cm^3	2.52[b]	2.52[b]	
Diameter	in.	0.625	2.125	
Length	in.	0.625	2.125	
Rod Arrangement in Vacuum Press Die				
Geometry	—	60° Triangular	60° Triangular	
Spacing	in.	0.25	0.25	
Die Outer Buffer Thickness	in.	2	2	
Batch Size, Actual				
Volume	m^3	0.289	0.454	
Mass	kg	466.796	732.443	
Number of Rods	—	1,067	145	
Batches Required	—	1	23	24
Batch Size, Average				
Volume	m^3	0.447		
Mass	kg	721.374		
Number of Rods	no. of rods	183.417		

[a] Based on design for GE-Hitachi PRISM MOD-A reactor core (see Dubberley, A. E.; Yoshida, K.; Boardman, C. E.; Wu, T. SuperPRISM Oxide & Metal Fuel Core Designs. *Proceedings of ICONE 8* **2000**, *8002*. *https://www.xylenepower.com/S-PRISM specs Dubberley.pdf* and GE-Hitachi. Attachment 2-Demonstration Sodium-Cooled Fast Reactor GE-PRISM. **2016**. *https://art.inl.gov/ART Document Library/Advanced Demonstration and Test Reactor Options Study/Attachment_2_GE_Hitachi_SFR_DR.pdf*).
[b] Full theoretical density of solid B_4C is assumed to be achieved by densification and sintering process.

Each process step and the associated equipment, materials, personnel, and process times are defined consistently with the DFMA® cost estimation methodology described in Section 4.1.1. Past Strategic Analysis, Inc. (SA) studies examined process and cost aspects similar in function to those needed for the proposed B_4C pellet pressing process in this current analysis.[57] Consequently, that data is adapted to represent the ROM costs for the actual hot vacuum press typically used in 3M's process. Table 67 lists key process parameters and assumptions used to cost model the hot vacuum press sintering process. Several process aspects not available in 3M's documentation and applicable from SA's past analyses (e.g., target temperatures, heating ramp rates, hold times, etc.) were taken from recent publications reporting research findings on B_4C hot vacuum press sintering.[58]

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57 James, B. D.; DeSantis, D. Manufacturing Cost and Installed Price Analysis of Stationary Fuel Cell Systems. *National Renewable Energy Laboratory Report* **2015**. *https://www.sainc.com/assets/site_18/files/publications/sa 2015 manufacturing cost and installed price of stationary fuel cell systems_rev3.pdf*, Prosser, J. H.; James, B. D.; Murphy, B. M.; Wendt, D. S.; Casteel, M. J.; Westover, T. L.; Knighton, L. T. Cost Analysis of Hydrogen Production by High-Temperature Solid Oxide Electrolysis. *Int. J. Hydrog. Energy* **2022**, *(In Press)*

58 Martin, H.-P.; Feng, B.; Michaelis, A. Pressureless Sintering and Properties of Boron Carbide Composite Materials. *Int. J. Appl. Ceram. Technol.* **2019**, *17*, 407–412. *https://doi.org/10.1111/ijac.13423*,

Table 67. Estimated boron carbide (B_4C) hot vacuum pressing process parameters.

No.	Process Step	Equipment Utilized	Material Inputs	Energy Inputs	Time	Temperature	Gas Pressure
—	—	—	—	—	hr/batch	°C	mtorra
1	Press Setup	Batch Hot Vacuum Uniaxial Press, Die Handler/Lift	Die	Electric	0.167	30	Atm.
2	Loading Powder into Press Chamber/Die	Powder Dispenser/Meter	B_4C Powder	Electric	0.167	30	Atm.
3	Evacuation and Purging with Simultaneous Ramp Pressing	Low-Grade Vacuum Pump with Filters, Inert Gas Dispensing Equipment	Argon Gas	Electric	1.000	30	40
4	Ramp Heating, Pressing Hold	Batch Hot Vacuum Uniaxial Press, High-Grade Vacuum Pump with Filters	None	Electric	4.492	Various	40
5	1st Intermediate Temperature Hold (Calcine), Pressing Hold	Batch Hot Vacuum Uniaxial Press, High-Grade Vacuum Pump with Filters	None	Electric	1.000	800	40
6	Continued Ramp Heating, Pressing Hold	Batch Hot Vacuum Uniaxial Press, High-Grade Vacuum Pump with Filters	None	Electric	0.875	Various	40
7	2nd Intermediate Temperature Hold (Spallation), Pressing Hold	Batch Hot Vacuum Uniaxial Press, High-Grade Vacuum Pump with Filters	None	Electric	1.000	1,300	40
8	Loading Powder into Press Chamber/Die	Batch Hot Vacuum Uniaxial Press, High-Grade Vacuum Pump with Filters	None	Electric	3.325	Various	40
9	Evacuation and Purging with Simultaneous Ramp Pressing	Batch Hot Vacuum Uniaxial Press, High-Grade Vacuum Pump with Filters	None	Electric	1.000	2,250	40
10	Ramp Heating, Pressing Hold	Batch Hot Vacuum Uniaxial Press, High-Grade Vacuum Pump with Filters	None	Electric	0.250	2,250	40
11	Heating Release, Pressing Release, Vacuum Break	Batch Hot Vacuum Uniaxial Press, Inert Gas Dispensing Equipment	Argon Gas	Electric	0.167	Various	Various
12	Pressurization with Continued Ramp Cooling and Pressing Release	Batch Hot Vacuum Uniaxial Press, Inert Gas Dispensing Equipment	Argon Gas	Electric	7.770	30	Various
13	Open and Relocate Die with Rods to Milling Station	Die Handler/Lift	None	Electric	0.167	30	Atm.

Following hot vacuum pressing to form high aspect ratio dense rods of B_4C, each rod is then laser cut to the appropriate length to generate slugs or pellets of the approximate height and diameter for loading into the SFR core fuel rods and pins. Energetic laser cutting is assumed possible and the most efficient since B_4C is the third hardest and toughest material known to man[59], therefore, cutting with an implement coated with another harder material (e.g., diamond) is not used or estimated. Post-cut polishing or grinding is assumed to follow for removing any irregular pieces of slag and undesirable roughness from the surfaces of each pellet. Automated laser cutters and polishers are estimated to handle an entire batch of pellets formed from a single press cycle using slow and gradual feeding. Multiple rods are assumed to be cut simultaneously using a high-powered laser cutter while individual pellets travel through a set of multi-axis/surface polishers to debur, smooth out its faces, and slightly resize by grinding away small amounts from the diameter and length/height of each pellet. Since these polishers are assumed to be mechanical in their application, most likely the elements contacting the pellets would have to be coated in a material harder than the pellet substrate, which we assume to be feasible. Leftover slag and dust/powder from the laser cutting and polishing sub-steps is assumed to be fully captured and recycled back to the pressing operation after large pieces are ground back to an adequate meshed powder. Table 68 contains our specific assumptions and parameter estimates for the pellet milling step.

Table 68. Estimated boron carbide (B_4C) pellet milling process parameters.

No.	Process Step	Equipment Utilized	Material Inputs	Energy Inputs	Time
—	—	—	—	—	hr/batch
1	Laser Cutter Setup Including Loading of Multiple Rods	Rod Handler/Lift, 12 kW Laser Cutter	Hot Vacuum Pressed B_4C Rods	Electric	0.167
2	Slicing Rods into Pellets/Slugs	12 kW Laser Cutter	None	Electric	2.759
3	Removing Slugs and Slag from Laser Cutter for Recycling	12 kW Laser Cutter	None	Electric	0.035
4	Polishing of Slugs	Belt/Disc Grinders	None	Electric	2.649
5	Pulverizing of Slag for Recycling	Pulverizer	None	Electric	2.083

We assume a 12 kW laser for B_4C rod laser cutting which produces a beam width of 0.65 mm capable of cutting at a speed of ~1,000 cm/s through 1 mm thick metallic material (Table 69). The volumetric equivalent cutting speed is then 6.5 cm^3/s which we reduce by a factor of ~10× (0.65 cm^3/s) to account for the extra material hardness and toughness of B_4C relative to standard metal cutting times.[60] Additionally, we assume an average of 2s per cut for laser cutter rastering and movement time to reposition for subsequent cuts. No explicit assumptions are made about the number of rods cut simultaneously except that the laser rastering is estimated to be an equivalent time for simultaneous cutting of all rods in a single batch. While this underestimates the actual rastering time, since, in reality, fewer rods would be cut at a time than the full batch, the magnitude of rastering relative to actual laser cutting time is so small that a decrease in the number of rods cut simultaneously does not significantly increase the total cutting time (order of minutes only).

59 Hazzan, K. E.; Pacella, M.; See, T. L. Laser Processing of Hard and Ultra-Hard Materials for Micro-Machining and Surface Engineering Applications. Micromachines 2021, 12, 895. https://doi.org/10.3390/mi12080895

60 https://www.machinemfg.com/laser-cutting-thickness-speed-chart/

Table 69. Assumed boron carbide (B_4C) laser cutter performance metrics and parameters.

Parameter	UOM	Value
Laser Cutting Power	kW	12
Laser Beam Width	mm	0.65
Laser Cutting Speed	cm^3/s	0.65
Laser Position Time, Average	s/cut	2

Finished pellet packaging is assumed to use metallic 55 US gallon drums lined with large-mil plastic bags and sealed with standard clamp-style metal lids having four placed on a wooden pallet and shrink wrapped before loading onto the transport vehicle (Table 70). A drum filling machine that can fill four drums set onto a wooden pallet is modeled. Intermediate transport of pellets from the milling station to the packaging station is assumed to be by a 10,000 lb. forklift carrying up to three batches at once for packaging in a 6,000 lb. forklift hopper over a couple hundred feet to ensure adequate driving time for the cost estimate. Final transport of the palletized drums would be by the same forklift from the packaging station to the loading bay/dock to put this on the final transport vehicle or set this in a temporary storage location prior to loading onto the transport vehicle which assumes another couple hundred feet of driving distance.

Table 70. Estimated boron carbide (B_4C) pellet packaging process parameters.

No.	Process Step	Equipment Utilized	Material Inputs	Energy Inputs	Time
-	—	—	—	—	hr/batch
1	Transporting Filled Pellet Hopper to Packaging Machine and Back to Pellet Milling	6,000 lb. Forklift Hopper, 10,000 lb. Forklift	Propane Fuel	Propane	0.250
2	Drum Packaging	Drum Packager with Palletizer	Plastic Liners, 55 US Gallon Steel Drums, Wooden Pallets, Plastic Wrap	Electric	0.433
3	Carrying Palletized Pellet Drums with Forklift to Loading Dock/Bay	10,000 lb. Forklift	Propane Fuel	Propane	0.083
4	Loading into Transport Vehicle or Storage Warehouse	10,000 lb. Forklift	Propane Fuel	Propane	0.083

Using the data contained in

Table 66 to Table 70, we further define and assume the production capacities and rates as given in Table 71 for a single-line B_4C pelletization process.

Table 71. Estimated and assumed boron carbide (B_4C) overall production parameters.

Parameter	UOM	Value
Number of Process Lines	-	1
Operating Time Weekly Annual	 day/week week/yr	 5 50
Annual Line Utilization	%	68
Production Rate	batch/yr	250
	kg B_4C/yr	171,230
	reactor/yr[a]	10.5
	MW_e/yr[a]	1,719

[a] Based on base reactor capacity of 471 MW_t/165 MW_e.

We estimate the costs associated with each of these three primary steps for the pelletization process by estimating the equipment and material capital costs, labor costs for operational and maintenance personnel, and miscellaneous costs associated with corporate financing such as taxes, interest, and overhead and profit markup. Table 72 contains the purchase capital costs, installation, maintenance, and miscellaneous expense factors, energy requirements, and the assumed total service life for each equipment component modeled within this pelletization process. Assumptions about taxes, interest, labor rates, and corporate markup are given in Table 73.

Table 72. Boron carbide (B_4C) pelletization process equipment capital cost parameters.

No.	Equipment Name	Base Capital Cost (BCC)	Installation Expenses	Maintenance + Miscellaneous Expenses	Energy Requirements	Service Life
—	—	2023 US $	% of BCC	% of BCC/yr	kW	years
1	Die Handler/Lift	10,000	20	5	1.00	20
2	Powder Dispenser/Meter	25,000	20	5	0.10	20
3	Batch Hot Vacuum Uniaxial Press	6,656,887	40	20	1,106	20
4	Low-Grade Vacuum Pump with Filters	2,495	40	10	0.75	20
5	High-Grade Vacuum Pump with Filters	4,990	40	20	0.40	20
6	Inert Gas Dispensing/Purging Equipment	5,000	40	10	0.05	20
7	Rod Handler/Lift	10,000	20	5	1.00	20
8	High-Powered Laser Cutter	3,834,244	40	20	32.40	20
9	Belt/Disc Grinders	25,000	40	20	6.34	20
10	Pulverizer/Grinder	25,000	40	20	1.50	20
11	6,000 lb. Forklift Hopper	5,000	5	0.5	0.00	20
12	10,000 lb. Forklift	60,000	10	30	47.13	20
13	Drum Packaging Machine	100,000	40	20	5.00	20

Table 73. Boron carbide (B_4C) pelletization process interest, taxes, labor rates, and corporate markup.

Parameter	UOM	Value
Capital Interest Rate	%	10.00

Corporate Income Tax Rate	%	20.00
Labor Rates		
Base		
Vacuum Press Operator	2023 US $/hr	50.00
Milling Operator	2023 US $/hr	40.00
Packaging Operator	2023 US $/hr	20.00
Burdened		
Vacuum Press Operator	% of base	30.00
Milling Operator	% of base	30.00
Packaging Operator	% of base	30.00
Total		
Vacuum Press Operator	2023 US $/hr	65.00
Milling Operator	2023 US $/hr	52.00
Packaging Operator	2023 US $/hr	26.00
Corporate Markup	% of production cost	100.00

Table 74 provides a breakdown of the annual B_4C pelletization costs by process step. Base capital costs were set from budgetary quotes for equipment with the exception of the hot vacuum uniaxial press, inert gas dispensing equipment, and drum packaging machine. For the hot vacuum uniaxial press, we assumed the approximate order of magnitude for the capital cost of the actual machine that would be used for this operation could be simply estimated by summing capital costs SA obtained in the past for HT batch furnaces primarily used in ceramic and metal oxide material sintering capable of achieving temperatures close to the 3M advertised maximum and stamp presses rated for the same level of force also reported by 3M. A purchase cost of 2023 US $5,000 for the inert gas purging components which would consist mostly of piping/tubing, valving, and instrumentation and controls to estimate the order of magnitude for the total cost of these items. For the drum packaging machine an even 2023 US $100,000 total purchase cost was assumed. Installation factors ranging from 1.05 applied to equipment with a lower degree of installation and higher degree of mobility up to 1.4 for heavy, stationary machinery as more permanent installations within the manufacturing facility, such as the hot vacuum press, were used to estimate the installed capital cost of each piece of equipment used in the process. Magnitudes of these factors are also consistent with those that SA has applied and used in the past for modeling costs of low to high-rate manufacturing/fabrication facilities.

Table 74. Estimated costs for boron carbide (B_4C) pellet production process.

Process Parameters	**UOM**	**B_4C Pelletization Requirements & Costs**						
Powder Densification (Step 1)	-	**Die Handler & Lift**	**Material Dispenser & Meter**	**Batch Hot Vacuum Uniaxial Press**	**Low-Grade Vacuum Pump with Filters**	**High-Grade Vacuum Pump with Filters**	**Inert Gas Dispensing Equipment**	**Total**
Lifetime	yr	20	20	20	20	20	20	—
Annual Operating Time	hr/yr	41.67	41.67	5,344.58	250.00	2,985.42	2,234.17	—
Energy Requirements	kW_e	1.00	0.10	1,106.00	0.75	0.40	0.05	—
Material Requirements	kg/hr	0.000	0.000	0.063	0.000	0.000	1.505	—
Total Capital Cost	2023 US $/yr	1,694	4,235	1,315,576	493	986	988	1,323,972
Total Maintenance + Misc. Expenses	2023 US $/yr	500	1,250	1,331,377	250	998	500	1,334,875
Total Energy Cost	2023 US $/yr	3	0	472,889	15	96	9	473,012
Total Material Cost	2023 US $/yr	0	0	56,966	0	0	57,068	114,034
Total Operating Cost	2023 US $/yr	3	0	529,855	15	96	57,077	587,046
Total Labor Costs	2023 US $/yr	2,708	2,708	347,398	16,250	194,052	145,221	708,338

Process Parameters	UOM	B4C Pelletization Requirements & Costs						
Total Production Cost	2023 US $/yr	4,906	8,194	3,524,206	17,008	196,132	203,786	3,954,231
Total Markup	2023 US $/yr	4,906	8,194	3,524,206	17,008	196,132	203,786	3,954,231
Total Commercial Cost	2023 US $/yr	9,811	16,387	7,048,412	34,015	392,264	407,572	7,908,461
Processing Cost, Specific, Average	2023 US $/kgB$_4$C	0.05	0.09	39.08	0.19	2.18	2.26	43.85
Pellet Sizing & Finishing (Milling) Process (Step 2)	**-**	**Die Handler & Lift**	**12 kW Laser Cutter**	**Belt/Disc Grinders**	**Pulverizer**			**Total**
Lifetime	yr	20	20	20	20	—	—	—
Annual Operating Time	hr/yr	41.67	740.21	662.34	520.83	—	—	—
Energy Requirements	kW_e	1	32.400	6.338	1.500	—	—	—
Material Requirements	kg/hr	0.000	0.000	0.000	0.000	—	—	—
Total Capital Cost	2023 US $/yr	1,694	757,747	4,941	4,941	—	—	769,323
Total Maintenance + Misc. Expenses	2023 US $/yr	500	766,849	5,000	5,000	—	—	777,349
Total Energy Cost	2023 US $/yr	3	1,919	341	63	—	—	2,325
Total Material Cost	2023 US $/yr	0	0	0	0	—	—	0
Total Operating Cost	2023 US $/yr	3	1,919	341	63	—	—	2,325
Total Labor Costs	2023 US $/yr	2,167	38,491	34,442	27,083	—	—	102,183
Total Production Cost	2023 US $/yr	4,364	1,565,006	44,718	37,087	—	—	1,651,174
Total Markup	2023 US $/yr	4,364	1,565,006	44,718	37,087	—	—	1,651,174
Total Commercial Cost	2023 US $/yr	8,728	3,130,011	89,436	74,173	—	—	3,302,348
Processing Cost, Specific, Average	2023 US $/kgB$_4$C	0.05	17.36	0.5	0.41	—	—	18.32
Pellet Packaging Process (Step 3)	**-**	**6,000 lb. Forklift Hopper**	**10,000 lb. Forklift**	**Drum Packaging Machine**				**Total**
Lifetime	yr	20	20	20.00	—	—	—	-
Annual Operating Time	hr/yr	20.83	34.72	36.11	—	—	—	-
Energy Requirements	kW	0.000	47.128	5.000	—	—	—	-
Material Requirements	kg/hr	0	0	479	—	—	—	-
Total Capital Cost	2023 US $/yr	741	9,317	19,763	—	—	—	29,820
Total Maintenance + Misc. Expenses	2023 US $/yr	25	18,000	20,000	—	—	—	38,025
Total Energy Cost	2023 US $/yr	0	200	14	—	—	—	214
Total Material Cost	2023 US $/yr	0	0	108,750	—	—	—	108,750
Total Operating Cost	2023 US $/yr	0	200	108,764	—	—	—	108,964
Total Labor Costs	2023 US $/yr	542	903	939	—	—	—	2,383
Total Production Cost	2023 US $/yr	1,308	28,419	149,466	—	—	—	179,193
Total Markup	2023 US $/yr	1,308	28,419	149,466	—	—	—	179,193
Total Commercial Cost	2023 US $/yr	2,616	56,839	298,932	—	—	—	358,386
Processing Cost, Specific, Average	2023 US $/kgB$_4$C	0.01	0.32	1.66	—	—	—	1.99
Total	**2023 US $/yr**							**11,569,196**
	2023 US $/kgB$_4$C							**64.15**

Corporate income taxes and interest on capital are assumed to be typical values of 26% and 10%, respectively, SA has applied in past estimates. These are applied to the installed costs and capitalized over the lifetime of each piece of equipment where all equipment is assumed to last for 20 years. Similarly, annual average combined maintenance and miscellaneous costs are assumed to range from ~1% to 30% of the base, uninstalled capital cost for each piece of equipment where more mechanically cycling equipment such as the forklift and hot vacuum press are assumed to require more annual maintenance than other more basic equipment such as the forklift hopper and die handler/lift. Electrical power costs are assumed to be a flat 2023 US \$0.08/kWh_e while costs for propane fuel needed for the gas-powered forklift are taken as 2023 US \$0.12/kWh_t, the most recent value reported by the US-EIA when our cost analysis was conducted (March 27, 2023).[61] Material costs for a large graphite die[62], argon gas[63] for inert purging, and packaging supplies[64] were obtained as quoted values from various sources. Base labor wages were assumed to be 2023 US $50/hr for hot vacuum press operators with a single operator assumed per shift of coverage for the entire duration of the vacuum press operation, 2023 US $40/hr for a single operator per shift and a single shift per day to run the pellet milling station, and 2023 US $20/hr for packaging operators with one operator per shift and a single shift per day. Employer burdened labor rates were assumed as 30% of total operator base wage which is a typical value applied previously by SA in other analyses. Corporate markup used to set the final commercial price is assumed to be 100% of the total production cost based on 3M's 2022 reported annual margin.[65]

B_4C pelletization costs are dominated by the powder densification and sintering step (step 1) due to the high costs of the hot vacuum pressing operation. This is followed by costs of dense B_4C milling with packaging being the cheapest part of the process. Since densified B_4C milling costs are estimated to be much lower, total pelletization costs could possibly be reduced if more milling and less pressing were possible; however, since we assume no material loss with full milling residue recycle possible, costs of a process that relies more on milling may not be accurately represented by this assumption and additional milling may only reduce costs to a certain degree.

Core Assembly Argon Gas Costs

Inert gases are used in two core assemblies: Gas Expansion Modules (GEMs) and fuel pins. GEMs are filled with inert gas and sealed. The inert gas responds to changes in sodium level due to the open bottom of the GEM that allows sodium coolant to enter and introduces significant negative reactivity, limiting the occurrence and level of temperature excursions. Metal fuel pins use a large fission gas plenum (typically filled with Argon), which accommodates fission gas release within the pin. The argon gas provides internal pressure and allows for tracing of fuel failures to a specific fuel assembly.

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61 https://www.eia.gov/dnav/pet/pet_pri_wfr_a_EPLLPA_PRS_dpgal_w.htm

62 ROM based on 50 mesh graphite powder/flake prices from https://www.northerngraphite.com/about-graphite/graphite-pricing/ which are assumed to be the same as US pricing, and these inflated by 100x to account for costs associated with die fabrication.

63 Pricing based on standard purity Ar (99.99 mol%) supplied in a 300 ft^3 high pressure cylinder from https://highprecisiongas.com/products/argon-ar-gaseous?variant=37465823314075 which includes this as a rented cylinder option with pricing quoted as $240/cylinder.

64 8-55 US gallon steel drums with lids based on pricing from https://www.uline.com/Product/Detail/S-10758/Drums/Steel-Drum-with-Lid-55-Gallon-Open-Top-Unlined, plastic bag-style liners for each drum based on pricing from https://www.uline.com/Product/Detail/S-14456/Drum-Liners/Round-Bottom-Drum-Liners-37-x-56-10-Mil, 2 standard wooden pallets to hold 4-55 US gallon steel drums each based on pricing from https://www.uline.com/Product/Detail/H-1125/Pallets/New-Wood-Pallet-48-x-48, & plastic shrink wrap for final wrapping of drum loaded pallet for offsite transportation based on pricing from https://www.uline.com/Product/Detail/S-3968/Uline-Stretch-Wrap/Uline-Stretch-Wrap-Cast-120-gauge-18-x-1000.

65 https://investors.3m.com/news-events/press-releases/detail/1753/3m-reports-fourth-quarter-and-full-year-2022-results.

The inert gas volume per reactor core is estimated as 0.12 Nm^3/reactor. Assuming Argon is the only inert gas used, the estimated weight of Argon is 0.19 kg/reactor. Pricing for industrial purity Argon was quoted at 2023 US $10.25/kg.[66] This leads to <$3/reactor associated with inert gas costs.

5.6.5.3 Core Assemblies

Core Assembly Design

The reactor core is assumed to have a heterogenous layout consisting of multiple core assembly types. These types include driver and blanket fuel, control, reflector, and shield assemblies. In addition, the reactor core modeled here uses GEMs for enhanced reactivity control and is assumed to operate in a breakeven fuel burnup mode. The reactor core assembly configuration is given in Table 75 and assumed to generate 471 MW_t of thermal power leading to an equivalent 165 MW_e of electrical power following thermal-to-electrical power conversion.

Table 75. Reactor core assembly configuration for a single baseline 471 MW_t/165 MW_e sodium-cooled fast reactor.

Core Assembly	Assembly Count per Reactor	Contents of Core Assembly
Fuel	54	Fuel pins loaded with pelletized fuel
Blanket[a]	45	Blanket pins loaded with pelletized fuel
Control	6	Absorber bundle housing control pins loaded with pelletized, enriched $^{10}B_4C$
Shutdown[b]	1	Absorber bundle housing control pins loaded with pelletized, enriched $^{10}B_4C$
Gas Expansion Module	3	Partially enclosed gas expansion chamber filled with Argon gas, bottom of chamber uses solid HT9 rods
Reflector	42	Solid HT9 reflector pins
Shield	102	Shield pins loaded with pelletized, natural $^{10}B_4C$
Total	**253**	

[a] Blanket assemblies are frequently subdivided into internal blanket assemblies and radial blanket assemblies. For the purposes of this study, both of these subtypes are assumed to be identical and are considered as one category.
[b] The shutdown assembly is assumed to be identical to the control assembly in design although it may be operated differently than the control assembly and may only be used for emergency reactivity control.

66 Pricing based on industrial purity Ar (>99.995%) supplied in a Size 300 (49 L) cylinder from https://www.airgas.com/Gases/Argon/category/604.

The core assemblies share a hexagonal duct that acts as a casing to contain the unique internals of each assembly, a handling socket situated at the top of the core assembly, and a nose piece installed on the bottom. The core assemblies are generally different from one another by the unique internal pins installed within the hexagonal duct (e.g., fuel pins loaded with fuel pellets inside of the fuel assembly versus pins loaded with $^{10}B_4C$ used in the control rods). A list of all core assembly internals including their corresponding dimensions and the quantities of each are tabulated in Table 76. Except for the Gas Expansion Modules, sodium flows into each core assembly through the nose piece up through the internals of the hexagonal duct, and exits through the handling socket. The specific design including dimensions and packing of the internal pins depend on the thermal, fluid, and neutronic dynamics occurring in the core during reactor operation. Establishing such designs are beyond the scope of our work; therefore, representative dimensions for the core assemblies and internal pins are derived from several sources for the purposes of representative cost estimation.[67,68,69,70] The dimensions of tubing, rods, and hexagonal ducting that must be procured prior to manufacturing of the core assemblies are listed in Table 77 to Table 78. The assumed pin counts are provided in Table 79 for each assembly type.

Table 76. Final dimensions and quantities of reactor core assembly nosepieces and pin cladding required for a baseline 471 MW_t/165 MW_e sodium-cooled fast reactor.

Component	Outer Diameter	Wall Thickness	Length	Number per Reactor
-	in.	in.	in.	-
Nosepiece Cylinder	6.82	0.17	11.39	253
Fuel Pin – Cladding	0.293	0.022	158.5	14,634
Blanket Assembly Pin – Cladding	0.473	0.022	158.5	5,715
Control / Shutdown Assembly Pin – Cladding	0.660	0.022	40.0	366 / 61
Shield Assembly Pin – Cladding	2.145	0.022	159.3	714

Table 77. Final dimensions and quantities of reactor core assembly plugs, pins, and other miscellaneous parts for a baseline 471 MW_t/165 MW_e sodium-cooled fast reactor.

Component	Outer Diameter	Length	Number per Reactor
-	in.	in.	-
Alignment Plug	3.25	2.74	253
Fluid Distributor	6.48	2.87	253
Fuel Pin – Upper End Plug Fuel Pin – Lower End Plug	0.249	1 44	14,634 14,634
Blanket Assembly Pin – Upper End Plug Blanket Assembly Pin – Lower End Plug	0.429	1 44	5,715 5,715
Control / Shutdown Assembly Pin – Upper End Plug Control / Shutdown Assembly Pin – Lower End Plug	0.616	1 1	366 / 61 366 / 61
Control / Shutdown Absorber – Latch	0.74	12.5	6 / 1
Control / Shutdown Absorber – Upper Plug Control / Shutdown Absorber – Lower Plug Control / Shutdown Absorber – Scram Arrest	2.47	38 12 27	6 / 1 6 / 1 6 / 1

67 B. S. Triplett, E. P. Loewen, and B. J. Dooies. PRISM: A Competitive Small Modular Sodium-Cooled Reactor. Nuclear Technology 2010, 178 (2), 195.

68 A. E. Dubberley, C. E. Boardman, K. Yoshida, and T. Wu, "S-PRISM Oxide and Metal Fuel Cord Designs," Proc. 8th Int. Conf. Nuclear Engineering (ICONE-8), Baltimore, Maryland, April 2– 6, 2000.

69 Sumner, Moisseytsev, Heidet, Wootan, Casella, and Nelson. Benchmark Specification for FFTF LOFWOS Test #13. 2022.

70 General Electric, Advance Nuclear Technology. "PRISM Preliminary Safety Information Document". 1987.

Component	Outer Diameter	Length	Number per Reactor
Gas Expansion Module – Shield Pin	0.724	27.5	183
Gas Expansion Module – Shield Block	6.136	38.0	3
Reflector – Shield Pin	0.738	160.25	2,562
Shield Assembly Pin – Upper End Plug Shield Assembly Pin – Lower End Plug	2.101	1 1	714 714

Table 78. Final dimensions and quantities of reactor core assembly hexagonal tubing for a baseline 471 MW_t/165 MW_e sodium-cooled fast reactor.

Component	Outer Diameter	Wall Thickness	Length	Number per Reactor
-	in.	in.	in.	-
Duct – General	6.82	0.17	164.47	250
Duct – Gas Expansion Module	6.82	0.34	164.47	3
Handling Socket	7.00	0.26	12.00	253
Control / Shutdown Absorber – Upper Inner Duct Control / Shutdown Absorber – Inner Duct Control / Shutdown Absorber – Lower Inner Duct	6.22	0.058	14 40 12	6 / 1 6 / 1 6 / 1

Table 79. Assumed reactor core assembly pin count.

Core Assembly	Pins per Core Assembly
Fuel	271
Blanket	127
Control	61
Shutdown	61
Gas Expansion Module	61
Reflector	61
Shield	7

Core Assembly Material

The pin cladding and assembly duct material must undergo significant thermal load in addition to irradiation. This can induce irradiation creep and swelling resulting in dimensional changes and mechanical failure. Two specific concerns are: (1) core assemblies becoming stuck in the reactor core, resulting in the inability to service and remove core assemblies; and (2) internal coolant channels becoming blocked causing inadequate cooling and the formation of local hot spots. High-chromium ferritic-martensitic (HCFM) steels have been identified as acceptable materials to use in advanced nuclear reactors due to their excellent thermal properties and low swelling characteristics.[71,72,73] In particular, HT9 (12Cr-1MoVW, wt.%) has extensive irradiation testing data from the Experimental Breeder Reactor-II (EBR-II) and the Fast Flux Test Facility (FFTF). The supply chain for HT9 is currently non-existent

71 R.L. Klueh, Elevated temperature ferritic and martensitic steels and their application to future nuclear reactors, International Materials Reviews 50(5) (2005) 287–310.

72 R.L. Klueh, A.T. Nelson, Ferritic/martensitic steels for next-generation reactors, Journal of Nuclear Materials 371(1) (2007) 37–52.

73 R.L. Klueh, D.R. Harris, High-Chromium Ferritic and Martensitic Steels for Nuclear Applications (ASTM, Conshohocken, 2001), Google Scholar.

although commercial entities such as TerraPower are soliciting interest in potential suppliers. For the purposes of this study, T91 (9Cr-1MoV, wt.%) was selected as a surrogate HCFM steel due to the greater availability of cost information. In general, the cost range for industry standard tubing sizes of T91 fall between 2023 US $350–770/tonne.[74] We therefore assume 2023 US $0.50/kg as a baseline material cost. As discussed in the following section, we model additional cost adders to estimate the cost of further processing the industry standard tubing to SFR specific component requirements.

Manufacturing of SFR-Specific Core Tubing, Rods, & Hexagonal Tubes

For industry standard tubing, the manufacturing process requires hot drawing or extrusion of metal billets. In general, there are seven distinct steps:

1. Billet heating
2. Hot drawing or extrusion
3. Quenching
4. Elongation
5. Cutting
6. Accelerated aging
7. Quality control including inspections and testing.

Core assemblies are built using long ducts and tubes with unusually thin walls relative to industry standard tubing. In addition, core assemblies are made of high strength HT9 material. These two factors contribute to a more complex manufacturing process for these SFR-specific components compared to the production of piping. High strength HT9 materials cannot be shaped using conventional cold extrusion processes for the direct formation of SFR-specific components. Consequently, the bulk deformation of the SFR-specific tubing, rods, and hexagonal ducting is assumed to occur during hot extrusion outlined above. Due to thermal deformation that occurs during cooling, the dimensions of the hot extrusion are not expected to be of sufficient tolerance for direct utilization. Thus, all SFR-specific components are assumed to require a secondary cold extrusion process to further refine wall thicknesses and overall dimensions.

The hot and cold extrusion processes mentioned above are handled as cost adders applied to industry standard tubing costs. The key assumptions for hot and cold extrusion processes are summarized in Table 80 and Table 81, respectively. Hot and cold extrusion processes are assumed to occur on pre-existing machinery owned by the tubing supplier.

Table 80. Manufacturing parameters used to estimate hot extrusion costs for sodium-cooled fast reactor core assemblies.[75]

Parameter	UOM	Value
Cost for Tooling	2023 US $/tooling	7,300
Scrap Rate	%	20
Setup Time	min/batch	1
Waste Time	min/batch	7

[74] See the following links for representative pricing: https://heyixinmetal.en.made-in-china.com/product/jwItYSEClNrK/China-High-Pressure-T91-P11-Heat-Exchanger-Rifled-Boiler-Tube-Round-Carbon-Steel-Seamless-Pipe-with-Good-Price-in-Stock.html; https://www.made-in-china.com/products-search/hot-china-products/T91_Steel_Pipe_Price.html.

[75] Representative parameters derived from aluminum extrusion featured in J. Nieto. Feature Based Costing of Extruded Parts. Thesis. 2010.

Batches	no./8-hr shift	10
Downtime	%	17
Extrusion Exit Speed	m/min	20
Laborers	no./line	3
Power Consumption	kW/line	500

Table 81. Manufacturing parameters used to estimate cold extrusion costs for sodium-cooled fast reactor core assemblies.[75]

Parameter	UOM	Value
Cost for Tooling	2023 US $/tooling	7,300
Scrap Rate	%	0
Setup Time	min/batch	1
Waste Time	min/batch	7
Batches	no./8-hr shift	10
Downtime	%	17
Extrusion Exit Speed	m/min	2
Laborers	no./line	3
Power Consumption	kW_e/line	500

Core Assembly Laser Cutting

While standard pipe and tube lengths are ~6m, many of the SFR components are significantly smaller. Semi-empirical cost correlations for part handling and laser cutting of Cr-Mo alloy were derived from data obtained from the DFM-CC® software. Key parameters for generic part handling and laser cutting are shown in Table 82 and Table 83, respectively.

Table 82. Manufacturing parameters used to estimate part handling costs for sodium-cooled fast reactor core assemblies.

Parameter	UOM	Formula
Total Handling Time	s	0.0497 * Part Volume [in^3] + 16.0071

Table 83. Manufacturing parameters used to estimate laser cutting costs for sodium-cooled fast reactor core assemblies.

Parameter	UOM	Value
Machine Rate	2023 US $/hr	51
Laborers	no./line	1
Cutting Speed	in./s	Various[a]
Setup Time	min/day	30

[a] Parameterized from the BDI DFM Concurrent Costing® software as a function of plate thickness.

Core Assembly Tube Hydroforming

The handling socket and nosepiece cylinder require specific shapes beyond a simple cylinder or hexagon to allow for easier lifting and placement into the core frame, and to ensure that the core securely seats into the base of the reactor at the bottom of the core inlet plenum. Additionally, the control/shutdown absorber inner duct must be shaped in order to house the absorber pins while also being attached to the control drive latch. These components are assumed to be shaped via tube hydroforming. Key assumptions for tube hydroforming are shown in Table 84.

Table 84. Manufacturing parameters used to estimate tube hydroforming costs for sodium-cooled fast reactor core assemblies.

Parameter	UOM	Value
Capital Cost of Hydroforming Machine	2023 US $	100,000
Cost for Tooling	2023 US $	7,300
Laborers	no./line	1
Power Consumption	kW_e/line	45
Cycle Time	s	60

Core Assembly Machining

Fluid channels must be introduced into the nosepiece and the control/shutdown absorber to facilitate flow of the sodium coolant. In addition, internal pins are slotted into machined holes within the pin alignment sheet to maintain equal spacing of the pin bundle. Key assumptions for nosepiece and pin alignment sheet machining are shown in Table 85.

Table 85. Manufacturing parameters used to estimate milling and machine cutting costs for sodium-cooled fast reactor core assemblies.

Parameter	UOM	Value
Capital Cost of CNC Machine	2023 US $/line	912,200
Capital Cost of Fixture	2023 US $/line	5,400
Capital Cost of Cutting/Milling Tool	2023 US $/line	21,600
Capital Cost of Automatic Loading/Unloading System	2023 US $/line	519,843
Total Capital Cost	2023 US $/line	1,459,077
Laborers	no./line	1
Power Consumption	kW_e/line	27
Machine Speed	m/min	2

Core Assembly Welding

Welding associated with core assemblies must be completed in multiple stages. First, the driver and blanket fuel, control/shutdown, and shield pins need their upper end plugs welded. Second, after assembly of each of the pins, the lower end plug must be welded. Third, a wire wrap is spot welded at the top and bottom of each driver and blanket fuel, control/shutdown, and shield pin. This wire wrap ensures adequate pin spacing within the core assembly for sufficient sodium coolant flow through each core assembly. Fourth, the driver and blanket fuel, control/shutdown, reflector, and shield assembly pins are welded to the pin alignment sheet forming a pin bundle. Fifth, the pin bundle can be directly welded to the hexagonal duct for the driver and blanket fuel, reflector, and shield assemblies. Sixth, the nosepiece components (nosepiece cylinder, alignment plug, and fluid distributor) are welded together to form the assembled nosepiece. Finally, the nosepiece and the handling socket are welded to the assembled hexagonal duct to complete the core assembly.

The control/shutdown assemblies first require the absorber to be assembled and welded together before the control/shutdown assemblies can be capped by the handling socket and the nosepiece. We model this as seven different components (latch, upper plug, upper inner duct, inner duct, lower inner duct, lower plug, and absorber pin bundle) that must be assembled and welded. In addition, a scram arrest is welded onto the nosepiece for the control/shutdown assemblies prior to final assembly and welding.

Each GEM requires a shield block to be welded to the top of the hexagonal duct that prevents sodium flow to the top of the GEM. A short pin bundle which provides shielding is welded to the bottom of the hexagonal duct similar to the other core assemblies.

Robotic MIG fillet welds are assumed for high volume components including pin plugs and pin bundles. Robotic MIG double-sided butt welds are assumed for pin wire wraps, nosepiece assembly, and final core assembly. Manual MIG double-sided butt welds are assumed for each absorber assembly. Empirical cost correlations for welding were derived from data obtained from the DFM-CC® software. Key assumptions for welding are shown in Table 86.

Table 86. Manufacturing parameters used to estimate welding costs for sodium-cooled fast reactor core assemblies.

Parameter	UOM	Value
Machine Rate - Robotic, MIG, Fillet	2023 US $/hr	24.69
Machine Rate - Robotic, MIG, Double-Sided	2023 US $/hr	24.69
Machine Rate - Manual, MIG/TIG, Double-Sided, Butt	2023 US $/hr	186.62[a]
Laborers	no./line	1
Power Consumption	kW_e/line	15
Welding Speed	in./s	Various[b]
Welding Material	lb.	Various[c]
Welding Material Cost	2023 US $/lb.	7.41[d]

[a] Inclusive of labor rate.
[b] Parameterized from the BDI DFM Concurrent Costing® software as a function of fillet size.
[c] Parameterized from the BDI DFM Concurrent Costing® software as a function of fillet size and weld length.
[d] Cost is for Cr-Mo.

Core Assembly Heat Treating

All welded parts need heat treating to relieve internal stress and enhance weld integrity. Heat treating of the long core assemblies is assumed to be carried out in large-scale batch-style furnaces. The following components are assumed to be heat treated separately: (1) Welded pins; (2) absorber; and (3) core assembly. A total heat-treating time of 393 min is assumed for each heat cycle per ASME Section III Division I requirements, and all welded elements having a wall thickness <1”. Based on the dimensions of the furnace and the dimensions of the individual pins, pins are assumed to be heat treated in batches of ~6,900. The absorbers and the core assemblies associated with one reactor are heat treated in two batches. Empirical cost correlations for heat treating were estimated from the ASME heat treating requirements and furnace equipment quoted by commercial vendors. Key assumptions for heat treating are shown in Table 87.

Table 87. Manufacturing parameters used to estimate heat treating costs for sodium-cooled fast reactor core assemblies.

Parameter	UOM	Value
Furnace Width	ft	15
Furnace Length	ft	40
Furnace Height	ft	10
Machine Rate	2023 US $/hr	412.67[a]
Laborers	no./line	1[b]

Power Consumption	kW/line	1,407
Total Heat-Treating Time	min	337.5[c]

[a] Includes 0.25 laborers per line.
[b] Only during loading and unloading.
[c] Includes heating time, hold time, and controlled cooling time.

Core Assembly X-Ray Inspection

X-Ray inspection is assumed for all welds. The following components must be inspected separately prior to additional assembly: (1) welded pins; (2) pin bundles; (3) nosepiece; (4) pin bundles within hexagonal ducts; (5) absorbers; and (6) core assemblies. Empirical cost correlations for x-ray inspection were derived from equipment quoted by commercial vendors. Key assumptions for x-ray inspection are shown in Table 88.

Table 88. Manufacturing parameters used to estimate x-ray inspection costs for sodium-cooled fast reactor core assemblies.

Parameter	UOM	Value
Machine Rate	2023 US $/hr	77.17
Laborers	no./line	1
Power Consumption	kW_e/line	15
Inspection Speed	s/in^2	10
Setup Time per Day	min/day	5

Core Assembly Non-Enumerated Components

Core assemblies are only one part of the reactor core and cannot be considered in isolation. The specific design of the handling socket and nosepiece are dependent on the reactor core design and may be modified depending on expected sodium flow rates and thermal loads. Since the core assembly design modeled here is approximated from literature sources, there may be missing elements that our analysis cannot capture due to these not being included in this literature. It is expected that the above manufacturing steps account for the majority of the costs, including general assembly. However, to account for any elements that were not explicitly identified and additional assembly time, a 20% contingency is applied to the total core assembly cost to represent non-enumerated or underestimated components.

Summary of Core Assembly Costs

A summary of the core assembly cost over a range of reactor production rates is provided in Table 89. The largest cost driver is the machining step due to the relatively low line utilization and high capital cost. The second largest cost driver is the cold extrusion process which is driven by a high labor rate and large total extrusion length for a single reactor.

Table 89. Estimated core assembly costs for different numbers of baseline 471 MW_t/165 MW_e sodium-cooled fast reactors.

Annual Reactor Production Rate	reactors/year	1	2	3	6	9	18	30	90
Annual Electrical Power Production Rate	MW_e/year	165	330	495	990	1485	2970	4950	14,850
Annual Manufacturing Cost									
Hot Extrusion - Custom Pipe	2023 US $k/year	71	115	158	289	420	812	1,335	4,005
Hot Extrusion - Custom Rod	2023 US $k/year	62	91	120	206	292	551	896	2,656

Hot Extrusion - Hexagon	2023 US $k/year	13	13	13	14	15	19	23	44
Cold Extrusion	2023 US $k/year	564	861	1,425	2,582	3,740	7,211	11,840	35,519
Cutting - Laser	2023 US $k/year	137	274	411	822	1,234	2,467	4,112	12,335
Tube Hydroforming	2023 US $k/year	54	55	55	57	59	65	72	109
Machining	2023 US $k/year	607	609	612	618	625	645	672	814
Pin Welding - Pin Plugs	2023 US $k/year	162	323	485	970	1,455	2,910	4,850	14,551
Pin Welding - Pin Bundle	2023 US $k/year	54	107	160	318	475	948	1,579	4,732
Core Welding Robotic	2023 US $k/year	16	33	50	99	149	297	495	1,486
Core Welding - Manual	2023 US $k/year	1	2	4	7	11	21	35	105
Core Welding - Final Assembly	2023 US $k/year	17	34	51	102	153	307	511	1,533
Inspection - X-Ray	2023 US $k/year	16	31	47	93	140	280	467	1,402
Heat Treating - Furnace	2023 US $k/year	90	197	296	592	887	1,775	2,958	8,873
Non-enumerated Components	2023 US $k/year	373	549	777	1,354	1,931	3,662	5,969	17,633
Total Annual Cost	**2023 US $k/year**	**2,237**	**3,295**	**4,663**	**8,125**	**11,586**	**21,969**	**35,814**	**105,797**
	2023 US $/kW$_e$	**13.55**	**9.99**	**9.42**	**8.21**	**7.80**	**7.40**	**7.24**	**7.12**
	2023 US $k/reactor	**2,237**	**1,648**	**1,554**	**1,354**	**1,287**	**1,221**	**1,194**	**1,176**

5.6.6 Account 58: Decommissioning

Decommissioning cost in 2023 US $ is estimated with the methodology presented in the GIF Economic Modeling Working Group (EMWG) cost estimating guidelines for a nuclear technology that is not a PWR or boiling water reactor (BWR):

$$Cost\ [million\ 2007\$] = 197 + 0.024\ (P[MW_t] - 1200)$$

Constant decommissioning cost for units less than 1,200 MW_t and greater than 3,400 MW_t are assumed. Decommissioning commences at the end of the plant's 60-year life. The initial fund necessary for decommissioning grows with a real discount rate of 5% and monthly compounding, yielding a 5.12% annual percentage yield (APY), to fully fund decommissioning with no further annual payments.

5.6.7 Account 59: Contingency on Capitalized Supplementary Costs

A 20% contingency is assigned for the capitalized supplementary costs.

5.7 Account 60: Capitalized Financial Costs

5.7.1 Account 61: Escalation

Capitalized financial costs are anticipated to increase at the general rate of inflation. Consequently, no costs due to escalation are incurred.

5.7.2 Account 62: Fees

Fees or royalties that should be capitalized with the plant are unknown and therefore are set to zero for this analysis. Annual fees for nuclear reactors are included in account 92.

5.7.3 Account 63: Interest

The interest during construction (IDC) is calculated by Equation 5.7.1 taken from the GIF EMWG's 2007 cost estimating guidelines.[76]

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[76] Generation IV International Forum & Economic Modeling Working Group. Cost Estimating Guidelines for Generation IV Nuclear Energy Systems. *GIF/EMWG/2007/004 Rev. 4.2* **September 26, 2007**. https://www.gen-4.org/gif/upload/docs/application/pdf/2013-09/emwg_guidelines.pdf..

$$IDC = \sum_{p=1}^{N} CF_p \cdot [(1+r)^{S-p} - 1] \quad 5.7.1$$

IDC is the total constant currency cost of interest accrued during construction for an annual cash flow (CF) during period p occurring over a total number of compounding periods N starting at the startup period S compounded at real discount rate r. To simplify our estimation, we assume that the quarterly draw on the TOC (sum of Accounts 10–50) as the cash flow/distribution of construction cost during plant build-up is constant and equal for the 5.7-year span of a construction loan bearing interest at an annual rate of 5% (5.12% APY). Furthermore, we treat the startup period (S) as being equal to the construction duration, indicating instantaneous startup and revenue realization immediately following construction completion. Per the GIF guidelines, either quarterly or annual compounding should be used for estimating the IDC at a discount rate between 5–10% with the preference being for annualized interest on a quarterly basis only resorting to annual compounding if quarterly cash flow estimates are not available. Therefore, we choose quarterly compounding as a reasonable frequency since we set the basic cash flows to the annual average TOC during the construction period. Furthermore, since we use the TOC to set cash flows, cost contingencies are included in the estimate for the IDC, a requirement per GIF guidelines.

As discussed previously, 5.7-years for plant construction corresponds to the average world-wide across various types of reactor technologies based on historical data for nuclear power plant construction. The EMWG stipulates that the schedule for NOAK plants may be accelerated where more aggressive construction timelines and work-week plans, such as rolling 4 × 10s, could yield a fully constructed plant within 40 months from first concrete to commercial operation. For the same milestones, a FOAK project schedule would be longer and could be at something like 80 months. Replication of SMRs is anticipated to enable rapid construction, indicating that an accelerated timeframe relative to more standard NPP construction is possible. In the case of an 80-month construction period, the capitalized financial costs would increase by about 20%. Thus, establishing a streamlined construction period should be prioritized.

5.7.4 Account 69: Contingency on Capitalized Financial Costs

A 20% contingency is included for capitalized financial costs.

5.8 Account 70: Annualized O&M Costs

The annualized costs are broken into three sections:

- Annualized O&M Costs
- Annualized Fuel Costs
- Annualized Financing Costs.

Financing costs tend to dominate the total annual cost of operating a NPP and the factors that determine its costs are generally not considered to prefer a particular nuclear technology. However, O&M is the second most significant annualized cost and is technology and design specific so is important to consider.

5.8.1 Account 71 to 73: Staff & Salary-Related Costs

The most significant O&M cost is staff and salary-related costs at 45% to 59% of the annualized O&M costs. The methodology for staffing estimates, salaries, and benefits are detailed in Section 4.5. The staffing estimate is based on CFR requirements for operators and a GE PRISM estimate with large 412 MW_e reactors compared to the 165 MW_e and 311 MW_e reactors considered in this project. The staffing estimate is scaled predominantly on quantity of reactors, so the staffing estimates on a per MWh_e basis are higher than if staffing is scaled on net facility output. If it is appropriate to scale staff with reactor quantity, increasing the reactor size could be one of the most meaningful ways to reduce the annualized non-financing costs.

5.8.2 Account 74: Operating Chemicals & Lubricants

Operating chemicals and lubricants are not estimated in this project.

5.8.3 Account 75: Spare Parts

Spare parts are estimated at 2% of equipment costs, inclusive of Accounts 22–26.

5.8.4 Account 76: Utilities, Supplies, & Consumables

Operating chemicals and lubricants are not estimated in this project.

5.8.5 Account 77: Capital Plant Upgrades

Capital plant upgrades are estimated based on a correlation derived from industry historical observations by Sargent & Lundy (Sargent & Lundy, Nuclear Power Plant Life Extension Cost Development Methodology, 2018). The annual capital cost correlation corrected for current year cost is:

$$\text{Annual Capital Plant Upgrade}\left(\frac{2023\$}{\text{kW}_e}\right) = \begin{cases} 1.23\ (17\ +\ 1.25\ \text{Age}), \text{up to 50 years of life} \\ 1.23\ \cdot\ 70, beyond\ 50\ years\ of\ life \end{cases}$$

The facility life is 60 years, and the discount rate is 5%.

5.8.6 Account 78: (A) Taxes & Insurance; & (B) Outage Costs

Annualized taxes, insurance, and outage costs are not estimated in this project.

5.8.7 Account 79: Contingency on Annualized O&M Costs

A 20% contingency is allocated for annualized O&M costs.

5.9 Account 80: Annualized Fuel Costs

Historically, and for more standard nuclear technologies such as LWRs, the cost of electricity from nuclear generation is relatively insensitive to the cost of nuclear refueling over the range of -50% to +50% fuel cost.[77] However, since we find that the initial core fuel load costs for our SFR as estimated for Account 55 are approximately 3.5–4× larger than the typical costs for equivalent sized LWRs, the annualized fuel costs will make up a significantly larger portion of the LCOE and will not be negligible for our SFR NPPs. We, therefore, estimate the various subaccounts in a semi-detailed fashion to determine the magnitude and cost contribution for each account.

5.9.1 Account 81: Refueling Operations

Refueling operations are modeled as two sets of activities all devised under a refueling plan used to coordinate both operations-based and maintenance-based tasks. The first is the operational actions required to remove and return the reactor module and associated equipment from service to allow for required refueling maintenance activities to occur as given by:

1. Removal from Service
    a. Inspection of reactor in-vessel transfer machine (IVTM) and rotatable plug for preparation of refueling.

[77] IEA. Projected Costs of Generating Electricity **2020**, IEA, Paris. *https://www.iea.org/reports/projected-costs-of-generating-electricity-2020*, License: CC BY 4.0.

b. Verification of reactor internal pressure with repressurization as needed to elevate reactor pressure to normal operational level.

c. Preparation of core reactivity level to below the critical state by insertion of control and shutdown rods.

d. Cooling of reactor internals to a cold-standby state.

e. Disconnection and raising of drivelines from reactivity control and shutdown rods.

f. Purging and purification of reactor cover gas.

g. Operation of IVTM, rotatable plug, and fuel transfer cask (FTC) for removal of spent fuel assemblies and replacement with fresh fuel assemblies.

2. Return to Service

   a. Shutdown and storage of IVTM in typical location within reactor module.

   b. Lowering of control rod drivelines and reconnection to control and shutdown rods.

   c. Inspection of reactor instrumentation.

   d. Verification of reactor internal pressure with repressurization as needed to elevate pressure to normal operational level.

   e. Startup of all pumps that were shutdown during refueling and re-establishment of normal operational flows.

   f. Preparation of steam generator for startup and return to full steam production.

   g. Gradual and partial withdrawal of reactivity control and shutdown rods for reactor internals heat-up and return to critical state.

   h. Full ramp-up to reactor normal operational power.

For these operational activities we do not explicitly estimate their costs and assume that all costs required for personnel labor, utilities, material, and equipment/tooling expenses are already accounted for in our estimation of the normal plant and equipment operations. We expect this to be reasonable due to the inherent and passive safety features and design aspects incorporated into our model SFR and affiliated equipment, so we propose that a single shift of regular operators that normally manage and monitor each reactor on a day-to-day basis that are scheduled for refueling are suitable to handle all required operational refueling activities in addition to any other routine activities for other plant equipment that they must manage. We therefore focus our estimate on the second category of activities that follow operational preparation of the equipment which are the maintenance tasks.

Once all equipment to be serviced during refueling are removed from operational service, various maintenance activities are conducted as described in the follow list:

1. Removal from Service

   a. Inspection of all facilities and equipment used for refueling.

   b. Preparation of reactor fuel handling cell (FHC), refueling enclosure (RE), FTC, and cask transporter (CT).

   c. Unloading and inspection of new replacement fuel assemblies from shipment packaging.

   d. Loading of new replacement fuel assemblies into FHC for temporary storage during refueling.

e. Transfer and loading of initial new replacement fuel assemblies into FTC (maximum capacity of three driver and two blanket assemblies for the base 471 MW_t/165 MW_e size reactor we consider) from the FHC.
f. Transport of RE to reactor head access area (HAA) from the fuel storage and transfer building (FSTB).
g. Positioning, temporary installation and connection, and preparation of RE for use as refueling shelter reactor module in HAA.
h. Positioning and final setup of CT within reactor tunnel on transport rails for use to shuttle fuel assemblies.
i. Preparation for reactor module access (i.e., opening of relevant access ports, rotatable plug, etc.).
j. Startup and initial positioning of IVTM.
k. Shuttling of FTC from FSTB to RE on CT with initial batch of new replacement fuel assemblies.
l. Removal of spent fuel assembly from in-vessel storage rack (IVSR) into FTC.
m. Removal of spent fuel assembly from reactor core into IVSR.
n. Removal of new fuel assembly from FTC and replacement into empty core fuel assembly slot.
o. Repetition of previous three steps two additional times.
p. Shuttling of FTC from RE to FSTB on CT with spent fuel assemblies.
q. Unloading of spent fuel assemblies into FHC.
r. Shuttling of FTC from FSTB to RE on CT with next batch of new replacement fuel assemblies.
s. Repetition of previous four steps until all target core assemblies are replaced.
t. Core support structure inspections for mechanical integrity examination.
u. Other reactor internals structure and internal equipment inspections for mechanical integrity examination.
v. Testing and servicing of pump motors and other electrical equipment including instrumentation.
w. Transfer of spent fuel assemblies to fuel cycle facility/building for processing and storage.

2. Return to Service

a. Closure and securement of reactor module rotatable plug and all access ports.
b. Transport of RE and CT from reactor building and access tunnel to normal storage locations.
c. Shutdown, decommissioning, and preparation for temporary mothballing of RE, FTC, CT, and FHC until next planned refueling use.
d. Spent fuel assembly processing for deep storage with shipment offsite.

A total duration of 27 days per reactor is assumed for all refueling activities to be completed consisting of both the operational and maintenance tasks. This amount of time is based on that estimated in the reference documents we use to establish our design basis[78] including an additional 20% contingency to account for extra time that may not have been explicitly included and any underestimation. We assume that each reactor is loaded in succession and non-concurrently throughout the year, entailing that plants with more reactors will have refueling operations extend longer periods throughout each operating year. To set the number of additional maintenance personnel required to accommodate the refueling tasks, we assume the following number of maintenance staff based on activity and function during the refueling process:

1. General Purpose – 2 staff members per reactor.
2. Fuel Reprocessing (working in fuel cycle facility) – 4 staff members per plant.
3. Fuel Handling Cell Management and Operation (working in FSTB) – 2 staff members per plant.
4. Fuel Transfer Cask and Cask Transporter Operation (working within FSTB, reactor access tunnels, and reactor building) – 2 staff members per plant.
5. Reactor Enclosure Operation – 1 staff member per plant.

We assume that these personnel work round-the-clock in shifts of 12 hours requiring a total of three shifts of personnel to cover 24-7 refueling operations for plants that have four reactors or less which requires about 3.5 months of total refueling time. For plants with more than four reactors (refueling periods that extend to longer than ~3.5 months), a total of four shifts are assumed to be on the payroll to allow for adequate personnel coverage with reasonable time off. Total labor expenses for each of these maintenance personnel are estimated as 50% more than those for standard plant maintenance personnel that perform typical day-to-day activities outside of refueling operations. Using this timeframe, the additional plant personnel postulated, and the assumed total personnel costs, we estimate the costs for refueling. We also include a refueling operations-specific contingency factor of 30% to adjust the estimated refueling costs to ensure that these are not underestimated.

5.9.2 Account 84: Additional Nuclear Fuel

The additional nuclear fuel required for end of cycle reloads and associated costs are based on the cycle length and the fraction of fuel reloaded during refueling cycles within the core. Table 12 includes the refueling intervals and fractions in each reactor core for both the driver and blanket fuel materials. Driver and blanket fuel quantities per reload are estimated and an average annual reloaded fuel mass is calculated from the reloading interval and used with the corresponding driver and blanket fuel costs to determine the total annual fuel replacement costs. Since the driver fuel comprises the majority of the fuel mass in the core, this is replaced at a higher frequency and a higher fraction of its total in the core for each reload, and since its fuel cost is the highest, annual costs for additional nuclear fuel is dominated by those for the replacement of the driver fuel (~70%) with the blanket fuel contributing a much lower amount to these costs (~30%).

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[78] GE-Advanced Nuclear Technology. PRISM-Preliminary Safety Information Document. *US DOE* **1987**, *Vol. 3*, Ch. 9–14, *9.1-21*. *https://www.nrc.gov/docs/ML0828/ML082880396.pdf.*

5.9.3 Accounts 86 & 87: Fuel Reprocessing Charges & Special Nuclear Materials

We assume that our model SFR NPP does not perform any fuel reprocessing and only fresh and new fuel is loaded into the reactor during the refueling process at the end of each fuel cycle. Therefore, we set the fuel reprocessing costs to zero. Likewise, no special nuclear materials outside of the fuel we assume for our SFRs are required and so costs for special nuclear materials are also set to zero.

5.9.4 Account 89: Contingency on Annualized Fuel Costs

A 20% contingency is applied to account for any potential annualized fuel costs that may have been missed or underestimated. This level of contingency is chosen to be consistent with our general use of the AACE Class 2 cost estimate.

5.10 Account 90: Annualized Financial Costs

Financial costs are separated into four subaccounts:

- Escalation
- Fees
- Cost of money
- Contingency

The costs are presented for each subaccount as costs per reactor. The total annualized financial cost is presented on the same basis as well as on a $/MWh$_e$ basis. The annual net electrical energy produced is calculated based on 8,760 hours/year, 93% capacity factor, and plant nominal net power. Annualized payments are computed based on 0% inflation indicating that a real discount rate is used in our analysis.

5.10.1 Account 91: Escalation

Annualized financial costs are anticipated to increase at the general rate of inflation (which is assumed to be 0% in this analysis). Consequently, no costs due to escalation are incurred.

5.10.2 Account 92: Fees

The NRC proposes annual operating fees. For the 2023 fiscal year, the fee is $5,492,000 per reactor as posted in 88 CFR 39120. Fees for other locations outside the US are not estimated. As this is a flat fee per reactor, it disadvantages lower power reactors. For the nominal 165 MW$_e$ reactor, fees equate to approximately ~2023 US $4/MWh$_e$.

5.10.3 Account 93: Cost of Money

Cost of money for operations is set to zero in our analysis. Since this is typically for the cost associated with borrowing money required to cover unanticipated operational expenses that an owner wouldn't be able to pay for during a particular year, such as fuel or something else required for the operation of the other equipment, we neglect this account and do not assign any cost amount to it.

5.10.4 Account 99: Contingency on Annualized Financial Costs

A 20% contingency is allocated for annualized financial costs.

5.11 Levelized Cost of Electricity

We compute the LCOE by totaling the levelized annual capital, O&M, fuel, and decommissioning costs. We calculate the levelized annual capital cost as the full principal repayment for the TCIC (Accounts 10 through 60) including interest at a 5% discount rate compounded annually over the life of the plant which we assume to be nominally 60 years. This annual capital repayment including interest is put on a $/MWh$_e$ basis to report as the electricity cost. Since we provide the cost for decommissioning as a separate electricity cost contributor, money initially borrowed to seed the decommissioning fund including its corresponding contingency amount are deducted from the TCIC but not the interest in loan repayment that would accrue for this amount. Annualized O&M costs that we estimate for Account 70 are reported directly as the O&M item in the LCOE breakdown, also reported on a $/MWh$_e$ basis. Direct reporting of the refueling costs estimated for Account 80 is similarly done to set this item in the LCOE breakdown.

GIF recommends examining both 5% and 10% real discount rates. Discount rates at 5% are suggested for plants operating as a more traditional "regulated utility" while those at 10% are for riskier "deregulated" or "merchant plant" environments. A 5% discount rate is selected for our cost estimate, but at a 10% discount rate annualized financing costs for the TCIC more than double. The discount rate for a project will likely be influenced by many factors including but not limited to government-backed guarantees, so the contribution of the financing repayment may differ substantially from our estimate for another case. As the annualized capital repayment costs dominate the LCOE, specific project-by-project considerations are needed for setting the most appropriate discount rate.

6. COMPARISON OF OTHER COST RESULTS & SCENARIOS

6.1 Baseline Comparison to the Energy Economic Database (EEDB)

The estimated costs we present in the previous section are for the baseline and different scales of the SFR NPP we define. Common sense and typical practice suggest that comparison of this estimate should be done to estimates devised for similar types of plants and technologies to ensure a uniform basis of comparison. Using this type of comparison basis also enables quantifying the impact of specific design differences and changes. Unfortunately, there are limited SFR cost estimates currently published that can be used to compare our results with, and none that we know of using our specific approach. Consequently, to provide an ROM validation of our SFR cost results, we compare these to an LWR NPP cost estimate for a similar electrical power output. Specifically, in Table 90 cost results for our nuclear BOAK SFR design case that utilizes four 311 MW$_e$ reactors (1,243 MW$_e$) are given with the four-loop PWR12-BE plant (1,144 MW$_e$). The PWR12-BE cost estimate is from the final installment of the EEDB program report and was further scrutinized and compared by ORNL in a later analysis of an advanced high-temperature reactor (AHTR) design case.[79]

[79] Holcomb, D. E.; Peretz, F. J.; Qualls, A. L. Advanced High Temperature Reactor Systems and Economic Analysis. *Oak Ridge National Laboratory Status Report* **September 2011**, *ORNL/TM-2011/364*. *https://info.ornl.gov/sites/publications/files/Pub32466.pdf.*

Table 90. Comparison of estimated costs for Accounts 10 through 60 of the between first-of-a-kind and N[th]-of-a-kind (BOAK) baseline sodium-cooled fast reactor versus those reported in the final version of the Energy Economic Database (EEDB) for the pressurized water reactor12 (PWR12) better experience (BE) cost estimate.

	Parameter	UOM	SFR (This Analysis)	PWR12-BE (EEDB)
	Plant Nominal Power	MW_e	1,243	1,144
Account	**Title**			
10	**Capitalized Pre-Construction Costs**			
11	Land & Land Rights	2023 US $/kW$_e$	9	7
12	Site Permits	2023 US $/kW$_e$	3	
13	Plant Licensing	2023 US $/kW$_e$	78	
14	Plant Permits	2023 US $/kW$_e$	10	
15	Plant Studies	2023 US $/kW$_e$	10	
16	Plant Reports	2023 US $/kW$_e$	10	
17	Other Pre-Construction Costs	2023 US $/kW$_e$	13	
18	Community Outreach & Education	2023 US $/kW$_e$	Not Included	
19	Contingency on Pre-Construction Costs	2023 US $/kW$_e$	26	
-	**Subtotal**	**2023 US $/kW$_e$**	**157**	**7**
20	**Capitalized Direct Costs**			
21	Structures & Improvements	2023 US $/kW$_e$	217	586
22	Reactor System	2023 US $/kW$_e$	460	865
23	Energy Conversion System	2023 US $/kW$_e$	551	638
24	Electrical Equipment	2023 US $/kW$_e$	229	232
25	Heat Rejection System	2023 US $/kW$_e$	79	140
26	Miscellaneous Equipment	2023 US $/kW$_e$	127	133
27	Special Materials	2023 US $/kW$_e$	0	
28	Simulator	2023 US $/kW$_e$	0	
29	Contingency on Direct Costs	2023 US $/kW$_e$	333	
-	**Subtotal**	**2023 US $/kW$_e$**	**1,995**	**2,594**
30	**Capitalized Indirect Services Costs**			
31	Factory & Field Indirect Costs	2023 US $/kW$_e$	501	682
32	Factory & Construction Supervision	2023 US $/kW$_e$	0	227
33	Commissioning & Start-Up Costs	2023 US $/kW$_e$	31	32
34	Demonstration Test Run	2023 US $/kW$_e$	0	
35	Design Services Offsite	2023 US $/kW$_e$	293	573
36	PM/CM Services Offsite	2023 US $/kW$_e$	32	34
37	Design Services Onsite	2023 US $/kW$_e$	0	
38	PM/CM Services Onsite	2023 US $/kW$_e$	78	24
39	Contingency on Indirect Services Cost	2023 US $/kW$_e$	187	
-	**Subtotal**	**2023 US $/kW$_e$**	**1,123**	**1,572**
40	**Capitalized Owner's Costs**			
41	Staff Recruitment & Training	2023 US $/kW$_e$	136	
42	Staff Housing	2023 US $/kW$_e$	10	
43	Staff Salary-Related Costs	2023 US $/kW$_e$	72	
44	Other Owner's Costs	2023 US $/kW$_e$	0	
49	Contingency on Owner's Costs	2023 US $/kW$_e$	44	
-	**Subtotal**	**2023 US $/kW$_e$**	**262**	**357**
50	**Capitalized Supplementary Costs**			
51	Shipping & Transportation Costs	2023 US $/kW$_e$	29	
52	Spare Parts	2023 US $/kW$_e$	22	
53	Taxes	2023 US $/kW$_e$	11	
54	Insurance	2023 US $/kW$_e$	33	
55	Initial Fuel Core Load	2023 US $/kW$_e$	900	160
58	Decommissioning	2023 US $/kW$_e$	15	
59	Contingency on Supplementary Costs	2023 US $/kW$_e$	202	
-	**Subtotal**	**2023 US $/kW$_e$**	**1,211**	**160**

	Parameter	UOM	SFR (This Analysis)	PWR12-BE (EEDB)
60	**Capitalized Financial Costs**			
61	Escalation	2023 US $/kW$_e$	0	
62	Fees	2023 US $/kW$_e$	0	
63	Interest	2023 US $/kW$_e$	759	779
69	Contingency on Financial Costs	2023 US $/kW$_e$	152	
-	**Subtotal**	**2023 US $/kW$_e$**	**911**	**779**
	Total Overnight Cost (Accounts 10 to 50)	**2023 US $/kW$_e$**	**4,748**	**4,691**
	Total Capital Investment Cost (Accounts 10 to 60)	**2023 US $/kW$_e$**	**5,659**	**5,469**

When comparing the SFR cost estimate with the PWR12-BE data some important differences are noted:

- The SFR initial fuel core load (Account 55) is over 2023 US $700/kW$_e$ larger than the PWR12-BE case. SFR fuel is estimated with 19.75% enriched fuel whereas PWR uses 5% enriched fuel. The feed-to-product ratio for these two enrichment levels is 2.6 and 10.6%, respectively. Additionally, higher enrichment also requires 5–10 times more processing. A combination of greater quantities of feed material and additional processing directionally results in a more expensive fuel.
- Contingency is built into every category of SFR costs and sums to over 2023 US $1,100/kW$_e$. Contingency can be reduced for the SFR estimate as more detailed and accurate designs and data become available.
- Costs for the SFR equipment included in Account 22, are estimated to be lower than the same corresponding equipment accounts of the PWR12-BE estimate. However, direct cost comparison is complicated by the difference in reactor service and size. While the PWR12-BE reactor is used in a more chemically corrosive environment, the SFR is operated at a much higher temperature but in a nearly non-chemically corrosive fluid. Such differences manifest possibly from different materials being used in one case compared to the other for analogous parts built to different construction requirements and tolerances such as different thicknesses. Furthermore, the SFR is composed of four 311 MW$_e$ reactors while the PWR12-BE case is a four-loop single 1,144 MW$_e$ reactor. As such, different reactor complexity and generational improvements in fabrication techniques/efficiencies may be able to explain this difference we observe. Additionally, uncaptured or underestimated cost elements and details could also contribute to the difference between these two cases. Future investigation is needed to validate our cost results and to understand the driving aspects of this difference.
- Building and improvements (Account 21) are over 2023 US $300/kW$_e$ larger for the PWR case. A portion of the discrepancy is attributed to differences in assigning costs to different accounts (i.e., a 2023 US $59/kW$_e$ reactor containment liner is included in Account 22 for the SFR but this is included in Account 212 for PWR12-BE). The bulk of the difference is attributed to a few buildings which are discussed in more detail below.
- Factory and field indirect, factory and construction supervision, and onsite PM/CM costs (Accounts 31, 32, and 38, respectively) are over 2023 US $100kW$_e$ greater for the PWR12-BE case. These three accounts are considered together because of the potential inconsistency between methods of assigning costs to accounts with overlap of main office expense, field supervision, and indirect overhead. The largest component of the PWR12-BE cost for these accounts is attributed to temporary buildings and facilities. For SFR, the costs were built up from construction data in RSMeans. Given NPP's history of long construction periods, our estimate may underestimate this cost, but there may also be appreciable room for general contractors to significantly improve NPP direct costs.

- The offsite design services (Account 35) is over 2023 US \$250/kW_e more expensive for the PWR12-BE case. With the SFR case having smaller reactors and being more modular, it is reasonable that SFR offsite design services would be lower.
- Estimates for shipping/transportation costs and decommissioning at about 2023 US \$50/kW_e are included for the SFR case, but not in the PWR12-BE case, thus accounting partially for the difference in TOC and TCIC.
- The energy conversion system for the PWR12-BE case is more than 2023 US \$75/kW_e greater and likely within the bounds of typical equipment size scaling for the different size turbines.
- The heat rejection system is over 2023 US \$60/kW_e greater in the PWR12-BE case. This was not expected to be substantially different between the SFR and PWR12-BE cases.
- The interest during construction (Account 63) is slightly larger for the PWR12-BE case owing to the higher costs and longer construction timeline (5.7-years for our SFR vs. 6-years for the PWR12-BE).
- The capitalized owner's costs, Account 40, is about 2023 US \$100/kW_e greater for the PWR12-BE case. The PWR12-BE case doesn't have a breakdown of Accounts 41–49, but the general difference is likely related to the expected headcount. This SFR case is estimated to have total staffing of 0.4 employees/MW_e, slightly higher than the 0.3 employees per MW_e in the S-PRISM reference case, and likely lower than the PWR12-BE case.

As mentioned previously, the estimate for structures and improvements, Account 21, varied over 2023 US \$300/kW_e between the estimate for SFR and the PWR12-BE reference. The subaccounts for Account 21 are each of the structures and improvements that provide more detail for examination (Table 91).

Table 91. Comparison of estimated costs for Account 21 of the between first-of-a-kind and Nth-of-a-kind (BOAK) baseline sodium-cooled fast reactor structure and improvement components versus those reported in the final version of the Energy Economic Database (EEDB) for the pressurized water reactor12 (PWR12) better experience (BE) cost estimate.

	Parameter	UOM	SFR (This Analysis)	PWR12-BE (EEDB)
	Plant Nominal Power	MW_e	1,243	1,144
Account	**Title**			
21	**Structures and Improvements**			
211	Site Preparation & Yard Work	2023 US \$/kW_e	34	71
212	Reactor Island Civil Structures	2023 US \$/kW_e	56	198
213	Energy Conversion Building	2023 US \$/kW_e	46	66
214	Security Building & Gatehouse	2023 US \$/kW_e	1	4
215	Reactor Service Buildings	2023 US \$/kW_e	3	53
216	Radwaste Building	2023 US \$/kW_e	16	41
217	Fuel Service Building	2023 US \$/kW_e	14	28
218A	Control Building	2023 US \$/kW_e	9	52
218B	Administration Building	2023 US \$/kW_e	6	19
218C	Operation & Maintenance (O&M) Center	2023 US \$/kW_e	1	N/A
218E	Storage Buildings	2023 US \$/kW_e	3	7
218K	Pipe Tunnels	2023 US \$/kW_e	1	1
218L	Electrical Tunnels	2023 US \$/kW_e	2	0
218N	Maintenance Shop	2023 US \$/kW_e	3	N/A
218Q	Foundations for Outside Equipment & Tanks	2023 US \$/kW_e	1	N/A
218R	Balance of Plant (BOP) Service Building	2023 US \$/kW_e	3	N/A
218S	Wastewater Treatment Building	2023 US \$/kW_e	2	2
218T	Emergency & Start-Up Power Systems	2023 US \$/kW_e	1	N/A
218W	Warehouse	2023 US \$/kW_e	3	N/A
218X	Railroad Tracks	2023 US \$/kW_e	5	N/A
218Y	Roads & Paved Areas	2023 US \$/kW_e	4	N/A
218Z	Reactor Receiving & Assembly Building	2023 US \$/kW_e	2	N/A

	Parameter	UOM	SFR (This Analysis)	PWR12-BE (EEDB)
219A	Training Center	2023 US $/kW$_e$	1	2
219K	Special Materials Unloading Facility	2023 US $/kW$_e$	1	N/A
	Fire Pump House	2023 US $/kW$_e$	N/A	1
	Emergency Feed Pump Building	2023 US $/kW$_e$	N/A	7
	Manway Tunnels	2023 US $/kW$_e$	N/A	2
	Non-Essential Switchgear Building	2023 US $/kW$_e$	N/A	2
	Main Steam & Feedwater Pipe Enclosure	2023 US $/kW$_e$	N/A	22
	Containment Equipment Hatch & Missile Shield	2023 US $/kW$_e$	N/A	1
	Control Room Emergency Air Intake Structure	2023 US $/kW$_e$	N/A	0
	Subtotal	**2023 US $/kW$_e$**	**217**	**586**

When examining the SFR structure and improvement cost estimates with the PWR12-BE reference data, some important differences are noted:

- The 2023 US $37/kW$_e$ difference for site preparation and yard work can be ascribed to the difference in allocation methods between the two cases. For the SFR NPP, the structure-associated excavation is tabulated with the structure, whereas in the PWR12-BE case, 2023 US $34/kW$_e$ of structure-associated excavation is captured in the site preparation and yard work account.
- The 2023 US $142kW$_e$ difference in reactor building (Account 212) can partially be accounted for with assignment of the containment liner (i.e., the containment liner is included in Account 22 for the SFR and 2023 US $59/kW$_e$ is captured in Account 212 for PWR12-BE). A special HVAC cost of 2023 US $5/kW$_e$ is not included in our estimate. Otherwise, other construction categories are generally accounted for, including expensive epoxy coatings, and proportional.
- One of the starkest differences is in the reactor service building cost (Account 215) at 2023 US $50/kW$_e$. In the case of the SFR estimate, Account 215 captures a high bay shop area. The associated building in the PWR12-BE case is unknown but is the fourth most expensive building. A more massive and expensive building may be necessary but is unknown to the authors at this time.
- The radwaste and fuel service buildings (Accounts 216 and 217) are roughly half of their counterparts in the PWR case. Directionally, the SFR is expected to consume less fuel and produce less waste which may justify the lower cost estimates based on smaller buildings.
- The SFR case is estimated with a combined control and administration building (Accounts 218A and 218B) that differs over 2023 US $50/kW$_e$ from the PWR12-BE case. The SFR building has 54,770 ft^2 of combined space at a total building cost of $20 million. The area-unit cost of 2023 US $370/ft^2 seems adequate based on the generic building design specifications. The PWR12-BE case captures an additional special HVAC that accounts for 2023 US $11kW$_e$ that the SFR estimate does not have, but it leaves 2023 US $40/kW$_e$ unaccounted for which may be attributed to more condensed controls, increased offsite staff, and other differences between designs.
- Several buildings are excluded from either estimate. In total, the additional buildings and improvements are less than 2023 US $10/kW$_e$ different between the SFR and PWR12-BE cases.

6.2 Comparison of Nuclear & Non-Nuclear Design & Construction Scenarios

Building an NPP has increased regulatory and quality assurance requirements compared to other non-nuclear power generation technologies. The methods established for this project are flexible enough so that differences in nuclear design, fabrication, construction, business, and regulatory costs can be adjusted or removed to quantify the impact (Table 92). Importantly, nuclear grade escalation (see Section 4.1.2.2) does not refer to altering safety systems, using different materials, or doing other design work, but is intended to capture the inherent added cost of regulatory and quality assurance that goes above and beyond sound non-nuclear construction practices. Increases for subcontractor overhead and profit, materials, labor, and additional security screening carry through the compilation of construction tasks and substantially increase the costs of the buildings and nuclear reactor (Accounts 21 and 22, respectively). Indirectly, the costs cascade through indirect costs as some estimations rely substantially on direct costs. The impact on field indirect construction supervision, offsite design services, and onsite management services (Accounts 31, 35, and 38, respectively) is mitigated partially as these costs are calculated based on total direct costs rather than only the accounts with nuclear grade markup. Although the percentage of markup on direct costs does not change substantially, the magnitude of cost is different and accounts for the added regulatory and quality assurance escalation in indirect costs. Eliminating nuclear escalation further cascades down to financing, affecting the capitalized and annualized financial costs. Adjusting the rates for nuclear escalation has no effect on pre-construction costs, owner's costs, supplementary costs, or O&M costs.

Table 92. Comparison of estimated costs for between first-of-a-kind and N^{th}-of-a-kind (BOAK) nuclear versus non-nuclear design and construction of the baseline sodium-cooled fast reactor.

	Parameter	**UOM**	**Nuclear (Escalation) Between First-of-a-Kind and N^{th}-of-a-Kind (BOAK)**	**Non-Nuclear (No Escalation) BOAK**
	Plant Nominal Power	MW_e	1,243	1,243
	Power Block Nominal Power	MW_e	622	622
	Reactor Nominal Power	MW_e	311	311
	Power Blocks/Plant	—	2	2
	Reactors/Plant	—	4	4
	Reactors/Power Block	—	2	2
Account	**Title**			
20	**Capitalized Direct Costs**			
21	Structures & Improvements	2023 US $/reactor	67,434,348	34,432,044
22	Reactor System	2023 US $/reactor	143,122,607	106,257,842
29	Contingency on Direct Costs	2023 US $/reactor	103,355,619	89,382,206
-	**Subtotal (for all of Account 20)**	**2023 US $/reactor**	**620,133,717**	**536,293,234**
		2023 US $/kW$_e$	**1,995**	**1,726**
30	**Capitalized Indirect Services Costs**			
31	Factory & Field Indirect Costs	2023 US $/reactor	155,777,590	107,902,199
35	Design Services Offsite	2023 US $/reactor	91,212,053	71,334,301
36	PM/CM Services Offsite	2023 US $/reactor	10,097,990	10,097,990
38	PM/CM Services Onsite	2023 US $/reactor	24,185,215	20,915,436
39	Contingency on Indirect Services Cost	2023 US $/reactor	58,171,410	43,966,826
-	**Subtotal (for all of Account 30)**	**2023 US $/reactor**	**349,028,460**	**263,800,953**
		2023 US $/kW$_e$	**1,123**	**849**
60	**Capitalized Financial Costs**			
63	Interest	2023 US $/reactor	235,947,542	170,411,100
69	Contingency on Financial Costs	2023 US $/reactor	47,189,508	34,082,220
-	**Subtotal (for all of Account 60)**	**2023 US $/reactor**	**283,137,050**	**204,493,320**
		2023 US $/kW$_e$	**911**	**658**
	Total Overnight Cost (Accounts 10 to 50)	**2023 US $/reactor**	**1,475,658,276**	**1,303,198,916**
		2023 US $/kW$_e$	**4,748**	**4,193**
	Total Capital Investment Cost (Accounts 10 to 60)	**2023 US $/reactor**	**1,758,795,326**	**1,507,692,236**
		2023 US $/kW$_e$	**5,659**	**4,851**

Removing nuclear escalation primarily impacts costs in accounts that have components designed and constructed to nuclear safety grade and rated standards. These accounts consist of Structures and

Improvements (Account 21) and the Reactor System (Account 22), and de-escalation produces about 50% of the cost reduction (~2023 US $225/kW$_e$ for our BOAK cases). As described above, the cost impact cascades down through many accounts and results in a 15% reduction in NPP TCIC or about 2023 US $808/kW$_e$ for our BOAK cases. While these cost savings are not currently obtainable within the current regulatory framework, even partial improvements in streamlining and minimizing unnecessary regulation can have an immense impact on making nuclear power more cost competitive.

6.3 Comparison of FOAK & NOAK Costs

Figure 5 graphically compares NPP TOC for the nuclear design and construction FOAK and NOAK scenarios including our baseline BOAK nuclear and non-nuclear grade cases. Consistent with our other reported costs, the lowest-power NPP utilizes a single 165 MW$_e$ reactor, whereas all other NPP cases utilize multiple 311 MW$_e$ reactors in modular groupings of 1–10. We find that BOAK non-nuclear design and construction under our markup and contingency assumptions is ~12–15% less costly than BOAK nuclear design and construction. As expected, cost results for the BOAK nuclear safety grade are bracketed by those for the nuclear FOAK and NOAK. The nuclear FOAK is ~30% higher than the nuclear BOAK for all cases examined, driven largely by the substantial increase in time of construction assumed in our analysis. The nuclear NOAK is ~20% lower than the BOAK nuclear baseline case, which, interestingly, is also projected lower in cost than the non-nuclear BOAK scenario. However, were the non-nuclear BOAK scenario devised to also incorporate NOAK aspects, it would most likely be much lower in cost than the nuclear NOAK case.

Economies of physical scale lead to a pronounced and sudden decrease in the TOC for all costing scenarios. This is seen in the difference between the two leftmost points of Figure 5 and is a result of the reactor and power block size increase from 165 MW$_e$ to 311 MW$_e$. For all larger plant sizes that rely on the 311 MW$_e$ reactor size (all points beyond 500 MW$_e$ plant electrical output power), the rate of cost decrease for every cost scenario appears to be about the same with each curve almost mirroring one another in a parallel fashion and these leveling off at a plant size of around 1 GW$_e$. This is indicative of a similar change in cost impact from an economy of manufacturing scale for each costing scenario. The magnitude of this cost decrease with increasing reactor and power block count is also less than that observed for a similar magnitude increase in reactor and power block size (comparing the change resulting between the first two points to the other points corresponding to larger plant sizes) indicating that the impact from the economy of physical size outweighs that from the economy of manufacturing scale in this reactor size and power level. Such a cost impact difference is because of the relatively low discount-like cost reduction we incorporate for BOP equipment included in the power blocks.

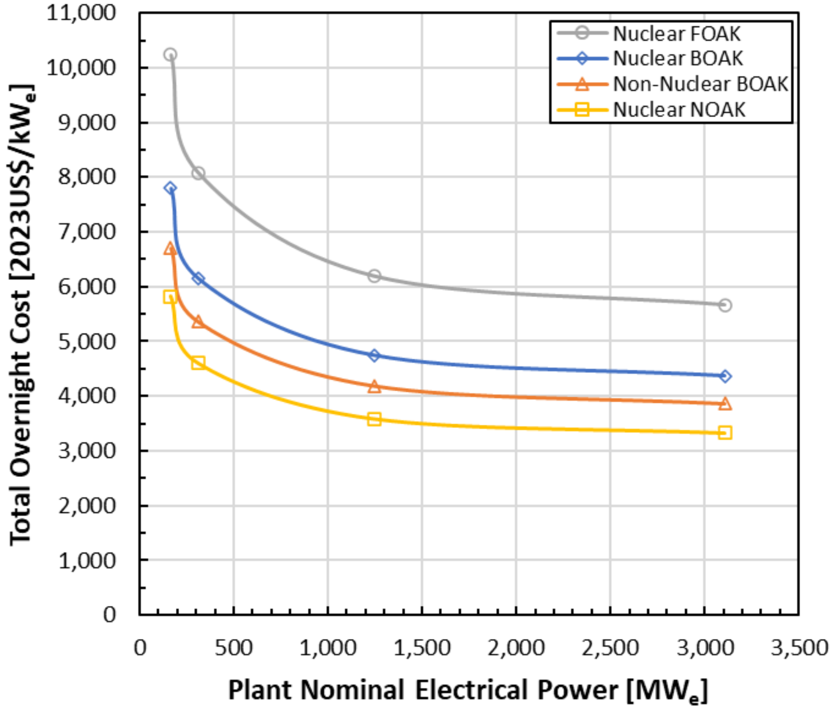

Figure 5. Comparison of the total overnight cost for four scenarios: non-nuclear between first-of-a-kind (FOAK) and Nth-of-a-kind (NOAK) or BOAK, nuclear BOAK, nuclear FOAK, and nuclear NOAK.

6.4 Cost Dependence on Reactor Size

TOC results are calculated for a range of equivalent reactor electrical power levels (165 to 311 MW_e) and NPP output electrical power levels (165 MW_e to 3.1 GW_e, corresponding to NPPs with 1–10 reactors, respectively) for the nuclear BOAK cost case and provided in Figure 6. Trends in these results indicate that, as previously noted, the TOC decreases with NPP power and increasing reactor size even for the same NPP power. This suggests that cost optimal SFR plants are expected for the largest plant size having maximally sized reactors. However, optimal reactor size will be determined by additional factors such as transportability, constructability, operability, and maintainability. Even though these results are specifically for our BOAK nuclear grade baseline scenario, behavior of the results for nuclear FOAK, nuclear NOAK, and a non-nuclear BOAK are expected to follow the same trends. Consequently, there is a much more pronounced cost reduction by adding groups of reactors to increase the plant power level than there is by increasing reactor power level. This decrease in cost is due to an economy of scale effect from BOP equipment and is consistent with the results from the previous section. In summary, cost is primarily minimized by increasing NPP power, and secondarily minimized by higher reactor power.

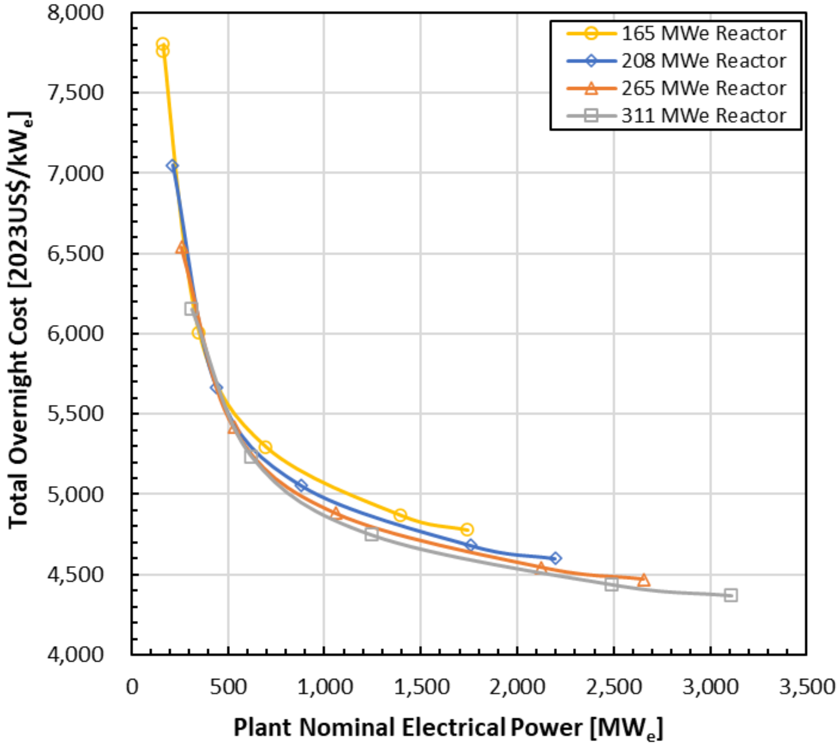

Figure 6. Total overnight cost dependence on reactor and facility power for the between first-of-a-kind and Nth-of-a-kind (BOAK) nuclear scenario included in Figure 5.

7. COST REDUCTION STRATEGIES & PATHWAYS

The focus of the analysis to date has been on development of a flexible cost model and its application to advanced SFR NPPs. Yet through this work, some cost reduction strategies have been preliminarily identified, although further work is needed to verify their reasonableness and feasibility. These potential cost reduction pathways include:

1. **Plant Simplification** – The NPP is a sprawling and complex engineered system. Design steps to simplify subsystems or eliminate parts, features, or components in their entirety are needed to achieve significant cost reduction. Subsystem components such as the steam generator and steam turbine generator are already mature products unlikely to be greatly improved beyond their current status. Thus, plant simplification may best be achieved by focusing on the reactor module, simplification of building designs, and the layout/connections between buildings.
2. **Increased Modularity** – Much has been written about SMRs and their cost reduction potential through lower plant design cost, factory-built components, and faster construction times. Our flexible model offers an opportunity to further analyze these effects.
3. **Reduced Re-Work** – Our analysis does not explicitly explore the cost impact of re-work other than through imposing different levels of contingency factors to each cost level when examining the non-nuclear BOAK and nuclear BOAK, FOAK, and NOAK scenarios. Re-work may lead to significant cost and plant construction time overruns which is a primary occurrence for the FOAK scenario.

4. **Reduced Nuclear Escalation Factors** – The cost of nuclear grade construction materials and labor has been previously estimated at 50% and 130%, respectively, due to more stringent requirements, record-keeping/tracking expenses, low quantity purchases, and, in the case of labor, a limited supply of highly-skilled tradesmen with nuclear certifications. A combination of expanding the labor pool, increasing the material supply, and design changes that limit the need for high-tolerance/unique fabrication, may be able to achieve significant cost reduction.
5. **Reduced Fuel Costs** – Cost of the initial fuel core load at ~$900/kW$_e$ is a significant fraction of the TOC. This cost is largely driven by raw uranium mining and the two-stage separation approach to achieve 19.75% ^{235}U enrichment. Better fuel management strategies that can reduce fissile inventory needs would go a long way to alleviating these costs. Additionally, this elevated cost may highlight the potential economic benefit of reprocessing spent nuclear fuels produced in other reactors.
6. **Increased Reactor Size** – While only considered briefly, TOC decreases for higher power reactors. A modest and steady reduction in cost is observed moving from 165 MW$_e$ sized reactors towards 311 MW$_e$ reactors. The practical upper limit of reactor power that also ensures consistency with our core assumptions of SM SFRs is not understood fully from our study. Additionally, there are many ways to scale the reactor core and containment vessel and the optimal manner has not been identified yet in our analysis.
7. **Larger Plants** – This analysis, which only examines two reactor power levels, suggests that TOC decreases with increasing plant power primarily due to scaling of the non-nuclear BOP equipment costs. This is due to the choice of scaling employed on both the reactor and the BOP components. Much depends on how the reactor core, vessel, and BOP equipment scale with increasing power. A tradeoff analysis will balance many parameters and is worthy of in-depth study.
8. **Improved System Thermal-to-Electrical Conversion Efficiency** – The energy conversion subsystem is estimated to cost ~2023 US $500 to 2023 US $700/kW$_e$ and yields a plant cost reduction of ~2023 US $100/kW$_e$ for a 1 percentage point improvement in conversion efficiency (based on the 37% baseline efficiency for >=311 MW$_e$ plants). While this somewhat obvious strategy is not readily achieved through technology improvement and redesign, higher operating temperatures, bottoming cycles, or other advanced cycles may be worth higher subsystem capital costs which are offset by the increased operating efficiency.
9. **Shift to Factory-Built Paradigm** – Fabrication and assembly costs are reduced when components are built in a controlled interior environment rather than outside and in the field. They are further reduced when fabricated at high manufacturing rates that allow for high machine utilization and thus superior amortization of machine capital cost. Business structures that maximize factory fabrication and achieve high machine utilization, either through a high number of NPP orders or other machinery uses and increased labor pool diversity for NPP component fabrication, will achieve lower costs.

As stated above, these are preliminary cost reduction observations based primarily on our findings and considerations of the behavior of the TOC with changing plant design and configuration. Additional study is needed to validate and expand on these ideas as well as explore the sensitivity in the TCIC and LCOE.

8. CONCLUSIONS & FUTURE WORK

Detailed first-principles cost estimates are performed to determine the total overnight cost (TOC) of a general sodium-cooled fast reactor (SFR) nuclear power plant (NPP) composed of several parallel 165 MW_e and 311 MW_e sized reactors with supporting thermal management and conversion equipment. The cost estimate for this system represents a between a first-of-a-kind (FOAK) and N^{th}-of-a-kind (NOAK) or BOAK type technology maturity cost estimate. We employ design for manufacture and assembly® (DFMA®) as the primary first-principles method for accurately enumerating and estimating costs for critical plant components. While DFMA® is widely known as a highly versatile and reliable method for cost estimation and design optimization of small parts and equipment items manufactured at massive scales and rapid rates of production, its use in cost estimation of large-scale nuclear reactor components and associated balance of plant (BOP) equipment has not been employed in the same way as this study. Through our analysis, we find that application of DFMA® allows for the development of flexible cost models that can apply to highly diverse and different equipment items. We further augment our bottom-up approaches by use of industry-accepted cost data and correlations to enhance the fidelity and flexibility of their cost coverage. In doing this, we develop the capability for our models to estimate non-nuclear versus nuclear design and construction costs which can be analyzed to understand areas of the plant that experience the greatest financial impacts associated with satisfying nuclear quality requirements.

We present the full costs of our generalized plants through the organization and categorization of the nuclear code of accounts (COA) recently devised by Idaho National Laboratory (INL). In addition to the TOC, we also determine capitalized financing costs to extend our TOC calculation to capture the plant total capital investment cost (TCIC). In comparing the TCIC for plants with different numbers of reactors, there is an observed decrease in the power levelized cost by about 2023 US $4,000/kW_e$ or roughly half of the total we estimate for a single reactor and power block plant. While the main goal of our analysis was to estimate the TOC with extension to the TCIC, we also compute a preliminary estimate of the annualized costs for the other remaining major accounts to determine approximate total annualized costs. From our initial assessment of these preliminary total annualized costs, we find that the scaling of operations and maintenance (O&M) staff and O&M-associated structures on a per reactor basis provides a direct cost savings incentive for larger reactors.

Comparison of our SFR NPP cost results to the pressurized water reactor 12 (PWR12) better experience (BE) estimate in the final report of the energy economic database (EEDB) program allows us to benchmark these against other past cost estimates. These comparisons reveal various cost differences between these two technologies due to their inherent technical differences as well as areas of discrepancy due to the lack of cost assignment for the PWR12-BE results or missing costs that we do not capture in our SFR analysis. We further evaluate costs of our BOAK nuclear concept and estimated costs for a hypothetical non-nuclear BOAK SFR NPP. From this we see the large burdening that nuclear requirements impose of plant costs. SFR NPP FOAK and NOAK nuclear costs are also computed and compared to the nuclear and non-nuclear BOAK costs to demonstrate the level of cost difference with technology maturity. We find that FOAK nuclear is the costliest option due to the inherent assumptions about longer plant development and construction times and having the highest applied contingencies to capture higher project unknowns. NOAK nuclear produces the lowest costs even (slightly) lower than the non-nuclear BOAK case where nuclear BOAK, by definition, falls between the FOAK and NOAK. All costs for all levels of technology maturity are observed to follow similar trends where these level off around plant sizes of ~1 GW_e.

From our analysis we propose several areas for potential cost reduction of SFR NPPs. In order to achieve the same cost level as that for other renewable resources that offer power availabilities comparable to nuclear (e.g., solar capture with diurnal energy storage), multiple plant design, construction, and configurational changes are required to achieve adequate cost reduction. Namely, reduced SFR fuel costs, increased reactor size, larger SFR plants, improved overall system thermal-to-electrical conversion efficiency, and shift to more of a factory-built paradigm is the main cost reduction pathway that could lead to nuclear electricity pricing matching or exceeding that of other renewables. Additional analysis to quantitatively determine the level of cost reduction from each of these strategies and their cumulative effect must be undertaken.

Even though our methodologies and cost models devised through them provide high flexibility over wide-ranging components, we observe limitations in a few instances of our results. The design basis for the reactor, site, and structures was taken from open-access literature with limited detail for a nine-reactor configuration and augmented by the authors' experience and judgment. Therefore, results should be viewed within the context of the documented assumptions and initial data. From a combination of the single-reactor and nine-reactor plant configurations, various scaling methodologies were applied to estimate basic geometric, size, and design parameters from which costs were estimated. As the configuration of the NPP deviates significantly from these design bases, the uncertainty of the estimate increases. Also, as the regulatory environment for the nuclear industry evolves and potentially becomes more inclusive of small modular reactor (SMR) and passive safety technologies, the applicability of some assumptions will require updating, such as the minimum number of operators required by the nuclear regulatory commission (NRC). While the required amount of maintenance personnel is significantly larger than that of the operations personnel, prevailing wage requirements of operations staff proposed from past analysis makes costs for these two staff functions comparable. Therefore, a more refined assessment of the proper number of operations and maintenance personnel within the plant is important to ensure the accuracy of our assumptions. Furthermore, updating such requirements may have profound effects on staffing-associated structures and their associated costs. Finally, results of our work can be used to highlight important and controllable costs for directing technology development.

Continued development, extension, and expansion of our methods and cost models to: (1) finalize and improve our estimates of other cost accounts that we did not focus on in this effort; (2) evaluate the extent of manufacturing rate impacts on cost savings; (3) explore in more detail the large nuclear fuel cost difference discovered between our results and typical fuel costs reported for more traditional light-water reactor (LWR) technologies; and (4) develop analogous cost estimations for other nuclear reactor technologies such as high-temperature gas-cooled reactors (HTGRs) will all be undertaken at a future point in time. Additionally, to better understand and identify the extent of reactor cost reduction that is expected with increasing reactor size and manufacturing rate, we will adapt and enhance the scaling relationships currently utilized in our cost models. Similarly, we will also explore the possible decrease in staffing and staffing-associated structure costs that we infer will occur for larger reactors. Furthermore, since most other accounts depend on the direct capital costs, reducing reactor and other associated equipment costs could have a drastic effect on the cost of these accounts. Since our nuclear fuel cost estimates are more than 2023 US $500/kW$_e$ greater than the typical fuel cost of LWRs, an in-depth review of our costing methodology will be conducted to provide further validation and understanding of the key differences and cost contributors. Lastly, we will use our current SFR cost modeling framework as a starting point to develop new cost models for other nuclear technologies which will facilitate quantification of the financial advantages of technology designs versus one another as well as provide cost guidance for engineers to use in optimizing technology and plant design.

Appendix A

PRISM Reference Drawings

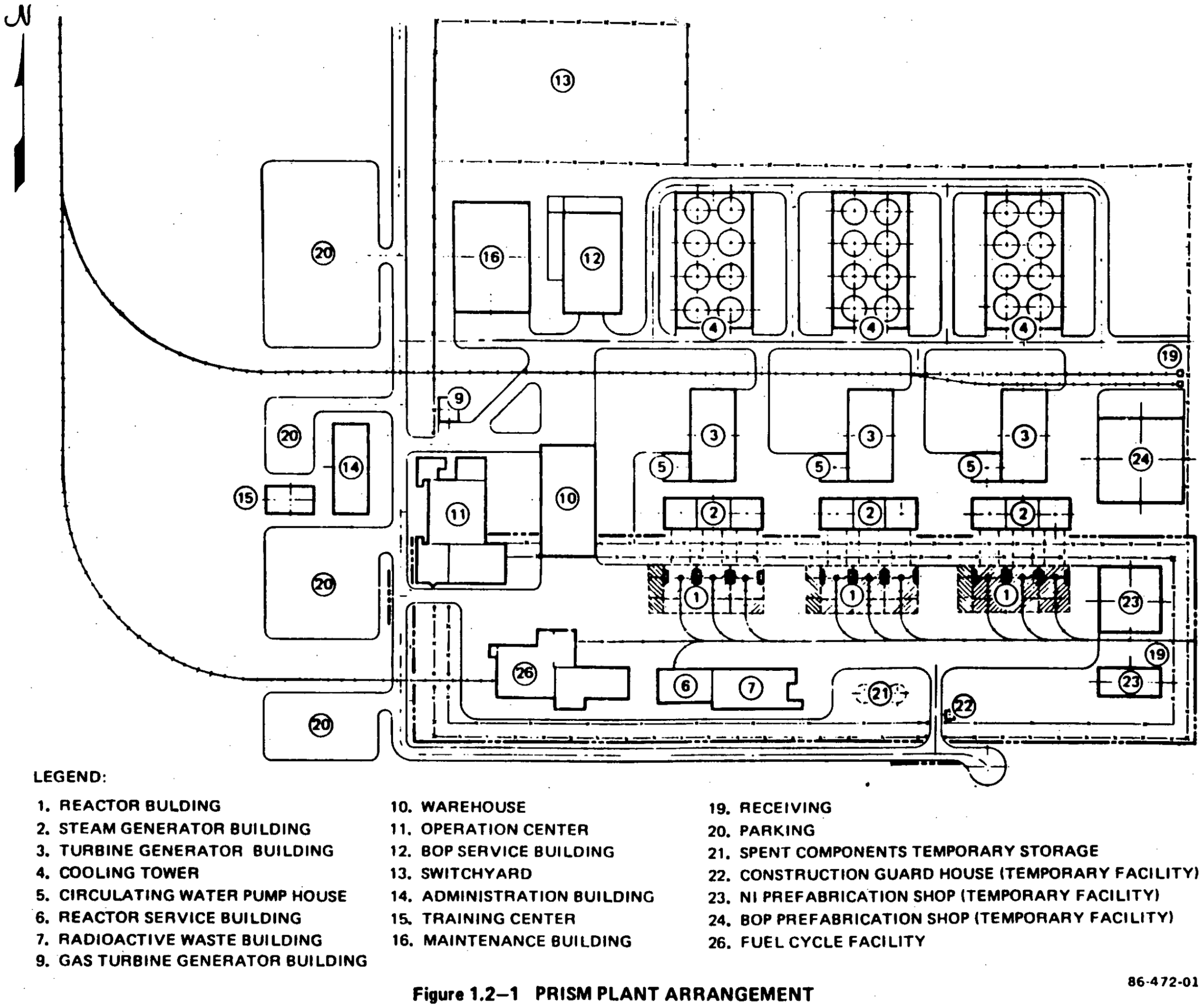

Figure A1. PRISM plant plot plan 1.[80]

[80] GE-Advanced Nuclear Technology. PRISM-Preliminary Safety Information Document. *US DOE* **1987**, *Vol. 1*, Ch. 1–4, *1.2-25. https://www.nrc.gov/docs/ML0828/ML082880369.pdf*

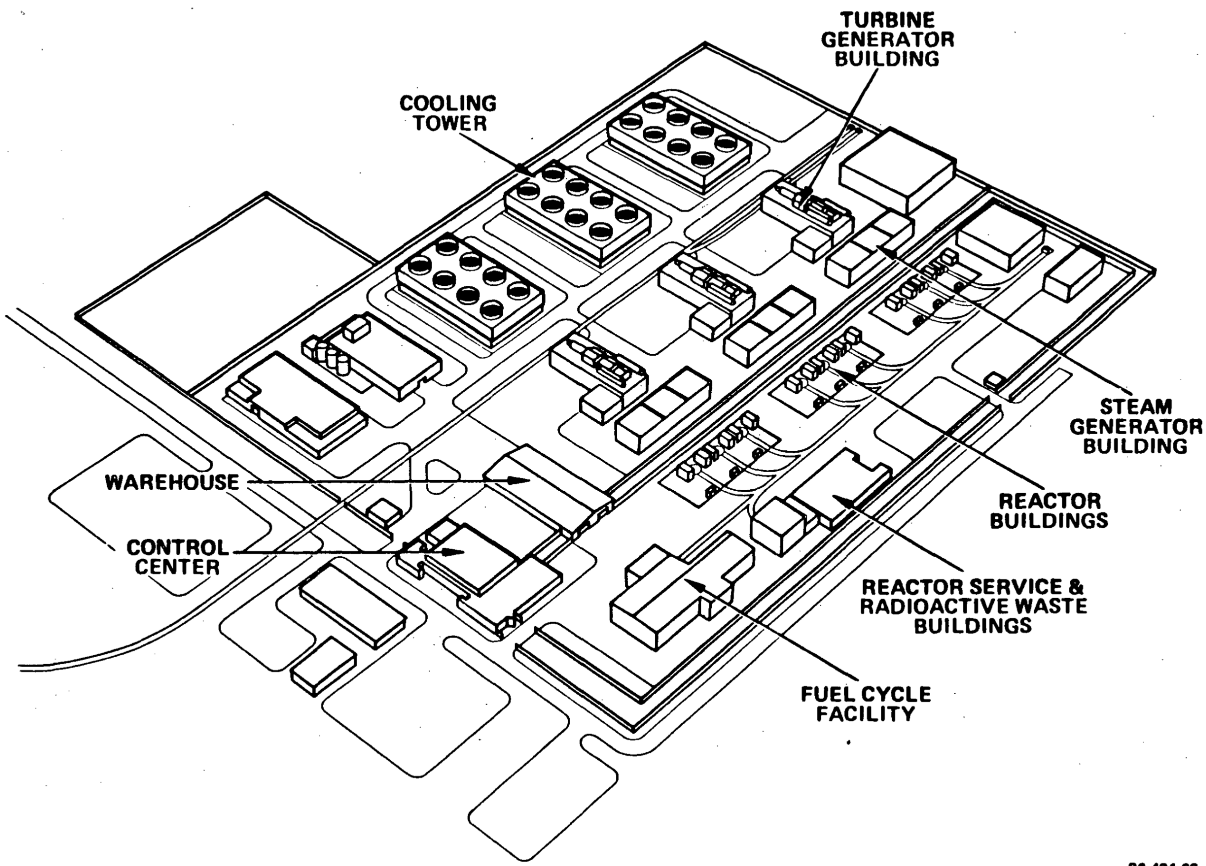

Figure 1.2–19 PRISM 1245 MWe POWER PLANT PERSPECTIVE

Figure A2. PRISM plant plot plan 2.[81]

[81] GE-Advanced Nuclear Technology. PRISM-Preliminary Safety Information Document. *US DOE* **1987**, *Vol. 1*, Ch. 1–4, *1.2-43*. *https://www.nrc.gov/docs/ML0828/ML082880369.pdf*

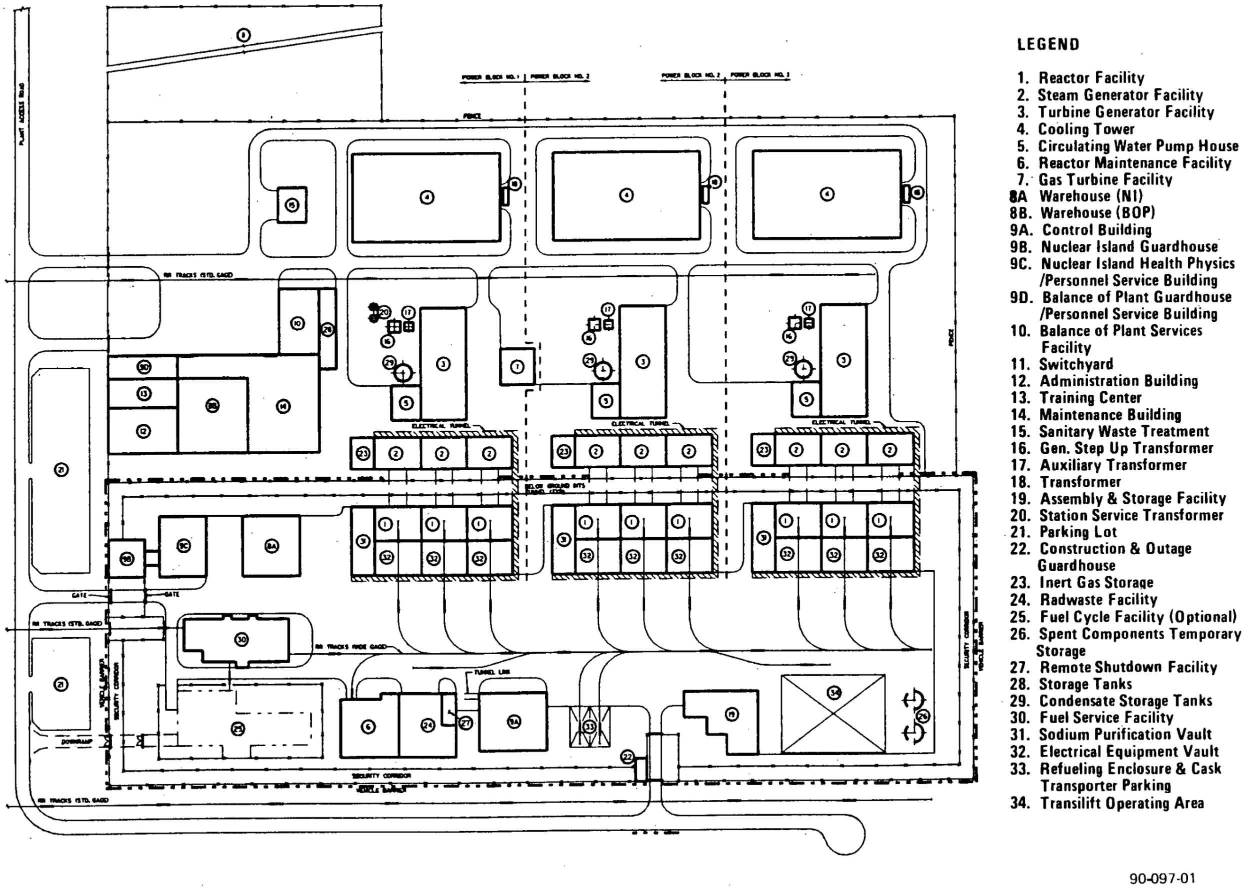

Figure G.4.14–1 ALMR PLANT PLOT PLAN

Figure A3. PRISM plant plot plan 3.[82]

[82] GE-Advanced Nuclear Technology. PRISM-Preliminary Safety Information Document. *US DOE-DE-ACO3-89SF17445* **1987 (1993)**, *Vol. 6*, App. G, *G.4.14-11. https://www.nrc.gov/docs/ML0828/ML082880400.pdf*