Woodruff Scientific, Inc

Revisit of the 2017 Costing for Four ARPA-E ALPHA Concepts
DE-AR001175

Award:	DE-AR001175
Sponsoring Agency	USDOE, Advanced Research Project Agency – Energy (ARPA-E)
Lead Recipient:	Woodruff Scientific
Project Team Members	Lucid Catalyst, Decisive Systems
Program Director:	Dr. Scott Hsu
Principal Investigator:	Dr. Simon Woodruff
Tech SETA:	Dr. Colleen Nehl
Date of Report:	10/19/2020

Acknowledgements

This work was performed in collaboration with Lucid Catalyst (Eric Ingersoll and Andrew Foss) and Decysive Systems (Ronald L. Miller). We acknowledge useful conversations with Laila El-Guebaly, Mark Tillack, Mike Zarnstoff, Dave Gates, Scott Hsu, and Malcolm Handley. We are indebted to the POCs at the four companies who carefully reviewed the material to provide input and constructive criticism: Peter J. Turchi, Brian Nelson, Samuel Langendorf, and Hafiz Rahman. We appreciated guidance and suggestions from Malcolm Handley and Scott Hsu. We are grateful to ARPA-E for supporting this work under contract no. DE-AR001175.

Executive Summary

This project re-examined the costing analysis performed for four ARPA-E ALPHA program concepts [1-3] in light of new reactor costing paradigms [4-5], addressing every assumption in the Cost Accounting Structure (CAS), and revisiting the analysis using the code developed for the four concepts, touching on most of the recommendations of the prior study and obtaining reviews by leading experts in the field [6-7]. The work was performed collaboratively between Woodruff Scientific, Lucid Catalyst, and Decysive Systems. The output from the short study is this public document, which presents averages of the four concepts and explanations for the assumptions and calculations given, and a new cost-sensitivity analysis. Proprietary documents were delivered to principal investigators of each of the four concepts. Primary findings of this cost analysis are that because of modular design, each concept can benefit from shorter construction times, cost savings due to centralized manufacturing (shipping complete subsystems), and lower total capital costs due to compactness. Relative to the prior costing analysis, Total Capital Costs have come down by nearly a factor of two, producing CapEx of ~2.4$/W and $1.2B, and an average Levelized Cost Of Electricity (LCOE) of 43 $/MWh for ~500-MWe power plants, with a range of 34–54 $/MWh for the four concepts.

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[1] *Conceptual Cost Study for a Fusion Power Plant Based on Four Technologies from the DOE ARPA-E ALPHA Program*, Bechtel National, Inc. Report No. 26029-000-30R-G01G-00001 (2017); http://woodruffscientific.com/pdf/ARPAE_Costing_Report_2017.pdf.

[2] S. Woodruff, J. K. Baerny, N. Mattor, D. Stoulil, R. L. Miller, T. Marston "Path to Market for Compact Modular Fusion Power Cores," J. Fusion Energy **31**, 305 (2012); https://doi.org/10.1007/s10894-011-9472-6.

[3] S. Woodruff, R. L. Miller, "Cost sensitivity analysis for a 100 MWe modular power plant and fusion neutron source," Fus. Eng. Design **90**, 7 (2015)); https://doi.org/10.1016/j.fusengdes.2014.09.020.

[4] *WHAT WILL ADVANCED NUCLEAR POWER PLANTS COST? A Standardized Cost Analysis of Advanced Nuclear Technologies in Commercial Development*, Energy Options Network (2017); https://www.innovationreform.org/wp-content/uploads/2018/01/Advanced-Nuclear-Reactors-Cost-Study.pdf.

[5] *The Future of Nuclear Energy in a Carbon-Constrained World*, *An Interdisciplinary MIT Study*, MIT Energy Initiative (2018); https://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf.

[6] L. El-Guebaly, L. Mynsberge, A. Davis, C. D'Angelo, A. Rowcliffe, B. Pint & ARIES-ACT, "Team Design and Evaluation of Nuclear System for ARIES-ACT2 Power Plant with DCLL Blanket," Fus. Sci. Tech. **72**, 17 (2017); https://doi.org/10.1080/15361055.2016.1273669.

[7] C.E. Kessel, J.P. Blanchard, A. Davis, L. El-Guebaly, L.M. Garrison, N.M. Ghoniem, P.W. Humrickhouse, Y. Huang, Y. Katoh, A. Khodak, E.P. Marriott, S. Malang, N.B. Morley, G.H. Neilson, J. Rapp, M.E. Rensink, T.D. Rognlien, A.F. Rowcliffe, S. Smolentsev, L.L. Snead, M.S. Tillack, P. Titus, L.M. Waganer, G.M. Wallace, S.J. Wukitch, A. Ying, K. Young, Y. Zhai, "Overview of the fusion nuclear science facility, a credible break-in step on the path to fusion energy," Fus. Eng. Design **135B**, 236 (2018); https://doi.org/10.1016/j.fusengdes.2017.05.081.

Principal findings

This project was focused on developing a costing framework for innovative, compact modular fusion energy systems supported by ARPA-E in the ALPHA program, with the aim of challenging each cost assumption from our prior work in 2017. We considered each concept and developed power balances, developed concepts for the power cores based on prior art or existing design points, and calculated the capital costs according to a Cost Accounting Structure (CAS), borrowed in part from earlier Gen IV fission costing studies, to calculate the Total Capital Cost (TCC) and total Capital Expenditure (CapEx). We also produced a Levelized Cost of Electricity calculation for the four fusion concepts. The results are presented in the following 3 tables in a manner that anonymizes the concept-specific results of the four proprietary reports that were delivered to the four companies participating in this study. Table 2 provides some over-arching parameters for the power cores, showing that the average net electric power is ~500MWe, and the number of modules in the power core N_{mod} varied from 2 to 4. Table 3 shows the capital costs that were calculated for each CAS, noting that there are still significant cost drivers that warrant further inspection and offer opportunities to further reduce costs. Table 4 shows the Cost of Electricity calculation (average of 43 $/MWh) as well as the CapEx (average of 2.4$/W and $1.2B). Note that these costs are favorable and price compact modular fusion systems competitively in the marketplace of the future.

The major changes relative to the 2017 study are as follows:

- construction time is shortened from 6 years to 3 years by use of centralized manufacturing and shipping pre-built subsystems by road or rail to be installed onsite (much in the same way that Wartsila is doing for their Modular Block concepts). This shortened construction time reduced the indirect cost categories significantly.
- all of the costs outside of the fusion power core in the balance of plant are updated according to recent cost analysis, such as by NETL, scaled with respect to power;
- while we revisited the power balances for each concept, there were no major innovations in the fusion power core, except for the use of additional modules, which increased the total cost of the the power plant, but brought down the cost of electricity;
- the contingency costs are omitted for this study on the basis that we are considering an n^{th} of a kind power plant, one in which the contingency ought to be close to zero.

Other innovations were reported for the fusion power cores for some concepts, which will be captured in the next phase of the ARPA-E costing project.

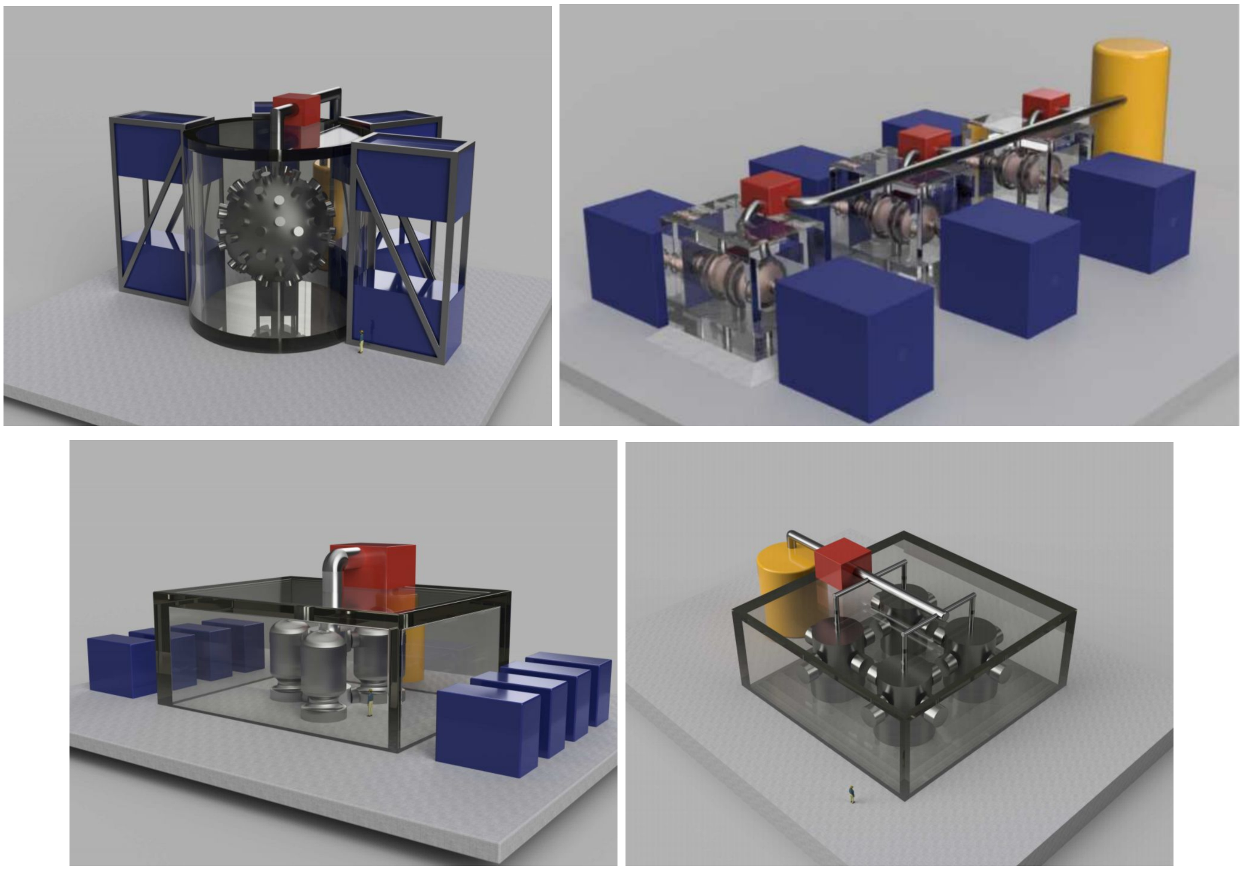

Figure 1. The four participating concepts - clockwise from the top left: Plasma-Jet Magneto-Inertial Fusion (LANL/HyperJet Fusion); Stabilized Liner Compressor (Compact Fusion Systems, Inc.); Staged Z-Pinch (MIFTI, Inc.); and, the Flow-stabilized Z-Pinch (Zap Energy, Inc.)

A computer code was developed as part of this work, which we are calling the 'ARPA-E Fusion Costing Code,' as it captures the essential philosophy of the new paradigm for most of the fusion projects supported by ARPA-E, namely: compactness, low development cost, innovative, and possibly wholly disruptive.

	Average	Low	High	
N_{mod}	3.0	2.0	4.0	
Fusion Power	1352.8	1044.0	1920.0	MW
Alpha Power	269.0	207.6	382.0	MW
Neutron power	1083.7	836.4	1538.0	MW
Thermal power	1554.4	1158.9	2208.4	MW
Net electric power	517.0	383.1	814.4	MW

Table 2. System parameters for the four fusion concepts, showing average, low and high values.

The cost categories are given here

20. Land/Rights
Purchase of land of requisite size.

21. Structures/Site
Site preparation and all buildings.

22. Reactor Plant Equip.
All equipment needed to provide steam to turbines.

22.1 Reactor Equip.
The fusion power core and all components necessary to sustain continuous operation.

22.2 Main Heat Transfer
Coolant loops from the fusion power core to the steam generators.

22.3 Auxiliary Cooling
All components needed to drive coolant, or provide cooling to other systems outside the reactor core.

22.4 Rad. Waste Treat.
Disposal facility for solid, liquid and gaseous waste.

22.5 Fuel Processing
Tritium handling and production systems, including fuel injection and recovery systems.

22.6 Other plant equipment
Maintenance systems for all reactor plant equipment.

22.7 Instrumentation and control
Primary systems for monitoring and controlling power core performance.

23. Turbine Plant Equip.
All systems for converting steam into mechanical motion of the turbines, up to and including the electrical generator..

24. Electric Plant Equip.
All systems for delivering generator power to the grid.

25. Misc. Plant Equip.
Everything not included in prior categories, which can include, for example, transportation, lifting equipment, communications equipment.

26. Heat Rejection
Primarily the cooling towers, but also includes any mechanical equipment such as water intake and

circulating water systems.

27. Special Materials
Primarily this cost category consists of the primary liquid metal coolant.

90. Total Direct Cost
Total direct costs consists of the sum of all prior cost categories.

91. Construction Services and Equipment
Construction management, temporary buildings, and equipment rental.

92. Home Office Engineering Services
Engineering services provided by off-site engineers for specific development projects.

93. Field Office Engineering Services
Engineering services in the field, cost of facilities.

94. Owners Cost
Site permits, plant studies and licenses, staff recruitment, training and housing during construction.

96. Contingency
Mark up to lower capital risk to construction contractor.

97. Interest During Construction
Fixed interest rate applied to capital costs on per annum basis.

99. Total Capital Cost:
Consists of the sum of all cost categories.

	Average	Low	High	
20. Land/Rights	14.0	10.3	22.0	M$
21. Structures/Site	234.7	173.9	369.7	M$
22. Reactor Plant Equip.	422.7	268.8	557.3	M$
22.1 Reactor Equip.	172.1	95.0	243.2	M$
22.1.1 First Wall/Blanket	57.3	3.6	116.5	M$
22.1.2 High Temp. Shield	24.9	22.7	28.5	M$
22.1.3 Coils	5.9	0.0	22.8	M$
22.1.4 Suppl. Heating	3.0	0.0	12.0	M$
22.1.5 Primary Structure	11.6	7.1	15.8	M$
22.1.6 Vacuum System	1.4	0.1	4.7	M$
22.1.7 Power Supplies	55.8	11.9	140.4	M$
22.1.8 Plasma Source	1.4	0.6	3.0	M$
22.1.9 Direct E. Conv.	0.0	0.0	0.0	M$
22.1.10 ECRH	0.0	0.0	0.0	M$
22.1.11 Assembly and installation	10.8	0.3	36.5	M$
22.2 Main Heat Transfer	113.2	63.6	184.2	M$
22.3 Auxiliary Cooling	2.6	1.3	4.2	M$
22.4 Rad. Waste Treat.	4.6	2.4	7.4	M$
22.5 Fuel Processing	123.8	92.3	176.0	M$
22.6 Other plant equipment	4.2	2.1	6.7	M$
22.7 Instrumentation and control	2.1	0.0	3.9	M$
23. Turbine Plant Equip.	137.5	101.9	216.6	M$
24. Electric Plant Equip.	58.9	43.7	92.8	M$
25. Misc. Plant Equip.	39.8	31.9	55.4	M$
26. Heat Rejection	55.3	41.0	87.1	M$
27. Special Materials	103.1	1.4	266.9	M$
90. Total Direct Cost	1066.1	711.0	1454.7	M$
91. Construction Serv./Mat.	26.1	19.2	33.7	M$
92. Home Office Eng./Serv.	31.3	23.0	40.5	M$
93. Field Office Eng./Serv.	10.4	7.7	13.5	M$
94. Owners Cost	37.8	27.7	48.8	M$
96. Contingency	0.0	0.0	0.0	M$
97. Interest During Constr.	51.7	37.9	66.8	M$
99. Total Capital Cost:	1223.5	837.7	1638.8	M$

Table 3. Capital costs showing the average, low and high values.

	Average	Low	High	
Capital cost C_{AC}	122.4	83.8	163.9	M$/annum
Scheduled Replacement Costs C_{SCR}	17.3	6.1	29.5	M$/annum
Operations and Maintenance Costs C_{OM}	48.2	42.0	61.3	M$/annum
Fuel Costs C_F	0.1	0.1	0.1	M$/annum
Decontamination and Decommissioning Costs C_{DD}	0.5	0.5	0.5	mills/kWh or M$/MWh
COE	51.1	39.7	66.8	mills/kWh or M$/MWh
COE2 capturing learning curve credits for CAS22	42.7	33.8	53.7	mills/kWh or M$/MWh
COE	5.11	3.97	6.68	c/kWh
COE2 capturing learning curve credits for CAS22	4.27	3.38	5.37	c/kWh
Dollar per Watt	2.4	2.0	3.3	$/W

Table 4. Cost of Electricity and CapEx costs for the 4 concepts.

Please see the following website for further information:
http://www.woodruffscientific.com/systems.