CHANGING WHAT'S POSSIBLE

FUSION POWER CAPITAL COST STUDY

- ARPA-E's ALPHA program seeks to create and demonstrate tools to aid in the development of new, lower-cost pathways to fusion power and to enable more rapid progress in fusion research and development. Assuming we achieve excess energy production from a fusion core, a next critical step is to understand the capital costs associated with a fusion power plant. An initial capital cost study was performed by Bechtel National's power plant cost team, augmented by members of the fusion community who have published in fusion cost estimating (Woodruff Scientific and Decysive Systems). The study was based upon four conceptual designs for a fusion core and present-day standard components for the balance of plant (heat exchanger, turbines, etc). The cost study team did not attempt to compose a levelized cost of electricity (LCOE) for a fusion power plant given the juxtaposition of the conceptual nature of the fusion core designs versus the level of granular knowledge commonly used as input for calculating an LCOE.

<u>Highlights of the cost study findings include:</u>

- Across four unique fusion core approaches, the estimated cost of the core in all cases constituted *less than half* of the total direct cost, and, in some cases, was not even the most expensive component. Accordingly, among the four fusion approaches considered, there is no outlier approach that should be singled out for emphasis or de-emphasis.

- We found that neither neutronics nor tritium handling were major capital cost drivers. However, much engineering work remains to reach solutions that (1) appropriately account for the effects of the high energy neutrons on various components, and (2) address tritium fuel extraction, transfer, and storage, among other considerations.

- The uncertainty in the pulsed power system design and lifetime under power plant conditions should be a focus area in future work. Using a reasonable range for the cost of the power input systems, sensitivity analysis found that power systems comprised 5-20% of the total direct cost (which includes reactor core, structures and site, turbine plant, etc.).

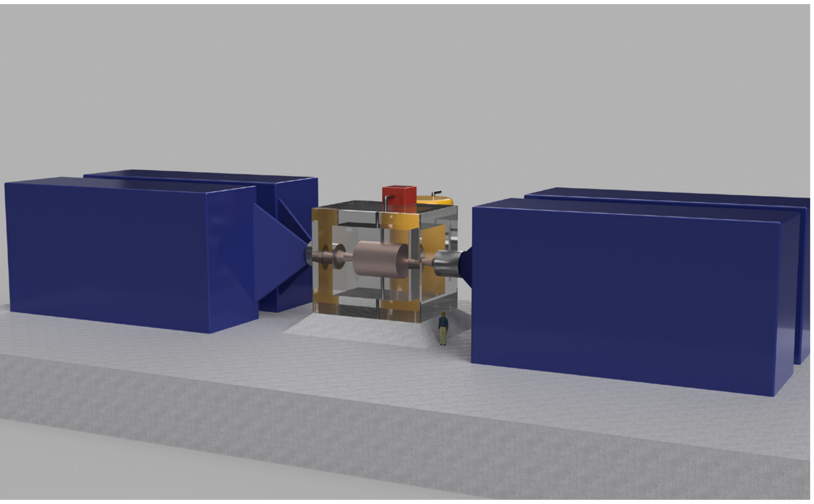
- The up-front capital costs of a fusion power plant, as with many other power plant approaches, are likely to hinge heavily upon the scale of the plant and the balance of plant components. For example, if one treats fusion like fission by borrowing its scaling factor of roughly 0.55, these 150 MW_e designs might scale to \$2-6 per Watt at a 1 GW_e scale.[1]

<u>Conclusions:</u>

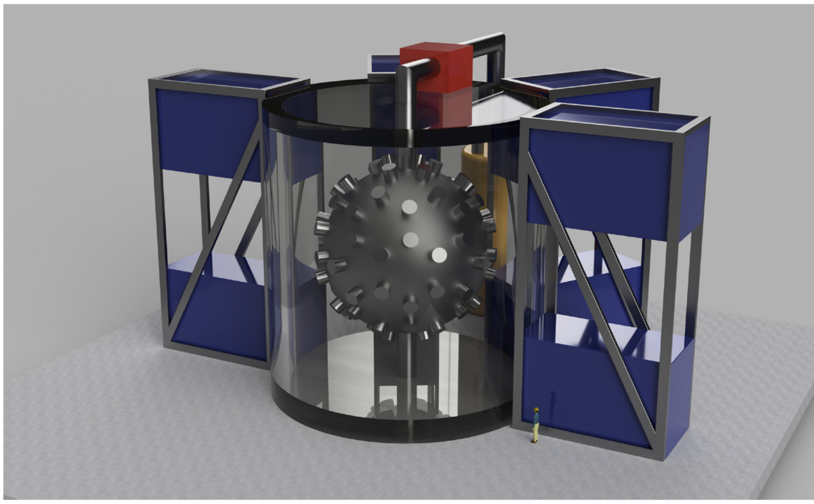
- *First*, we conclude it is best to aggressively pursue multiple options for the fusion core in light of the cost study finding that the economics of a fusion plant are relatively insensitive to which of the four fusion approaches is chosen. Fortunately, the cost of pursuing multiple approaches does not appear to be prohibitive—the four approaches considered in this cost study are believed to follow inherently more affordable development paths than the more mature magnetic or inertial confinement approaches.

- *Second*, it would be prudent to link the ramp-up of the expensive engineering effort for the tritium systems and neutronics to marked progress on the fusion core. While tritium systems and neutronics will be important, their costs will not dominate the initial capital cost of a fusion power plant.

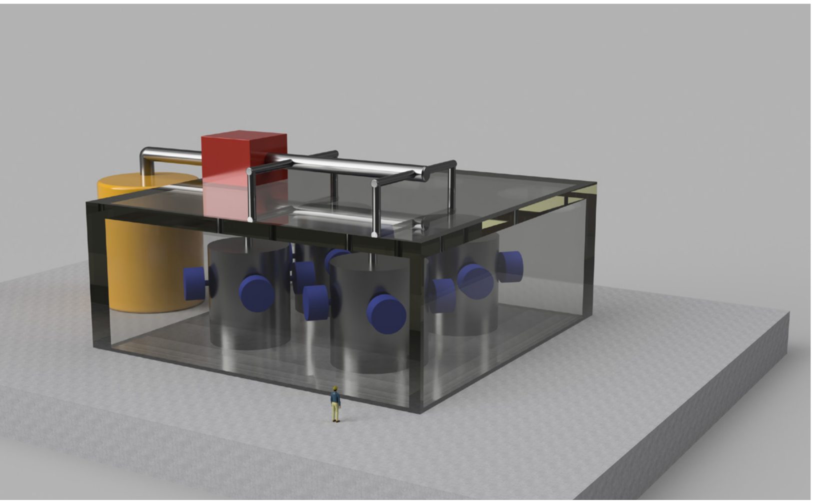
[1] A common approach to estimating "to-be" power plant capital cost is via a scaling law based on "as-built" capital cost: $\mathrm{Cost}_{\text{to-be}} \sim \mathrm{Cost}_{\text{as-built}} \times (\mathrm{Power}_{\text{to-be}} / \mathrm{Power}_{\text{as-built}})^{sf}$, where sf is the empirically determined scaling factor. There is today no "as-built" cost for a fusion power plant, but one could apply a mid-range scale factor for nuclear plants (~0.55) in order to examine potential cost ranges.



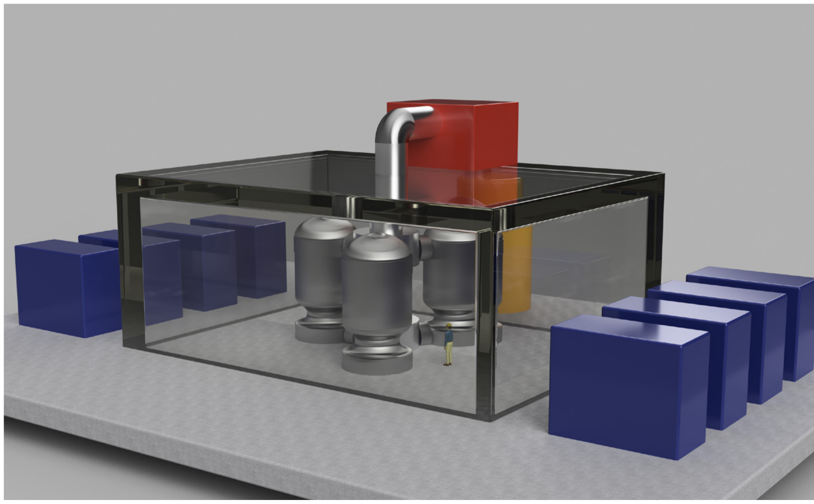
Stabilized Liner Compressor



Plasma Jet Driven Magneto-Inertial Fusion



Staged Z-Pinch



Sheared Flow Stabilized Z-Pinch

Conceptual Cost Study for a Fusion Power Plant Based on Four Technologies from the DOE ARPA-E ALPHA Program

Bechtel National, Inc.
Woodruff Scientific, Inc.
Decysive Systems

Bechtel National, Inc.
Report No. 26029-000-30R-G01G-00001

February 2017

The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000757. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

TABLE OF CONTENTS

Acknowledgements

The authors would like to thank Dr. Patrick McGrath and Dr. Ryan Umstattd of DOE ARPA-E and Dr. Colleen Nehl, technical support to ARPA-E (Booz Allen Hamilton), for their guidance and input during the study and their review of the study report.

We would also like to acknowledge the efforts of the technology proponents who provided the key technical inputs to the study and thank them for their review of the study report. These individuals include:

- Dr. Peter Turchi for the Stabilized Liner Compressor technology being developed by NumerEx, LLC;
- Dr. Scott Hsu for the Plasma Jet Driven Magneto-Inertial Fusion technology being developed by Los Alamos National Laboratory and HyperV Technologies Corporation;
- Dr. Frank Wessel for the Staged Z-Pinch technology being developed by Magneto-Inertial Fusion Technologies, Inc.; and
- Dr. Uri Shumlak for the Sheared Flow Stabilized Z-Pinch technology being developed by the University of Washington and Lawrence Livermore National Laboratory.

Abbreviations & Acronyms

ALPHA	Accelerating Low-Cost Plasma Heating and Assembly
ARIES	Advanced Reactor Innovation and Evaluation Study
ARPA-E	Advanced Research Projects Agency - Energy
BOP	Balance of plant
CAD	Computer-aided design
CBS	Cost breakdown structure
DOE	U.S. Department of Energy
D-D	Deuterium-deuterium
D-T	Deuterium-tritium
EPRI	Electric Power Research Institute
ESECOM	Senior Committee on Environmental Safety and Economics of Magnetic Fusion Energy
ETS	Energy transfer and storage
FLR	Fast Liner Reactor
FPC	Fusion power core
FPP	Fusion power plant
FRC	Field reversed configuration
FW	First wall
HP	High pressure
HTS	High temperature shield
HVAC	Heating, Ventilation, and Air Conditioning
HyperV	HyperV Technologies Corporation
I&C	Instrumentation and control
ICF	Inertial confinement fusion
IEEE	Institute of Electrical and Electronics Engineers
IFE	Inertial Fusion Energy
ITER	International Thermonuclear Experimental Reactor
kWh	Kilowatt hour
LANL	Los Alamos National Laboratory
LCOE	Levelized cost of electricity
LLNL	Lawrence Livermore National Laboratory
LOCA	Loss of coolant accident
LP	Low pressure
LTD	Linear transformer driver
MCF	Magnetic confinement fusion
MFE	Magnetic fusion energy

MG	Mega gauss
MHD	Magnetohydrodynamic(s)
MIF	Magneto-inertial fusion
MIFTI	Magneto-Inertial Fusion Technologies, Inc.
MTF	Magnetized target fusion
MW	Megawatt
MWe	Megawatt electric
MWth	Megawatt thermal
NEA	Nuclear Energy Agency
NIF	National Ignition Facility
NPP	Nuclear power plant
NRL	Naval Research Laboratory
NumerEx	NumerEx, LLC
O&M	Operations and maintenance
OB	Outer blanket
PdV	Pressure times volumetric change
PJMIF	Plasma Jet Driven Magneto-Inertial Fusion
PJMTF	Plasma Jet Driven Magnetized Target Fusion
PLX	Plasma Liner Experiment
RFP	Reversed field pinches
SFS	Sheared flow stabilized
SLC	Stabilized Liner Compressor
SMR	Small modular reactor
TBR	Tritium breeding ratio
TCOE	Total cost of electricity
TFTR	Tokamak Fusion Test Reactor
USD	U.S. dollars
UW	University of Washington

List of Tables

List of Figures

1. Executive Summary

The U.S. Department of Energy's (DOE's) Advanced Research Projects Agency-Energy (ARPA-E) is sponsoring research into a number of approaches to fusion power generation under the Accelerating Low-Cost Plasma Heating and Assembly (ALPHA) program [Reference 1]. The ALPHA program seeks to create and demonstrate tools to aid in the development of new, lower-cost pathways to fusion power and to enable more rapid progress in fusion research and development.

Most fusion research currently focuses on one of two approaches to confining plasmas: magnetic confinement, which uses magnetic fields and lower-than-air ion densities; and inertial confinement, which uses heating and compression and involves greater than solid densities. The ALPHA program aims to create additional options for fusion research by developing the tools for new, lower-cost pathways to fusion, and with a focus on intermediate densities in between these two approaches. These new intermediate density options may offer reduced size, energy, and power density requirements for fusion reactors and enable low-cost, transformative routes to economical fusion power.

Of the nine projects being pursued by the ALPHA program, four have been subjected to a conceptual design/capital cost study, including a sensitivity analysis of cost drivers, for preliminary designs of power plants based on each of the four approaches. This study was led by Bechtel National, Inc. [Reference 2], and supported by Woodruff Scientific, Inc. [Reference 3], and Decysive Systems [Reference 4]. The four concepts are:

- Stabilized Liner Compressor (SLC) by NumerEx, LLC (NumerEx);
- Plasma Jet Driven Magneto-Inertial Fusion (PJMIF) by Los Alamos National Laboratory (LANL) and HyperV Technologies Corporation (HyperV);
- Staged Z-Pinch by Magneto-Inertial Fusion Technologies, Inc. (MIFTI); and
- Sheared Flow Stabilized Z-Pinch (SFS Z-Pinch) by the University of Washington (UW) and Lawrence Livermore National Laboratory (LLNL).

For each of the four fusion approaches, a conceptual design was created of a deuterium-tritium (D-T) fueled fusion power core (FPC), as part of a central-station electric power plant at an approximate 150 MWe output. A common cost model was developed and applied across the four conceptual designs to provide sensitivity analysis on key cost drivers among the plant subsystems and components, as well as conceptual capital cost estimates.

The cost model was based on the pre-conceptual design detail available from the technology providers. For the FPC, the following methodology was used for cost assessment: first, a power balance was determined, then the FPC was built radially, with the assumption that the primary reaction will be D-T and produce neutrons to be absorbed in a blanket. Individual systems analyses for each of the four reactor visions were then performed. Costing for the Turbine Island and Balance of Plant (BOP) structures and systems was based on previous power plant designs and similar structures, adjusted as needed for the heating power, power output, and the pre-conceptual design information available from the developers.

The key conclusions of the study are:

- The calculated cost was relatively insensitive to changes within the range of expected uncertainty in FPC materials costs or radial build costs (consisting of the first wall, shield, and blanket).
- Current uncertainties in the primary power system for the fusion core could result in significant impacts on the total estimated cost, with the primary power system potentially approaching 20% of the total direct capital cost.

- Using a point design for 150 MW of electric power, the total estimated overnight cost encompassing the four pre-conceptual fusion power plants (FPP) ranges from approximately $0.7 billion to $1.93 billion (in 2016 U.S. dollars). The average estimated overnight cost is approximately $1.32 billion. The cost estimate and the pre-conceptual designs of the FPCs and associated systems are not adequately developed and detailed at this time to be used for scaling up the estimated overnight costs for potential larger capacity plants (e.g., in the 1 GWe range).
- Cost categories had varying degrees of uncertainty, with the principal areas of uncertainty being in the FPC, heat exchanger, and tritium handling system. All principal uncertainties can be reduced by further work.

The study results provide a costing framework and capital cost estimate range for each technology provider to eventually produce supportable levelized cost of electricity (LCOE) estimates when more detailed design data and information is developed in the future. It is recommended that additional analysis and design be conducted to develop more detail on the FPC and associated systems. The next steps would allow uncertainties in the costing analysis to be further mitigated by advancing the least certain design points beyond the pre-conceptual level and moving to the conceptual level. Recommendations include increased physics modeling, neutronics analysis, electrical engineering of the primary power systems, conceptual design of the tritium handling systems, and costing for the main heat exchanger.

Due to the current state of the technologies, it should be recognized that this study is not intended to provide definitive cost estimates for the subject technologies. ARPA-E and the technology providers understand that the report does not contain sufficient accuracy or detail to be meaningful in connection with any securities offering or other financing effort and due to the status of the technology development, the uncertainties as to time horizon in which any of these technologies could be commercially deployed, and the limited scope of the review, this report is not intended to be relied upon by any third party in making investment decisions.

2. Introduction

2.1 Overview

The ARPA-E ALPHA program is focused on creating and demonstrating tools to aid in the development of new, lower-cost pathways to fusion power and to enable more rapid progress in fusion research and development. The fusion technologies sponsored, in part, by the ARPA-E ALPHA program include:

- Stabilized Liner Compressor by NumerEx;
- Plasma Jet Driven Magneto-Inertial Fusion by LANL and HyperV;
- Staged Z-Pinch by Magneto-Inertial Fusion Technologies, Inc.; and
- Sheared Flow Stabilized Z-Pinch by UW and LLNL.

The purposes of this study were to:

(1) Using current design information available in the fusion power technology sector, perform a literature review and conceptual capital cost estimate of the fusion power technologies identified above including parametric/sensitivity studies of key cost drivers; and

(2) Perform a limited assessment of other costs including tritium handling, operations and maintenance, waste disposal, and decommissioning using publicly available data that would be applicable to a generic fusion power technology.

To form the basis for the capital cost estimates, the key features and operational attributes of the four fusion technologies were characterized at the pre-conceptual level. Important features of the FPC include the geometric layout of the subsystems (magnetic coils, plasma facing components, tritium producing blanket, neutron shields, auxiliary heating systems, etc.). Key considerations included:

- Attaining the minimum Lawson criterion value (triple product, $n\tau T$);
- Attaining an adequate fusion power gain Q = (fusion power output)/(plasma heating input) based on a scaling relationship to be determined; and
- Attaining a low recirculating power fraction, ε = (housekeeping plus heating power)/(gross electric power output), used to define an engineering Q value, $Q_E = 1/\varepsilon$.

An analytic scaling model using adiabatic compression and basic costing was used to develop the FPC design and related cost estimate information. From this model, individual systems analyses of the four fusion technologies were developed per published systems analysis. Data was collected on the four technologies and evaluated to ensure that the bases and assumptions of the capital cost estimate were appropriately determined. Information collected from the four technology developers to support the evaluation included:

- Description of conceptual design including any available information on materials, sizes, weights, costs, etc.;
- Design requirements;
- Electrical power requirements;
- Scaling approaches;
- Primary and connected systems and structures;

- Support systems and structures;
- Drawings, schematics, figures, etc.; and
- Other available information.

The cost estimate for the Turbine Island and BOP structures, systems, and components was developed using historical data from previous power plant designs with similar systems and structures, adjusted as needed for the thermal power, electrical power output, and the pre-conceptual design information available from the fusion technology developers. For the purposes of this study and to allow for consistent evaluation across the technologies, a single, generic site with a common Turbine Island and BOP layout and structures was developed.

A general cost breakdown structure was developed, with sub-elements distinguishing among the several approaches. The cost model was based on the level of design detail available from the pre-conceptual FPC designs and the performance of limited parametric and sensitivity studies of key cost drivers (e.g., reactor high temperature shield thickness).

The limited assessment of other costs including tritium handling, operations and maintenance, waste disposal, and decommissioning was based on publicly available data for fusion technologies, tritum production technologies, small modular reactors, and advanced reactors. These other costs are highly uncertain because the four fusion technologies studied are still in early development stages and have yet to reach the requisite design maturity for commercialization. Additionally, no commercial FPP has been built or operated. Therefore, no actual historical construction or operational cost data are available to serve as the baseline for these other cost estimates.

2.2 Background

The deuterium (^{2}H)-tritium (^{3}H) [D-T] reaction is considered to be the most accessible of the collection of light-isotope fusion reactions, described as

$$^2\text{H} + {}^3\text{H} \rightarrow {}^4\text{He}\ (3.52\ \text{MeV}) + {}^1\text{n}\ (14.06\ \text{MeV}) \qquad (1)$$

with a helium nucleus (3.52-MeV alpha particle) and neutron (14.06 MeV = 2.25 pJ) produced as fusion products sharing (as kinetic energy) the fusion energy (17.58 MeV per fusion event) released. Secondary D-D fusion reactions, with approximately equal probability, are

$$^2\text{H} + {}^2\text{H} \rightarrow {}^3\text{H}\ (1.01\ \text{MeV}) + {}^1\text{p}\ (3.03\ \text{MeV}) \qquad (2)$$

$$^2\text{H} + {}^2\text{H} \rightarrow {}^3\text{He}\ (0.82\ \text{MeV}) + {}^1\text{n}\ (2.45\ \text{MeV}) \qquad (3)$$

To overcome the Coulomb barrier repelling the positively charged nuclei (and give a desirable fusion reaction parameter, R_{ij} (m^3/s) = $<\sigma v>_{ij} \equiv$ the fusion microscopic cross section, σ(m^2) averaged over the (Maxwellian) ion velocity distribution), fusion fuel must operate at elevated temperature ($T \approx 10$ keV), stripping the electrons from the atoms and resulting in plasma conditions. For binary plasmas with fuel ion densities n_i and n_j, the local fusion power density, p_f (W/m^3) = $n_i n_j R_{ij} E_{ij}$, with the energy release per fusion given in Joule units.

Radioactive tritium (half-life is 12.32 a) is not available in nature in practical quantities, but can be produced (bred) from the reactions

$$^{6}\text{Li} + {}^{1}\text{n} \rightarrow {}^{4}\text{He} + {}^{3}\text{H} + (4.86\ \text{MeV}) \qquad (4)$$

$$^{7}\text{Li} + {}^{1}\text{n} \rightarrow {}^{4}\text{He} + {}^{3}\text{H} + {}^{1}\text{n} - (2.87\ \text{MeV}) \qquad (5)$$

using the fusion-product neutrons as they thermalize in a lithium-bearing ‘blanket’ surrounding the fusing plasma. The isotopic fractions of natural lithium are ^{6}Li (7.59 %) and ^{7}Li (94.41 %). It may be desirable to enrich the fraction of ^{6}Li (at some processing cost) to optimize the blanket performance in terms of tritium breeding ratio (TBR ≡ tritium atoms produced per neutron) and blanket energy multiplication (M_n ≡ thermal energy released in the blanket per invested neutron energy ≈ 1.1-1.3). Blanket performance optimization requires neutronics calculations beyond the scope of this study.

A spectrum of approaches, ranging from Magnetic Fusion Energy (MFE) systems to Inertial Fusion Energy (IFE) systems have been explored in the quest to develop and commercialize fusion energy production for central-station electric power plants and other applications. MFE systems tend to incorporate low-density plasmas confined by external and internal magnetic fields. Confinement approaches of interest worldwide include tokamaks (e.g., JET, ITER, and low-aspect-ratio NSTX and MAST), stellarators (e.g., W7-X), and reversed field pinches (RFPs), spheromaks, and field reversed configurations (FRCs). The goal is long-pulse or steady operation with refueling and (often) current drive. Typical central-station conceptual power plant sizes are 1 - 1.2 GWe (net), with the plant size determined in part by economies of scale. IFE systems are driven by high-power lasers [e.g., National Ignition Facility (NIF)] or ion beams with pulsed operation (~5 – 1 Hz). Cryogenic fuel capsules are injected into the reactor chamber and compressed to greater than solid density for a brief burn time. Again, typical conceptual power plant sizes are ~1 GWe (net).

The physics operation regime of interest to the ALPHA program and the four approaches of interest to this study falls between the MFE and IFE regimes and has been described as the Magneto-Inertial Fusion (MIF) regime [References 6, 7]. Such an operating regime is consistent with smaller fusion plant sizes [References 8, 9] motivated in part by considerations of small modular (fission) reactors [References 10, 11]. The performance scaling of these exploratory concepts is not as well-known as that for tokamaks, for example. Several metrics, under consideration for fission small modular reactors (SMRs), may apply in similar fashion to the class of smaller fusion systems. These metrics [pg. 94 of Reference 11] include upfront capital costs, interest during construction, maximum cash outlay, time to first revenue, and sensitivity to market changes.

For either steady or pulsed fusion systems, time-averaged thermal power, P_{TH} (Wth), is removed from the FPC by a primary coolant/breeder moving at a mass flow rate, w(kg/s) = $P/(\Delta T)/c_p$, where the mixed-mean coolant temperature rise is $\Delta T(C) = (T_{outlet} - T_{inlet})$ and c_p (J/kg-C) is a representative heat capacity of the coolant material. The coolant follow speed, v(m/s), can be derived from w (kg/s), the coolant mass density, ρ (kg/m^3), and a representative coolant pipe area, A_{pipe} (m^2). For pulsed systems, coolant temperature fluctuations must be equilibrated in the hot leg of the primary coolant piping to provide steady operation of the steam generator and turbine generator equipment.

3. Fusion Reactor Concepts

A general description of each fusion technology is provided in this section based on a literature review related to each technology and discussions with the proponent groups. The physics and basic reactor concept of each technology are presented.

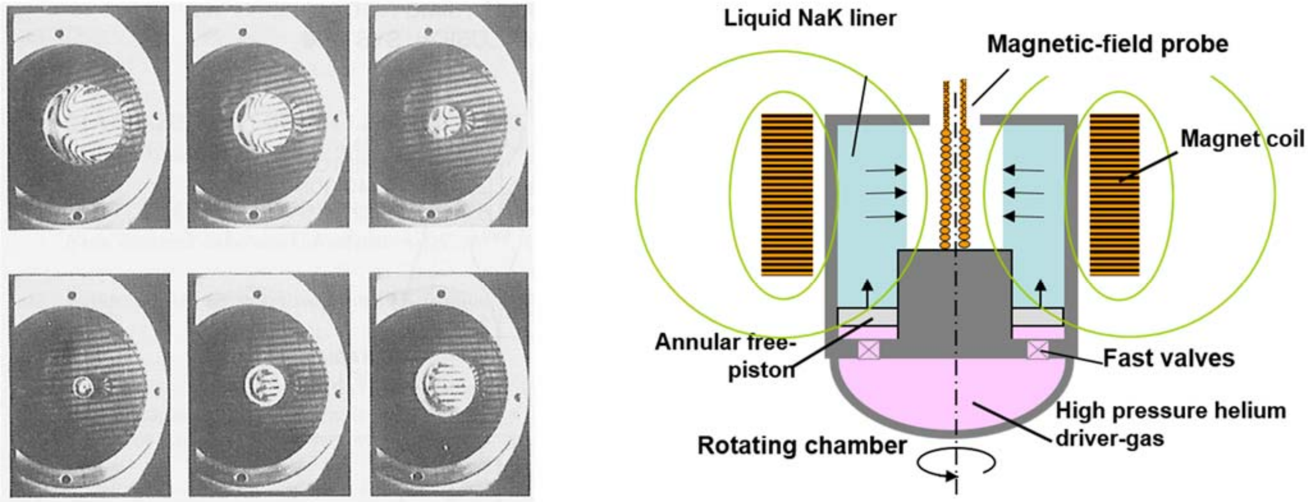
3.1 Stabilized Liner Compressor (NumerEx, LLC)

The SLC technology concept is being developed by NumerEx, LLC. The stabilized liner compression concept derives from work on the slowly imploding liner (LINUS) concept at the Naval Research Laboratory (NRL) in the 1970s and early 1980s. Documents included in the literature review related to the SLC technology are identified in References 12 through 26.

The concept and physics background for the SLC technology was described in a presentation by NumerEx, LLC at the 2016 ALPHA program annual meeting [Reference 12]:

> There appears to be an operating regime [1], known variously as Magnetized Target Fusion (MTF) or Magneto-Inertial Fusion (MIF) between the mainline programs of magnetic confinement and inertial confinement fusion. This regime offers reduced size and cost for controlled fusion reactors, but depends on operation with magnetic fields at megagauss levels. These field levels require dynamic conductors, e.g., imploding shells, aka, liners. Two broad approaches follow from the communities attracted to MIF, respectively, an ICF-related side at higher energy-density interested in ignition, enabled in part by high magnetic fields, and an MCF-side, typically interested in arrangements that represent extensions of MCF to much higher fields than conventional programs. The latter harken to back to US and Soviet programs of the 1970’s [1,2]. Recently, ARPA-E has initiated the ALPHA program for technologies that will enable development of low-cost controlled fusion by MIF. Such development requires techniques that permit low-cost, repetitive experiments to create the necessary plasma targets for liner compression. It also demands that these techniques can extend to break-even experiments and an economical fusion power reactor. The Stabilized Liner Compressor (SLC) aims to satisfy these requirements by means of repetitive implosions in which Rayleigh-Taylor instabilities are avoided by free-piston drive and liner rotation, and the liner serves as the first wall and blanket to protect the reactor from high energy neutrons [2]. We describe the principles for reactor operation and our progress towards designing SLC for near term experiments.

The SLC concept builds on technology from the NRL LINUS program as shown in Figure 1; the SLC concept is shown in Figure 2 (both located on the following page).



P.J. Turchi , et al, "Review of the NRL Liner Implosion Program," in Megagauss Physics and Technology, ed. P.J. Turchi (Plenum, 1980). P. 375.

Figure 1. The SLC Concept is Based on the NRL LINUS Precursor [Reference 17].

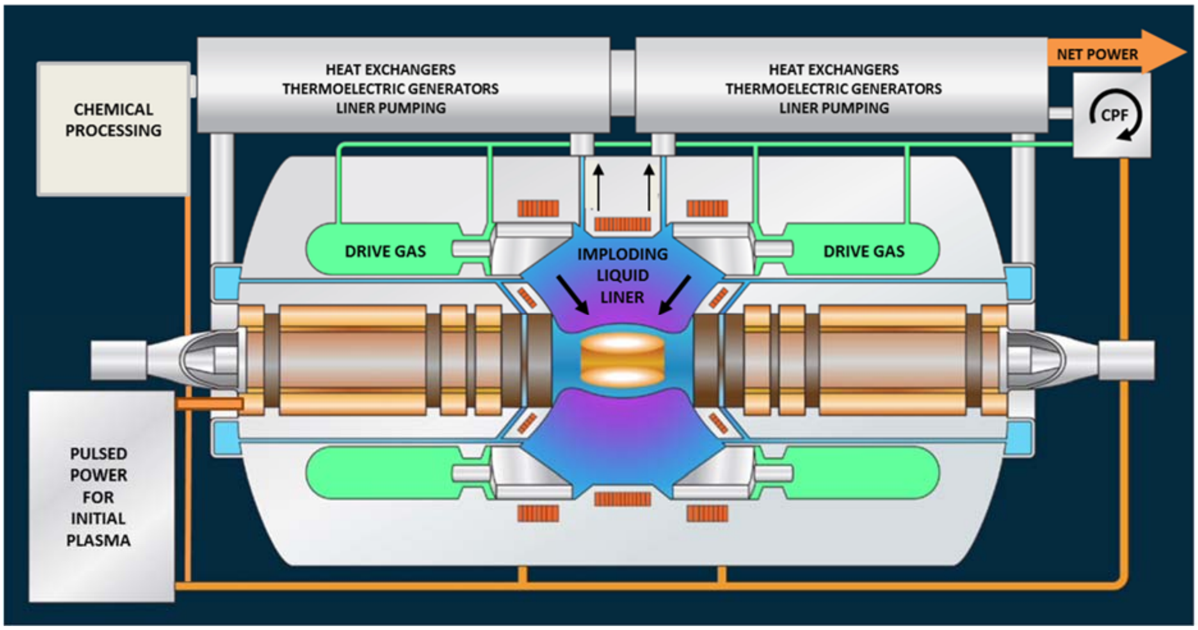


Figure 2. SLC Reactor Concept [Reference 12].

3.2 Plasma Jet Driven Magneto-Inertial Fusion (LANL/HyperV)

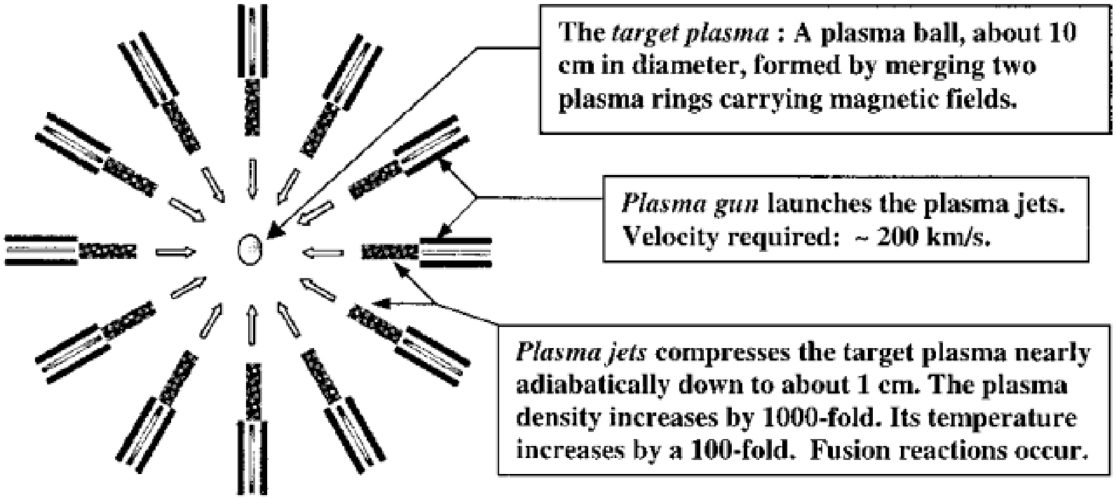
The PJMIF technology concept is being developed by Los Alamos National Laboratory and HyperV Technologies Corporation. Documents included in the literature review related to the PJMIF technology are identified in References 24, 25, and 27 through 37.

Several approaches to magneto-inertial fusion (MIF) or magnetized target fusion (MTF) incorporate in situ plasma formation using front-end apparatus that is necessarily destroyed by the energy released in the fusion pulse. The Plasma Jet approach seeks to avoid the complications and costs of such approaches by moving the plasma source a suitable standoff distance from the fusion pulse. Specifically, an array of numerous plasma jets, inwardly directed in a spherical arrangement towards the origin, converge to fuel a pre-injected plasmoid. The supersonic plasma jets are produced by plasma guns fired simultaneously [Reference 31]. The concept is under experimental investigation in the Plasma Liner Experiment (PLX) at LANL and is supported by other institutions. The present emphasis is the study of the merging of neighboring plasma jets [Reference 32].

These plasma jets are produced by highly efficient electromagnetic accelerators. They also carry the main fusion fuel. The implosion dynamics is studied in three phases:

1. The preliminary shock heating and compression;
2. The acoustic compression; and
3. The containment of the burning target and liner.

The PJMIF concept is shown in Figure 3.



The *target plasma* : A plasma ball, about 10 cm in diameter, formed by merging two plasma rings carrying magnetic fields.

Plasma gun launches the plasma jets. Velocity required: ~ 200 km/s.

Plasma jets compresses the target plasma nearly adiabatically down to about 1 cm. The plasma density increases by 1000-fold. Its temperature increases by a 100-fold. Fusion reactions occur.

Figure 3. The PJMIF Concept [Reference 29].

Mathematical models were developed to model these three phases of the implosion dynamics and have been implemented in a suite of computer codes. The model is applied to study the liner requirements to implode a specific target with an initial radius (50 mm) and an initial D-T density (1024 m^{-3}) to a final radius (2.5 mm) with an initial implosion velocity (125 km/s) at impact with the liner, versus the length of confinement time.

The PJMIF concept shares with Fast Liner Reactor (FLR) and Z-IFE the need for a blast confinement chamber. An initial design point for a reactor was presented at the ARPE-E meeting in August 2016 [Reference 35], for a liner with M = 20 g with a 50 km/s Xenon liner and D-T after-burner, the parameters shown in Table 1 are obtained.

Table 1. Parameters for 130 MJ of Fusion Yield with PJMIF.

Parameter	Value	Units
Initial Plasma Radius, r_o	0.1	m
Final Plasma Radius, r_f	0.004	m
Density, n_f	5×10^{21}	cm^{-3}
Temperature, T_f	10	keV
Pressure, P_f	150	Mbar
Mass, M	5	mg
Magnetic Fields, B_f	300	T
Dwell Time, T_D	0.3	µs
Fuel Burn-up, f_b	8	%
Fusion Yield, *Y*	130	MJ
Initial Liner Kinetic Energy, KE_o	25	MJ
Gain *	20	-
Pulse Repetition Rate	1	Hz
Fusion Pulse Time	1	µs

** Energy gain = (fusion energy) / (total initial plasma energy)*

Figure 4 shows the reactor concept plasma at peak compression.

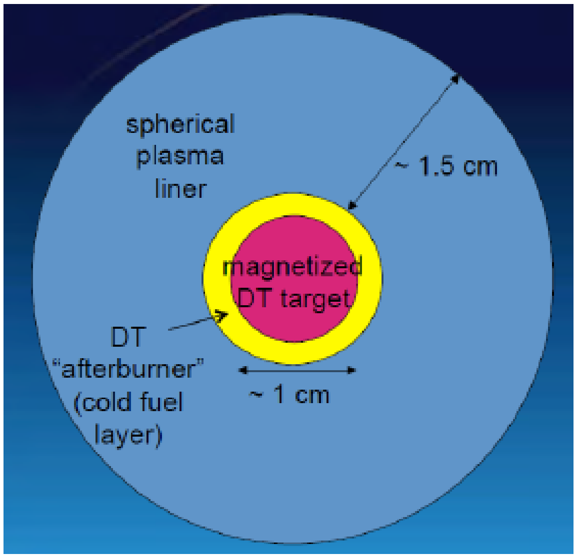


Figure 4. Reactor Concept: Plasma at Peak Compression.

3.3 Staged Z-Pinch (MIFTI)

Z-pinches are produced by driving current in a plasma column, usually produced by electrodes. Balance of the radial plasma pressure gradient and the magnetic pressure yields the ‘pinch effect’ produced by the inward pressure of the azimuthal-magnetic field on the outward plasma pressure. The Bennett relation determines the pinch current I for a given line density of plasma. When axial magnetic field is included, the pinch is often called a ‘screw pinch’ since the resulting magnetic topology will be helical.

The Staged Z-Pinch technology is being developed by Magneto-Inertial Fusion Technologies, Inc. (MIFTI). Documents included in the literature review related to the Staged Z-Pinch technology are identified in References 24, 25, and 38 through 44.

The MIFTI concept is a staged z-pinch target that implodes a high Z (e.g., Kr) plasma liner onto a low Z (D-T) plasma target [Reference 43], with typical dimensions 1 cm high × 1 cm diameter. An axial magnetic field is applied (using an external Helmholtz coil) and azimuthal-magnetic field forms as current flows in the cylindrical liner. The target is imploded radially and while the liner might implode unstably, the target implodes stably due to the propagation of a shock in a flux buffer between RT-unstable liner and stable pinch. See Figure 5.

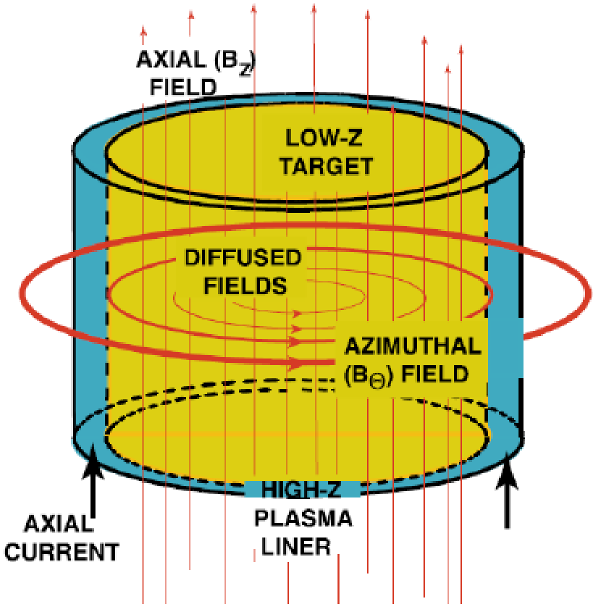


Figure 5. The Staged Z-Pinch Concept. [Reference 43]

In Reference 40, an idealized Ag liner imploding onto a DT target configuration (SZP), using realistic pulsed-power parameters was simulated using the MACH2 (2.5D) MHD code with driver parameters $\tau_{1/4}$ = 130 ns, I_{peak} = 22 MA, and E_{stored} =22 MJ. It was found that the target plasma is stable to final compression, achieving a convergence ratio of $C_{target} = r_{targetinitial} / r_{targetfinal} = 100$. However, compression alone is not sufficient to produce the temperature and density needed for high-yield fusion; shocks must be included, as they fundamentally alter the implosion dynamics, energy coupling, and stabilization of the Rayleigh-Taylor instability and arise due to the large difference in atomic number between the liner and the target, producing a stagnation layer at the liner-target interface and transporting current and azimuthal-magnetic field radially inward, at a rate higher than expected by classical diffusion. Near peak compression, the azimuthal-magnetic field is flux-compressed to $B_{theta} > 200$ MG (20,000 T), which is sufficient to trap fusion-alpha particles that deposit their energy in the target plasma, producing ignition. The simulated neutron-output yield is $Y > 3.75 \times 10^{19}$, the fusion energy output is $E_{fusion} > 100$ MJ, the fusion energy gain is $Q = E_{fusion} / E_{ion} > 100$, and the total-energy gain is $G = E_{fusion} / E_{stored} = 5$, where E_{stored} is the capacitor bank energy. At the 2016 August ARPA-E annual meeting, Wessel presented some experimental results from the SZP experiment [Reference 43] shown in Table 2 and Figure 6.

Table 2. Staged Z-Pinch Experimental Parameters from Wessel, et. al. [Reference 43]

Parameter	Value	Units
Initial radius, r_o	12	mm
Initial liner thickness, Dr_o	5	mm
Final radius, r_f	0.6	mm
Convergence ratio, $C_r = r_o / r_f$	20	--
Pinch length, l	0.88	in
Initial axial magnetic field, B_{zo}	10^{-2}	T
Final axial magnetic field, B_{zf}	50	T
Initial liner density, $n0_{Ar}$	5×10^{17}	cm^{-3}
Final liner density, nf_{Ar}	$< 2 \times 10^{20}$	cm^{-3}
Implosion velocity, v_r	35 – 40	cm/ms
Final temperature, T_f	500	eV

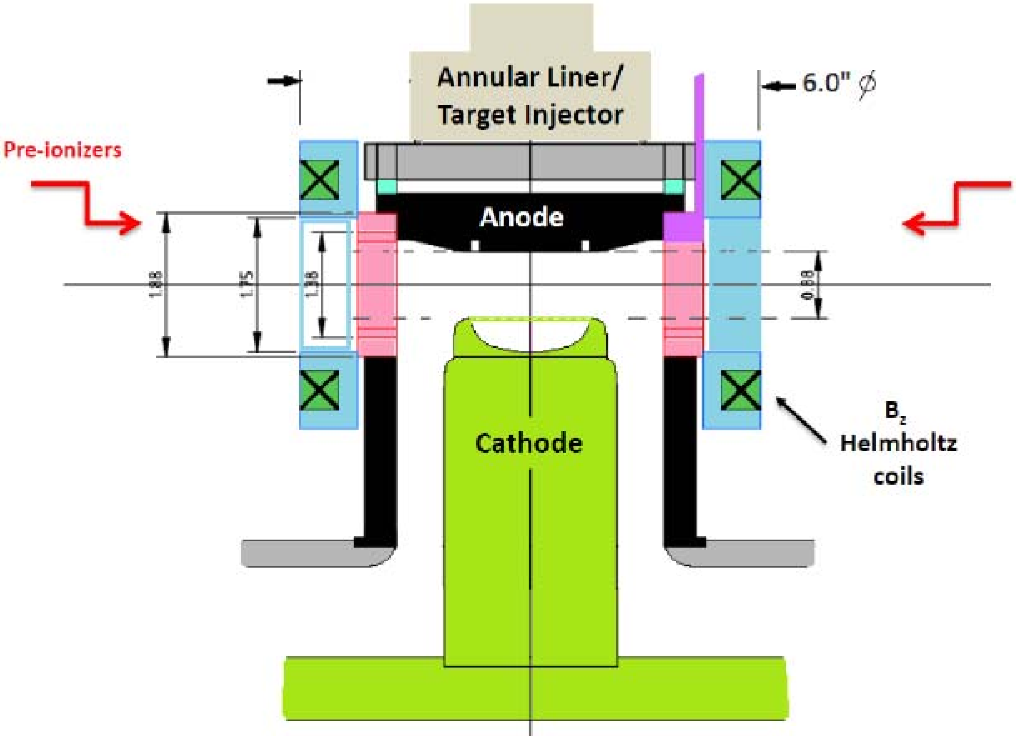
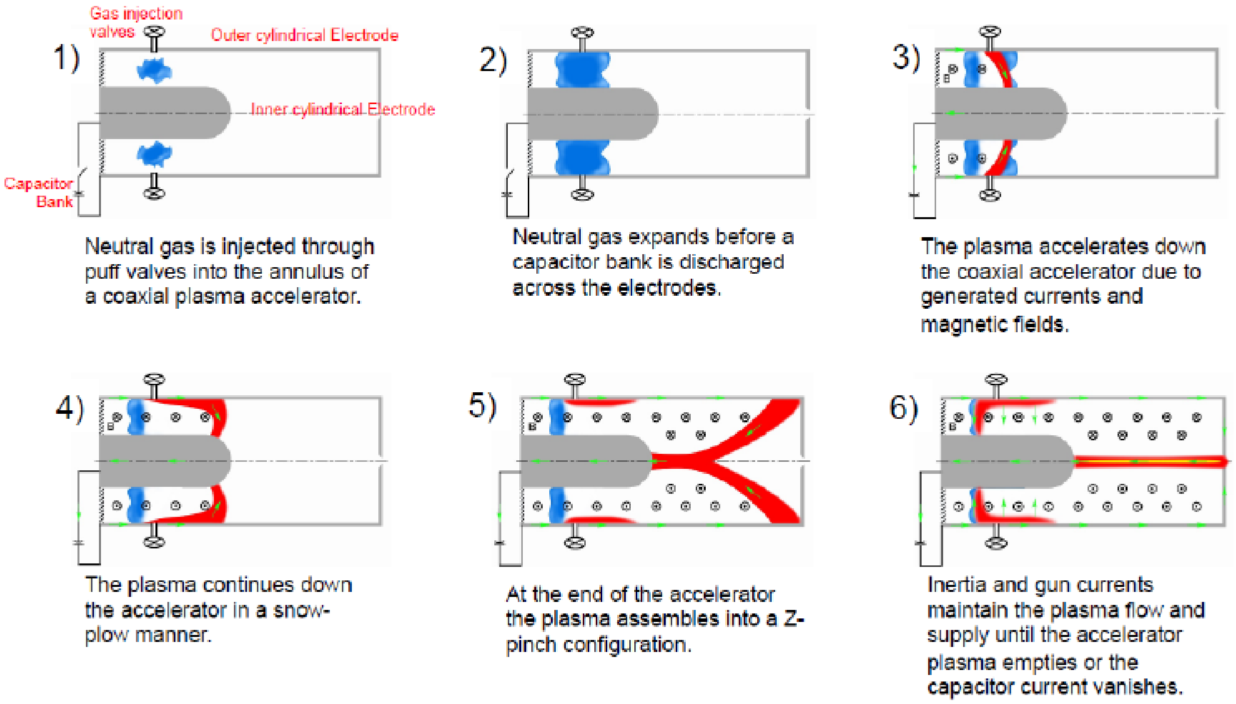


Figure 6. Diagram of the Staged Z-Pinch [Reference 43].

3.4 Sheared Flow Stabilized Z-Pinch (UW/LLNL)

The SFS Z-Pinch technology is being developed by the University of Washington and Lawrence Livermore National Laboratory. Documents included in the literature review related to the SFS Z-Pinch technology are identified in References 24, 25, and 45 through 58.

The flow-stabilized z-pinch is formed in a coaxial electrode system (see Figure 7): a current sheet forms in the inter-electrode region and then is accelerated towards a cylindrical chamber in which the z-pinch forms on the geometric axis. Typical results so far have been in a 1 m long, 1 cm diameter pinch with a 50 kA plasma that is stable for 40 μs.



1) Neutral gas is injected through puff valves into the annulus of a coaxial plasma accelerator.

2) Neutral gas expands before a capacitor bank is discharged across the electrodes.

3) The plasma accelerates down the coaxial accelerator due to generated currents and magnetic fields.

4) The plasma continues down the accelerator in a snow-plow manner.

5) At the end of the accelerator the plasma assembles into a Z-pinch configuration.

6) Inertia and gun currents maintain the plasma flow and supply until the accelerator plasma empties or the capacitor current vanishes.

Figure 7. The SFS Z-Pinch Concept [Reference 56].

The sheared flow stabilization of the m = 1 kink mode in z-pinches was explored numerically first in 1995 [Reference 47]. This was done by reducing the linearized MHD equations to a one-dimensional displacement equation, and generating an equilibrium that is made marginally stable against the m = 0 sausage mode by tailoring its pressure profile. The principal result reveals that a sheared axial flow stabilizes the kink mode when the shear exceeds a threshold that is dependent on the location of the conducting wall. For the equilibria studied here the maximum threshold shear (v'_z / kV_A^0) was about 0.1.

Device parameters for the intermediate stage towards a reactor concept have been presented by McLean at the August 2016 ARPA-E meeting [Reference 56] and are shown in Table 3 on the following page.

Table 3. Parameters for Next Devices Beyond ZaP (Existing at UW).

Parameter	ZaP	ALPHA (FUZE)	Reactor
Pinch Current (kA)	50	300	1,500
Total Discharge (kA)	150	500	1,700
Pinch Radius (mm)	10	0.7	0.05
Ion Density (m^{-3})	1E+22	2.5E+24	3E +27
Temperature (eV)	50-100	2,500-4,000	25-50,000
Magnetic Field (T)	1	90	6,000
Lawson $n\tau$ (m^{-3} sec)	1E+17	1E+19	1E+21
D-D Neutron Yield	1E+11 – 4E+11		
Radiation Power (MW)	10		

Target design points include: Q = 5; I_{plasma} = 1.7MA at 22kV; repetition rate of 10 Hz with a pulse length of 230 μs, giving fusion energy per pulse of 19 MJ and average fusion power of 190 MW.

Figure 8 shows a conceptual reactor [Reference 45]. Conceptual D-T and D-D fusion reactors are discussed based on magnetic confinement with the high-plasma-density Z-pinch. The reactor concepts have no “first wall”, the fusion neutrons and plasma energy being absorbed directly into a surrounding lithium vortex blanket. Efficient systems with low re-circulated power are projected, based on a flow-through pinch cycle for which overall Q values can approach 10. The conceptual reactors are characterized by simplicity, small minimum size (100 MWe) and by the potential for minimal radioactivity hazards.

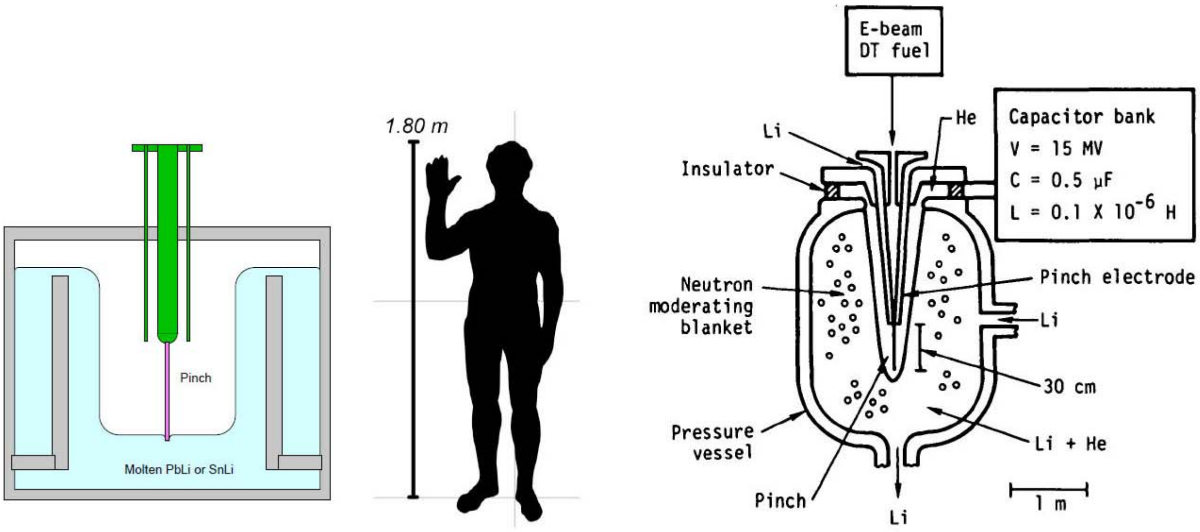


Figure 8. Z-Pinch Reactor Concepts. Left from Reference 56, Right from Reference 45.

4. Fusion Power Plant Concepts

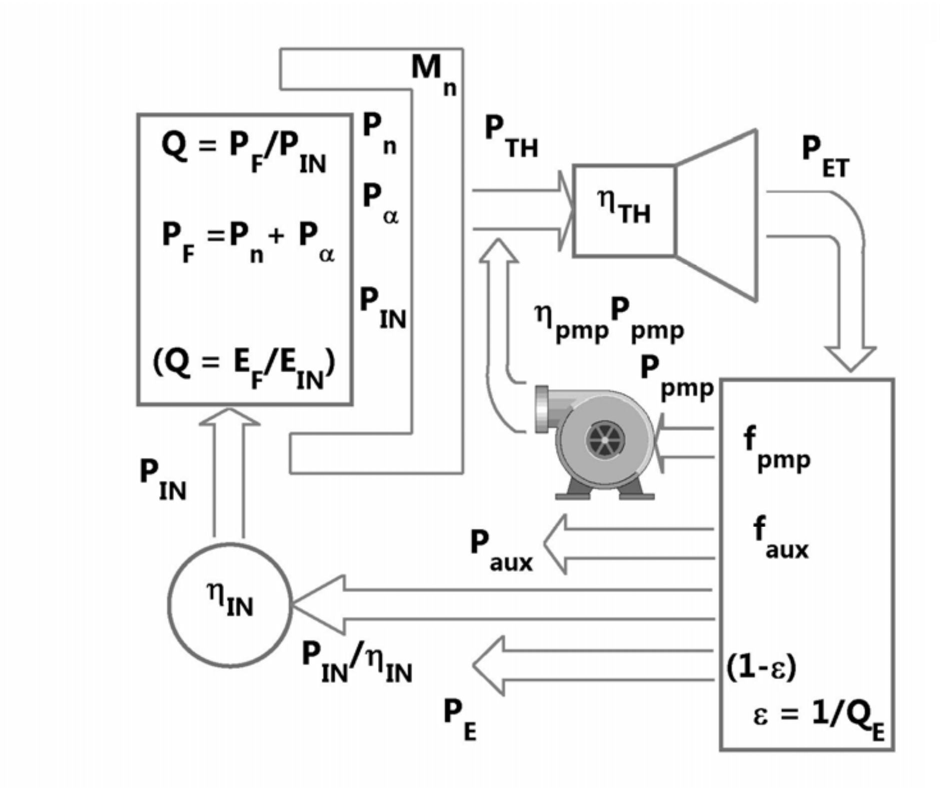
This section describes the conceptual FPC (Reactor Island), Turbine Island, and BOP structures, systems, and components.

4.1 Fusion Power Core (Reactor Island)

The methods used to develop the power balance, radial build, and main system parameters for each of the four fusion technologies are described in this section.

4.1.1 Power Balance

Figure 9 is a general power flow diagram for fusion systems. “Aux” refers to auxiliary or housekeeping systems. This diagram can be applied to steady systems or to pulsed systems wherein an energy storage reservoir (e.g., capacitor bank) is charged up by a power PIN during the dwell time between pulses and dumped into the FPC) target/plasma as an energy E_{IN}. The gain Q relates the fusion energy E_F released per pulse to the input energy E_{IN}. The recirculating power fraction, ε, is used here as a figure of merit (strictly, start-up power and P_{IN} may be components of site power not produced by the FPC itself). Exoergic reactions in the tritium producing blanket multiply the D-T neutron energy by a factor M_n = 1.1, typically. High efficiencies for input/driver systems, η_{IN}, or the thermal-to-electric conversion system, η_{TH}, allow lower values of Q. The four approaches under consideration in this study are pulsed (Q and repetition rate consistent with P_{TH} = 500 MWth).



P_f, Fusion Power
P_α, Alpha Fusion Power
P_n, Neutron Fusion Power
M_n, Neutron Energy Multiplier
P_{TH}, Thermal Power
η_{TH}, Thermal Conversion Energy
P_{ET}, Total (Gross) Electric Power
f_{pmp}, Pumping Power Fraction
f_{aux}, Auxiliary Power Fraction
η_{IN}, Input Power Efficiency
P_{IN}, Input Power
$Q = P_f / P_{IN}$, Scientific Q
ε, Recirculating Power Fraction
$Q_E = 1/\varepsilon$, Engineering Q
$P_E = (1 - \varepsilon)P_{ET}$, Output Power

Figure 9. Power Flow Diagram.

With certain distinctions, Figure 9 applies to both steady and pulsed FPPs. Input power, P_{IN}, is either continuously injected into the fusion reaction chamber or accumulated in an energy transfer and storage (ETS) device (e.g., capacitor bank or equivalent) and switched in in a pulsed fashion. The efficiency of the injection process is η_{IN} (wall plug to plasma). The efficiency, η_{IN}, is the product of η_{ETS} and the aggregated coupling efficiencies, η_C, stepping through the leads ending in plasma heating/compression.

The fusion energy gain in the continuous case is expressed in power terms as $Q = P_F/P_{IN}$ (fusion power/input power) or in the pulsed case as $Q = E_F/E_{IN}$ (fusion energy yield/input energy). Even in a pulsed system, the time-averaged P_F can be expressed. For a D-T fueled system, $P_F = P_n + P\alpha$, 14 MeV neutron plus 3.5 MeV alpha particle power. Small contributions from D-D and other fusion reactions are ignored here. Exoergic neutron interactions (involving tritium breeding in Li) in the blanket multiply the neutron power by a factor, $Mn \sim 1.1$, such that the useful thermal power is $P_{TH} = M_n P_n + P\alpha + P_{IN} + \eta_{pmp} P_{pmp}$, where the last term is a small contribution to the thermal power from the pump circulating the primary coolant.

The thermal power, P_{TH}, is converted to gross (total) electrical power, P_{ET}, by a turbine generator with efficiency, η_{TH}. Power needed to run the plant includes P_{IN}/η_{IN} plus P_{pmp} plus P_{aux} (auxiliary equipment, housekeeping, etc.). Although such power may come from the grid, it is a convenient figure of merit to define the recirculating power fraction as $\varepsilon = (P_{IN} / \eta_{IN} + P_{pmp} + P_{aux})/P_{ET}$, such that the remaining net electrical power, $P_E = (1 / \varepsilon)P_{ET}$, is available to output to the grid for sale. A net plant efficiency can be defined as $\eta_P = \eta_{TH}(1 - \varepsilon)$.

The fusion gain, Q, is defined in terms of the various efficiencies and other terms of the power flow diagram as

$$Q = \frac{1}{(0.2 + 0.8M_n)} \left[\frac{\left(\frac{1}{\eta_{TH}} - f_{pmp}\eta_{pmp}\right)}{\eta_{IN}(\epsilon - f_{pmp}\eta_{pmp} - f_{aux})} - 1 \right] \qquad (6)$$

Rearrangement of this equation allows for display of a design space in terms of η_{IN} and η_{TH} with isoquants of Q for the indicated fixed parameters. Higher efficiency values allow for lower values of Q.

With certain terms assumed as nominal values and a target recirculating power fraction taken to be $\varepsilon = 0.20$, a FPP design space can be defined in terms of thermal conversion efficiency, η_{TH}, and input (driver) efficiency, ε_{IN}, in order to display isoquants of the necessary value of fusion gain, Q. This design space is generalized; power terms do not appear explicitly, but once any specific power is selected, all other power terms are determined. The highest values of η_{IN} may be impractical and values of η_{TH} approaching 0.60 require advanced Brayton cycle technology.

The FPP design space is shown in Figure 10. With advanced thermal conversion features [Reference 24], including a Brayton cycle, η_{TH} can approach 0.60. A more conventional thermal cycle should yield η_{TH} in the range 0.40 - 0.45.

Figure 10 (located on the next page) depicts the reactor design space in terms of η_{IN} versus η_{TH} for the indicated fixed parameters. Contours of constant Q are shown indicating that for lower efficiencies (lower left corner) higher values of Q are required. This design space is generic (independent of specific powers cf. Figure 9). A lower target value for recirculating power fraction, ε, would require higher Q performance, all else being equal. A self-consistent design point must be determined.

The power balance parameters shown in Figure 10 were developed for each technology.

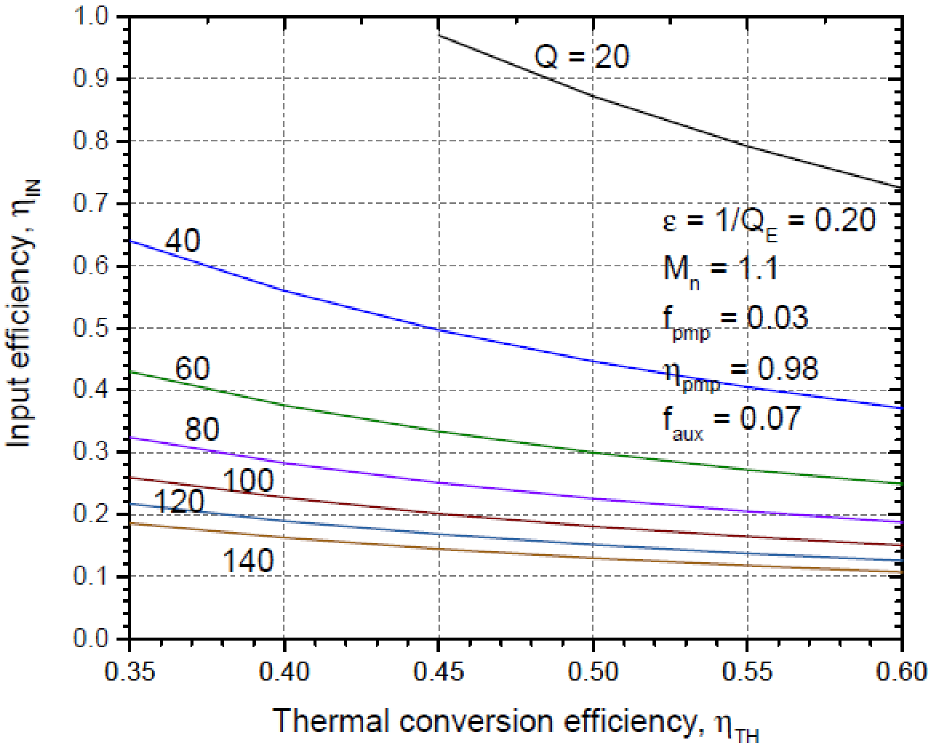


Figure 10. Power Balance Design Space.

4.1.2 Other Fusion Power System Parameters

The method for developing FPC design and costing was through the use of an analytic scaling model (excel) based for adiabatic compression and basic costing, and then developing individual systems analyses of the four reactor visions, per published systems analysis.

The fusion system parameters developed for each technology included:

- Radial Build

  Per ARIES methodology, the radial build was modeled analytically to determine volumes of first wall, blankets, shield, diverters, and coils. Volumetric fractions were used to determine composition and then cost factors applied to determine cost.

- Main System Parameters

  The following main system parameters were developed for each technology:

  - Fusion power (MW);
  - Neutron power (MW);
  - Thermal power (MW);
  - 1st wall surface area (m^2);
  - Plasma injection opening (m^2);

- — Neutron wall loading (MW/m^2);
- — Total wall loading (MW/m^2);
- — Mass of FPC (wet) (tons); and
- — Mass of FPC (dry) (tons).

CAD-generated renderings of each design and simplified diagrams of the main coolant system were also developed. The renderings for each design are shown on the cover of this report.

4.2 Electric Power Conversion (Turbine Island)

The Turbine Island for the FPP will include an electrical power conversion system for converting an estimated 500MWth power to a gross electric power of 150MWe similar to small modular reactor technology.

The turbine plant equipment will consist of a single-reheat Rankine steam cycle with a multi-stage feedwater heating system. The superheated steam from the fusion power heat transport system's steam generator is supplied to the turbine where it provides the motive power to the electric generator. The degree of superheat of the steam is compatible with the temperature gradient in the steam generator based on the operating temperature of the reactor coolant (Lead-Lithium, Pb-Li). The steam is condensed in the surface condenser and returned to the steam generators through a series of low pressure (LP) feedwater heaters, a deaerator, and high pressure (HP) feedwater heaters. Condensate extraction and feedwater pumps provide the flow of water from the condenser to the steam generator. The schematic arrangement of the steam/feedwater system is shown in Figure 11.

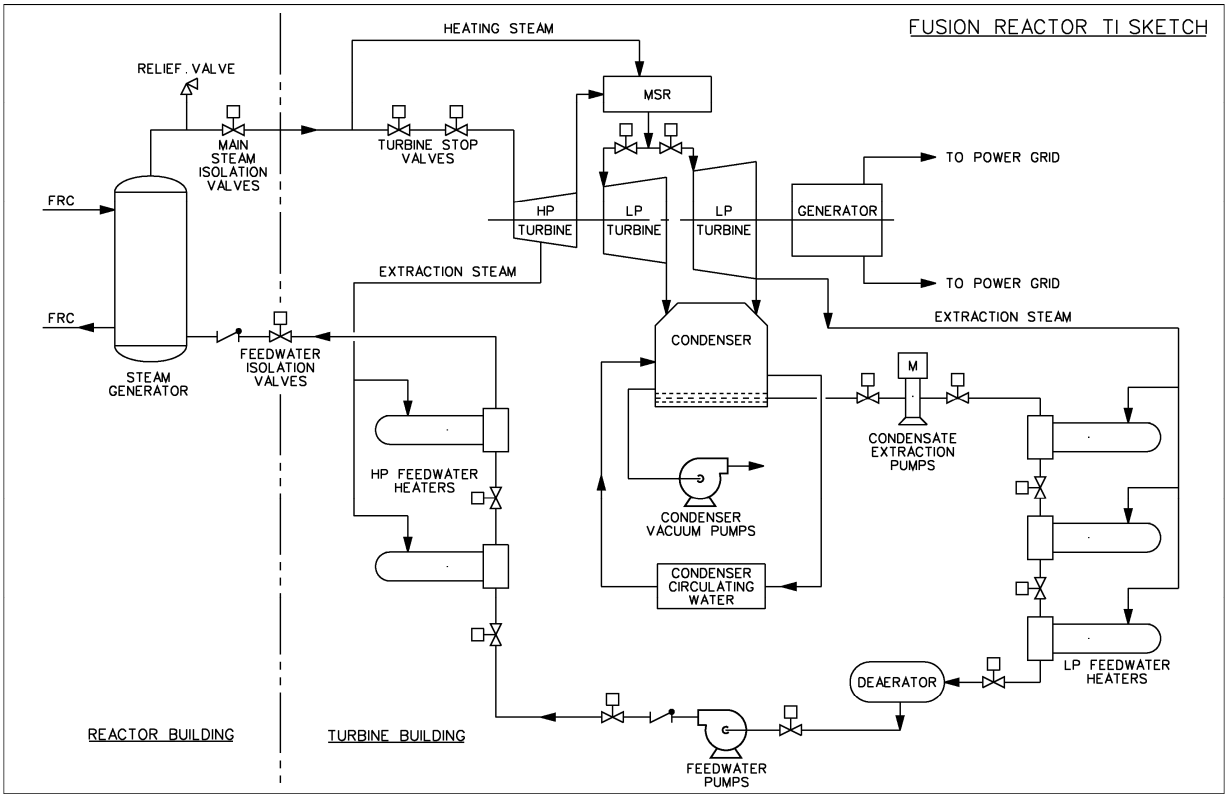


Figure 11. Schematic Arrangement of a Fusion Power Plant Turbine Island Steam/Feedwater System.

The electric power is produced at the 60 Hz cycle, and the electric power generated by the turbine generator is supplied to the power grid via the main step-up transformers and a 138kV switchyard. The turbine building will house all of the systems and equipment noted in the schematic arrangement. However, the major electrical equipment (e.g., switchgear and load centers) will be housed in an ancillary electrical building(s) adjacent to the turbine building.

The cost estimate bases for the Turbine Island includes the equipment and systems described in this section, along with associated piping, fittings, valves, structural supports, fire protection, lighting, and other miscellaneous components. The turbine building and electrical building structures consist of skin steel walls with a concrete structure for the turbine supports (table top) and condensers.

4.3 Ancillary and Support Systems (Balance of Plant)

The Balance of Plant (BOP) equipment provides support for the operation of the Fusion Island system and equipment, as well as the Turbine Island and associated energy conversion systems and equipment. The cost estimate for BOP includes the equipment and buildings associated with the systems and structures described in this section.

The cooling towers provide the ultimate heat sink for the condenser and service water cooling. The cooling towers will be mechanical draft (fans) rectangular cell-type towers. Additionally, the site is assumed to be located near a surface water source for makeup water needs of the plant.

BOP systems include:

- Condenser cooling water towers;
- Cooling tower makeup water intake;
- Cooling tower blowdown discharge;
- Fire water storage and distribution;
- Raw water storage and distribution;
- Demineralized water production/storage/distribution;
- Compressed gas (H_2/N_2/Ar);
- Plant switchyard;
- Main and auxiliary transformers;
- Standby power (diesel generators); and
- Service water system.

BOP structures include:

- Makeup water intake structure and pump house;
- Cooling towers;
- Plant water discharge structure;
- Fire water pump house;
- Demineralized water production facility;
- Compressed gas storage;

- Plant switchyard;
- Plant administrative building;
- Security/access buildings and sally port;
- Lab facility;
- Maintenance shop; and
- Parking lots.

Figure 12 provides a representative plant layout for the Fusion Island, Turbine Island, and BOP buildings and structures.

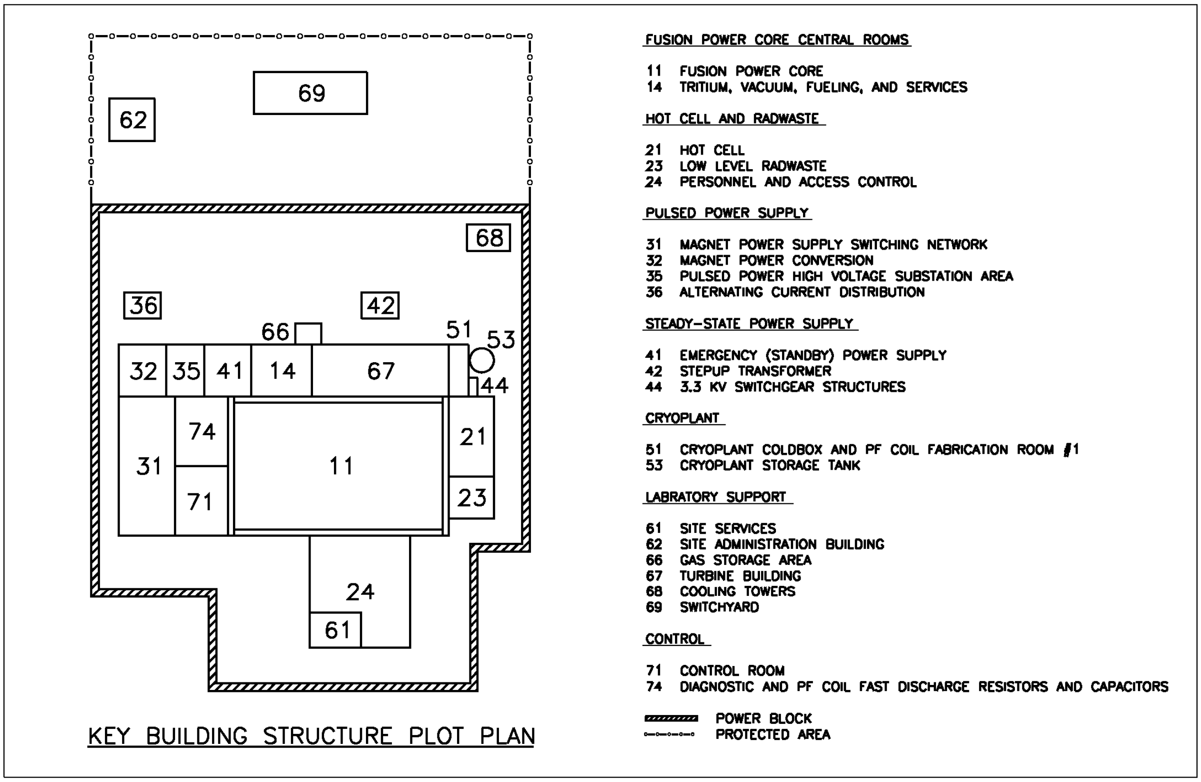


Figure 12. Representative Fusion Power Plant Layout.

5. Estimate Basis

This section describes the cost breakdown structure (CBS) and the bases and assumptions used in determining the conceptual costs.

5.1 Cost Breakdown Structure

The conceptual cost estimates for the four fusion technologies were categorized according to a common CBS to allow for a consistent evaluation of the capital costs associated with each technology. Table 4 provides a listing and description of each of the CBS elements and sub-elements used in developing the conceptual cost estimate.

Table 4. Cost Breakdown Structure

CBS #	Cost Element	Description
20	**Land & Land Rights**	Includes land and land rights to ensure adequate distance to site boundary in the event of a postulated release of radiation.
20.1	Land & Privilege Acquisition	
20.2	Relocation of Buildings, Utilities, Highways, etc.	
21	**Structures & Site Facilities**	Includes site improvement and facilities, fusion buildings, turbine building, cooling structures, power supply and energy storage buildings, and miscellaneous buildings.
21.1	Site Improvements & Facilities	
21.2	Reactor Building	
21.3	Turbine Building	
21.4	Cooling Tower Systems	
21.5	Power Supply & Energy Storage Building	
21.6	Miscellaneous Buildings	
21.7	Ventilation Stack	
22	**Reactor Plant Equipment**	
22.1	Reactor Equipment	Includes first wall (liquid metal), outer high temperature shield, primary structure and support, vacuum system for pump out between shots, power supplies (banks and charging supplies) for energizing plasma, and electrodes.
22.2	Main Heat Transfer & Transport Systems	Includes lead-lithium coolant as primary coolant and water as secondary coolant.
22.3	Auxiliary Cooling Systems	Includes auxiliary cooling system.
22.4	Radioactive Waste Treatment & Disposal	Includes radioactive waste treatment facility.
22.5	Fuel Handling & Storage Systems	Includes fuel processing system, fuel storage, atmospheric tritium recovery and water detritiation system.
22.6	Other Reactor Plant Equipment	Includes other reactor plant equipment.
22.7	Instrumentation & Control	Includes I&C system.
23	**Turbine Plant Equipment**	Consists of turbine generator, main steam system, heat rejection system, condensing system, feedwater system, instrumentation and controls, other turbine plant
23.1	Turbine Generator(s)	
23.3	Condensing Systems	

Table 4. Cost Breakdown Structure

CBS #	Cost Element	Description
23.4	Feed Heating System	equipment, and all associated BOP systems and equipment.
23.5	Other Turbine Plant Equipment	
23.6	I&C Equipment	
23.7	Miscellaneous Turbine Generator Equipment	
24	**Electric Plant Equipment**	Includes switchgear, station service equipment, switchboards, protective equipment, electrical raceways, wiring containers, power and control wiring, and electrical lighting.
24.1	Switchgear	
24.2	Station Service Equipment	
24.3	Switchboards (including heat tracing)	
24.5	Electrical Structures & Wiring Containers	
24.6	Power & Control Wiring	
24.7	Electrical Lighting	
25	**Miscellaneous Plant Equipment**	Includes transportation and lifting equipment, air and water service system, communications equipment, and furnishing and fixtures.
26	**Heat Rejection**	Includes heat exchangers, water pumps, and piping to remove waste heat from the condenser and reject the heat at the cooling tower.
27	**Special Materials**	Includes the reactor liquid metal coolant/breeder, intermediate coolant, turbine cycle working fluids, reactor building cover gas, and other miscellaneous items.
90	**Direct Cost**	Total capital costs from CBS 20 through 27.
Indirect Costs		
91	**Construction Services & Equipment**	Includes temporary facilities and equipment required to install permanent facilities.
92	**Home Office Engineering & Services**	Includes cost required to perform the engineering work for the permanent facilities and systems.
93	**Field Office Engineering & Services**	Includes cost required to perform the field engineering support work for the permanent facilities and systems.
94	**Owner's Costs**	Includes owner's costs to support the miscellaneous expenses required to execute the project.
95	**Process Contingency**	Includes costs to cover the process uncertainties.
96	**Project Contingency**	Includes costs to cover the project uncertainties.
97	**Interest During Construction**	Not included because this is an overnight cost estimate.
98	**Escalation During Construction**	Not included because this is an overnight cost estimate.
99	**Total Overnight Project Costs**	Sum of direct and indirect costs.

5.2 Estimate Bases and Assumptions

Due to the limited amount of engineering and design information currently developed for these technologies, the conceptual cost estimate developed in this study is classified as Class 5, Concept Screening, as defined by the cost engineering standards organization, AACE International [Reference 59]. According to the standard, Class 5 estimates are generally prepared on limited information (i.e., engineering design is from 0% to 2% complete) and subsequently have fairly wide accuracy ranges. They are typically used to help to define / determine items such for project screening, project feasibility, concept evaluation, and preliminary budget approval. Typically, Class 5 estimates are comprised of engineering documents such as plant capacity, block schematics, and indicated layout.

The bases and assumptions used to develop the Class 5 conceptual cost estimate for the four fusion technologies are as follows:

1. The FPC is 10th-of-a-kind and the BOP is nth-of-a-kind.
2. Modular design and factory construction of all subsystems is possible.
3. Indirect costs are estimated as a percentage of direct costs, based on publicly available DOE studies.
4. Contingency is included commensurate with a Class 5 estimate classification.
5. This is an overnight cost estimate based on December 2016 U.S. dollars. Thus, no interest expenses (CBS 97) or escalation (CBS 98) are included. Reference 60 defines an overnight cost as “a measurement of capital investment that excludes any interest expense or escalation of costs that may occur during the construction period, as if the project had literally been built overnight.”
6. The Turbine Island and BOP design and costing information is based on a scalable comparison to the gross electric output power of similar size nuclear power plants, cost / capacity curves, and other parametric and modeling techniques as follows:
   - Civil work is based on buildings with sizes, areas, and volumes comparable to the reference plant;
   - Mechanical work is based on an equipment list for systems with capacities and ratings of a 150MWe power output;
   - Piping work is based on a systems list with sizes and types of material required for the project;
   - Electrical work is based on an equipment list for systems with capacities and ratings of a 150MWe power output; and
   - Electrical bulks such as raceways and power / instrumentation cables are based on a reference plant.
7. Publicly available data was used to the extent possible for the development of parametric cost factors and other system pricing.
8. FPC equipment, materials, systems, etc. are based on evaluations using proprietary data provided by each of the technology developers.
9. The reactor and its supporting equipment are located in the reactor building.

10. Turbine Island and BOP estimates are based on Bechtel proprietary cost data (underlying data is not included).
11. The reactor coolant system operates in a vacuum condition which results in no high loss of coolant accident (LOCA) pressures or temperatures in the reactor building.
12. The shield structure around the FPC provides protection from neutrons and any equipment susceptible to neutron activation will be located outside the shield.

6. Cost Estimate Summary

6.1 Overnight Cost Estimate

The cost model was developed based on the limited level of detail available on the FPP conceptual designs and selected parametric and sensitivity studies of key cost drivers (e.g., fusion vessel thickness).

The method used to develop the cost model with the available FPC design was the development of an analytic scaling model (excel) based for adiabatic compression and use of basic costing parameters. Then, individual systems analyses on the four technologies were performed per published systems analysis.

The BOP systems and structures design and costing is based on Bechtel historical data for previous power plant designs and similar systems and structures, adjusted as needed for the heating power, power output, and the pre-conceptual design information available from the developers. A single BOP layout and structure concept was developed that is representative for all four technologies and a single, generic site.

A graphical representation of the cost estimate model and sources is provided in Figure 13.

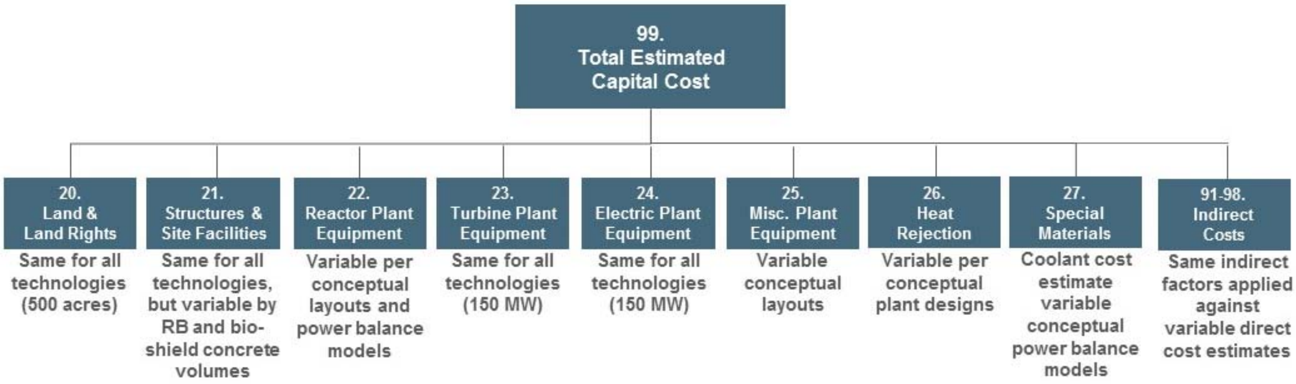


Figure 13. Cost Estimate Model and Sources.

Table 5 (located on the next page) provides the cost estimate summary broken down by CBS cost elements for the engineering, procurement, construction, and commissioning of an approximately 150 MWe FPP. The costs are presented in a range that encompasses all four technologies (note that some costs are the same regardless of technology used). The cost distribution by major CBS elements is presented in Table 6 (located on page 27). Key results are:

- The total estimated overnight cost for this Class 5 estimate ranges from \$701 million to \$1.925 billion in 2016 USD based on each technology’s various engineering parameters. The average estimated overnight cost is approximately \$1.313 billion.
- Three direct cost categories are the largest contributors to the total estimated direct cost. CBS 21, Structures & Site Facilities, accounts for 11% to 15% of the total estimated costs; CBS 22, Reactor Plant Equipment, accounts for 15% to 24% of the total; and CBS 23, Turbine Plant Equipment, accounts for 8% to 14% of the total.

- Direct costs are 54% to 55% of the total estimate and indirect costs are 45% to 46% of the total.

There is a wide range of estimated costs for CBS 21.2 (Reactor Building), CBS 22.1 (Reactor Equipment), and CBS 22.2 (Main Heat Transfer & Transport Systems). This range is a result of the differences in the four fusion power technologies and the uncertainty in the FPC designs and heat exchanging systems. Estimated costs for CBS 22.5 (Fuel Handling and Storage Systems) are based on the uncertainty in tritium handling system designs and estimated costs as described further in Section 7.

Table 5. Cost Estimate Summary Range of Four Fusion Power Plant Technologies

		Estimated Overnight Cost ($M) (2016 USD)	
CBS #	Cost Element	Low	High
20	**Land & Land Rights**	**$13**	**$21**
20.1	Land & Privilege Acquisition	$11	$18
20.2	Relocation of Buildings, Utilities, Highways, etc.	$2	$3
21	**Structures & Site Facilities**	**$106**	**$218**
21.1	Site Improvements & Facilities	$2	$5
21.2	Reactor Building	$7	$55
21.3	Turbine Building	$17	$27
21.4	Cooling Tower Systems	$6	$10
21.5	Power Supply & Energy Storage Building	$8	$13
21.6	Miscellaneous Buildings	$66	$107
21.7	Ventilation Stack	$1	$1
22	**Reactor Plant Equipment**	**$106**	**$464**
22.1	Reactor Equipment	$16	$287
22.2	Main Heat Transfer & Transport Systems	$55	$120
22.3	Auxiliary Cooling Systems	$1	$1
22.4	Radioactive Waste Treatment & Disposal	$2	$3
22.5	Fuel Handling & Storage Systems	$30	$49
22.6	Other Reactor Plant Equipment	$2	$3
22.7	Instrumentation & Control	$1	$1
23	**Turbine Plant Equipment**	**$95**	**$155**
23.1	Turbine Generator(s)	$22	$36
23.3	Condensing Systems	$2	$4
23.4	Feed Heating System	$5	$8
23.5	Other Turbine Plant Equipment	$18	$30
23.6	I&C Equipment	$13	$21
23.7	Miscellaneous Turbine Generator Equipment	$34	$56

Table 5. Cost Estimate Summary Range of Four Fusion Power Plant Technologies

CBS #	Cost Element	Estimated Overnight Cost ($M) (2016 USD) Low	Estimated Overnight Cost ($M) (2016 USD) High
24	**Electric Plant Equipment**	**$35**	**$57**
24.1	Switchgear	$7	$12
24.2	Station Service Equipment	$12	$20
24.3	Switchboards (including heat tracing)	$2	$3
24.5	Electrical Structures & Wiring Containers	$6	$10
24.6	Power & Control Wiring	$6	$10
24.7	Electrical Lighting	$2	$3
25	**Miscellaneous Plant Equipment**	**$17**	**$56**
26	**Heat Rejection**	**$11**	**$25**
27	**Special Materials**	**$1**	**$36**
90	**Direct Cost**	**$385**	**$1,032**
	Indirect Costs		
91	**Construction Services & Equipment**	**$56**	**$151**
92	**Home Office Engineering & Services**	**$18**	**$51**
93	**Field Office Engineering & Services**	**$38**	**$101**
94	**Owner's Costs**	**$18**	**$51**
95	**Process Contingency**	**$87**	**$329**
96	**Project Contingency**	**$98**	**$211**
97	**Interest During Construction**	Not Included	Not Included
98	**Escalation During Construction**	Not included	Not included
91-96	**Total Indirect Costs**	**$316**	**$893**
99	**Total Overnight Project Costs**	**$701**	**$1,925**

Table 6. Cost Distribution by Major CBS Element

CBS #	Cost Element	Cost as % of Total Project Cost	
		Low	High
20	Land & Land Rights	2%	1%
21	Structures & Site Facilities	15%	11%
22	Reactor Plant Equipment	15%	24%
23	Turbine Plant Equipment	14%	8%
24	Electric Plant Equipment	5%	3%
25	Miscellaneous Plant Equipment	2%	3%
26	Heat Rejection	2%	1%
27	Special Materials	<1%	2%
90	**Total Direct Costs**	**55%**	**54%**
91-96	Total Indirect Costs	45%	46%
99	**Total Overnight Project Costs**	**100%**	**100%**

6.2 Sensitivity/Parametric Analyses

As shown in Table 5, CBS 22, Reactor Plant Equipment, is a significant percentage of the total estimated FPP costs. Sensitivity analyses were performed for this CBS for each technology in three main areas—FPC materials cost, radial build costs, and primary power system. The sensitivity analyses were performed by varying costs by a factor from 0.25 to 5 and determining the impact of the costs on the total estimated project cost.

The results of the sensitivity analyses show:

- The total estimated FPP cost is relatively insensitive to changes in FPC materials costs because (1) large changes in the market price of bulk materials costs are rare, and (2) FPC components are a small fraction of the total plant.
- Varying the radial build costs (consisting of the first wall, shield, and blanket) would result in only small changes the total estimated FPP cost.
- There is significant uncertainty in the conceptual design of the primary power system and this could result in impacts on the total estimated FPP cost.

6.2.1 Materials Cost Sensitivity

The impact on estimated total project costs for variations in FPC material cost was assessed by varying FPC materials costs by a factor of 0.25 to 5. The materials include steels used for the high temperature shield (HTS), lead-lithium primary coolant used in the outer blanket (OB) and tungsten first wall (FW) components. The results are shown in Figure 14 (located on the following page). This cost variation may result from a shift in market price for bulk materials, although it is rare that such large swings in material costs occur. The plot shows that the estimated total project cost remains somewhat insensitive to the materials costs primarily because these are used only in some components of the FPC, which itself is only a small fraction of the total project estimated cost.

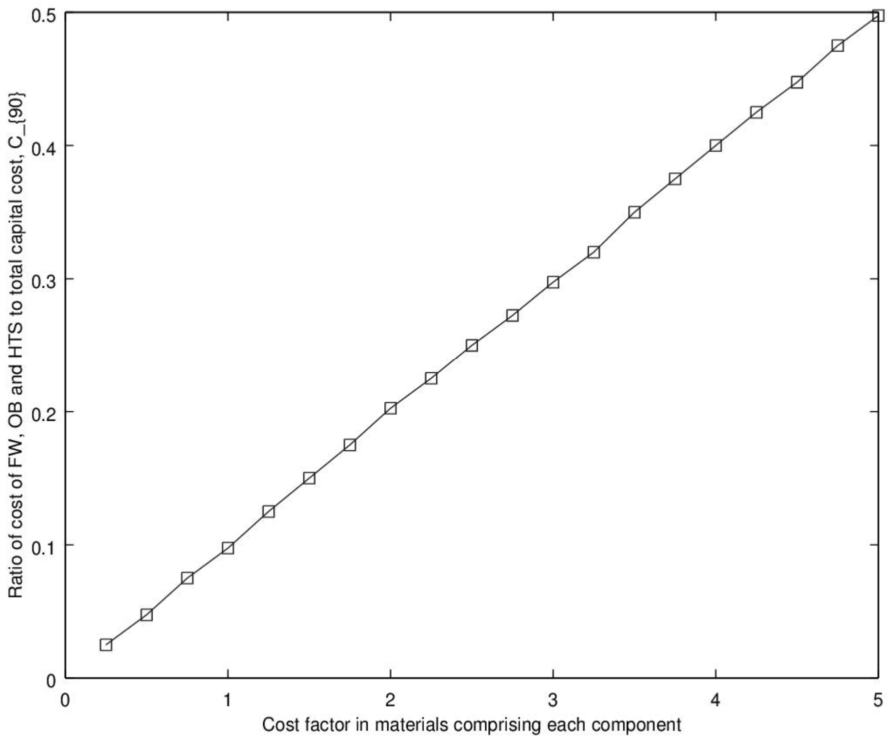


Figure 14. Cost of Components—First Wall (o), Blanket (*), and Shield (+)—Versus Cost Factor Applied to Materials Used to Manufacture Components.

6.2.2 Radial Build Sensitivity

The impact on estimated total project costs for variations in radial build costs was assessed by varying the total cost of the first wall, shield, and blanket by factors of 0.25 to 5, as shown in Figure 15 (located on the following page). This cost study was performed prior to any neutronics analysis of the FPC components and an optimization of the FPC components may be possible by reducing the total mass of the materials needed (perhaps by halving the thickness of the HTS). As shown in Figure 15, even if radial build costs are varied over a large range, the total estimated project cost is relatively insensitive to costs of components in the FPC, mainly because these costs (CBS 22.2) are themselves only a small fraction of the total project cost.

6.2.3 Power Supply Sensitivity

The impact on estimated total project costs for the impact of power supply costs (CBS Category 22.1.7) was assessed by varying the total costs by factors of 0.25 to 5, as shown in Figure 16 (located on the following page). This was performed because prior to any detailed electrical engineering of the power systems, this cost has some uncertainty. Figure 16 shows the ratio of the power supply costs to total capital costs as a function of the cost factor.

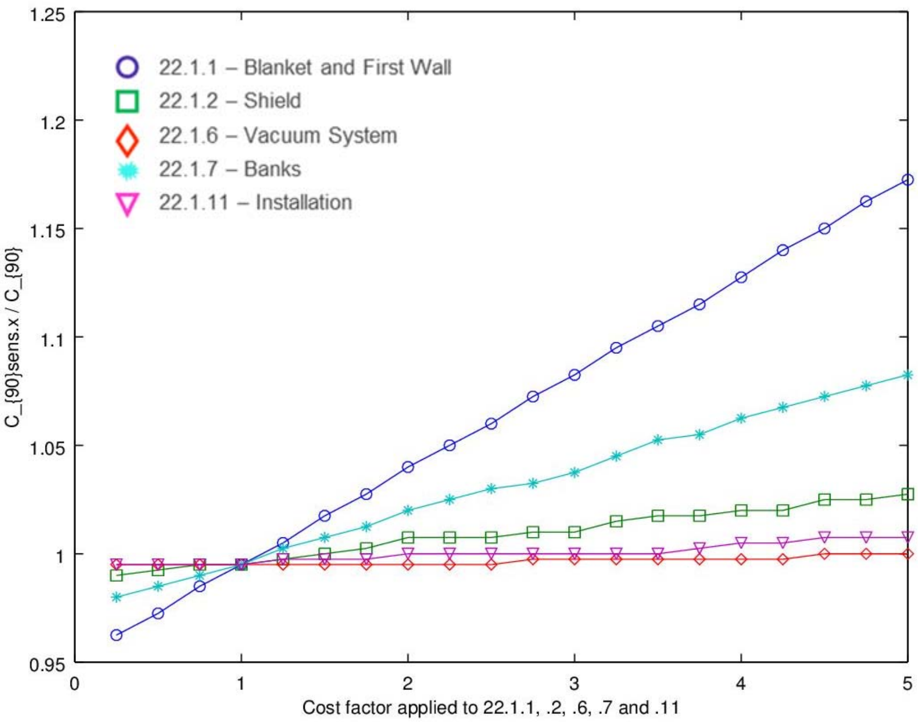


Figure 15. Ratio of Total Capital Costs When Costs Are Varied (in Cost Categories 22.1.1, 22.1.2, 22.1.6, 22.1.7, and 22.1.11) to Total Capital Cost When Costs Are Fixed.

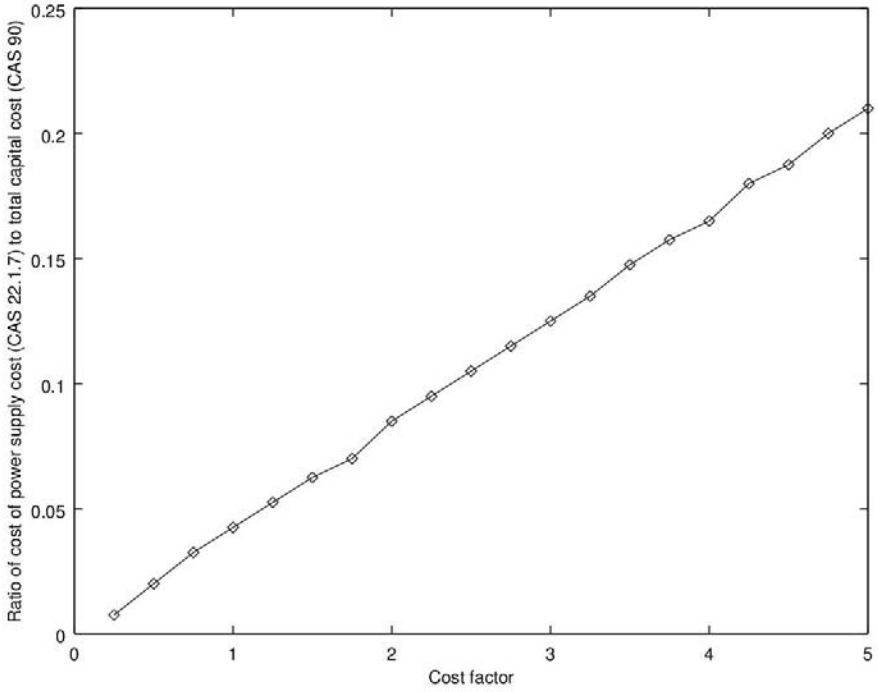


Figure 16. Ratio of Power Supply Costs (Cost Category 22.1.7) to Total Project Cost as a Function of Cost Factor.

6.3 Scaling

As described in a 2011 study by the Nuclear Energy Agency (NEA) [Reference 61], the overnight capital cost per MWe of installed capacity has historically been shown to be reduced as the size of nuclear power plants are increased. “This is due to economies of raw materials and optimization that could be realised while building larger reactors” [Reference 61].

Reference 61 identifies a scaling function for assessing this:

$$\text{Cost (Plant 1)} = \text{Cost (Plant 2)} \times (\text{Plant 1/Plant 2})^{n} \qquad (7)$$

The scaling factor, n, for small modular reactors is described as in the range of 0.4 to 0.7 when the plant size increases from 300 MWe to 1300 MWe for the entire plant. In another study [Reference 62], a mean scaling factor of 0.59 is identified for small modular reactors.

According to the NEA study, the use of a scaling factor is appropriate only when no significant design changes take place on transition to a larger or smaller size plant. And, the scaling may be limited if there are physical limitation to increase dimensions of some systems or components (e.g., reactor core, fuel rods, and turbine blades). Different plant components or systems may require very different scaling factors.

No FPP has yet been constructed and there is no experience or historical cost data at this time to support the development of an appropriate scaling factor or set of scaling factors for FPPs. Further, the results of this conceptual cost study for the four fusion reactor pre-conceptual designs are Class 5 cost estimates with a wide range. These estimates and the underlying FPC and associated systems designs are not adequately developed and detailed at this time to be used for scaling up the estimated overnight costs to potential larger capacity plants (e.g., in the 1 GWe range). Additional analysis and design on the FPCs and associated systems is needed to develop more precise overnight capital cost estimates before appropriate scaling factor(s) could be developed and applied.

7. Other Costs

Other cost items necessary for the operation of a commercial FPP were assessed as part of this study including tritium plant capital cost, start-up tritium cost, annual operations and maintenance (O&M) cost, Decommissioning cost, and annual waste disposal cost.

These other costs for a conceptual commercial FPP are highly uncertain because the four fusion technologies studied are still in the early development stage and have yet to reach the requisite design maturity for commercialization. Additionally, no commercial FPP has been built or operated. Therefore, no actual historical construction or operational cost data are available to serve as the baseline for these other cost estimates.

The cost data used in this study are taken from several preliminary conceptual pilot / demonstration fusion reactor and FPP design reports and papers. These cost data are mostly decades-old gross cost estimates and were adjusted to 2016 USD.

7.1 Tritium Plant Capital Cost

The shortage of external tritium sources for FPPs using the deuterium-tritium process necessitates the breeding of tritium in the fusion process. The initial start-up of a full size commercial FPP requires several kilograms of tritium, and its continued operation requires a large supply of tritium that would incur a significant annual operating fuel cost. In reality, operation of the International Thermonuclear Experimental Reactor (ITER) and emerging commercial FPPs would quickly consume all of the known tritium supplies in a short time. Thus, it is not considered feasible for a commercial FPP to rely on an external tritium supply. Therefore, it is prudent for D-T type commercial FPP designs to include a tritium plant system in order to provide a self-sustaining tritium supply.

Publicly available cost study reports and technical papers related to FPP tritium plants were collected and reviewed. These reports and papers provided a number of conceptual capital cost estimates for several different fusion reactor designs, including STARFIRE, ARIES, and ITER. These FPP tritium plant capital cost estimates are listed in Table 7. Only the STARFIRE and Generomak estimates provide breakdowns for conceptual systems and subsystems.

In order to establish a supportable basis for this tritium plant conceptual capital cost estimate, these existing conceptual cost data were first adjusted to 2016 USD using the U.S. Department of Labor Bureau of Labor Statistics CPI Inflation Calculator and scaled to the standard FPP net electricity output of 150 MWe. The net electricity output scaling is calculated using the following equation with a power factor of 0.55 (close to a square root):

$$\text{FPP Cost} = \text{Published Conceptual Cost x (Conceptual Plant Output/150 MWe)}^{0.55} \qquad (8)$$

Based on this equation, the scaled FPP conceptual tritium plant capital costs are tabulated in the far right column of Table 7. Note that all the identified conceptual FPP designs are tokamak type design, while the four conceptual FPP designs evaluated in this conceptual cost study are non-Tokamak type concepts, including two different Z-Pinch concepts, one plasma jet magneto-inertial concept, and one stabilized liner compression concept. The Tokamak type blanket design is normally bigger in size than the non-tokamak type blanket design. Therefore, the application of the available conceptual tritium plant capital cost data to these four non-Tokamak type FPP designs would be conservative.

Table 7. Fusion Power Plant Tritium Plant Capital Costs

Fusion Reactor Design	Capital Costs	Capital Costs (2016 USD) [Reference 63]	Capital Costs Scaled to 150 MWe (2016 USD)
STARFIRE (1200 MWe) [Reference 64]	\$38.6 M (1980 USD)	\$112.43 M	\$35.82 M
Generomak – ESECOM* (1200 MWe) [Reference 65]	\$60.5 M (1986 USD)	\$132.49 M	\$42.22 M
ARIES-1 (1000 MWe) [Reference 66]	\$43.0 M (1980 USD)	\$125.25 M	\$44.12 M
ESECOM-He/Li2O* (1200 MWe) [Reference 67]	\$58.0 M (1980 USD)	\$168.94 M	\$53.83 M
ESECOM-V/Li* (1200 MWe) [Reference 67]	\$112.0 M (1980 USD)	\$326.22 M	\$103.95 M
Magnetic Fusion Production Reactor (336 MWe) [Reference 68]	\$45.0 M (1979 USD)	\$148.76 M	\$95.47 M
ITER (500 MW_{fusion} = 150 MWe) [Reference 68]	\$36.6 M or 36.6 kIUA (1989 USD)	\$70.84 M	\$70.84 M
Magnetic Fusion Production Reactor (336 MWe) [Reference 69]	\$45.0 M (1982 USD)	\$111.92 M	\$71.82 M
HYLIFE-II (1000 MWe) [Reference 70]	\$4.6 M (1988 USD)	\$9.33 M	\$3.29 M

** ESECOM = Senior Committee on Environmental Safety and Economics of Magnetic Fusion Energy*

For the ITER fusion reactor, there is no net electricity output since it is not a full size commercial electricity generation fusion plant. It is assumed that the 500 MW_{fusion} fusion power output would translate into 150 MWe electrical output in this study.

The STARFIRE and Generomak reports provide a breakdown of the conceptual cost estimates for tritium plant subsystems. The cost breakdowns are provided in Table 8 for these two conceptual FPP designs.

Table 8. STARFIRE and Generomak Sub-System Cost Breakdown

Cost Code	Sub-System	STARFIRE (1980 USD) [Reference 64]	Generomak (1986 USD) [Reference 71]
22.05.00.00	Fuel Handling & Storage Systems (Total)	\$38.6 M	\$60.5 M
22.05.01.00	Fuel Purification Systems	\$8.8 M	\$11.7 M
22.05.02.00	Liquefaction	Included in 22.05.01	Included in 22.05.01
22.05.03.00	Fuel Preparation Systems	\$0.3 M	\$0.5 M
22.05.04.00	Fuel Injection	\$1.4 M	\$0.9 M
22.05.05.00	Fuel Storage	\$2.0 M	\$2.7 M
22.05.06.00	Tritium Extraction and Recovery	\$5.4 M	\$7.1 M
22.05.07.00	Atmospheric Tritium Recovery System	\$20.7 M	\$27.6 M

Considering the level of detail presented in the STARFIRE design and the lack of supportable conceptual design details presented in other fusion reactor designs, the STARFIRE capital cost estimate of $35.8 M (2016 USD) was selected as the standard 150 MWe FPP tritium plant conceptual capital cost for this study. Table 6 above presents the conceptual capital cost range of a 150 MWe FPP tritium plant is $3.3 M to $104 M (2016 USD) based on previous designs and studies. However, applying the Tokamak type sub-system cost breakdown presented in Table 8 above to the four non-Tokamak type FPP designs is not recommended.

It is also noted that:

- All four non-Tokamak FPP designs may require a more simplified tritium plant;
- The STARFIRE tritium plant conceptual cost estimate is conservative; and
- Not all the tritium plant subsystems or equipment are scalable in size or cost.

For the FPP designs evaluated in this study which may require more than one module to achieve a 150 MWe total new electricity output, an individual module-specific tritium plant is recommended.

7.2 Start-Up Tritium Cost

The start-up of a commercial D-T FPP will require the introduction of a pure deuterium-deuterium (D-D) process to test the reactor, systems, components, and equipment. The cost of deuterium fuel is much lower than tritium and has a negligible impact of the overall FPP operating cost. As an advantage, the D-D process would breed a small quantity of tritium during the start-up testing phase—this small quantity of tritium would only meet a small portion of the plant’s start-up tritium needs [Reference 71].

If a commercial FPP uses the D-D process to accumulate the quantity of tritium required for plant start-up, it would take approximately one year to accumulate a tritium supply for one full power day of full power operation of a 2400 MW FPP with the acknowledged tritium breeding ratio of 1.1 and burn-up fraction of 20% [Reference 71]. This approach would require the FPP to pay for O&M costs without any electricity generated, resulting in no revenue during the pre-operational accumulation period. The annual tritium consumption of a 1000 MW_{fusion} FPP is approximately 55.6 kg per full power year or 152 grams per full power day [Reference 71]. It may be more economical to buy the quantity of tritium needed for starting up the FPP for full operation and generate electricity for revenue.

The latest ITER tritium plant [Reference 31] is designed to produce tritium with a throughput (unused tritium output from internal breeding process) of approximately one kg per hour. It is assumed that 10 to 15% of the tritium throughput would be required to begin the D-T breeding process. The required start-up tritium quantity would be 150 grams for the 500 MW_{fusion} ITER FPP. The introduction of the initial tritium quantity would kick start the D-T process. During the introduction of start-up tritium fuel into the fusion reactor, some tritium would end up in permeable spaces in the blanket. Therefore, a quantity of 200 grams of start-up tritium is recommended for a standard 150 MWe FPP.

Due to its scarcity, tritium costs $109,570 to $169,570 per gram in 2016 USD [Reference 64]. Therefore, the one-time start-up tritium cost ranges from $22 M to $34 M (2016 USD) for a standard 150 MWe FPP.

7.3 Annual Operations and Maintenance Costs

Publicly available FPP annual O&M-related cost study reports and technical papers have been collected and evaluated. These reports and papers provide a number of annual O&M cost estimates for several different fusion reactor designs, including STARFIRE, ARIES, and ITER. As shown in Table 9, these past O&M cost estimates are adjusted to 2016 USD using an inflation calculator [Reference 63] and scaled to the standard FPP electricity output of 150 MWe (except for those O&M costs estimated in mills per kWh). The electricity output scaling is calculated using Equation (8). The scaled FPP O&M costs are tabulated in the right-hand column of Table 9.

Table 9. Fusion Power Plant Annual Operations and Maintenance Costs

Fusion Reactor Design	Annual O&M Cost	O&M Cost (2016 USD) [Reference 64]	O&M Cost Scaled to 150 MWe (2016 USD)
STARFIRE (1200 MWe) [Reference 68]	$19.4 M (1980 USD)	$56.51 M	$18.01 M
Generomak – ESECOM (1200 MWe) [Reference 65]	$8.9 mills/kWh (1986 USD)	$19.49 mills/kWh	NA
ARIES-1 (1000 MWe) [Reference 66]	$11.0 M (1980 USD)	$32.04 M	$11.29 M
ESECOM-He/Li2O* (1200 MWe) [Reference 66]	$2.0 M (1980 USD)	$5.83 M	$1.86 M
ESECOM-V/Li* (1200 MWe) [Reference 66]	$3.0 M (1980 USD)	$8.74 M	$2.78 M
Magnetic Fusion Production Reactor (336 MWe) [Reference 67]	$68.0 M (1979 USD)	$224.8 M	$144.26 M
ITER (500 MW_{fusion} = 150 MWe) [Reference 68]	$188 M (1989 USD)	$363.88 M	$363.88 M
ARIES I/II/III/IV (1000 MWe) [Reference 74]	7.5 or 9.2 mills/kWh (1995 USD)	11.81 or 14.49 mills/kWh	NA
Magnetic Fusion Production Reactor (336 MWe) [Reference 69]	$41.0-67.0 M (1982 USD)	$101.97 - $166.64 M	$65.44 M - $106.94 M
Generic Magnetic Fusion Reactor (1000 MWe) [Reference 69]	$99 M (2016 USD)	$99 M	$34.9 M
Generic Magnetic Fusion Reactor (1200 MWe) [Reference 70]	$49.1 M (1983 USD)	$118.32 M	$37.7 M
HYLIFE-II (1000 MWe) [Reference 70]	2.24¢/kWh (1988 USD)	4.54¢/kWh	NA
Small Modular Reactors (335MWth) [Reference 77]	7.1 - 36.2 $/MWh (2014 USD)	7.2 – 36.7 $/MWh	NA

Two of the published reports [References 64, 76] provide a breakdown of cost items for annual commercial FPP O&M activities. These cost items include staffing, supplies, equipment, services, general and administrative, coolant makeup, process material, fuel handling, and miscellaneous items.

Considering the more robust design and cost details presented in the STARFIRE design and the lack of supportable conceptual design details presented in other fusion reactor designs, the study authors give credence to the STARFIRE O&M estimate of $18.1 M per year (2016 USD). Since the Generic Magnetic Fusion Reactor designs and cost estimates were based on the STARFIRE data, credence is also given to these estimated O&M costs, which are $34.9 M and $37.9 M per year, respectively (2016 USD).

Hence, for this conceptual FPP cost study, an O&M cost range of $18 M to $38 M per year for a standard 150 MWe FPP is indicated. A small modular reactor O&M cost is provided for comparison.

7.4 Annual Waste Disposal Cost

Only two reports were found to mention annual waste disposal cost for a conceptual commercial FPP [References 65, 76]. The cost estimates presented in these reports are based on the same cost data for the standard commercial light water reactor NPP cost estimate of one mill per kWh. This annual cost estimate is conservative because NPP waste disposal requirements are expensive due to the type of waste produced, its higher volume, and the complex, stringent regulations surrounding its disposal.

The recent light water reactor NPP waste disposal cost of 5% of Total Cost of Electricity (TCOE) generated is provided in Table 10 for comparison purpose.

Table 10. Fusion Power Plant Waste Disposal Costs

Reactor Design	Annual Waste Disposal Cost
Generic Magnetic Fusion Reactor (1200 MWe) [Reference 69]	1 mill/kWh (1983 USD)
Generomak (1200 MWe) [Reference 63]	1 mill/kWh (1986 USD
Light Water Reactor [Reference 75]	~5% of TCOE generated

7.5 Decommissioning Cost

Publicly available FPP decommissioning-related cost study reports and technical papers have been collected and evaluated. These reports and papers provide a number of decommissioning cost estimates for several different fusion reactor designs, including Tokamak Fusion Test Reactor (TFTR), Generic Magnetic Fusion Reactor (STARFIRE), ARIES, and ITER. As shown in Table 11, these past decommissioning cost estimates are adjusted to 2016 USD using an inflation calculator [Reference 63] and scaled to the standard FPP electricity output of 150 MWe (except for those decommissioning costs estimated in mills per kWh). The electricity output scaling is calculated using Equation (6). The scaled FPP O&M costs are tabulated in the right-hand column of Table 11.

Table 11. Fusion Power Plant Decommissioning Costs

Reactor Design	Decommissioning Cost	Decommissioning Cost (2016 USD) [Reference 63]	Decommissioning Cost Scaled to 150 MWe (2016 USD)
TFTR (51 MWth = 17 MWe) [Reference 78]	$36.7M (Actual 2002 USD)	$48.96 M	$162.16 M
ITER (500 MW_{fusion} = 150 MWe) [Reference 79]	$335 M (1989 USD)	$648.41 M	$648.41 M
ARIES I/II/III/IV (1000 MWe) [Reference 74]	0.3 or 0.5 mills/kWh (1995 USD)	0.47 or 0.79 mills/kWh	NA
Generic Magnetic Fusion Reactor (1200 MWe) [Reference 76]	0.5 mill/kWh (1983 USD)	1.2 mill/kWh	NA
Connecticut Yankee NPP (560 MWe) [Reference 81]	$226 M (Actual 1997 USD)	$337.95 M	$163.76 M
Trojan NPP (1095 MWe) [Reference 80]	$764 M (Actual 1997 USD)	$1,142.46 M	$382.84 M
San Onofre NPP (2232 MWe) [Reference 81]	~$2 M/MWe (2014 USD)	~$2 M/MWe	NA

The TFTR was the only fusion test reactor decommissioned in the United States. However, it did not include any power generation systems; thus, its final decommissioning costs are not fully representative of the potential cost of decommissioning associated with a commercial electricity generating FPP.

Similarly, the ITER is a more updated and scaled up fusion test reactor, which does not include any commercial electricity generation systems. The estimated decommissioning costs would not fully represent the potential cost of decommissioning a commercial electricity generating FPP.

Decommissioning costs for three large-scale light water reactor NPPs (Connecticut Yankee (actual), Trojan (actual) and San Onofre (estimated) are provided for comparison purposes.

8. Conclusions and Recommendations

The key conclusions of the study are:

- The calculated cost was relatively insensitive to changes within the range of expected uncertainty in FPC materials costs or radial build costs (consisting of the first wall, shield, and blanket).
- Current uncertainties in the primary power system for the fusion core could result in significant impacts on the total estimated cost, with the primary power system potentially approaching 20% of the total direct capital cost.
- Using a point design for 150 MW of electric power, the total estimated overnight cost encompassing the four pre-conceptual fusion power plants ranges from approximately $0.7 billion to $1.93 billion (in 2016 U.S. dollars). The average estimated overnight cost is approximately $1.32 billion. The cost estimate and the pre-conceptual designs of the FPCs and associated systems are not adequately developed and detailed at this time to be used for scaling up the estimated overnight costs for potential larger capacity plants (e.g., in the 1 GWe range).
- Cost categories had varying degrees of uncertainty, with the principal areas of uncertainty being in the FPC, heat exchanger, and tritium handling system. All principal uncertainties can be reduced by further work.

The four fusion technology concepts under consideration can be considered to be at a low level of technical readiness [Reference 83]. The (early) identification of cost drivers can affect design decisions and accelerate progress, as in any product-development trajectory. It is recommended that additional analysis and design be conducted to develop more detail on the FPC systems. The next steps would allow uncertainties in the costing analysis to be further mitigated by advancing the least certain design points beyond the pre-conceptual level and moving to the conceptual level. Recommendations include:

- Physics modeling of the neutron-producing plasma should be increased in fidelity to determine fastidiously key parameters such as attainable repetition rate.
- Neutronics analysis should be used to determine optimum component sizes for neutron absorption and tritium breeding. This work should go hand in hand with deeper mechanical and thermal analysis of the power core.
- Electrical engineering of the primary power systems used to energize the plasma should be performed to more narrowly specify the principal cost driver in all four systems.
- Tritium handling system will be very different for each of the four cases; this should be advanced to the conceptual level for each concept.
- Main heat exchanger costing should be sought from an experienced equipment manufacturer, otherwise advanced to the conceptual design level.
- LCOE calculations should drive all of the analysis, and be used to specify the target engineering and physics parameters (following the usual method of “roll-back planning”).

9. References

1. https://arpa-e.energy.gov/?q=arpa-e-programs/alpha

2. http://www.bechtel.com/

3. http://woodruffscientific.com

4. http://www.decysive.com

5. J. Kaslow (panel chair), *et al*., “Criteria for Practical Fusion Power Systems: Report from the EPRI Fusion Panel,*” Journal of Fusion Energy*, Vol. 13, Nos. 2/3, (1994) 181-182.

6. R. Lindemuth, R. E. Siemon, “The fundamental parameter space of controlled thermonuclear fusion," Am. J. Phys. 77, pp. 407-416, (May 2009).

7. G. A. Wurden, S. C. Hsu, T. P. Intrator, T. C. Grabowski, J. H. Degnan, M. Domonkos, P. J. Turchi, E. M. Campbell, D. B. Sinars, M. C. Herrmann, R. Betti, B. S. Bauer, I. R. Lindemuth, R. E. Siemon, R. L. Miller, M. Laberge, and M. Delage, “Magneto-Inertial Fusion,” Journal of Fusion Energy, (2016) 35:69-77. Available: http://dx.doi.org/10.1007/s10894-015-0038-x.

8. A. Sykes, A. E. Costley, M. P. Gryaznevich, D. Kingham, J. Hugill, et al., “Opportunities and Challenges for Compact Fusion Energy,” Fusion Science and Technology, 68, 2 (September 2015) 237-244.

9. S. Woodruff and R. L. Miller, “Cost sensitivity analysis for a 100 MWe modular power plant and fusion neutron source,” Fusion Engineering and Design, 90 (2015) 7-16.

10. M. D. Carelli and D. T. Ingersoll (eds.), Handbook of Small Modular Nuclear Reactors, (Woodhead Publishing Series in Energy: Number 64, Elsevier, 2014).

11. D. T. Ingersoll, *Small Modular Reactors: Nuclear Power Fad or Future?* (Woodhead Publishing Series in Energy: Number 90, Elsevier, 2016).

12. P.J. Turchi, S.D. Frese, M.H. Frese CONTROLLED FUSION REACTOR BASED ON STABILIZEDLINER COMPRESSION OF MAGNETIZED PLASMA Presentation at the 2016 ARPA-E progress review meeting August 9th 2016.

13. M. J. Schaffer, T. A. Parish Background Study of Liner Fusion Systems of Transmuting Fission Reactor Wastes Final Report AP-1644 Research Project 921-1 EPRI Fusion Program - Advanced Power Systems Division.

14. P. J. Turchi, A. L. Cooper, R. D. Ford, D. J. Jenkins, and R. L Burton, “Review of the NRL Liner Implosion Program,” MegaGauss Physics and Technology, (Plenum Press, New York and London, 1980) 375-386.

15. A. E. Robson, “A Conceptual Design for an Imploding Liner Fusion Reactor,” MegaGauss Physics and Technology, (Plenum Press, New York and London, 1980) 425.

16. R. L. Miller and R. A. Krakowski, “Assessment of the Slowly Imploding Liner (LINUS),” Proceedings of the Fourth ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, King of Prussia, PA (October 14-17, 1980) (published July 1981) Vol. III, 825-833.

17. P. J. Turchi, A. L. Cooper, D. J. Jenkins, and E. P. Scannell, “A LINUS Fusion Reactor Design Based on Axisymmetric Implosion of Tangentially-Injected Liquid Metal,” Naval Research Laboratory Memorandum Report 4388 (April 2, 1981).

18. P. J. Turchi, “Issues of Liner-Plasma Compression,” 2006 International Conference on Megagauss Magnetic Field Generation and Related Topics, Santa Fe, NM, Nov 2006.

19. P. J. Turchi, “Imploding Liner Compression of Plasma: Concepts and Issues,” IEEE Transactions on Plasma Science, 36, 1 (February 2008) 52-61.

20. P. J. Turchi, S.D. Frese, M. H. Frese, C.H. Mielke, M.C. Hinrichs, D.N. Nguyen, Stabilized Liner Compressor (SLC): The Return of Linus Paper NO4-00005 American Physical Society, Division of Plasma Physics Meeting 16 – 20 November 2015, Savannah, GA.

21. P. J. Turchi, S.D. Frese, M.H. Frese CONTROLLED FUSION REACTOR BASED ON STABILIZED LINER COMPRESSION OF MAGNETIZED PLASMA Presentation at the 2016 ARPA-E progress review meeting August 9th 2016.

22. P. J. Turchi, S.D. Frese, M.H. Frese CONTROLLED FUSION REACTOR BASED ON STABILIZED LINER COMPRESSION OF MAGNETIZED Bull. Am. Phys. Soc. San Jose (2016).

23. C. E. Knapp and R. C. Kirkpatrick, “Possible Energy Gain for a Plasma Liner-Driven Magneto-Inertial Fusion Concept,” Phys. Plasmas, 21(7), 1 (2014).

24. A. E. Dabiri, “Thermal Energy Conversion Systems Overview for Fusion Reactors,” Fusion Technology, 16, 2 (September 1989) 211-234.

25. W. R. Meier, “Systems Modeling for Z-IFE Power Plants,” Fusion Science and Technology, 52, 4 (November 2007) 948-952.

26. R. L. Miller, “Liner-Driven Pulsed Magnetized Target Fusion Power Plant,” Fusion Science and Technology, 52, 3 (October 2007) 427-431.

27. S. Woodruff, R. L. Miller Cost sensitivity analysis for a 100 MWe modular power plant and fusion neutron source Fusion Engineering and Design Volume 90, Pages 7-16 (2015).

28. Y. C. F. Thio, E. Panarella, R. C. Kirkpatrick, C. E. Knapp, F. Wysoki, P. Parks, And G. Schmidt, “Magnetized Target Fusion in a Spheroidal Geometry With Standoff Drivers,” Current Trend in International Fusion Research-Proceedings of the Second International Symposium, Ed. E. Panarella, Published by the National Research Council of Canada, Ottawa, Canada (1999) 113.

29. Y. C. Francis Thio, C. E. Knapp, R. C. Kirkpatrick, R. E. Siemon, and P. J. Turchi, “A Physics Exploratory Experiment on Plasma Liner Formation,” J. Fusion Energy, 20, 1/2 (June 2001).

30. J. T. Cassibry, R. J. Cortez, S. C. Hsu, and F. D. Witherspoon, “Estimates of confinement time and energy gain for plasma liner driven magneto-inertial fusion using an analytic self-similar converging shock model,” Physics of Plasmas, 16 112707 (2009).

31. F. D. Witherspoon, et al., “A contoured gap coaxial plasma gun with injected plasma armature,” Review of Scientific Instruments, 80, 083506 (2009).

32. J. Loverich and A. Hakim, “Two-Dimensional Modeling of Ideal Merging Plasma Jets,” J. Fusion Energy, (14 Aug. 2010).

33. S. C. Hsu, et al., “Spherically Imploding Plasma Liners as a Standoff Driver for Magneto-Inertial Fusion,” IEEE Trans. Plasma Sci. 40, 1287 (2012).

34. S. C. Hsu, et al., “Plasma Liners and the Potential for a Standoff Magneto-Inertial Fusion Reactor” LA-UR-13-28241 (2013).

35. S. C. Hsu, et al., “The PLX-*α* Project: Progress and Plans” Bull. Am. Phys. Soc. San Jose (2016).’

36. A. Yu. Chirlov and S. V. Ryzhkov, “The Plasma Jet/Laser Driven Compression of Compact Plasmoids to Fusion Conditions,” J. Fusion Energy (2012) 31:7-12.

37. C. E. Knapp and R. C. Kirkpatrick, “Possible Energy Gain for a Plasma Liner-Driven Magneto-Inertial Fusion Concept,” Phys. Plasmas, 21(7), 1 (2014).

38. F. J. Wessel, F. S. Felber, N. C. Wild, H. U. Rahman, A. Fisher, and E. Ruden, “Generation of high magnetic fields using a gas-puff Z pinch,” Applied Physics Letters, 48, 48 (1986) 1119.

39. H. U. Rahman, F. J. Wessel, and N. Rostocker, “Staged Z Pinch,” Physical Review Letters, 74 (1995) 714.

40. H. U. Rahman, F. J. Wessel, P. Ney, R. Presura, Rahmat Ellahi, and P. K. Shukla, “Shock waves in a Z-pinch and the formation of high energy density plasma,” Phys. Plasmas, 19 (2012) 122701:1–13.

41. F. J. Wessel, H. U. Rahman, et al., “Fusion in a Staged Z-pinch,” AIP Conf.Proc., (March 2015).

42. Frank J. Wessel, Hafiz-Ur-Rahman, Paul Ney, and Radu Presura “Fusion in a Staged Z-Pinch,” IEEE Transactions on Plasma Science, Vol. 43, No. 8, (August 2015) 2463-2468.

43. F. J. Wessel, ARPA-E Annual Alpha Meeting, (August 9-11, 2016) Seattle, WA.

44. C. E. Knapp and R. C. Kirkpatrick, “Possible Energy Gain for a Plasma Liner-Driven Magneto-Inertial Fusion Concept,” Phys. Plasmas, 21(7), 1 (2014).

45. C. W. Hartman, G. Carlson, M. Hoffman, R. Werner, and D.Y. Cheng. A conceptual fusion reactor based on the high-plasma-density z-pinch. Nuclear Fusion, 17(5):909, 1977.

46. C. W. Hartman, J. L. Eddleman, R. Moir, and U. Shumlak. The Flow-Through Z-Pinch For Fusion Energy-Production. Fusion Technology, 26(3, Part 2):1203-1206, Nov 1994.

47. U. Shumlak and C. W. Hartman. Sheared flow stabilization of the m=1 kink mode in Z pinches. Physical Review Letters, 75(18):3285-3288, Oct 1995.

48. U. Shumlak and N. F. Roderick. Mitigation of the Rayleigh-Taylor instability by sheared axial flows. Physics of Plasmas, 5(6):2384-2389, 1998.

49. U. Shumlak, R. P. Golingo, B. A. Nelson, and D. J. Den Hartog. Evidence of stabilization in the Z-pinch. Physical Review Letters, 87(20):205005, Oct 2001.

50. R. W. Moir, R. H. Bulmer, T. K. Fowler, T. D. Rognlien, and M. Z. Youssef. Spheromak magnetic fusion energy power plant with thick liquid-walls. Fusion Science and Technology, 44(2):317-326, September 2003.

51. U. Shumlak, B. A. Nelson, R. P. Golingo, S. L. Jackson, E. A. Crawford, and D. J. Den Hartog. Sheared flow stabilization experiments in the ZaP flow Z pinch. Physics of Plasmas, 10(5):1683-1690, 2003.

52. R. P. Golingo, U. Shumlak, and B. A. Nelson. Formation of a sheared flow Z pinch. Physics of Plasmas, 12(6): 062505, 2005.

53. U. Shumlak, C. S. Adams, J. M. Blakely, B.-J. Chan, R. P. Golingo, S. D. Knecht, B. A. Nelson, R. J. Oberto, M. R. Sybouts, and G. V. Vogman. Equilibrium, flow shear and stability measurements in the Z-pinch. Nuclear Fusion, 49(7):075039 (9pp), 2009.

54. U. Shumlak, J. Chadney, R. P. Golingo, D. J. Den Hartog, M. C. Hughes, S. D. Knecht, W. Lowrie, V. S. Lukin, B. A. Nelson, R. J. Oberto, J. L. Rohrbach, M. P. Ross, and G. V. Vogman. The Sheared Flow Stabilized Z-Pinch. Fusion Science and Technology, 61(1T):119–124, Jan 2012.

55. B. A. Nelson, U. Shumlak, C. Bowers, S. Doty, R.P. Golingo, M.C. Hughes, S.D. Knecht, K. Lambert, W. Lowrie, N. Murakami, M.C. Paliwoda, E. Ransom, T. Robinson, M.P. Ross, H.C. Stankey, and J. Thiele LONG, STABLE PLASMA GENERATION IN THE ZAP FLOW Z-PINCH 2013 EPR Workshop 12 – 15 Feb 2013.

56. H. S. McLean, U. Shumlak, B. A. Nelson, R. Golingo, E.L. Claveau, T.R. Weber, A. Schmidt, D.P Higginson, K. Tummel Development of a Compact Fusion Device based on the Flow Z-Pinch 2016 ARPA-E Annual Review Seattle, WA.

57. H. S. McLean, U. Shumlak, B. A. Nelson, R. Golingo, E.L. Claveau, T.R. Weber, A. Schmidt, D.P Higginson, K. Tummel Development of a Compact Fusion Device based on the Flow Z-Pinch Bull. Am. Phys. Soc. San Jose (2016).

58. C. E. Knapp and R. C. Kirkpatrick, “Possible Energy Gain for a Plasma Liner-Driven Magneto-Inertial Fusion Concept,” Phys. Plasmas, 21(7), 1 (2014).

59. AACE International Recommended Practice No. 18R-97, “Cost Estimate Classification System – As Applied in Engineering, Procurement, and Construction for the Process Industries,” March 1, 2016.

60. AACE International Recommended Practice No. 16R-90, “Conducting Technical and Economic Evaluations – As Applied for the Process and Utility Industries,” April 1991.

61. Current Status, Technical Feasibility and Economics of Small Nuclear Reactors, Nuclear Energy Agency, Organisation of Economic Cooperation and Development, June 2011.

62. G. Locatelli and Mauro Mancini, Small-medium sized nuclear coal and gas power plant: A probabilistic analysis of their financial performances and influence of CO_2 cost, Energy Policy 38 (2010) 6360-6374.

63. 2016 dollar values calculated using US Department of Labor Bureau of Labor Statistics CPI Inflation Calculator at https://www.bls.gov/data/inflation_calculator.htm.

64. Argonne National Laboratory, “STARFIRE C.C. Baker, et al – A Commercial Tokamak Fusion Power Plant Study, Volume II,” ANL/FPP-80-1 (September 1980) [pg. 22-79, Table 22-36].

65. Oak Ridge National Laboratory, “Generomak – Fusion Physics, Engineering and Costing Model,” ORNL/TM-10728 (June 1988) [pg. 20, Table 3.2].

66. L.J. Wittenberg, “The Cost of Tritium Production in a Fusion Reactor,” 4th Topical Meeting on Tritium Technology in Fission, Fusion, and Isotopic Applications (November 1991) [pg. 3, Table 2].

67. J.D. Lee, “Economic Analysis of a Magnetic Fusion Production Reactor,” Journal of Fusion Energy 6, 1 (1987) [pg. 62, Table II].

68. International Atomic Energy Agency, “Summary of ITER Final Design Report,” ITER EDA Documentation Series 22 (July 2001) [pg. 72, Table 9.1-2].

69. R.W. Moir, “Feasibility Study of a Magnetic Fusion Production Reactor,” Journal of Fusion Energy 5, 4 (1986) [pg. 264, Table III].

70. R.W. Moir, “HYLIFE Inertial Confinement Fusion Power Plant Design,” Particle Accelerators 37-38, pp. 467-480, (1990) [pg. 479, Table 2].

71. M. Glugla, A. Antipenkov, S. Beloglazov, C. Caldwell-Nichols, I.R. Cristescu, I. Cristescu, C. Day, L. Doerr, J.P. Girard, and E. Tada, “The ITER Tritium Systems,” Fusion Engineering and Design 82 (2007) [pg. 474].

72. S. Zheng, D.B. King, L. Garzotti, E. Surrey, and T.N. Todd, “Fusion Reactor Start-Up Without An External Tritium Source,” Fusion Engineering and Design 103 (2016) [pg. 13].

73. S. Willms, R. Allgood, S. Belglazov, P. Camp, O. Kazachenko, G. Lentini, L. Lepetit, A. Perevezentsev, W. Shu, and M. Glugla, “Progress on the ITER Tritium Plant,” Tritium 2013, 10th International Conference on Tritium Science and Technology (2013) [pg. 3].

74. R. Krakowski, “Simplified Fusion Power Plant Costing: A General Prognosis and Call for New Think,” Los Alamos National Laboratory, Fusion Technology [pg. 7, Table 1B], Volume 27, Number 2, March 1995, Pages 135-151.

75. J. Sheffield and S. Milora, “Generic Magnetic Fusion Reactor Revisited,” American Nuclear Society, *Fusion Science and Technology* (July 2016) [pg. 20].

76. J. Sheffield, R.A. Dory, S.M. Cohn, J.G. Delene, L.F. Parsly, D.E.T.F. Ashby, and W.T. Reiersen, “Cost Assessment of a Generic Magnetic Fusion Reactor,” Oak Ridge National Laboratory, ORNL/TM-9311 (March 1986) [pg. 99].

77. G. Locatelli, C. Bingham, and M. Mancini, “Small Modular Reactors: A Comprehensive Overview of Their Economics and Strategic Aspects,” *Progress in Nuclear Energy* 73 (2014) [p.80].

78. E. Perry, J.H. Chrzanowski, C. Gentile, R. Parsells, K. Rule, R.L. Strykowsky, and M. Viola, “Decommissioning of the Tokamak Fusion Test Reactor,” Princeton Plasma Physics Laboratory, PPPL-3895 (October 2003) [Section IX].

79. International Atomic Energy Agency, “Summary of ITER Final Design Report,” ITER EDA Documentation Series 22 (July 2001) [pg. 78, Section 9.5].

80. Nuclear Energy Agency, “Costs of Decommissioning Nuclear Power Plants,” NEA No. 7201, Organisation for Economic Cooperation and Development (2016) [pg. 75, Table 3.11].

81. 2014 Decommissioning Cost Analysis of the San Onofre Nuclear Generating Station Units 2 & 3, EnergySolutions, LLC, (September 5, 2014) [pg. 6, Table 1-1].

82. World Nuclear Association, “Radioactive Waste Management,” WNA website (October 2016).

83. M. S. Tillack, et al., “An Evaluation of Fusion Energy R&D Gaps Using Technology Readiness Levels,” Fusion Science and Technology, 56, 2 (August 2009) 949-956.