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Alternative Commercialization Pathways for Fusion Energy Systems

Proceedings of a Workshop

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ALTERNATIVE COMMERCIALIZATION PATHWAYS FOR FUSION ENERGY SYSTEMS

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The Agency’s Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is “to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world’’.

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PROCEEDINGS OF A WORKSHOP

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Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 26007 22529
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
www.iaea.org/publications

For further information on this publication, please contact:

Physics Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Email: Official.Mail@iaea.org

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FOREWORD

Nuclear fusion energy has significant potential to fulfil the future demand for low carbon energy sources. Coordinated international efforts by States, supported by the IAEA, have pushed fusion development steadily forward in the past several decades. In recent years, a number of alternative approaches have been proposed that would open up new pathways to commercialization of fusion energy systems. Such new approaches have found more than US $1 billion of investment in total as of 2020, and strides in the development of fusion energy systems that might meet the market demands of the near future are being made.

In response to this new development, the IAEA organized the first IAEA Workshop on Fusion Enterprises in June 2018 in the United States of America. The purpose of the workshop was to analyse the potential role of fusion energy in electricity markets, to capture the status of different fusion energy systems on the path to commercialization, to present an overview of the existing private fusion enterprises, and to understand how they can contribute to the commercialization of fusion as a reliable future source of energy.

This publication was prepared from contributions of workshop participants. It is intended as the first IAEA publication to analyse the role and contributions of fusion enterprises towards the commercialization of fusion. This publication sketches an outline of a roadmap for the development of fusion energy systems in the coming decades, bringing together input from expert stakeholders from the diverse range of disciplines that are essential to fusion’s commercial success.

The IAEA gratefully acknowledges the contributions of the participants, and S. Woodruff and R.L. Miller (United States of America) for compiling the first draft of this publication. The IAEA officers responsible for this publication were S.M. Gonzalez de Vicente and S. Takeda of the Division of Physical and Chemical Sciences.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

International public support has pushed fusion energy development forward in the last several decades. The world's largest international scientific experiment, ITER, is under construction and is scheduled to achieve the first plasma by the end of 2025; Wendelstein 7X, a billion-dollar class stellarator in Germany, is producing experimental results that meet expectations; JT-60SA, a joint research tokamak device of the European Union and Japan, completed its construction in March of 2020, to name a few advances.

However, in recent years, a number of innovative fusion devices have been proposed by private fusion enterprises that potentially can open up new approaches to faster commercialization of smaller fusion energy systems. Such new approaches have found over 1 billion USD total investments, as of 2020 [1], catalysing strides in the development of commercial fusion systems.

1.2. OBJECTIVE

The International Atomic Energy Agency (IAEA) organized the First IAEA Workshop on Fusion Enterprises from 13 to 15 June 2018 in Santa Fe, United States of America (USA) to analyse recent scientific and technical developments and to understand how these can contribute to the commercialization of fusion as a reliable future source of energy. The objective of this publication is to provide a summary and contributed papers of this workshop, which gathered 42 experts, mostly from the USA but also from the United Kingdom (UK), Canada and China.

1.3. SCOPE

This publication highlights several critical aspects to consider for the new pathways for fusion energy systems. It is intended as the first Agency publication that sketches an outline of a roadmap for the commercial development of alternative fusion energy systems, bringing together input of expert stakeholders from the diverse range of disciplines that are essential to fusion's commercial success.

1.4. STRUCTURE

The First IAEA Workshop on Fusion Enterprises was organized into five sessions: Market (chaired by Ms Sehila M. Gonzalez de Vicente), Commercialization Pathways (chaired by Mr Eric Ingersoll), Reactor Core Designs (chaired by Mr Ryan Umstattd), Constraints (chaired by Mr Simon Woodruff), and the Technologies (chaired by Mr Thomas Weber). Sections 2 to 6 of this publication provide the summaries of each workshop session. In Section 2, the future markets for fusion energy systems are discussed in the context of the global utility market, taking into consideration climate change and projected economic growth. In Section 3, various strategies for mitigating risks for the development of fusion energy systems are presented. In Section 4, methods for designing, building, and cost estimations of fusion reactors are discussed. Section 5 considers other major conditions that need to be satisfied for fusion commercialization to be successful, including licensing, safety, and possible nearer term revenue sources from fusion neutron sources. In Section 6, the overview of the current state – of – the – art of fusion devices and enabling technologies is presented. Finally, in Section 7, general conclusions and suggestions for further work are presented that would support the new pathways for fusion energy systems. Contributed papers of the workshop participants follow the main text, organized by sessions.

2. MARKET

2.1. INTRODUCTION

The global energy demand is expected to grow rapidly in the coming decades. The IAEA expects the world energy consumption to increase 18% by 2030 and 38% by 2050, at an annual growth rate of about 1% (Fig. 1) [2]. The U.S. Energy Information Authority (EIA) International Energy Outlook 2019 Reference Case projects a similar picture, with non-OECD nations calculated to account for 69% of the global energy consumption by 2050 [3].

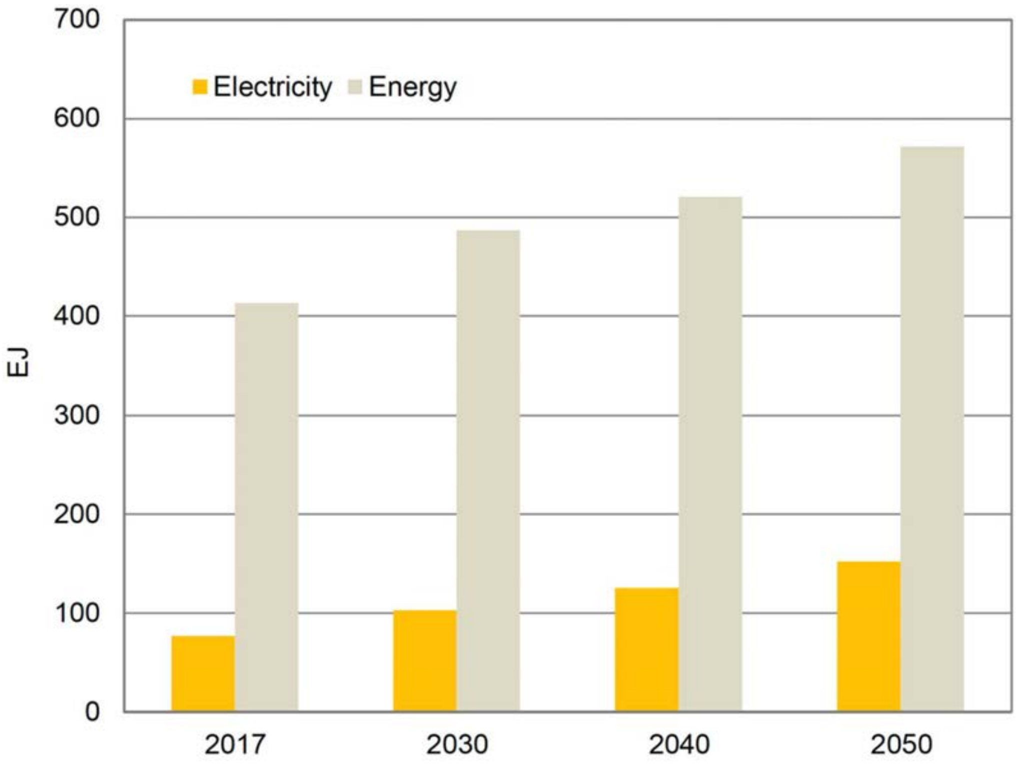

FIG. 1. The IAEA's Projection of World Final Consumption of Energy and Electricity [2].

Among all energy sectors, electricity use is projected to grow at more than double the pace of overall energy demand in the International Energy Agency (IEA)'s Stated Policies Scenario [4]. IEA predicts that renewable energy sources will become the technology of choice in the power sector, making up almost two-thirds of added global capacity in the year 2040 (Fig. 2), thanks to declining costs and continuation of supportive government policies. This is transforming the global power mix, with the share of renewable energy sources in electricity generation rising to over 40% by 2040, from 25% today. Nuclear demand falls in developed countries although it is predicted to make up ⅙ of total demand in developing countries [4].

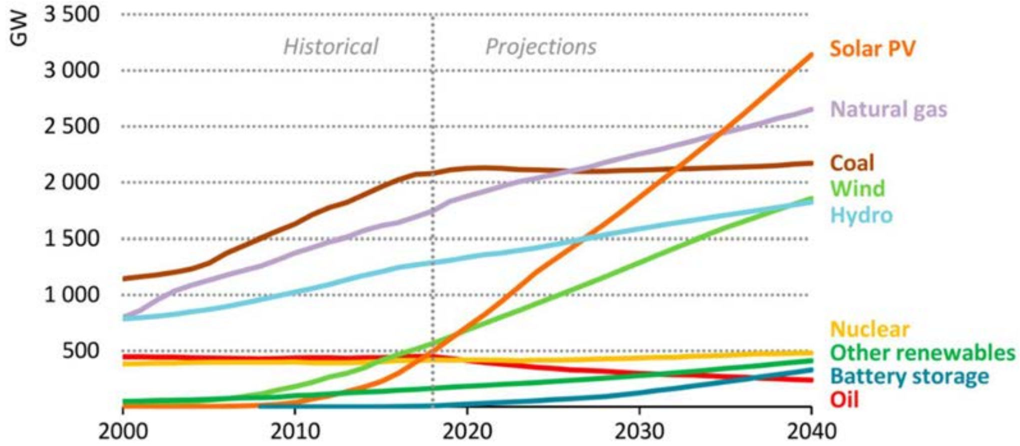

FIG 2. Change in global power capacity between 2000–2040 (IEA STEP Scenario) [4].

While the global energy investment has fallen over the last three years from 790 to 750 billion USD/year, according to the estimates of IEA, investments in energy efficiency are increasing and are driven by government policy; total investment has shifted towards renewable energy sources and associated networks and flexibility, and clean energy investment is on the rise (globally by 13% in 2017, driven by US spending) [3]. Additionally, ESG (Environmental, Social and Governance) investment, also known as sustainable investment, is gaining momentum worldwide [5]. Many funds are starting to shift from what is considered stranded assets (i.e. fossil-fuel-related investments) to sustainable investments. As a result, corporate investments in new energy technology companies are growing strongly, reaching their highest ever level of just over USD 6 billion in 2017 [6]. Notably, Information Communication and Technology (ICT) companies are making strategic investments in energy technologies [6] to get a stake in potentially key new technology areas in the last few years, as shown in Fig. 3.

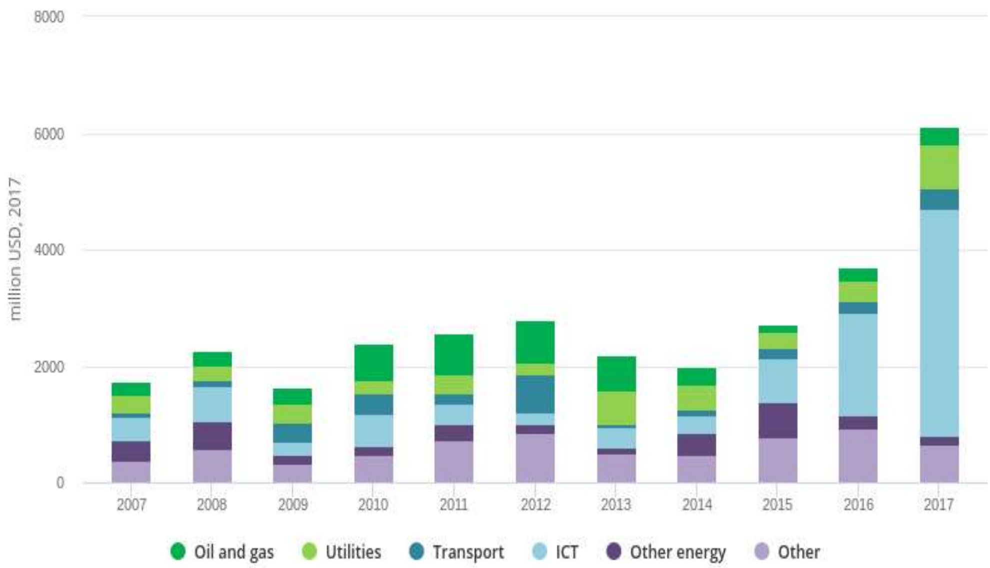

FIG. 3. Investments in new energy technology companies by sector of investing company [6].

Where does fusion fit into this context of the world energy market? In many States, the governments are investing primarily in fusion energy sciences, as part of a portfolio of technologies that may be deployed in the future [7]; fusion energy generation is a technology viewed with low technology readiness. A recent Electric Power Research Institute (EPRI) study also resonates with this view [8]. However, small programmes are starting in a few States to support the ambitions of private fusion enterprises, most notably the ARPA-E Programme by the U.S. Department of Energy [9].

2.2. CLIMATE CHANGE AND FUSION ENERGY

Climate change mitigation is one the central concerns of the global community today. To facilitate worldwide coordination toward solving this vast and complex issue, the Paris Agreement was adopted in 2015, signed by 197 parties under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC). The central aim of the agreement is to strengthen the global response to climate change to hold 'the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels' [10].

However, some States are struggling to develop clear strategies to achieve a drastic reduction in carbon dioxide emissions while providing an abundant amount of energy for continued economic growth. The World Meteorological Organization (WMO) currently predicts the global temperature rise to be 3 to 5 degree Celsius by the end of this century [11]. This projection indicates that current efforts might be insufficient to meet the 2.0-degree target or the more ambitious 1.5-degree target. The Intergovernmental Panel on Climate Change (IPCC) published projections of the temperature changes for several trajectories of the future greenhouse gas concentrations in its Fifth Assessment Report as Representative Concentration Pathway (RCP) (Fig. 4) [12]. These trajectories suggest that, in order to achieve the Paris Agreement goals, the global community has to follow RCP 2.6 and bring the greenhouse gas emissions down to zero by around 2070.

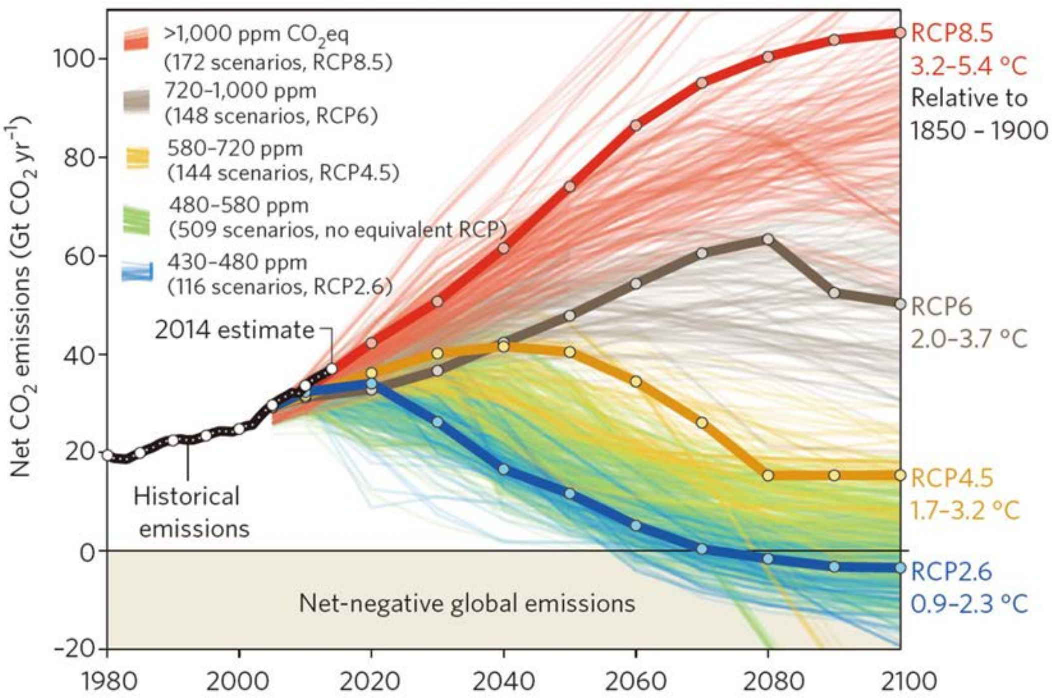

FIG 4. Emission projections based on the IPCC representative concentration pathways [13]

Fusion energy may potentially contribute to achieving this ambitious global goal, similarly to other low-carbon energy sources such as Photovoltaic (PV), wind, hydroelectric, and nuclear fission (see Fig. 2). Earlier studies estimate that the life cycle greenhouse gas emissions for electricity generation with fusion (~10 g CO_2-eq/kWh) might be about half of that of fission (~20 g CO_2-eq/kWh) and about one-fifth of that of solar PV (~50 g CO_2-eq/kWh, depending of the location) [14, 15]. While these estimates are early results, they indicate fusion energy could significantly reduce the greenhouse gas emissions in the power sector when commercialized.

Policy makers around the globe are already planning long term strategies to achieve the Paris Agreements goals. For instance, the European Commission presented its long term vision in November 2018, in which the Commission drew a path for EU toward achieving the 1.5-degree target (Fig. 5) [16]. This illustrated trajectory presents a path toward achieving net-zero emissions by 2050 for the EU. As part of those efforts, the trajectory of greenhouse gas emissions from electricity generation (the power sector) are projected to be reduced to near zero by 2040. This implies that, to achieve the Paris Agreement goals, the energy transition to low carbon sources in the power sector would have to be completed as early as 2040. This publication discusses alternative and faster commercialization pathways for fusion energy systems with the aim of accelerating the commercialization of fusion to support achieving Paris Agreement targets.

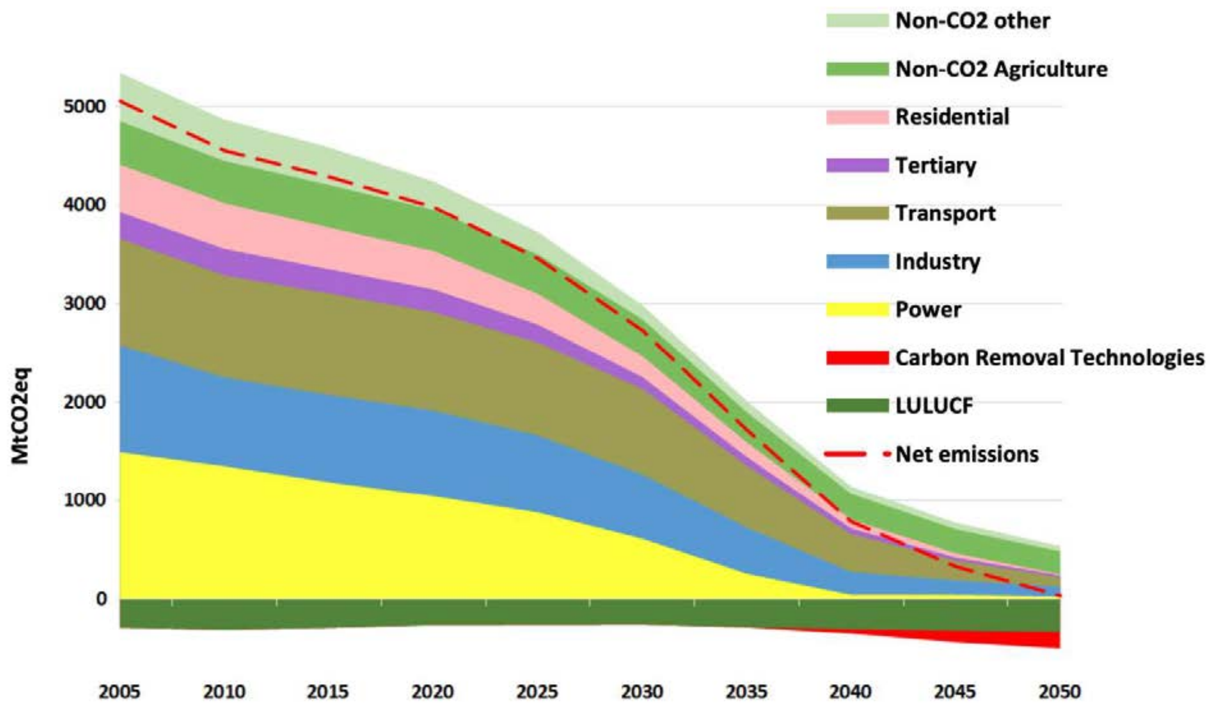

FIG 5. Greenhouse gas emissions trajectory by the European Commission for the 1.5-degree target [16]

For fusion energy systems to make a significant contribution to the global energy transition, it is desirable that the technology becomes commercialized in the first part of the 21st century, with an initial installed capacity of a few GW by 2050 [17]. This is one of the key reasons why the fusion community must involve policy makers and governments in this effort as well as explore new ways of financial support to pave faster pathways toward commercialisation of the technology.

2.3. SUMMARY OF THE SESSION

In this session, the global energy market was reviewed with a focus on electricity markets, considering projections presented in the preceding section.

For the successful commercialisation of fusion energy, it is important for the fusion industry to learn the perspectives of the utility companies from the early stage of development. Perspectives from two utility companies in the U.S. were presented as case studies with the aim of helping to shape up fusion development roadmaps toward a faster and successful commercialisation. Four main points crystallised from the discussion. First, the importance of considering the balance of plant (BOP) for fusion power plant was raised, both to estimate costs accurately and to increase the credibility of fusion vendors. Secondly, it was suggested that the fusion community may have to engage with the licensing authorities for appropriate licensing frameworks at an early stage. Thirdly, it was recommended that the fusion community seek short-term, non-electricity production avenues (e.g., hydrogen production, neutron source, etc.) in parallel to the electricity production. Finally, the importance of politics in the development of technology was remarked upon.

To summarise the session on market, the market potential for fusion energy is growing, driven both by the improvements in quality of life in non-OECD countries as well as by the needs to replace ageing power plants in OECD countries with low-carbon energy sources. While this publication primarily focuses on the electricity market, the possibility of other markets for fusion were also discussed to seek a faster commercialisation pathway. There are many applications for fusion energy systems – such as neutron sources and hydrogen production. Technical discussions on these applications are also presented as papers at the workshop (see section SESSION I: Market).

The following workshop participants contributed to Session I: Eric Ingersoll (Managing Director, Energy Options Network) on the global market context for fusion energy in which cost reduction strategies are encouraged at an early stage in the technology development; Ryan Umstattd (Senior Commercialization Advisor, ARPA-E U.S. Department of Energy) on portfolio considerations in fusion energy development, in which the competitive landscape for fusion is outlined, and fusion adoption scenarios are presented. Further, perspectives of two utility companies are shared by Joseph Kowalczyk (Southern Company) and Thomas Fallgren (PNM).

3. COMMERCIALIZATION PATHWAYS

Commercialization is the process of introducing a new product to a market. In other terms, it is the shift of a technology from the R&D phase to the generation of revenues. Various models can be considered for the commercialisation of a new technology.

3.1. FOUR COMMERCIALIZATION PATHWAYS

Figures 6–9 present four possible commercialization pathways for fusion energy systems and their advantages and disadvantages. In the 'moonshot' commercialisation pathway (Fig. 6), the scientific break-even is aimed at a technical demonstration of the concept, before the technology is built as a power-producing system. Typically, a start-up seeks funding from numerous sources - from high-net-worth angel investors, from venture capital, sources, and from the government (e.g., ARPA-E) of up to 100 million USD to demonstrate the concept of the technology. The next step towards power production is more expensive, as high as 500 million USD or more, which might be performed as part of a Public-Private Partnership. The drawbacks of this commercialization pathway are that the revenues lie far in the future and that there is a high capital risk.

The moonshot pathway has distinctive advantages over other pathways, such as:

- It is a very focused approach;
- The investors could cash-in early;
- This model has the shortest timeline to the goal.

However, on the other hand, it has the following shortcomings:

- Needs firm venture capital support from;
- Revenues cannot be expected earlier than 10 years or more;
- Large initial capital risk.

FIG 6. 'Moonshot' commercialisation pathway for fusion energy.

The pharmaceutical industry has organized large technology-specific 'mega-funds' in the past (Fig. 7). Investments are made to multiple companies of similar type, with the view that with enough number of companies, a small number would succeed and produce revenues. While there are currently enough fusion concepts to put into a single fund, there is only one fusion-specific fund in existence as of 2020[1].

[1] Strong Atomics: https://strong-atomics.com/

The pros of the mega-fund commercialization pathway are:

- Focused approach;
- Synergy among concepts;
- Large business ballast.

While the cons of the approach are:

- Limited number of investors are capable to invest billions of USD;
- Long time to revenues;
- Many distinct concepts are needed.

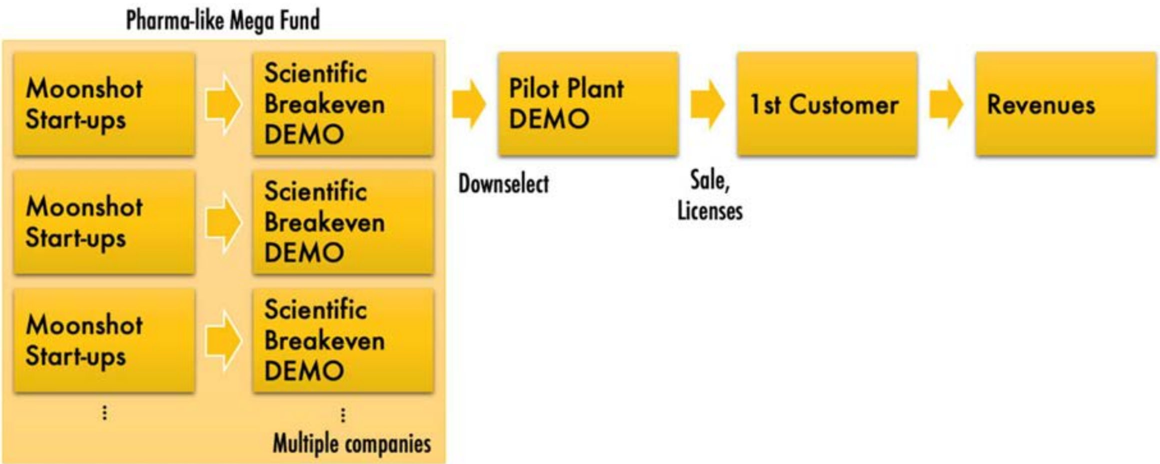

FIG 7. 'Mega-fund' commercialisation pathway for fusion energy.

In the 'spin-out' path (Fig.. 8), start-up companies develop underlying technology to produce revenues as soon as possible, e.g., novel high-temperature superconducting materials. The reactor core technologies are then built from the spin-off technologies that already have commercial traction. The principal benefit is that the investment requirements are reduced, and the company can be cash-neutral very early. The major drawback is that there may not be sufficient focus on the longer-term goals. This model has worked well. For example, the Small Business Innovation Research (SBIR) programme has provided 150 thousand USD of seed for a concept in Phase I and up to 1.1 million USD for the development to commercialize the product in Phase II.

The pros of the spin-out commercialization pathway are:

- Can focus on necessary technology;
- Fund raising from Venture Capital is easier with some technology;
- Revenues targeted in shortest timeline.

While the cons of the approach are:

- Some dilution of effort due to commercial focus;

— Intellectual Property management could become complicated;
— Longest timeline to fusion energy.

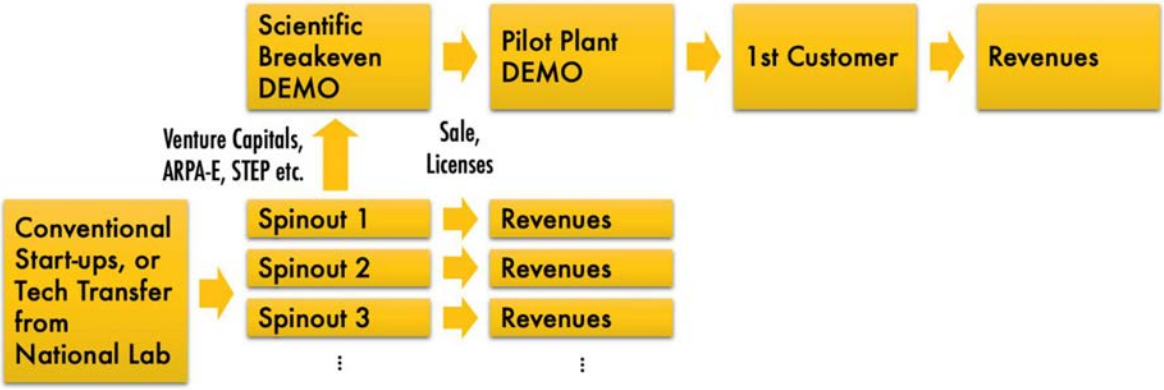

FIG 8. 'Spin-out' commercialisation pathway for fusion energy.

In the 'national emergency' model (Fig. 9), national security is the priority and technical development is driven by government spending, typically historically by the defence budget. This is essentially the model that was followed for the development of the nuclear weapons programme during World War II in the U.S. [18].

The pros of the national emergency commercialization pathway are:

— Very focused approach;
— Less stress for short-term investment.

While the cons of the approach are:

— Defence, not civilian focused;
— Revenues may never happen;
— Longest timeline to revenues.

FIG 9. 'National emergency' commercialisation pathway for fusion energy.

3.2. TECHNOLOGY READINESS LEVELS

The market readiness of a product is sometimes denoted by the Technology Readiness Levels (TRLs, Fig. 10) which can be instructive for the fusion industry. TRL was originally developed at the National Aeronautics and Space Administration (NASA) in the 1970s to assess technology readiness for its space programmes. TRL1 implies that a paper study has been performed; TRL5 means that components have been integrated and tested; and TRL9 means that all of the subassemblies have been tested and the system is pre-commercial [19]. Most fusion components are at TRL3 [20], which means that they have not yet seen a sufficient fluence of neutrons to assess performance of components in their intended use environment, i.e. in a fusion reactor.

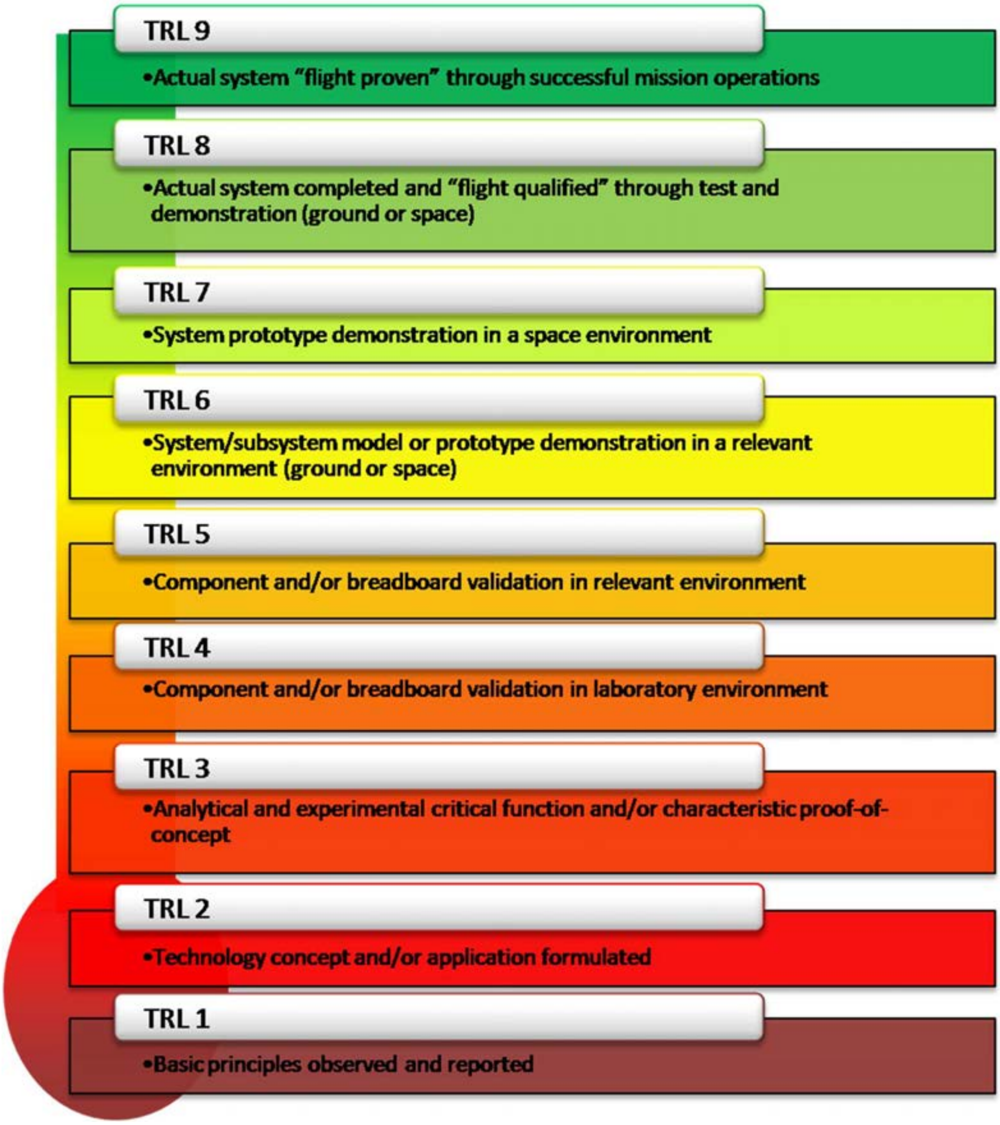

FIG 10. National Aeronautics and Space Administration (NASA) Technology Readiness Level (TRL) descriptions [19].

In the U.S. nuclear fusion sector, the concepts in the TRL range of 1–2 are supported by the Office of Science Fusion Energy Science programme. Recently, the Advanced Research Project Agency for Energy (ARPA-E) supported a small, focused fusion programme with the aim of moving some concepts along their development path from TRL 3 to 5. However, there is a growing number of small fusion enterprises aiming for the moonshot of net fusion gain on short time-horizons (commercialization pathway depicted in Fig. 6). These organizations are focusing on the development of more compact and simpler engineer systems and are making great technical strides towards their goals. These new concepts are benefitting from technologies developed for larger systems and further afield, such as high temperature superconductors, and from decades of advances in modelling and simulation capabilities. Because some of these fusion concepts are physically small (1–10 meters in scale), their total capital requirements are relatively modest, and so small companies have attracted investment from venture capitalists, angel investors, and strategic corporate investors. At the moment, capital is entering this space, aiming to bridge the gap from TRL of 3–6 by the 2030s and demonstrate scientific validity of alternative concepts.

3.3. SUMMARY OF THE SESSION

Combining multiple commercialization pathways for fusion energy systems were presented and compared: a moonshot company may secure venture investment with an energy specific goal, but also then find that they need to spin out technologies with nearer-term revenues to satisfy investors; a company with government grant support may focus on the near-term revenues only to find that they need the focus and acceleration that equity investment brings. There is no single commercialization pathway that would work for all fusion energy technologies. However, the aim of all commercialization pathways is to introduce new products to the market that can generate the largest possible revenues in the shortest time possible.

Currently, investments are flowing into the private fusion industry to advance the technology from TRL 3 to 6 by the 2030s. Investment strategies also vary; however, there is a commonality in the approaches to reducing capital risks. Investors reduce risks by identifying a portfolio of concepts and technologies that, as an aggregate, have a higher probability of success if invested in together. This portfolio approach is the same as that adopted by the pharmaceutical industry, wherein a single fund may invest in multiple related companies with the long term view that one company will succeed and generate revenues (a 'mega fund'). The first fusion fund of this nature was started in 2017 in the U.S. and has made investments in a subset of fusion concepts. Within this fund and companies supported by the fund, further risk-reduction strategies were developed, such as sharing diagnostics or development of pulsed power systems that serve multiple concepts. Such strategies have been part of small government programmes in the last 20 years, most notably by ARPA-E [21].

It should also be noted that the commercialization of fission systems was brought about principally as a consequence of a national emergency pathway that concentrated resources into the technical development without focus on commercial viability. Perhaps climate change might provide a similar impetus for fusion, although fusion energy will have to economically compete against other low-carbon energy options such as hydro, wind, solar, nuclear fission, and fossil fuel with carbon capture.

Spinout technologies that generate nearer-term revenues are considered by some as an essential step to commercialization, and by others as a distraction from the energy goal. In a small business, cash is a critical matter – without it, businesses fail; therefore any view the primary aim of the business needs to include any revenue stream that provides cash neutrality. This view leads to integrating additional fusion technologies (e.g. for neutron sources for nuclear waste transmutation, medical isotope production [22], materials, or fuel related research) into targets.

Within the companies themselves, there are risk reduction efforts, including knocking down the highest technical risks first and reducing risks associated with science before engineering (following regular Design Review procedures), which helps build credibility, community engagement, and further funding. Technical development now nearly universally progresses through TRLs that are well-defined by government agencies and adopted by investors to make progress towards technical milestones understandable.

Commercialization pathways are therefore diverse (from 'moonshot' to 'national emergency') and the path that any business takes is likely to evolve as the company develops intellectual property and proves aspects of the technologies. Investment is more likely if the company can demonstrate energy technology to be lower risk both for scientific risks and subsequent engineering risks and to do so with an eye on nearer-term revenues. Investment strategies embrace a wide range of options from mega-funds comprising multiple fusion technologies in a single fund, to co-investing in one fusion company.

The individual contributions on this topic are available in Session II: in which Eric Ingersoll (Managing Director, Energy Options Network) draws lessons from investment strategies used in big pharmaceutical investments, comparing timelines, capital requirements and risks; David Plant (Director, General Fusion) discusses the commercialization strategy of General Fusion, noting that the risks involved with a project are not just technical in nature; Malcolm Handley (Founder and Managing Partner, Strong Atomics) presents perspectives on the multiple ways to de-risk an investment; Sam Wurzel (angel investor in fusion) shares perspectives on the major possible pitfalls for fusion energy technology development and ways to mitigate those from a business perspective; Gordon Goodman (Former President of E.I. du Pont de Nemours & Co.) gives an example of a nuclear technology that was commercialized, driven by societal pressures; Jay K. Anderson (Senior Scientist, University of Wisconsin-Madison) and Shutaro Takeda (Graduate School of Advanced Integrated Studies in Human Survivability, Kyoto University) propose non-electricity commercialization pathways for fusion energy.

4. FUSION POWER CORE DESIGN

At the simplest level, the fusion power core serves to sustain a fusion reaction and capture energetic D-T neutrons in a tritium-breeding blanket that transforms the kinetic energy of particles into heat while breeding tritium for fusion fuel. The primary coolant from the blanket is pumped to a heat exchanger to extract thermal energy. Other systems considered part of the core include pumps systems, fuel injection, exhaust, diagnostics (sensors), and systems relating to remote maintenance (robot arms, etc) [23]. An example of the fusion power core is illustrated in Fig. 11 [24]. The majority of the current fusion power plant designs assume that everything outside of the BOP resembles that of a pressurised water reactor (PWR) nuclear power plant: steam turbines, transformers, and equipment to get electrons onto the grid. Fusion power core design has been under development for decades, with economy of scale being the principal driving factor in making systems larger [25]. Costing has been driven by similar costing analyses in the fission power industry (most notably the Gen IV costing [26]) and scaling for subsystem cost-categories obtained by scaling from ~1 GW systems.

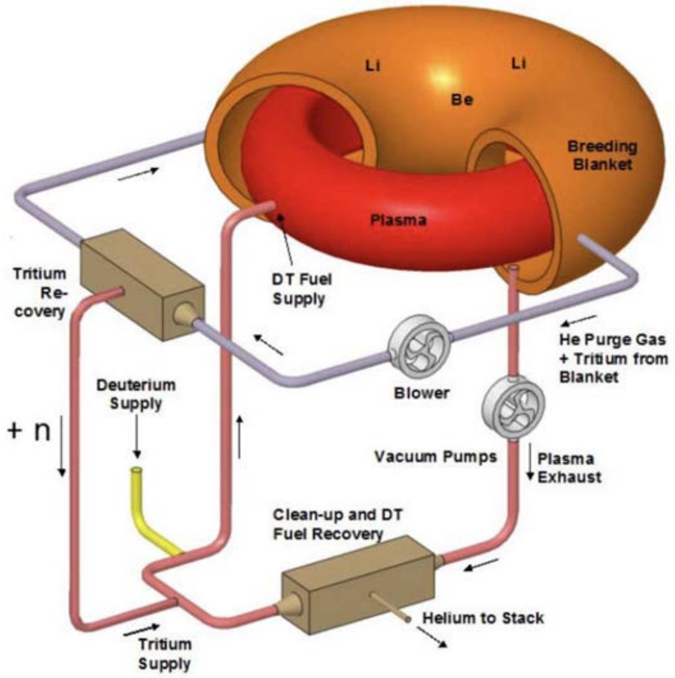

FIG 11. Example of a Fusion Power Core [24]. Note: while not explicitly depicted in the picture, the kinetic energy of particles is transformed into heat in the Breeding Blanket and removed by the primary coolant.

While the basic design of the power core has remained somewhat the same, more recently the net power has been tuned to meet the market demand in the developed world, resulting in smaller units [7]. While the economy of scale is lost by making units smaller, it might be recovered by significant cost savings in centralized manufacture and modularization, together with shorter construction times, echoing recent developments in SMRs [27]. However, due to the physics of magnetic confinement fusion, there are intrinsic challenges in scaling down the power of fusion reactors by a factor 10 or more while maintaining the engineering Q value [28]. Therefore, the consequences in terms of performances in passing from economy of scale to economy of serial production for fusion reactors have to be investigated further in the future.

Power core design usually starts with a well developed set of physics scenarios that define the plasma equilibrium and the shape and position of magnets in the system. A power balance is developed for the system producing neutrons, which defines the spatial distribution of neutrons on the first wall. The 'radial build' comprises all of the wall elements (blankets, structure, and shielding out to external coils) that serve to capture neutrons for power production and provide safety for external components that will serve for life of the plant. Making everything smaller does not necessarily remove the complexity; in design there are multiple physics and engineering challenges that must be resolved self-consistently, taking each into consideration of the other. Towards this end, power core design usually embraces a team of physicists plus a team of nuclear, mechanical, and electrical engineers (see e.g. ARIES [29] or efforts for nuclear science facilities [30]). With a power balance and build in hand, Total Capital Cost (TCC) and Levelized Cost of Electricity (LCOE) can be calculated.

4.1. SUMMARY OF THE SESSION

Fusion reactor design falls into standard methodologies that have been developed by teams of experts over the last 40 years. Most fusion power core designs in the public sector have been performed for a narrow range of powers - usually 1 GWe, similar to fission Gen IV systems. Fusion has also inherited the Cost Accounting Structure (CAS) from Gen IV to obtain the Total Capital Costs and many of the methods for computing time-dependent or indirect costs to obtain the Levelized Cost of Electricity.

Irrespective of the plasma configuration (e.g., stellarator, tokamak, and spheromak), usually the system is built from the plasma outwards. The standard operating modes for the plasma are chosen based on performance and stability first, then a first wall of a certain size (so as not to exceed power deposition limits) is built around the plasma. The blanket is built outside of that, the neutronics optimized to provide a sufficient tritium breeding ratio (TBR) and to sufficiently attenuate high energy neutrons to shield components outside of the vessel from damage to ensure that costly components can survive for the life of the plant. These design aspects require iterative cycles between engineers and neutronics experts. Outside of the blanket and shield are typically the magnet systems as well as the tritium handling systems – the systems needed to extract tritium fuel that has been bred in the blanket. Beyond the blanket are the pumping systems that take blanket fluid to heat exchangers. B beyond those are the components of BOP, consisting of the steam turbines, generators and transformers needed to put power on the grid.

More recent studies depart from the convention of 1 GWe and the associated economy of scale, finding that smaller (~100 MWe) units are still competitive due to deep learning curve credits derived from rapidly transition from First of a Kind to Tenth of a Kind and centralized manufacturing building nearly complete modules that are shipped by rail or road for fast installation, thereby reducing build time and capital requirements. However, because these smaller units depart so markedly from Gen IV 1 GWe related scaling, the costing methodology needs to be renewed and, in some cases, completely reformulated. Therein lies both an opportunity and a challenge: it will be possible to break from prior costing paradigms and adopt more recent costing methodologies, but to do so may require all subsystems to be costed somewhat uniquely for each specific fusion concept.

In summary, costing methodologies are mature for larger systems; however, applying those same methodologies to much smaller fusion concepts leaves much to be desired due to inapplicability of scalings derived from SMRs and Gen IV fission costings. Each fusion concept is, by near necessity, costed uniquely by considering specific design aspects. This presents a great opportunity to break with existing cost paradigms and adopt new ones, such as ‘Design to cost’.

The reactor core designs themselves are in various stages of development; some have had teams of technologists and scientists working on the extremely complex details for decades. Others are almost able to pull together analytic models for a power balance and sketch the components they might need in the power core. This reflects the fact that some fusion systems performed well early in fusion’s history and were adopted as the standard workhorses. The methodology of developing fusion reactor designs has been well-mapped out by numerous teams and is discussed in this publication. It is evident from the discussion that the engineers and scientists in the community have established how to design and build these systems, at least to take them to an engineering design sufficient for something to be built and tested. Some of the less developed concepts can now take much larger strides in their development because of the methodology and modelling that was developed for more mature systems. Further, there is a supply chain lining up to start building these systems commercially.

The individual contributions on this topic are available under Session III: Fusion Power Core Design: Ronald Miller (Co-founder, Compact Fusion Systems) presents the basis and assumptions made in calculating costs of electricity from fusion energy systems; Laila El-Guebaly (Distinguished Research Professor Emeritus, University of Wisconsin-Madison) discusses the constraints placed on radial build due to Tritium breeding and shielding requirements; Simon Woodruff (Founder, Compact Fusion Systems) presents an overview of the ARPA-E fusion costing exercise performed with Bechtel in 2017, for 4 of the smaller modular fusion energy systems supported in the ALPHA programme; Charles Kessel (Principal Engineer, Princeton Plasma Physics Laboratory) presents an introduction to all of the subsystems necessary for a fusion power core, and what is usually included in a pre-conceptual power plant study.

5. CONSTRAINTS OF FUSION ENERGY SYSTEMS

The topics covered in this section pertain to licensing, safety, and nuclear aspects. Although the D-T fusion reaction itself only produces helium and neutron, fusion reactor cores (in the surrounding blanket) generate tritium, for use as a fuel, from lithium. While the risks to human health from tritium is minimal [31], as a radioactive substance, it must be controlled safely. The energy generated from fusion reactions (in the form of kinetic energy of neutrons and alpha particles) is captured by the surrounding structure with carefully designed absorbing blankets and shields. The activation of structures and components can be minimized by carefully selecting materials, although this is still one of the major issues and a challenge in the design of any fusion system. In the event of an accident, fusion reaction will in all cases extinguish rapidly (usually in the order of milliseconds) and therefore such facilities are considered to be inherently safe [32]. These aspects are informed by an already substantial body of work on these topics, either in the context of government-lead reports, such as Holdren's 'Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy (ESECOM)' report from 1987 [33], through to contemporary planning as part of the 2018 National Academy of Sciences fusion study [34]. There is therefore over 30 years of work in this area to inform any new activities, the most recent relevant to ITER [35].

5.1. SUMMARY OF THE SESSION

Many constraints will be imposed on the development of commercial fusion energy systems, primarily by national governments and regulatory bodies (but also by the general public, policymakers and utilities intending to deploy fusion systems). It might be time to start discussions on what those constraints will be. In some States, regulatory bodies are aware of private fusion enterprises and are already engaged with some of them. However, there is not yet a collective licensing strategy defined for the concepts being put forward in the private sector as possible vehicles for fusion energy development.

Some participants urged engagement with the regulatory body as early as possible, in order to have at least informal discussions of the process and to start to define how the engagement may take shape. There are already private organizations engaged in this discussion (such as Shine and Phoenix in the USA and General Fusion in Canada), and the licensing process might be relatively rapid. When is the best time to start this process? The answers varied from engaging now with some very preliminary discussions for a range of concepts, to waiting until the fidelity of modelling and engineering designs have been sufficiently developed to have a defensible position. However, it was noted that the ITER licensing process was not started at the end of the engineering design, but much earlier, since there are some aspects of the licensing recommendations that may work into the engineering design [35].

In summary, regulation is a critical unknown of fusion commercialization both in terms of cost and timeline. Presently, there is no consensus on a common approach to engagement with the regulatory bodies for private fusion enterprises. Whether this occurs collectively or on an individual company basis, remains open for discussion.

Considering what it would take to provide electricity to the grid beyond power balances and technology of the power cores, the fusion development community must study all aspects of tritium, including accounting, production, burning, safety and regulation, including incidental and accidental scenarios, and decommissioning. The issues related to the activated materials are also major issues both during operation and decommissioning. Some private fusion enterprises are already starting to engage in this discussion, and this may happen organically, although it needs to be noted that how the community approaches the topic could impact timelines and costs for all fusion development.

The individual contributions on this topic are available under Session IV: CONSTRAINTS OF FUSION ENERGY SYSTEMS: Kirk Hollis (Team Leader, Los Alamos National Laboratory (LANL) discusses the tritium fuel cycle safety, outlining experience from ITER and TSTA; Amy Roma (Partner, Hogan Lovells) presents the legal perspectives on licensing from, and how discussions with the Nuclear Regulatory Commission (NRC) ought to come at an early stage; Laila El-Guebaly (Distinguished Research Professor Emeritus, University of Wisconsin-Madison) provides existing and prior activities to define the regulatory framework for fusion and a full set of answers to the questions on safety.

6. TECHNOLOGIES OF FUSION ENTERPRISES

There are three broad categories into which nearly all fusion concepts fall: Magnetic Fusion Energy (MFE), offering concepts that work in steady-state (like the stellarator and tokamak); Magneto-Inertial Fusion (MIF), that work in a cyclic manner, compressing a magnetized target to ignition; and Inertial Fusion Energy (IFE), which employs lasers or ion beams to compress solid targets. These three categories represent low (MFE), intermediate (MIF), and high (IFE) density approaches to fusion energy.

The technologies relating to the BoP of fusion power plants was out of scope for this section. It has to be acknowledged that the nuclear fusion community can focus their development efforts on fusion reactors by relying to some extent upon the technology, knowledge and know-how developed by the fission community in 70 years of NPP development and deployment.

6.1. GOVERNMENT INVESTMENT IN FUSION TECHNOLOGIES

In the U.S., IFE research has historically been funded through the DOE National Nuclear Security Administration (NNSA) primarily as Inertial Confinement Fusion (ICF), while MFE research has been funded by the DOE Office of Science (OS), Office of Fusion Energy Sciences (FES). This segregation of funding, and consequently communities, is largely echoed internationally, except in Japan. In the past, government-funded fusion programmes pursued many different approaches. In MFE, a wide variety of ‘confinement concepts’ were investigated, e.g., mirror machines, pinches, and a multitude of different toroidal devices, nearly always driven with some form of pulsed power. A similar diversity could be found in ICF research, although in this case, the various approaches could broadly be categorized by the type of driver used, e.g., indirect (X ray) drive using long-pulse lasers, long-pulse laser-driven direct-drive, direct or indirect drive using pulsed power, heavy or light ion beams, or initiated using short-pulse lasers. Recently, in both IFE and MFE, the scope of publicly funded research has narrowed to one dominant primary approach and, at a much lower level, a single ‘alternative’. In the case of MFE, the Tokamak, specifically the ITER project, is the primary approach with the Stellarator as the alternative; and in IFE, indirect-drive laser fusion, as pursued by the National Ignition Facility (NIF), is the main approach, with pulsed-power driven concepts, such as those studied at the Sandia Z-machine, as an alternative. However, with the realization that achieving ignition on the NIF is going to be much more difficult than originally anticipated, there appears to be increasing interest in pulsed-power-driven ICF (along with concepts that could also be considered MIF) within the NNSA. While not a new concept, MIF has received a much lower level of attention than either MFE or IFE and has seen sporadic funding through both the NNSA and FES (although FES no longer funds MIF research). Currently, MIF research is predominantly taking place in privately funded small businesses, though this situation is beginning to motivate increased funding from government agencies like ARPA-E through their ALPHA programme [21].

With tens of billions of dollars going toward the primary IFE and MFE approaches, epitomized by ITER and NIF, hundreds of millions spent on the ‘alternative’ approaches, e.g., at W7X (stellarator) and Z, and all signs indicating that these approaches scale to enormous power plants; other less technically mature concepts that offer a potentially lower development cost path to fusion are attracting private investors.

6.2. SUMMARY OF THE SESSION

This session discussed some of the specific fusion technologies that aim for faster commercialization. While the fusion power core technologies are manifold, falling into camps defined primarily in terms of density regimes (low: MFE, medium: MIF and high: IFE), they only form part of a spectrum of technologies that are needed for commercialization, which are broadly termed 'enabling technologies.' In MFE, the enabling technologies include high temperature superconducting magnets, beams, and novel materials for first wall components. In IFE, the enabling technologies include compact high average power lasers, but also fibres, laser coatings, and waveguide technologies. In MIF, the enabling technologies include fast repetition plasma sources, liquid metal injection systems, and novel pulsed power systems (e.g. high power and high rep-rate switches). These enabling technologies themselves are often already straddling many other markets and can be commercialized for many other applications.

The individual contributions on this topic are available in Session V: Daniel Brunner (Chief Technology Officer, Commonwealth Fusion Systems) presents an overview of steady-state magnetic confinement fusion energy concepts being pursued by private fusion industry; Michael Campbell (Director, Laboratory for Laser Energetics) gives an overview of IFE concepts under development in the private sector; Scott Hsu (Staff Scientist, LANL) gives an overview of Magneto-inertial fusion and other intermediate-density pulsed concepts; Peter Turchi (Co-founder, Compact Fusion Systems) discusses three necessary conditions that any fusion energy development needs to meet to be viable are proposed; Thomas Schenkel (Group Leader, Lawrence Berkeley National Laboratory) gives an overview of some enabling technologies for fusion power from the perspective Lawrence Berkeley National Laboratory.

7. CONCLUSIONS

The first IAEA Workshop on Fusion Enterprises, held in 2018, gathered 42 experts to discuss the alternative pathways for the commercialization of fusion energy systems. Discussions at the workshop were meaningful and consequential and have led to the setup of a discussion forum encompassing private and public sector within the widening and broader fusion community.

In particular, the workshop participants wished to emphasize the following findings and follow up actions:

(a) Fusion enterprises need to make efforts to engage with the national regulatory authorities to establish regulatory frameworks for fusion concepts from early stages. Regulation is one of the critical unknown factors of fusion commercialization both in terms of cost and timeline. Efforts have already been started by the fusion community to establish a baseline for licensing discussions, and the community has a good understanding of how and where fusion is different from fission. Based on the previous findings, a licensing paradigm could be defined if the community takes the initiative from the early stages. It also needs to identify similarities and differences between various approaches and how common (or confinement concept specific) regulations might apply.

(b) The fusion community is encouraged to take initiatives in strengthening international coordination toward establishing the basis for safety including radioactive waste management for fusion power systems. The efforts to establish the basis for safety and radioactive waste management need to be coordinated internationally. Fusion energy systems have been developed through international collaborations since early times. It is for the best interest of fusion enterprises to have internationally consolidated bases for safety including radioactive waste management, and the fusion community is encouraged to take the initiatives toward it.

(c) The fusion community is advised to make every effort to reason with society that fusion energy systems would contribute to the global climate change mitigation efforts by 2050. This would not only improve the public acceptance of the technology but also bring more investors (investment funds, oil and gas utility companies, IT enterprises, etc.) to support fusion. The ESG (Environmental, Social and Governance) investment, also known as the 'sustainable investment,' is gaining momentum worldwide. Investors are starting their shift from the stranded assets (i.e., fossil fuel-related investments) to more sustainable assets. As a result, corporate investments in new energy technology companies are growing strongly, reaching their highest ever level of over 6 billion USD in 2017. Fusion enterprises need to make every effort to make investors recognize that 1) fusion energy has the potential to be commercialized in the coming decades and that 2) investment in fusion is 'green and sustainable' to bring more investors to support fusion and seek diversification of the investing parties.

(d) Expanding the public-private partnerships would be beneficial to both parties. Commercialization pathways for fusion energy systems are various, and there is not one single means for moving concepts from laboratories, prototyping solutions to commercial power plants. However, there ought to be a discussion that embraces both private equity investment and government investment in the fusion community; broader public-private partnerships would be beneficial to both parties. Fusion energy systems entail not only fusion power core concepts but a much wider set of enabling technologies; the fusion community entails not only public institutions and laboratories but an increasing number of small businesses and enterprises.

(e) Fusion enterprises are encouraged to actively seek and survey market opportunities internationally, including the non-electricity markets. Fusion enterprises need to make active efforts to survey market opportunities internationally and to understand non-energy related commercial opportunities for fusion systems. While the market discussion in this publication is focused primarily on the U.S. utility market, almost 70% of the total electricity consumption would be in non-OECD countries in 2040 (2019 EIA Reference Scenario [36]). As such, fusion enterprises are encouraged to actively seek and survey international market opportunities. In addition, it would be helpful for the fusion community to seek short-term, non-electricity production avenues (e.g. including neutron production for various applications, heat generation for water desalination or hydrogen production, and carbon removal, etc.) in parallel to the electricity production to reduce the investment risks and increase business attractiveness.

REFERENCES

[1] NUTTALL, W. J., KONISHI, S., TAKEDA, S., Commercialising Fusion Energy - How small businesses are transforming big science, IOP Publishing, Bristol (2021).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Energy, Electricity and Nuclear Power Estimates for the Period up to 2050, Vienna (2018).

[3] U.S. ENERGY INFORMATION ADMINISTRATION, International Energy Outlook 2019, Washington D.C. (2019), https://fossil.energy.gov/app/DocketIndex/docket/DownloadFile/627

[4] INTERNATIONAL ENERGY AGENCY, World Energy Outlook 2019, IEA, Paris (2019), https://www.iea.org/news/world-energy-outlook-2019-highlights-deep-disparities-in-the-global-energy-system

[5] BOFFO, R. and PATALANO, R., ESG Investing: Practices, Progress and Challenges, OECD, Paris (2020), https://www.oecd.org/finance/ESG-Investing-Practices-Progress-Challenges.pdf

[6] INTERNATIONAL ENERGY AGENCY, World Energy Investment 2019, OECD, Paris (2019), https://read.oecd-ilibrary.org/energy/world-energy-investment-2019_4f4f25b4-en

[7] UNITED STATES DEPARTMENT OF ENERGY, Quadrennial Technology Review (2015), Washington, DC (2015), https://www.energy.gov/quadrennial-technology-review-2015

[8] ELECTRIC POWER RESEARCH INSTITUTE, Program on Technology Innovation: Assessment of Fusion Energy Options for Commercial Electricity Production (2012), https://www.epri.com/research/products/1025636

[9] NEHL, C., UMSTATTD, R., REGAN, W., HSU, S. C., and MCGRATH, P., Retrospective of the ARPA-E ALPHA fusion program, J. Fusion Energy **38** (2019) 506–521.

[10] UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE,The Paris Agreement (2021), https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

[11] WORLD METROLOGICAL ORGANIZATION, WMO Provisional Statement on the State of the Global Climate in 2019, Geneva (2019), https://library.wmo.int/doc_num.php?explnum_id=10108

[12] STOCKER, T., Climate change 2013: The physical science basis, in contribution of Working Group I to the Fifth assessment report of the Intergovernmental Panel on Climate Change, Cambridge University Press (2013).

[13] FUSS, S. *et al.*, Betting on negative emissions, Nat. Clim. Chang. **4** 10 (2014) 850.

[14] UEMURA, S., YAMAZAKI, K., ARIMOTO, H., OISHI, T., and SHOJI, T., Environmental Assessment of Fusion Reactors by the Calculation of CO_2 Emission Amount, Trans. At. Energy Soc. Japan **8** 1 (2009) 34–39.

[15] TOKIMATSU, K., HONDO, H., OGAWA, Y., OKANO, K., YAMAJI, K., and KATSURAI, M., Evaluation of CO_2 emissions in the life cycle of tokamak fusion power reactors, Nucl. Fusion **40** 3Y (2000) 653.

[16] EUROPEAN COMMISSION, A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy EC, Brussels (2018), https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773

[17] GI, K., SANO, F., AKIMOTO, K., HIWATARI, R., and TOBITA, K., Potential contribution of fusion power generation to low-carbon development under the Paris Agreement and associated uncertainties, Energy Strategy Rev. **27** (2020) 100432.

[18] KELLY, C. C., Manhattan Project: The Birth of the Atomic Bomb in the Words of Its Creators, Eyewitnesses, and Historians, Black Dog & Leventhal Publishers, New York (2009).

[19] NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, Technology Readiness Level (2021), https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

[20] TILLACK, M. *et al.*, An evaluation of fusion energy R&D gaps using technology readiness levels, Fusion Sci. Technol. **56** 2 (2009) 949–956.

[21] Advanced Research Projects Agency - Energy, ALPHA Program Overview, https://arpa-e.energy.gov/sites/default/files/documents/files/ALPHA_ProgramOverview.pdf

[22] Nuclear Energy Agency of the OECD, The Supply of Medical Isotopes: An Economic Diagnosis and Possible Solutions, OECD Publishing, Paris (2019), https://doi.org/10.1787/9b326195-en.

[23] NAJMABADI, F. *et al.*, The ARIES-AT advanced tokamak, advanced technology fusion power plant, Fusion Eng. Des. **80** 1–4 (2006) 3–23.

[24] GLUGLA, M. *et al.*, Review of the ITER DT Fuel Cycle Systems and recent progress, 9th International Conference on Tritium Science and Technology; Tritium Plant Section, Japan, (2010).

[25] SHEFFIELD, J. *et al.*, A study of options for the deployment of large fusion power plants, Fusion Sci. Technol. **40** 1 (2001) 1–36.

[26] INTERNATIONAL FORUM, Cost Estimating Guidelines for generation IV Nuclear Energy Systems, Paris (2007), https://www.gen-4.org/gif/upload/docs/application/pdf/2013-09/emwg_guidelines.pdf

[27] INTERNATIONAL ATOMIC ENERGY AGENCY, Deployment Indicators for Small Modular Reactors - Methodology, Analysis of Key Factors and Case Studies, IAEA, Vienna (2018), https://www.iaea.org/publications/13404/deployment-indicators-for-small-modular-reactors

[28] TAKEDA, S., PEARSON, R., Nuclear Fusion Power Plants, Power Plants in the Industry, IntechOpen, London (2019), 101–121, https://www.intechopen.com/chapters/62970

[29] KESSEL, C. *et al.*, The ARIES Advanced and Conservative Tokamak (ACT) Power Plant Study, Princeton Plasma Physics Lab, Princeton, New Jork (2014).

[30] MENARD, J. *et al.*, Prospects for pilot plants based on the tokamak, spherical tokamak and stellarator, Nucl. Fusion **51** 10 (2011) 103014.

[31] CANADIAN NUCLEAR SAFETY COMMISSION, Health Effects, Dosimetry and Radiological Protection of Tritium, (2010), http://nuclearsafety.gc.ca/pubs_catalogue/uploads/CNSC_Health_Effects_Eng-web.pdf

[32] TAYLOR, N., CORTES, P., Lessons learnt from ITER safety & licensing for DEMO and future nuclear fusion facilities, Fusion Eng. Des. **89** 9–10 (2014) 1995–2000.

[33] HOLDREN, J. *et al.*, Summary of the report of the senior committee on environmental, safety, and economic aspects of magnetic fusion energy, Lawrence Livermore National Lab., CA USA (1987).

[34] NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE. 2019. Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research. Washington, DC: The National Academies Press.

[35] PERRAULT, D., NIEL, J.-C., and BRUNA, G., Nuclear Fusion Reactors. Safety and radiation protection considerations for demonstration reactors that follow the ITER facility, Institute for Radiological Protection and Nuclear Safety, France (2017), https://www.irsn.fr/EN/Research/publications-documentation/Scientific-books/Documents/ITER-VA_web_non_imprimable.pdf

[36] U.S. ENERGY INFORMATION ADMNISTRATION, International Energy Outlook 2019, https://www.eia.gov/outlooks/aeo/data/browser/#/?id=1-IEO2019&region=0-0&cases=Reference&start=2010&end=2039&f=A&sourcekey=0

PAPERS PRESENTED AT THE MEETING

SESSION I: MARKET

THE GLOBAL MARKET CONTEXT FOR FUSION ENERGY

E. INGERSOLL
Energy Options Network
Lucid Strategy, Laguna Beach, U.S.

1. INTRODUCTION

The world needs large amounts of low-carbon energy to avert severe climate change. With rapid increase of global population, GDP per capita, and energy intensity of GDP, comes rapid increase in CO_2 emissions. In order to avert severe climate change, the CO_2 intensity of energy sources must rapidly decrease. According to the International Energy Agency (IEA) [1] and the U.S. Energy Information Administration (EIA) [2], carbon intensity of electricity between 1990 and 2014 has roughly remained the same. Worldwide, the primary source of energy remains fossil fuels: up to 80% of the total primary energy has been produced this way for the last 30 years.

More people live in developing economics than in develop economics, according to the classifications by the UN World Economic Situation and Prospects [3], with relatively low energy per capita consumption. Studies suggest that the energy consumption per capita and the income scale approximately linearly; this indicates that the energy per capita consumption would increase as standard of living increases. Population growth is strongest in non-OECD countries: it is expected to grow by 35% in the next 35 years, with strongest growth in Africa, where the population is expected to double. GDP is also increasing rapidly in non-OECD countries, and is expected to more than double there in the next 35 years. In particular, India (102%), China (36%) and other countries in Asia (65%) are expected to drive the growth of non-OECD countries to 17% on average. The implication, therefore, is that CO_2 emissions will also increase rapidly unless CO_2 intensity of energy source decreases dramatically. Currently, CO_2 emissions from non-OECD countries are expected to increase by 38% in the next 35 years, while those from OECD countries will increase by 5%.

2. KEY ASSUMPTIONS OF ENERGY SCENARIOS

Key assumptions of the EIA Reference Case [4] are that there will be: significant improvements in global energy efficiency; little growth in GNI per capita in Africa (2.3 billion people at 4,000 USD/capita); decreasing energy use per capita, even for countries going through the most energy intensive phases of industrialization; and, a higher population. All of these factors are even more important in the post 2050 period. There are also four very large but un-modelled applications that could impact the forecasting: the electrification of vehicles; non-fossil heat for industrial processes; hydrogen and synthetic fuels; and atmospheric CO_2 removal. However, it is clear that to get to net negative global CO_2 emissions, some drastic action will be required. Air capture is needed for 50% of required negative emissions; capture, compression and disposal require ~250 kWh/tonne; 10 $GtCO_2$/year would require over 300 GW of baseload fusion plants. Delaying significant emissions reductions will increase required negative emissions.

There are gains in performance and economy by other energy sources, namely the natural gas combined cycle, nuclear/advanced nuclear, solar, wind, and advanced geothermal [5]. Natural Gas Combined Cycle projected levelized costs of electricity to 2050 could be as low as 300 USD/MWh. LNG is a global commodity today but would be even more global in 2050 – a number of new natural gas resources are being discovered around the world. Large projects (multi-units) are already going in at 2040–2050 prices. Nuclear costs are also projected to fall. There are many reasons for this, including procedural controls for costs during construction and smaller system sizes and even 'design to cost' methodology (see chart in Fig. 1 that shows the spread in the costs for advanced fission).

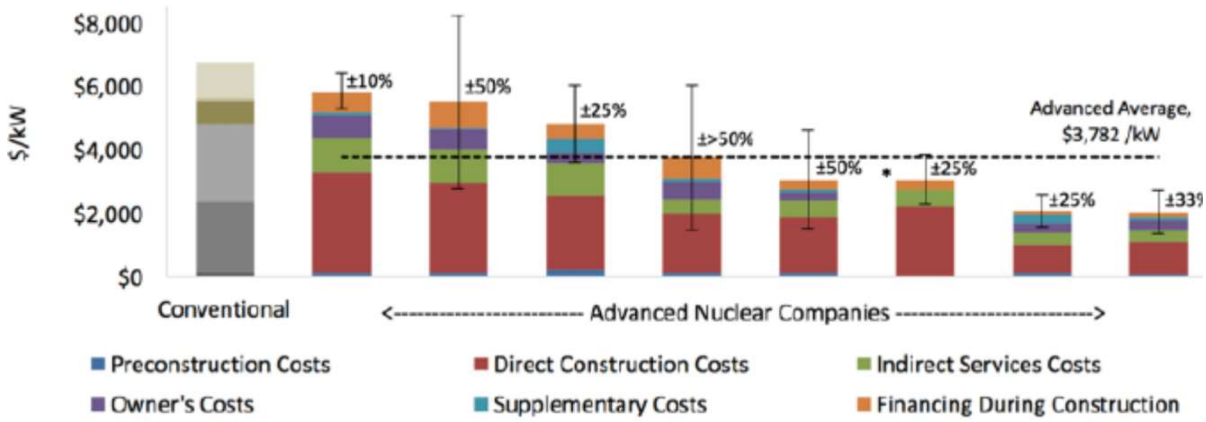

FIG 1. Costs and cost categories of Advanced Nuclear Companies relative to conventional [5].

3. PROJECTED COSTS OF RENEWABLE ENERGY SOURCES

Regarding the renewable energy sources, standalone solar PV (without storage) in large projects could be 35 to 47 USD/MWh and solar PV with storage (without subsidies) could be in the range of 60 to 90 USD/MWh. For wind power plants, multi megawatt class of offshore turbines have been commercialised, and intensive focus on cost reduction innovations by developers has led to a 50% reduction in cost over 2 years. Supercritical steam geothermal projects, which use hotter geofluid from deeper resources for much better power plant efficiency compared with hydrothermal systems, benefit from lower viscosity (higher flow rate) and higher enthalpy (more energy content per kg into heat exchanger, e.g. 900 kJ/kg at 200 degree Celsius and 1,800 kJ/kg at 400 degree Celsius) getting the cost down to 25 to 45 USD/MWh.

In addition, there are several key market opportunities for high-temperature heat sources in the coming decades. Synthetic fuels ($CO + H_2$) production can be achieved with high-temperature heat sources at >

800 degree Celsius. The target cost for such fuels would be 12 to 15 USD/GJ for current oil industry, or 2 to 4 USD/GJ for the heat. Coal plant conversion needs would be there for ~2,000 'modern' coal plants in 2030 with Supercritical steam at > 500-degree Celsius heat, with the target cost of 2 to 3 USD/GJ. Key market opportunities and cost targets for electricity include: atmospheric carbon removal at 200 to 250 kWh/tonne CO_2 with potential annual turnover of 10 GW per year primarily in the EU; Combined Heat and Power (CHP) for cities with winter heating and/or summer cooling/desal with the total demand in hundreds of GW.

4. CONCLUSION

In conclusion, to reduce the cost of fusion energy effectively, the fusion community has to start as early as possible with a good cost model. Risks on the cost have to be identified early in the design, and the cost targets have to be cascaded to subsystems (i.e. design the plant from the cost, not calculate the cost from the design). It is also important to note that there is always a good possibility that the energy market would not go as projected. We have to be always prepared for disruptions to reduce the impact on the design/product/opportunity for fusion. And finally, the fusion community must ask itself how to design a product that is a good fit for the world market of tomorrow.

REFERENCES

[1] INTERNATIONAL ENERGY AGENCY, Consistent, Accurate and Timely Energy Data and Statistics (2021), https://www.iea.org/statistics/?country=WORLD&year=2016&category=Energy%20supply&indicator=TPESbySource&mode=chart&dataTable=BALANCES

[2] U.S. ENERGY INFORMATION ADMINISTRATION, International Energy Outlook 2017, Washington D.C. (2017), https://www.eia.gov/outlooks/ieo/pdf/0484(2017).pdf

[3] UNITED NATIONS DEPARTMENT OF ECONOMIC AND SOCIAL AFFAIRS, World Economic Situation and Prospects (2021), https://www.un.org/development/desa/dpad/document_gem/global-economic-monitoring-unit/world-economic-situation-and-prospects-wesp-report/

[4] U.S. ENERGY INFORMATION ADMINISTRATION, Energy Information Administration's Reference Case Projections (2021), https://www.eia.gov/outlooks/aeo/tables_ref.php

[5] ENERGY TECHNOLOGIES INSTITUTE, Lucid Strategy and CleanTech Catalyst for the UK Energy Technologies Institute, Nuclear Cost Drivers (2018),

https://www.eti.co.uk/news/cost-drivers-identified-to-support-investment-in-new-nuclear-power-and-its-role-in-the-uks-future-low-carbon-energy-system

[6] ENERGY INNOVATION REFORM PROJECT, Lucid Strategy for Energy Options Network & Energy Innovation Reform Project, What Will Advanced Nuclear Power Plants Cost? (2017), https://www.innovationreform.org/2017/07/01/will-advanced-nuclear-power-plants-cost/

PORTFOLIO CONSIDERATIONS IN FUSION ENERGY DEVELOPMENT

R. UMSTATTD
Senior Commercialization Advisor
ARPA-E U.S. Department of Energy, Washington D.C., U.S.

1. INTRODUCTION

The electricity market needs new players — debates on the energy system development have to go beyond baseload vs intermittent. Today and in the foreseeable future, wind and solar PV levelized cost of electricity are relatively low [1–3]. As a result, in a carbon-conscious environment, low-carbon electricity generation (including fusion energy systems) will likely compete against the combined cost of electricity generation and storage for intermittent renewable energy sources, in addition to the natural gas-based production that includes carbon capture and sequestration (CCS). This creates a market for new, right-sized economical load-followers. Fusion energy systems may need to match both cost and load-following capability of competitors to capture the market share. Fusion-specific benefits include power density and geographic and seasonal independence. In some developed countries, GW-scale plants are phasing out in favour of community-scale power generation, as can be seen in the U.S. (Fig. 1).

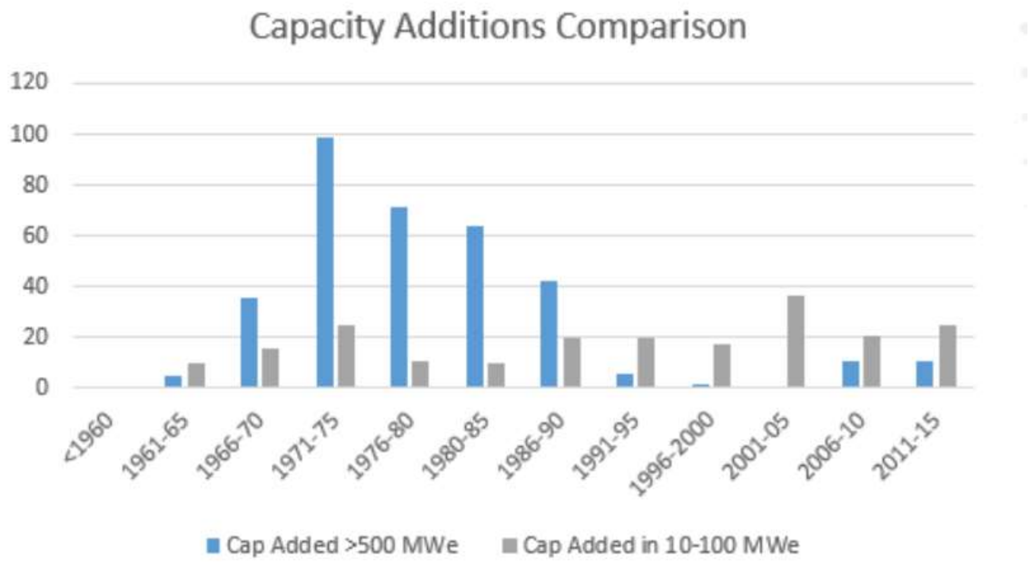

FIG. 1. Capacity additions in the range >500MWe and in the range 10–100MWe in the U.S. [4].

2. DEMAND FOR DISTRIBUTED POWER SOURCES

Community choice aggregates are regions of ~100 thousand customers that can make choices about their energy supply mix, taking the place of the legacy investor-owned utility. Financers appreciate smaller total up-front costs which also tend to lead to more manageable and/or predictable projects. New power plants may need to drive down cost by numbers of units sold rather than by scale of a single unit. Most of the market for new power plants stem from retiring capacity rather than growth in the electricity demand in developed nations (by a factor of 6-to-1 in the U.S.) [4]. In the U.S., as of 2016, the capacity-weighted average lifetime of a power plant is 54 years, which will heavily influence any timeline for technology insertion. If fusion energy systems were proven feasible by the 2050s, building fusion plants could be 15–125 billion USD/year industry for the U.S. alone. For scale comparison, the global Li ion battery market is projected to climb above 70 billion/year in the early 2020s. In contrast to the well-established (but still evolving) electricity markets in the developed nations, there are significant parts of the future global power plant market that will be driven by growth rather than by replacement of retirements. There is wide variation in the maturity, health, and scale of different regions' transmission and distribution infrastructure. The two factors above may very well lead to an opportunity for a first-mover advantage if fusion power plants can compete favourably with other mature plant technologies. Some desirable attributes defined by utilities (see e.g. [5–6]) are to provide load-following capability and frequency support where power cores are sized to match load growth. Lower capital cost capacity additions are desired, as are more distributed and incremental options with smaller footprints which in turn provide more options for sites. Enhanced safety–security is desired, as are shorter construction timelines and smaller operational staff.

3. PRIVATE FINANCING FOR FUSION

When executed correctly, private financing can support fusion development. The issues are to match investors with fusion development: for example, philanthropic investors are more mission-oriented and patient, and comprise a small but growing subset of general venture capital. Technology development paths need well-defined stage gates, which would allow step-chances in valuation during development to be demonstrated, which in turn would demonstrate quantified risk reduction. A portfolio approach for both investors and the technologies would help manage risk, particularly if the approaches are diverse and independent. Opportunities for early revenue streams should be consistent with a path to fusion energy.

REFERENCES

[1] UNITED STATES DEPARTMENT OF ENERGY, Revolution Now 2016 Update The Future Arrives for Five Clean Energy Technologies (2016), https://www.energy.gov/eere/downloads/revolutionnow-2016-update

[2] PLATT, J., PRITCHARD, J. O., BRYANT, D., Analyzing Energy Technologies and Policies Using DOSCOE, SRNN (2017), https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3015424

[3] BUDISCHAK, C., SEWELL, D., THOMSON, H., Cost-minimized Combinations of Wind Power, Solar Power and Electrochemical Storage, Powering the Grid up to 99.9% of the Time, J. Power Sources **225** (2013) 60–74.

[4] U.S. ENERGY INFORMATION ADMINISTRATION, All data from Form EIA-860 (2020), https://www.eia.gov/electricity/data/eia860/

[5] KASLOW, J., Criteria for Practical Fusion Power Systems: Report from the EPRI Fusion Panel, J. Fusion Energy **13** (1994) 181–182.

[6] VONDRASEK, R. J., Utility Requirements for Fusion AP-2254 Research Project 1413-1, Topical Report, prepared by BURNS AND ROE, INC 185 Crossways Park Drive Woodbury, New York 11797 (1982).

[7] ELECTRIC POWER RESEARCH INSTITUTE PROGRAM ON TECHNOLOGY INNOVATION, Assessment of Fusion Energy Options for Commercial Electricity Production, Technical report (2012), https://publicdownload.epri.com/PublicDownload.svc/product=000000000001025636/type=Product

PERSPECTIVES ON FUSION ENERGY FROM UTILITY COMPANIES

J. KOWALCZYK
Nuclear Research Engineer
Southern Company, Atlanta, U.S.

T. FALLGREN
Vice President of Generation
Public Service Company of New Mexico, Albuquerque, U.S.

1. INTRODUCTION

For a successful commercialisation of fusion energy systems, the industry needs to understand the perspectives of its primary customers – the utility companies. Therefore, it is of the essence for the fusion industry to learn their perspectives from the early stage of its development. In this section, perspectives from two differently sized utility companies in the U.S. are provided with the aim of helping to shape fusion energy system development roadmaps toward a faster and successful commercialization.

Southern Company is a gas and electricity utility company headquartered in Atlanta, Georgia. The company provide utility to a 310,000 km^2 territory with the total of 8.93 million customers (electricity and gas combined) [1].

Public Service Company of New Mexico (PNM) is a utility holding company based in Albuquerque, New Mexico. The company provides electricity to more than 520,000 customers, where 30% of the electricity is generated from nuclear power plants [2].

2. PERSPECTIVE OF JOSEPH KOWALCZYK, NUCLEAR RESEARCH ENGINEER, SOUTHERN COMPANY

Firstly, from the perspective of a utility company, technology developers may need to understand the electricity market better. Often, research communities do not fully understand who the utility companies are or what the demand was projected at.

Secondly, it also seems important for the fusion industry to start having a strategy on the construction of power plants. The main reason of the high costs of current fleet of fission reactors are construction costs, not the engineering design costs. When fusion energy system vendors start to have the piping and instrumentation diagrams (P&IDs) and engineering drawings, they would understand that the BOP makes up a huge cost. It may only be then the fusion energy system vendors gain more credibility from the utility companies. Many fusion engineers assume that fusion power plants could utilize the BOP from off-the-shelf pressurized water fission reactors (PWRs). However, as an engineer in a utility company that is currently building the only two nuclear fission reactors in the U.S., I can attest that the BOP is not that simple.

Third, the Nuclear Regulatory Commission (NRC) currently has the licensing authority for fusion in the U.S. The research community, particularly the private sector, either need to unite and try to negotiate so that fusion plants are not regulated by the NRC or start preparing for how they will go through the NRC regulation process. The Electric Power Research Institute (EPRI) has published several papers on the electricity market as well as the Owner-Operator guide for the advanced fission reactors [3]. It would be worth it for fusion energy system vendors to understand this guide and even engage the EPRI to provide input, as this is driven by the needs of the utility companies.

Finally, fusion energy system vendors should also start to think of non-electricity production avenues (desalination, process heat, etc.). These non-electricity productions may open short-term avenues to make revenues while pursuing the end goal of a power plant.

3. PERSPECTIVE OF THOMAS FALLGREN, VICE PRESIDENT OF GENERATION, PUBLIC SERVICE COMPANY OF NEW MEXICO (PNM)

PNM is excited to participate at the early stages of fusion development. The fusion energy systems seem promising, and as a utility company, PNM is eager to see the plan to bring closer to commercialization.

Currently, there is a growing shift in the utility industry to carbon free resources to maximize environmental benefits. Because of this, it is desirable to have technology developers understand the business and more so the political environment for utilities. The fusion industry should not underestimate the importance of the politics in the development of the science, even down to the terminology.

It is exciting to see more and more potential venture capitalist are showing interests in further fusion development. However, it should also be noted that, it is generally the large utility companies that has the interest for the commercialisation for the first-of-a-kind power sources, not companies with the size of PNM.

REFERENCES

[1] SOUTHERN COMPANY, Facts and Figures, (2019), https://www.southerncompany.com/about-us/facts-and-figures0.html

[2] PNM: Powering New Mexico For a Century, Fact Sheet (2019), https://www.pnm.com/documents/396023/440009/2018+PNM-Powering+New+Mexico+Fact+Sheet.pdf

[3] ELECTRIC POWER RESEARCH INSTITUTE, Program On Technology Innovation: Owner-Operator Requirements Guide (ORG) for Advanced Reactors, Revision 0 EPRI Product Id: 3002011802 (2018),
https://www.epri.com/#/pages/product/3002011802/?lang=en-US

SESSION II: COMMERCIALIZATION PATHWAYS

A PORTFOLIO APPROACH TO FUNDING AND COMMERCIALIZATION

E. INGERSOLL
Managing Director
Energy Options Network / Lucid Strategy, Laguna Beach, U.S.

1. INTRODUCTION

While there are many challenges to investing in transformative technologies, a new financing concept is being used in other areas of investment [1]. In this section, a new financing concept for fusion energy systems is suggested based on experience accumulated in other areas of investment. De-risking strategies are also discussed, and supportive policy changes are outlined.

2. EXISTING CHALLENGES

There are a number of risks inherent to investing in early-stage energy technologies: final product fails to work as expected; there might be delays in the development and/or commercialization process; unexpected costs/interrupted funding; market may change; the competition landscape may shift; or the pace and extent of adoption may change. Why can't these efforts be funded by venture capital (VC)? The reason is, the VC model has proven itself to be ill-suited for capital-intensive technology development that requires long development timelines. VC is often considered to be the only source of early-stage funding for innovative energy technology. However, it is not capitalized enough, nor allows for investments that require hundreds of millions of dollars or a > 5-year development/commercialization pathway. In light of past failures [1], VCs are now targeting 'capital lite' downstream business models and IT/web-based businesses that scale quickly relative to investment. Large, multinational energy strategies have also largely been unwilling to take on the inherent risks associated with building, large first-of-a-kind (FOAK) power generation technology. Investments in many transformative technologies do not fit within the traditional suite of asset classes available to investment managers (e.g., VC, fixed income, project finance, etc.). Financial markets are serving a subset of technologies and projects where investment profiles align with technology maturity and traditional financing mechanisms. It is essential to find new ways of allowing large commercial financiers to comfortably participate in funding breakthrough technologies and projects.

Governments and policymakers have not always been successful in dedicating the resources or enacting policies to spur the innovation leaps necessary to dramatically improve our low-carbon energy options. Government may not have enough funding or the right funding model: the majority of supports are for deployment of existing technologies; funding decisions may become political; it sometimes lacks dedicated capital and highly risk averse investors; it may not be able to 'pick winners' or fund entire the development path for capital intensive technologies; R&D programmes often provide only small funding.

National and international policies have not created the enough signals for investors to invest in higher risk/higher impact climate solution technologies. Due to the binding but difficult to enforce international agreements, waiting for enforceable and sufficiently aggressive climate policies can be a risky strategy.

In some cases, governments may not be willing to perform the same role as the private sector: governments sometimes only fund a small portion of innovative projects outside of more traditional projects. Government budgets are in some cases limited. The 2012 – 2017 cumulative ARPA-E budget was 1.7 billion USD, while all private capital investment in cleantech in the same period was ~18.3 billion USD. Vast amounts of capital are therefore looking for climate-based investments. The Green Infrastructure Investment Coalition (GIIC) [2] whose members manage 43 trillion USD in assets, signed statements about the importance of acting quickly on climate change, saying they 'stand ready to invest in climate solutions.' The insurance industry, which manages approximately 33 trillion USD in assets, doubled its climate investments from 2014–2015 and committed to a 10x increase by 2020 (equating to ~450 billion USD). Multinational Development Banks and large investment banks have committed hundreds of billions of dollars over the next 10 years for climate-based investments [3]. Institutional investors are calling for strong political leadership and more ambitious policies in order to scale up their climate-based investments. Green bonds are one of the most effective options for tapping into institutional capital and meeting the growing demand for green investments [4]. A vast majority of green bond holders have indicated that they intend to deploy more capital into this type of instrument as quality deal flow continues [5]. The Climate Bonds Initiative believes that with the right supports in place, 1 trillion USD of green bonds could be issued a year by 2020 [6].

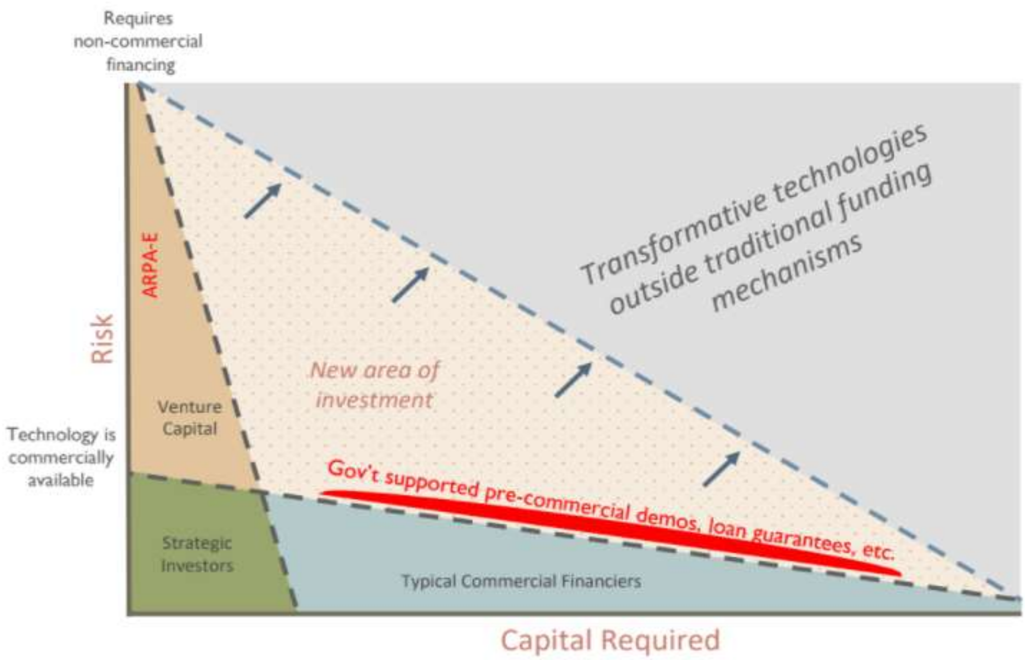

FIG. 13. Plot of risk vs capital requirements for different kinds of investors, and an outline of an area where new kinds of investments are needed to move transformative technologies through to market.

A properly structured investment fund could accelerate technology development that generate highly attractive returns. Investing in a portfolio of early-stage technologies and applying various risk allocation strategies can enable investment in otherwise too risky (and, oftentimes, too costly) endeavours. Investing across a portfolio reduces the uncertainty/risk exposure by investing in individual companies. Investment horizons can be tailored to suit the development expectations and capital requirements of the portfolio projects. This strategy would enable investment in technologies not currently being served by capital markets due to a misalignment of technology maturity and traditional financing mechanisms.

3. A NEW FINANCING CONCEPT

A new type of investment structure could enable investment in a suite of early-stage companies with ‘home run’ potential and offer the potential for attractive, risk-adjusted returns, providing access to opportunities outside the traditional VC/private equity deal-flow universe. A new structure would reduce the risks that would be associated with structuring these investments as traditional venture capital deals and enable investments in home run deals without the risk to principal typically associated with these types of investment.

A mega-fund is a large, diversified portfolio of companies or products with un-correlated development risk [7] [8]. Mega-funds enable the ability to invest in across a portfolio of otherwise too risky (and again, oftentimes, too costly) endeavours and combine many risky projects into a single financial entity. They are designed to access debt market capital and investment horizons can be tailored to suit the development horizons of the portfolio projects. Financing can be structured to allow for more patient capital by specifying longer maturities.

The fund structure is specifically designed to reduce the probability of loss of principal, enable earlier cash flows, increase returns, and improve overall expected value. Each of the fund investments has the potential to become a dominant player in the global energy marketplace. In addition, they have the capacity to produce lucrative spin-out companies with nearer-term revenue. One success is enough to pay for the entire fund. The fund incrementally allocates project capital and iteratively assesses progress to determine whether a project receives follow-on funding. The fund leverages the benefits of: enhanced diversification (fund invests in a portfolio of diverse technologies with high transformative capacity); spin-out company value (each company is developing either primary or secondary technologies that have multiple applications in non-energy markets); and company/ technology synergies (companies are individually developing technologies (or components therein) that can enable the success of other portfolio companies). The fund uses portfolio company exits to pay back fund investors.

4. DE-RISKING STRATEGIES

The probabilities of success of individual projects determine how many projects are needed to make the fund successful. A basic example of the benefits of portfolio investing is as follows. If each project has a 90% success probability, you only need 2 projects for a 99% probability of 1 succeeding. If there are 2 projects, the probability of both failing is 10% x 10% = 1%. Thus, there is a 99% probability of at least one of the two projects succeeding. In other terms, you just need 2 projects to succeed 99% of the time. However, if each project only has a 10% success probability, you need 44 projects for the same certainty of success.

Staged investment with spin-out opportunities can enhance the value. Many companies are developing technologies that are valuable beyond each company's core application. It may be worthwhile to spin-out and commercialize these technologies. The fund reserves the ability to capitalize spin-out companies, dedicated to monetizing enabling technologies developed by portfolio companies. This improves returns by providing supplemental income earlier than the project's ultimate product and insuring against possibility that late phases might hit technical barriers and ultimate product might not launch; and, saving money from not doing investment phases if earlier phases hit technical barriers. Technologies can also reduce market risks by gaining access to a larger number of markets. The staged investments allow for smaller steps in value, requiring less capital and many of the targeted markets present lower risk business propositions. Spinout companies will only be pursued if they present an easier opportunity to generate early revenue.

Both success and failure of individual projects affect the value of other portfolio projects. Success of one portfolio project amplifies the value of other projects. Even if one track toward a critical subsystem does not succeed, other track can succeed (or if both succeed, they could use the easier/cheaper option). There are cost/risk reduction synergies across in material development, sourcing, power plant design, controls/software, simulation tools, admin overhead, etc. These are independent of fusion reactor technology.

The fund can be designed to leverage risk profiles of different investor classes. Financial commitments are based on several pre-conditions, including achieving specific milestones; Investors don't invest until called upon. All investors are committed at the outset. Repackaging a pool of cash flow-generating assets into discrete tranches allows investors to invest at their desired risk/return profile. Benefits of trenching are that: it un-bundles risk and prices it more efficiently; it enables creation of investment grade bonds, granting access to wider group of prospective bond-holders; and, it isolates junk-rated risk for investors with an appetite for a higher risk/return profile. This is a widely used strategy, in the field of mortgage-backed securities, CDOs, credit card debt, auto loans, etc.

There are many ways to improve the credit profile of the underlying bond in order to make it more attractive to the market. The first might be to pay an insurance company to either insure or re-insure senior bond tranches (3rd party validation; Enables larger percentage of investment-grade bonds). Next might be overcollateralization – bond issuance raises more capital than necessary. Yield spread: establish a reserve of excess spread (i.e., the positive difference between portfolio revenue and obligations) to cover losses; and, Surety bonds - insurance policy provided by a rated and regulated insurance company to reimburse the bond investor for any losses incurred.

Establishing a customer engagement group that ensures designs will meet customer requirements will reduce uptake risk. Through a Customer Engagement Group, prospective customers can provide input into the design process to make sure the design meets their requirements. They can pre-order units and pay for geographic/market exclusivity. They might also obtain priority for first commercial units; and, exercise options for preferred equity ownership. Increasing customer involvement/investment prior to market readiness can reduce the risk for market uptake.

5. POLICY SUPPORT

Policies aligned with the government's goals of technology innovation can benefit investors considering fund participation. Establish an Investment Tax Credit (ITC) for qualifying fund investments: the fund would receive a tax credit for qualifying investments (i.e., typical, depreciable assets) and sell that tax credit on the open market. Proceeds from the tax credit sales could be used to pay the bond coupon and/or be set aside for credit enhancement purposes. Research and Experimentation Tax Credit (or R&D Tax Credit) could be claimed credit against alternative minimum tax and payroll taxes. Finally, repatriation of offshore profits would help over 2 trillion USD in corporate profits are to be stockpiled overseas in low-tax countries. Instead of taxing those profits, companies should be able to invest that capital into the fund. The companies can receive tax-free returns from the investment until they reach the amount of the original investment, after which, returns are tax at the appropriate rate.

REFERENCES

[1] GADDY, B., SIVARAM, V., O'SULLIVAN, F., Venture Capital and Cleantech: The Wrong Model of Clean Energy Innovation, An MIT Energy Initiative Working Paper (2016), https://energy.mit.edu/wp-content/uploads/2016/07/MITEI-WP-2016-06.pdf

[2] GREEN INFRASTRUCTURE INVESTMENT COALITION, Increasing The Flow Of Institutional Investor Capital Into Green Infrastructure (2021), http://www.giicoalition.org/

[3] THE WORLD BANK, World Bank Group Announces $200 billion over Five Years for Climate Action, The World Bank PRESS RELEASE NO: 2019/CCG/92 (2018), https://www.worldbank.org/en/news/press-release/2018/12/03/world-bank-group-announces-200-billion-over-five-years-for-climate-action

[4] BLOOMBERG PROFESSIONAL SERVICES, Blossoming green-bond market growing toward $250 Billion Year (2018), https://www.bloomberg.com/professional/blog/blossoming-green-bond-market-growing-toward-250-billion-year/

[5] MERRILL LYNCH, Impact Investing: The Performance Realities (2016), https://olui2.fs.ml.com/Publish/Content/application/pdf/GWMOL/ME-impact-investing-white-paper.pdf

[6] CLIMATE BONDS INITIATIVE, Year 2015 Green Bonds Final Report (2015), https://www.climatebonds.net/resources/reports/year-2015-green-bonds-final-report

[7] FAGNAN, D. E., FERNANDEZ, J.M., LO, A., Can financial engineering cure cancer? Am. Econ. Rev. **103** 3 (2013) 406–411.

[8] FERNANDEZ, J.M., STEIN, R., LO, A., Commercializing Bio-medical Research Through Securitization Techniques, Nature Biotechnology **30** (2012) 964–75.

GENERAL FUSION'S APPROACH TO COMMERCIALIZATION

D. PLANT
Director of Programme Management
General Fusion, Burnaby, Canada

1. INTRODUCTION

General Fusion's Magnetized Target Fusion (MTF) technology uses liquid metal to compress a magnetized self-organized hydrogen isotope plasma, which in-turn heats until the hydrogen isotopes fuse into helium, and release energy.

MTF technology is an MCF (Magnetically Confined Fusion) - ICF (Inertial Confined Fusion) hybrid. During the MTF process a plasma is first formed with a strong self-supported magnetic structure, then the plasma is physically compressed on a time scale less than the characteristic plasma thermal lifetime to fusion conditions at moderate densities. General Fusion has selected MTF as the basis for its technology due to its commercially attractive approach to fusion power that avoids many of the technology hurdles associated with MCF or ICF technology.

The magnetized plasma is formed in the injection system by passing a large electric current through a low-density gas in the presence of a strong static magnetic field. The gas is ionized creating a conductive plasma. The current flowing in the conductive plasma interacts with the static magnetic field, causing the current to loop upon itself, creating a self-organized structure, with closed magnetic flux surfaces, called a compact torus (CT).

The CT is injected into a cavity within a spherical compression vessel. The cavity is produced by a liquid metal filled porous structure, within the compression vessel, that spins about its central axis.

The CT is then compressed by radially injecting liquid metal into the compression vessel, through the porous structure. The fluid is injected by a constellation of synchronized pistons that surround the compression vessel. As the liquid metal converges towards the centre of the vessel, the cavity's volume is rapidly decreased, compressing the confined magnetized plasma.

As the cavity encloses the CT, the confined magnetic field induces electrical currents in the liquid metal cavity wall. The induced wall currents produce magnetic fields that push the CT away, and inwards, from the shrinking cavity wall, rapidly compressing and heating the enclosed CT. As the CT is compressed it becomes denser and heats, eventually to the point where its constituent hydrogen isotopes fuse into helium.

The liquid metal liner shields the fusion vessel structure from damaging neutron flux, and provides the medium to convert fusion energy, primarily in the form of high energy neutrons, into thermal energy - energy that is, in turn, used to generate power. The liquid metal is a lithium-containing alloy that breeds a small amount of tritium due to the neutron flux. The intrinsic tritium production provides a closed loop supply of hydrogen isotope fuel for the system.

2. STRATEGIC DEVELOPMENT PLAN

General Fusion's goal is to commercialize Magnetized Target Fusion. Rather than seek to raise the capital required to build a large-scale demonstration plant from the beginning, the company has taken a risk reduction approach, examining the relative risks associated with the components of the fusion system and prioritizing development of the highest risk components.

This approach is highly incremental and agile. Technologies and systems are often developed with a degree of independence from each other. Results and learnings from development efforts are rapidly shared across the organization, informing the basis of the MTF architecture, and further de-risking efforts. Small scale projects embrace the 'fail fast – fail early' ethos to limit resources spent on dead-end investigations. Individual programmes and projects are designed to address risks to achieving the company goal to commercialize MTF.

While there are a great number of risks to such an ambitious effort, they can largely be grouped into a couple of categories.

Key Science Risks – These are the big issues that are critical to viability of General Fusion's MTF scheme. They sometimes stem from gaps in the scientific understanding supporting the technology. Work on these problems can be slow, and the results often have material effects on the system architecture. While this fundamental work takes time and produces results slowly, the results are instrumental in engaging the academic, and scientific community, as well as the company's peers. This careful, slow but steady progress builds credibility allowing General Fusion to attract critical talent, both in staff and in external collaborators.

Engineering Risk – Engineering risk is the collection of things that are known to be possible but have schedule and cost risk. They are often associated with technologies that the company does not yet have a good understanding of, or they are challenges that require first-of-a-kind (FOAK) solutions. Engineering that is not core to General Fusion's technology, or is in mature fields, is often outsourced to external expertise. The company internally focuses on projects that address the highest risk challenges, and shorter well-defined projects that have demonstrable milestones. Significant, physical and demonstrable results from these projects are key to demonstrating progress to the investment community. In addition to demonstrating progress, the actual physical realization, and testing of complex FOAK designs expose hidden challenges early in the development cycle. Once the engineered solutions are physically demonstrated the design can be put into 'inventory', to be used when General Fusion embarks on building an integrated test facility.

Risk due to lack of access to field experts and talent – As a small company with limited resources, General Fusion was challenged to attract field experts. Fusion energy research and development requires significant specialized expertise, which is not widely available. Much of General Fusion's expertise has been self-created by carefully recruiting talented staff and working closely with university co-operative programmes. At any time 5%-10% of the company's staff are short term paid interns, and graduate students, from international universities. These relationships and the volume of students that pass through the company's intern programme allows the company to select and recruit exceptional permanent staff. The company's scientific development programme, open communication at conferences and symposiums and it's publishing of the company's progress in key scientific areas has been successful in attracting field experts, both as collaborators and as full-time staff. General Fusion actively works to build a community and form collaborations with universities, the open-source software community, government/national labs and industrial partners. This helps to bring the expertise, collaboration, and resources needed to build the foundational technologies that General Fusion needs to reach its goal.

Financing Challenge – Financing fusion development can be challenging, as science development and foundational technologies, such as computer modelling codes and models, have long development cycles with little to show, initially, for a significant amount of effort. Even though these foundational efforts have low visibility, they are absolutely necessary for success and require significant funding. Foundational technologies, such as computer modelling codes, support the development of the company's key science objectives. Ensuring that the development programme has a mix of effort between physical engineering activities, development of foundational technology, and science creates visible progress. Achieving salient challenging, physically demonstrable milestones helps build the investor confidence, that's needed to fund the longer-term efforts in foundational technology and science.

General Fusion's strategy has been to incrementally address these risks with a strategic development plan that addresses science and engineering risks incrementally, while continuously developing foundational technologies. This approach creates a development cycle (Fig. 1) that facilitates the long term science experimental programmes, and fosters collaboration, while rapidly producing demonstrable physical hardware.

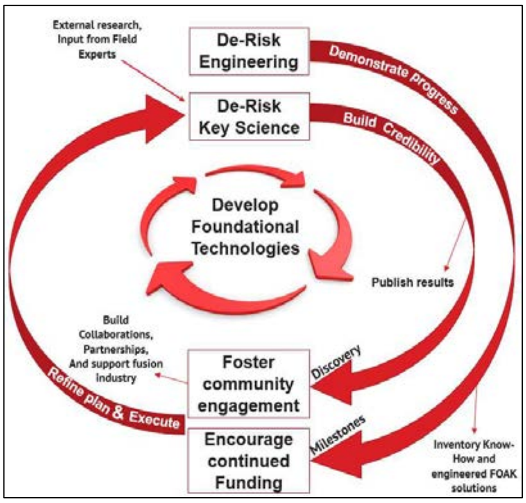

FIG. 1. Strategic Incremental Development.

Major subsystems such as the liquid metal cavity formation system, synchronized piston compression system and large-scale CT Plasma injectors, have been the focus of successful campaigns. These campaigns developed, demonstrated, and de-risked the major components.

3. FUSION DEMONSTRATION PLANT (FDP)

General Fusion has demonstrated magnetic, and explosively driven compressive heating of large- and small-scale magnetized CT plasmas. The company is also producing target CT's with thermal lifetimes that are sufficiently long to allow mechanical compression on a demonstration plant scale. Piston based drivers with the energy density and timing precision necessary to drive a symmetrical liquid metal compression cycle have also been demonstrated.

The pieces are now in place to start development of a liquid metal compressor that can compress plasma to temperatures that will yield fusion energy. General Fusion is embarking on the development and construction of a large-scale integrated machine, and test facility, to demonstrate these fusion conditions called the Fusion Demonstration Plant (FDP), see Fig. 2.

The FDP facility will operate a sub scale version of a commercial MTF system. The FDP scale will be approximately 70% of a commercial MTF power plant. It will demonstrate key MTF technologies and de-risk technology needed to commercialize an MTF power plant.

The primary FDP goals are to demonstrate the ability to create MTF fusion in a process that could be capable of producing electricity using General Fusion's architecture, demonstrate the fusion systems performance at large scale, and confirm predicted power plant economic projections. The FDP will not generate significant energy but will clearly demonstrate the ability to heat a CT to fusion conditions, by compressing it with a liquid metal liner.

By systematically reducing the risks associated with the integrated demonstration plant, before commencing this project, the company has built the technical capabilities and credibility to raise the capital for a project of this magnitude.

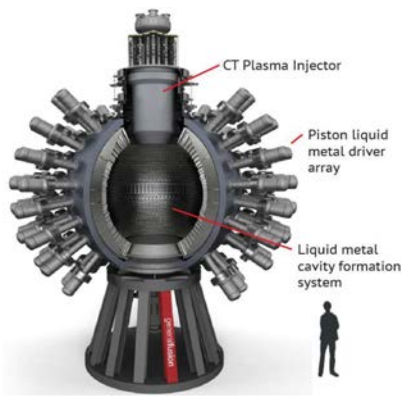

FIG. 2. Simplified FDP image.

REDUCING RISKS TO COMMERCIAL FUSION

M. HANDLEY
Founder and Managing Partner
Strong Atomics, San Francisco, U.S.

1. INTRODUCTION

This paper illustrates the challenges involved in getting to fusion energy on the grid, as well as how to evaluate companies and public and private ways to reduce the risks and costs. There are several steps for any company or investor hoping to get fusion power on the grid. The key steps can be identified as follows:

- Selecting an approach;
- Science: demonstrating energy breakeven and reactor-relevant energy gain;
- Engineering: demonstrating a working reactor;
- Market: competing in the energy market.

Each of these key steps will be examined below. In Section 2, the pathways to fusion and means for assessing progress towards these goals are outlined in terms of Technical Readiness Levels (TRLs); in Section 3, some of the principal scientific risks and how to mitigate those are outlined; in the Section 4, the technology risks are discussed. Finally, in Section 5, the economic aspects of fusion are discussed.

2. SELECTING AN APPROACH

History shows us that it's possible to make rapid and sustained progress toward energy breakeven in fusion. Currently, many nations are backing ITER as the primary option. However, the fusion industry might have to fund multiple approaches beyond ITER for a faster commercialization. NASA's technical readiness levels (TRLs) are a framework for managing a portfolio of possible technical solutions to a problem and determining how many approaches need to be funded as their maturity increases.

3. SCIENCE: DEMONSTRATE ENERGY BREAKEVEN

Since fusion energy systems have not yet achieved the energy breakeven for a sustained time (i.e. extracting more energy than is required to sustain the fusion reaction), the first question is whether it's possible to get to breakeven with the selected approach. A secondary yet important question is how much it will cost and how long it will take to get there. Designs that are smaller tend to be cheaper and faster to build, which enables more rapid progress. These advantages are likely to also apply to the engineering and market phases of the project.

The following are the several potential pathways of reducing the cost and risks for fusion start-ups.

Shared software: most fusion companies are using codes that they have modified heavily or developed from scratch. This makes peer review hard and should make investors uncomfortable. When incentives are considered it's even worse: the people developing this software know what answer is desired and have a strong, if unconscious, incentive to deliver it. If everyone used one code, or a small number of codes, many of these problems would be reduced. Unfortunately, there are many different codes in use because it's hard to write one code that can be used in many different situations. Further, the best codes tend to be classified, which prevents any company from using them, let alone all companies. Developing a new general-purpose code is expensive and hard to fund from licensing fees paid by underfunded fusion start-ups.

Shared pulsed power: pulsed approaches to fusion require high-power systems to drive them, and these components can easily be more than 30% of the entire budget. If they could be shared between companies each company could move faster and spend less. Unfortunately, different approaches require different discharge times, currents and other characteristics. Additionally, sharing physical infrastructure requires that experiments are performed in one place or that the infrastructure is moved around. Either way, different experiments can't be performed at once. This level of sharing might be achievable for a single company but seems unworkable as a cooperation between companies.

Rollup: one way to enable the types of sharing discussed above is to buy up several fusion start-ups and combine them into one company. There could be shared teams for power, diagnostics and software; and teams working on each approach to fusion. This sharing should reduce costs. With everyone in one place and working for one company, there should be much more collaboration. Investigating novel approaches to fusion would be easier because of the range the equipment and scientists on site so it's likely that more approaches would be tried. However, this too has downsides. Teams which currently compete fiercely might have trouble cooperating and the lack of competition might reduce their drive. Additionally, setting this up would involve complicated logistics and negotiations and could disrupt the work of the companies involved. Finally, some companies are unwilling to join something like this and may be reluctant to take investment from a rollup, since it would be competing with them as well as investing in them.

Holding company: a holding company might solve many of these problems. It would invest in companies rather than trying to combine them, but it would still create shared infrastructure in cases where enough portfolio companies need the same thing. The most likely example of this is software but it could be extended to hardware as well, albeit with some of the problems described above. The primary problem with this approach is that it is unclear that there are enough promising companies to justify this, especially when one considers how much they overlap in their software or hardware needs.

4. ENGINEERING: DEMONSTRATING WORKING REACTOR

There are many challenges in going from a demonstration of reactor-relevant gain to a working reactor, including handling and breeding tritium, shielding components from neutrons, handling radioactive waste and handling high currents. These challenges vary in scope depending on the approach selected for fusion. For example, designs that have a solid first wall probably have greater challenges with material lifetimes than ones that can use a liquid liner. Understandably, fusion start-ups view these challenges as secondary to the task of demonstrating gain and intend to tackle them only after gain has been achieved.

This leads to two conclusions:

— Since these challenges will only be faced many years from now, they cannot, by definition, be front-loaded. Thus, it's desirable to pick a design with more tractable engineering problems. When forced to choose between reducing science problems and reducing engineering problems, the latter may be more important.
— There's a large role for government and academic laboratories to play in confronting these engineering challenges. Doing so now may help companies to make better design decisions and make it easier for them to raise money.

5. MARKET: COMPETING IN THE ENERGY MARKET

For any fusion reactor to matter, it must compete against other sources of electricity and win. In particular, fusion power plants must get built and must sell competitively priced energy. To assess the likely competitiveness of a reactor, the fusion community need to know what metrics to use. The traditional metrics for assessing the economics of a power station are the levelized cost of energy (LCOE, measured in USD/kWh) and overnight construction cost (OCC, measured in USD/W). However, it would be advantageous to use the total overnight construction cost (TOCC, measured in USD) instead of OCC.

Total overnight capital cost: the problem with OCC is that it doesn't capture the required size of a plant. If a fusion reactor has a highly competitive OCC of 1 USD/W but must be 50 GW to work, then the plant will cost 50 billion USD and will never be built. A design with a higher OCC that can be built smaller will be more successful. Because of this, TOCC may be a more relevant measure in many cases.

Implications of LCOE: the LCOE of a plant is the sum of all fixed and variable costs, including construction cost, interest, maintenance, fuel and staff, divided by the amount of energy sold, both over the lifetime of the reactor as described later in Section 4.2. An important component is the capacity factor (also sometimes called as the availability factor), which is the amount of energy sold as a fraction of the energy that could have been produced if the plant operated throughout the year. Fusion start-ups often assume that their plants will have a capacity factor of 0.9, as fission reactors usually have. However, renewable energy sources are already flooding the market with nearly-free energy at certain times of day and this will only be more common by the time that fusion reactors hit the market. Making a fusion reactor demand-following does not help since its fixed costs are high and its variable costs are low. Instead, operating the reactor less means that the costs stay the same, but less energy is sold, increasing the LCOE.

The implication of this is that a fusion reactor must run as close to continuously as possible in order to better amortize the high fixed costs. When a demand-following (or load-following) plant is desired from the market, the fusion core should be coupled with lower-variable-cost hardware that can be demand-following. One example of this is using the hot molten salts as energy storage and having a demand-following turbine to generate electricity when there is demand. This way, the LCOE of the fusion power plant can be minimised while making it load-following. In addition, the increased revenues by operating demand-following might compensate the increased cost of the additional equipment for demand-following.

6. CONCLUSION

Some important ways to increase the chances of getting fusion power on the grid are to: balance scientific and engineering risks and minimize risks that cannot be front-loaded; and match the likely future market for energy, which probably means designing for a high capacity factor with integrated thermal storage to keep the LCOE down and targeting a low total overnight construction cost.

SPINOFFS FROM EARLY STAGE FUSION COMPANIES

S. WURZEL
Angel Investor

1. INTRODUCTION

From 1950 through to the 1990s, fusion research was mainly government funded. In recent years, venture capitals became involved, helping sufficiently de-risked approaches (in the eyes of investors) sprint towards a demonstration of fusion breakeven and potentially a large return on investment. This framework, of a large and consistent background of governmental funding of basic research with venture funded sprints to breakeven is a healthy model when the conditions of steady governmental funding and available venture funds exist.

In reality, government funding waxes and wanes as policy priorities change, and the willingness of venture capitals (and high-net-worth individuals) to invest in fusion depends on many factors outside of the control of researchers and entrepreneurs. There is a third way of sustaining fusion activities: the creation of profitable spinoff companies which emanate from fusion research. In this model, profits from the spinoffs sustain the parent organization until the point at which enough technical risk has been retired and an investor can fund a sprint to breakeven[2].

However, this approach comes with major pitfalls, and consequently, the evaluation of spinoffs from early stage fusion research must be analysed with a critical eye. On paper, spinoffs appear to be a panacea for companies that don't capture enough government grants or are not sufficiently de-risked to raise private funding. Cash flow from spinoffs is non-dilutive, only subject to the forces of the market, and in theory can be consistent. In reality, birthing spinoffs can be a major distraction from the main mission of the company (fusion R&D) and skim off already scarce resources from struggling organizations.

A short taxonomy of spinoffs is listed at the end of this section. However, with an eye towards the critical evaluation of spinoff concepts, some of the major risks of all spinoffs will be summarised first.

2. RISKS OF SPINOFF

Creating a profitable business is hard and may be a major distraction to research and development
The creation of any profitable business involves a significant amount of non-technical work. Skills in sales, marketing, management and operations are different from the technical skills needed to develop

[2] Related to this model, but outside the scope of this note are spinoffs from venture funded approaches to fusion created when the anticipated fusion roadmap is not achieved in order to provide return on investment for investors.

fusion concepts. These skills may not exist within the organization and hiring for these roles takes brings additional risk to the organization.

Profitable businesses suck up resources and investments

If the spinoff does make money, it is a business law of nature that investment will be driven back towards the profitable arm of the business with the goal of making even more money. Ensuring that some level of profits is distributed back towards fusion R&D requires real discipline.

It is unlikely that spinoffs can fund large machine construction

Fusion research is an expensive endeavour and it's unlikely that any spin-off will support a sprint towards break-even costing on the order of tens or hundreds of millions of USD to be spent over a relatively short timescale. Rather, spinoffs are a means to an end: keeping day to day operations running smoothly while technical risk is reduced to an appropriate point at which investors can be brought in.

3. TYPES OF POTENTIAL SPINOFF BUSINESSES

Types of potential spinoff businesses from fusion companies are as follows, in order of increasing value:

Consulting

Consulting revenue only scales with time spent; customers are demanding, and contracts come and go. Fusion start-ups should avoid consulting unless the work is directly tied to technical risk reduction, for example development of core technology or analysis which is also relevant to the client's needs.

Sales of bespoke equipment or equipment with high levels of required customer support

Custom equipment manufacturing suffers from high levels of distraction. It also attracts engineering talent since the best engineers like to solve hard problems and custom equipment is an endless source of these hard problems. However, if the equipment is related to the fusion effort, a case may be made.

Commodity sales

Sales of a commodity are promising since there is a lower (albeit nonzero) sales effort required on the part of the company. Typically, commodity sales are only profitable if there is some secret sauce which allows for the manufacturing of the commodity at lower cost than competitors.

Licensing of technology to third parties

Licensing of technology to third parties has the advantage that the third party bears the costs of overhead of sales and marketing. In general, any licensing agreement should include a revenue share component so the licensor can partake in any large success of the licensee.

4. CONCLUSION

To sum up, profitable spinoffs are hard and are not replacements for governmental funding or private investment. Rather, they are a means to an end: steady, non-dilutive cash flow to allow an organization to retire technical risk and demonstrate sufficient progress to attract funding from private investors or government grants.

HISTORY LESSONS FROM DU PONT FOR THE SUCCESSFUL DEVELOPMENT OF FUTURE PUBLIC-PRIVATE PARTNERSHIPS IN FUSION ENTERPRISES

G. GOODMAN
Former President
E.I. Du Pont De Nemours & Co., Wilmington, U.S.

1. INTRODUCTION

At the outbreak of the World War II, the U.S. government asked E.I. du Pont de Nemours & Co. (DuPont) to rapidly build industrial scale fission reactors and plutonium separators using new and untried technology involving nuclear fission. DuPont was chosen by the U.S. military to work in close partnership with the University of Chicago and its Metallurgical Laboratory, which was then under the direction of Dr. Enrico Fermi. General Leslie Groves felt that only DuPont had the ability to undertake this project. Based on this request, DuPont designed, built and operated the Hanford Reservation in the State of Washington, which was the largest chemical plant it had ever constructed at that time. It was completed on time, close to budget, and it successfully worked to produce the plutonium that was used in the second atomic weapon dropped at Nagasaki. In 1946, and in accordance with its contract, DuPont turned over operation of the Hanford Reservation to the U.S. government. The Hanford Reservation then proceeded to produce most of the plutonium that was used in creating the U.S. arsenal of nuclear weapons for the next forty years—largely based on industrial designs for nuclear fission reactors and plutonium separators that DuPont had prepared during World War II.

2. DUPONT'S STRATEDY DURING WW2: THREE QUESTIONS

Here are three of the questions that will be addressed in this section: first, how did DuPont succeed in taking an unproven, laboratory-based technology (i.e., nuclear fission reaction) and commercialize it on a grand industrial scale in a few short years? Second, based on the DuPont/University of Chicago/Metallurgical Laboratory experience, what would be key elements needed to develop successful public-private partnerships? Third, could the same or a similar approach be used to rapidly commercialize fusion reactors at the present time?

In response to the first question, DuPont's success was based on the following:

Cost plus $1 Contract: DuPont insisted that it be reimbursed only for its actual costs at Hanford plus 1 USD. This emphasized that DuPont was performing this service for patriotic reasons and not to make money off the government. On the other hand, DuPont gained enormous technical and process knowledge through managing this massive industrial undertaking.

In House Engineering: DuPont had a well-developed chemical engineering organization that had recently been involved in designing high temperature/high pressure facilities for many of its newer chemical products. This experience prepared it for the technical requirements that would be needed to succeed at Hanford.

Sole Source Contracting: DuPont was solely responsible for the industrial designs (as opposed to the conceptual designs prepared by the Met Lab), the construction, and initial operation of the Hanford Reservation. This consolidation of authority insured a seamless transition from construction through start-up and allowed for the extraordinary speed of the project.

Technical Breakthroughs: DuPont implemented numerous technical achievements at Hanford including one of the first major uses of the Critical Path Method (CPM) in large scale construction projects, the use of Teflon as an improved gasket material, and the use of closed circuit television cameras to allow for remote operations around hazardous materials.

In response to the second question, key elements were as follows:

Metallurgical Lab Success: Before starting this project, the Met Lab was able to demonstrate successful nuclear fission reaction in their laboratory at the University of Chicago. This lab success gave DuPont confidence that they could scale up the reaction to an industrial scale.

Design Conservatism: DuPont insisted on applying design conservatism to its industrial designs that overcame significant flaws in the initial conceptual designs prepared by the Met Lab. Building industrial facilities is not the same as building small scale laboratory facilities.

Avoiding Normal Delays: By insisting that it be solely responsible for industrial design, construction, and initial operations, DuPont did not have to wait on building consensus with other entities and could make decisions quickly. The downside to this approach is that DuPont would have been solely responsible if there had been a failure. This fear of failure brought the full attention of all DuPont senior officers and directors to this project.

In response to the third question of whether this could be applied to an industrial scale fusion reactor project, the observations can be made:

Competition, not Consensus: In looking to build a fusion reactor, most projects have emphasized large scale cooperation and consensus building across many organizations and nations. In many ways, World War II was a form of competition that led to rapid innovation. Literally life and death decisions were involved. Bringing competition between organizations and nations into the development of fusion reactors might be what is needed going forward.

The Right University, the Right Laboratory, and the Right Corporation: For a modern version of the Manhattan Project (perhaps a Fusion Engineer District), the right university, the right laboratory, and the right corporation should work towards building a large-scale fusion reactor with the appropriate government sponsor. Hopefully, there will be many different industrial fusion projects in many countries. All of these elements are present today.

REFERENCES

[1] B REACTOR MUSEUM CORPORATION, The DuPont Company The Forgotten Producers of Plutonium (2017),
http://b-reactor.org/wp-content/uploads/2017/03/Lost_In_The_Telling-Rev_3.pdf

[2] ATOMIC HERITAGE FOUNDATION, Manhattan Project Spotlight: E.I. du Pont de Nemours & Company (2014),
https://www.atomicheritage.org/article/manhattan-project-spotlight-ei-du-pont-de-nemours-company

[3] ATOMIC HERITAGE FOUNDATION, Hanford Cleanup: The First 25 Years (2014),
http://www.oregon.gov/energy/facilities-safety/safety/Documents/Hanford%2025%20Year%20Report.pdf.

[4] NDIAYE, P.A., Nylon and Bombs. Translated by ElborgForster. Baltimore, MD: Johns Hopkins University Press (2007).

[5] THAYER, H., Management of The Hanford Engineer Works In World War II, New York, NY, ASCE Press (1996).

FUSION NEUTRON SOURCE AS A DEVELOPMENTAL STEP TO COMMERCIALISATION

J. ANDERSON
Senior Scientist
University of Wisconsin, Madison, U.S.

1. INTRODUCTION

The realization of controlled fusion energy requires materials and components robust to a high neutron flux. A dedicated neutron source is required to develop and test such materials with both a long lifetime and minimal activation when subjected to a high neutron flux. In addition to the fusion materials development, neutrons are also valuable for commercial applications. For this reason, development of a compact, high flux fusion neutron source would provide another pathway toward the commercialisation of fusion. Such neutron source would use a steady state plasma confined in a variant of the simple magnetic mirror: a long solenoidal field terminated at each end by a much stronger field.

Using a mirror for generating neutrons is not a new idea and appears to scientifically sound. However, only very recently have the key physics elements been validated experimentally [1–3]. In addition, two emerging technologies each at the forefront of their respective development paths, high temperature superconductivity and liquid lithium walls, can greatly improve the concept. However, there are several development steps needed to before a reliable steady-state neutron factory can be built for users. A successful demonstration will advance this concept to a point where other funding, quite possibly in the private sector, brings it to fruition with only one additional step, namely the application of steady-state high-power neutral beam heating that drives fusion.

Neutron sources are extremely valuable but costly to build. There are many commercial applications for neutrons, including neutron radiography, neutron diffraction for residual stress analysis, semiconductor doping, medical isotope production, and fission actinide transmutation. There are also academic research applications, including neutron activation analysis, fusion and fission reactor materials testing, biological imaging, and protein structure formation. Today, these markets are served by nuclear fission reactors and spallation neutron sources. Both of these technologies require massive facilities that are extremely expensive to build and maintain. Fission reactors also face severe regulatory challenges in the US, causing shutdowns of some of the few remaining facilities that provide neutron irradiations services. This has caused many in the marketplace to utilize reactors in Canada and other foreign countries.

Two Wisconsin companies, SHINE Medical Technologies and Phoenix Nuclear Labs (PNL), are working to commercialize a fusion-based technology to provide a high-yield neutron source. PNL has developed a neutron generator that utilizes a microwave ion source, 300 kV DC accelerator and gaseous deuterium target to achieve deuterium-deuterium neutron yields of 3×10^{11} n/s. Near-term advancements are projected to allow for deuterium-tritium neutron production of 5×10^{13} n/sec. SHINE will couple this neutron generator to a subcritical fission assembly to produce a total neutron source strength of over 5×10^{15} n/cm^{2}s.

2. MARKET POTENTIAL

Many commercial applications have been identified that can be served by the PNL/SHINE technologies, but others will require even higher neutron outputs to be economically viable. Additionally, a system that can achieve source strengths of $>10^{15}$ n/s without the use of tritium or fissile material would be highly advantageous from a licensing and cost perspective. A market analysis performed by SHINE suggests that a single 10^{17} n/s system could generate 70 million USD/year in revenue by serving customers outside of the medical isotope market.

3. FUSION COMPONENTS AND MATERIALS

It is widely recognized that a dedicated neutron source is necessary for fusion energy development. Studies based on a variety of magnetic confinement schemes for a so-called Fusion Nuclear Test Facility, including tokamaks and spherical tokamaks. From a dollars-per-neutron metric considering construction, operation and tritium consumption, simple mirrors would clearly be the most economic path to implement a fusion components testing facility.

4. THE NEXT STEP

Magnetic confinement of high-energy ions could yield the reaction rates needed for a high-flux fusion neutron source. Unlike the gas-target sources developed by PNL and SHINE, the ions are trapped in a magnetic field, allowing a much greater probability for fusion reactions. Recent experiments using a simple magnetic mirror geometry called the Gas Dynamic Trap (GDT) have demonstrated plasma confinement close to the physical limits allowed by charged particle interactions. The GDT has easy-to-build circular and planar magnet coils with inherent capability for steady-state operation. One such experiment is located in Novosibirsk, Russia and operated by collaborators of the University of Wisconsin, and one of the co-inventors of the GDT concept is a University of Wisconsin plasma physicist.

The GDT concept may be game changing due to its (1) demonstrated plasma stability, (2) a very large ratio for the plasma-to-magnetic-field pressure, which maximizes neutron production in a given magnetic field, and (3) high electron temperature, which decreases ion energy loss due to collisions with electrons. The neutron production in the Russian GDT is limited by its low magnetic field and short-pulse neutral hydrogen beam injectors, which are the source for energetic ions confined in the plasma. The major steps needed to complete the development of GDT are to increase the magnetic field, increase the energy of the fast ions, demonstrate a steady-state energetic ion source, and demonstrate steady-state operation of a GDT plasma. An industrial source also requires optimization of the plasma-facing materials and sample-volume exposure geometry. A second game-changer has emerged that makes GDT an especially ripe opportunity, namely practical high-temperature REBCO tape superconductors that are enabling key industrial applications such as improved MRI magnets. Very importantly, these superconductors have already been used to build magnets as high as 25 Tesla, and the GDT's simple planar coil geometry facilitates early application of the REBCO technology for plasma confinement.

5. NEUTRON SOURCES ARE ON ROADMAPS TO FUSION

Beyond the applications of a power-consuming neutron source, building a next-step mirror may be a disruptive change to the magnetic confinement fusion power generation paradigm. The magnetic mirror is an idea previously discarded in mainstream fusion research in the US (and mirror fusion research is not currently funded by the Office of Fusion Energy Sciences). Meanwhile, dramatic experimental physics advances in Russia have demonstrated a stable plasma at a high value of pressure (normalized to magnetic field strength) with an electron temperature of nearly 1 keV. These parameters are sufficient for producing a high flux neutron source with an increase in magnetic field and ion energy, but an energy producing fusion reactor would be quite long: when properly stabilized, the mirror has a fusion gain proportional to length. The current mirror throat confinement puts a breakeven reactor at about 1 km length. The device length shortens proportionally with discovered confinement increases, through increased mirror ratio or electrostatic trapping.

6. CONCEPTUAL DESIGN AND INITIAL THEORETICAL RESULTS

Researchers at the University of Wisconsin have carried out a preliminary theoretical design of a neutron factory that exploits the technological and physics advances that make such a machine now possible. The device uses (1) off-the-shelf MRI magnets for an inexpensive central cell, (2) state-of-the-art small and planar high field REBCO magnet for plugs, (3) 2.45 GHz whistler waves for creating a high density target plasma (with 140 GHz gyrotrons as a contingency), (4) a magnetic beach geometry to localize neutron yield away from sensitive high field magnets at edge, (5) radio-frequency heating on the magnetic beach to enhance neutron yield, (6) an expanding liquid lithium diverter for heat removal, electron thermal barrier and MHD stability.

Using advanced equilibrium modelling of the magnetic geometry and equilibrium, the researchers have designed a magnetic field coil set that can be built. To optimize the neutron production, the researchers have used the CQL3D/GENRAY suite of codes developed by Harvey et al. and now supported by CompX company. These codes model the plasma heating and the neutron production. Initial results were extremely promising. 5 MW of neutral beam injection power and 5 MW of rf heating at 15 MHz generated 10^{15} n/sec in a DD plasma. Use of tritium increases the neutron yield to 10^{17} neutrons/sec. Note that the 10^{19} n/sec needed for a fusion materials test facility would requires an increase in total power to approximately 50 MW.

7. CONCLUSION

A development path is envisioned that can rapidly move toward the operation of a full-scale compact GDT neutron source. A three-year construction period is anticipated for a moderate pulse length (~100 ms) prototypic device, operating at 1 T central field with 25 T mirror coils. This performance extension device is required for risk retirement of outstanding physics issues and exploit state-of-the-art technology. Several of the main goals are to establish a high-density target plasma for beam deposition (fuelling, pumping); to identify MHD stability limits (outflow and rotation; shaping in expander region); and to identify kinetic stability limits with a stationary fast ion distribution (where neutral beam pulse length is substantially longer than the fast ion classical slowing time). Understanding and controlling electron confinement are key experimental efforts to undertake. The construction of a next step GDT might be a good strategic move: while not providing energy to the grid, it speeds the process to fusion materials testing and drives several enabling technologies (HTS, NBI, steady state operation, tritium handling, etc) common to most magnetic confinement schemes. As an added benefit, the high flux neutron source has myriad industrial applications, and can be an example where fusion is seen by the public as a safe, controlled, and profitable endeavour.

REFERENCES

[1] MOLVIK, A., IVANOV, A., KULCINSKI, G.L., A Gas Dynamic Trap Neutron Source for Fusion Material and Subcomponent Testing, Fusion Sci. Technol. **57** 369 (2010).

[2] BAGRYANSKY, P.A., SHALASHOV, A.G., GOSPODCHIKOV, E.D., Threefold Increase of the Bulk Electron Temperature of Plasma Discharges in a Magnetic Mirror Device, Phys. Rev. Lett. 114, 205001 (2015).

[3] IVANOV, A.A., PRIKHODKO, V.V., Gas-dynamic trap: an overview of the concept and experimental results, Plasma Phys. Control. Fusion 55, 063001 (2013).

FUSION AS A HIGH-TEMPERATURE HEAT SOURCE FOR FUEL PRODUCTION

S. TAKEDA
Associate Professor
Graduate School of Advanced Integrated Studies in Human Survivability
Kyoto University, JAPAN

1. INTRODUCTION

One of the unique advantages of fusion is that reactors can be designed to generate high-temperature heat. This will enable fusion to be utilized for chemical and other high-temperature heat processes. There are a number of processes that would benefit from a low-carbon high-temperature heat source: particularly, fuel production with fusion is one of the most promising applications.

At a high temperature, biomass feedstocks can be turned into synthetic gas ($H_2 + CO$) through a chemical process known as gasification, shown in Eq.1. The synthetic gas can then be converted to either liquid fuel [1] or hydrogen [2].

$$(C_6H_{10}O_5)n + nH_2O = 6nH_2 + 6nCO - 814n \text{ kJ} \qquad (1)$$

2. FUSION FUEL PRODUCTION PLANT

Efficient gasification of biomass requires significant temperatures (over 1,000 degrees Celsius [3]), and fusion is one of the very few low-emission energy sources that could sustainably provide such high-temperature heat. A simple plant configuration of a fuel production plant with fusion reactor is illustrated in Fig. 1.

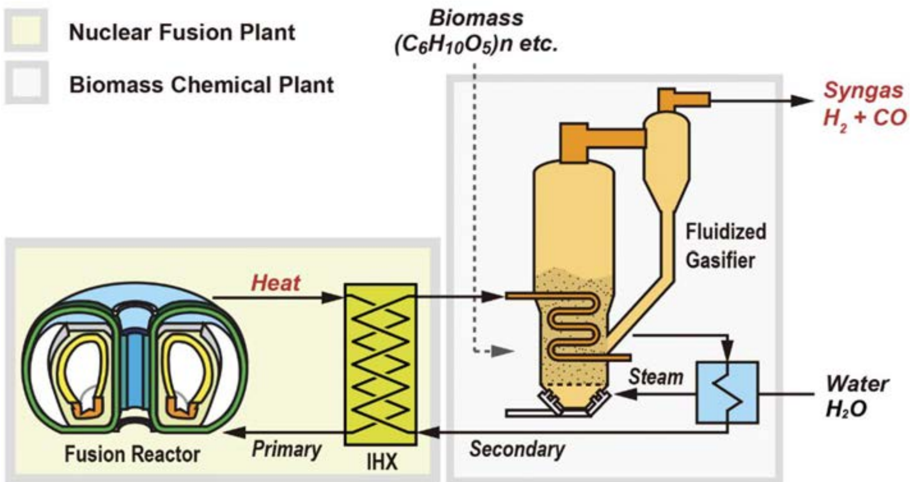

FIG. 1. Example of a Fusion Fuel Production Plant Diagram.

3. BENEFITS OF FUEL PRODUCION WITH FUSION

This high-temperature heat source application of fusion for fuel production may provide a faster path to commercialization because of the following reasons:

The 'energy multiplication effects' through the fuel production process would enable small fusion reactors to achieve engineering breakeven: one of the greatest advantages of the biomass chemical process is that the plant can produce more than three times of energy of the Rankine cycle from the same reactor, as illustrated in Fig. 1.

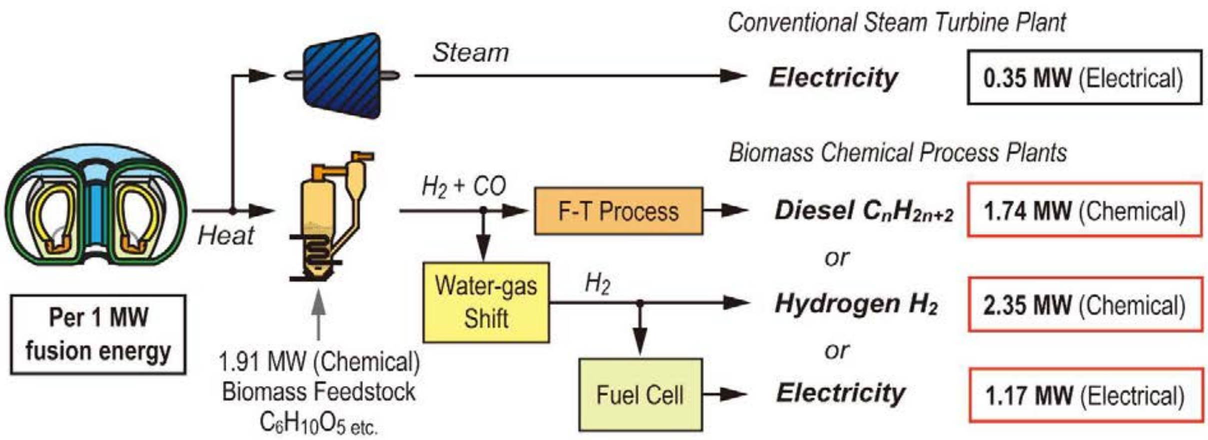

FIG. 1. Estimated Energy Production Amount for Fusion Fuel Production.

Fig. 1 shows the efficiencies of the biomass plants seemingly exceeding 100%; e.g., 1.17 MW electricity from 1 MW fusion energy. This is due to the additional input of chemical energy from the biomass feedstock. This 'multiplication' of energy production leads to a much lower engineering breakeven conditions for fusion which is greatly beneficial to small reactors.

Lower engineering breakeven conditions lead to faster a commercialization of fusion: one of the common preconceived notions in fusion science is that fusion reactors have to be large in its scale and its Q values to achieve engineering breakeven. However, with the fuel production process, fusion can achieve net-positive electricity generation with Q ~ 5 and Pfus ~ 100 MW [4]. This would dramatically speed up the commercialization of fusion.

The fuel production plant is economically more advantageous as a distributed power source: due to its higher efficiencies, it is estimated to be less expensive to produce energy through a biomass process than through a conventional steam turbine cycle, even considering the larger capital expenditures associated with the biomass facilities. Fig. 2 compares the cost of electricity generated from the same fusion reactor through a conventional steam turbine cycle and through biomass + fuel cell cycle.

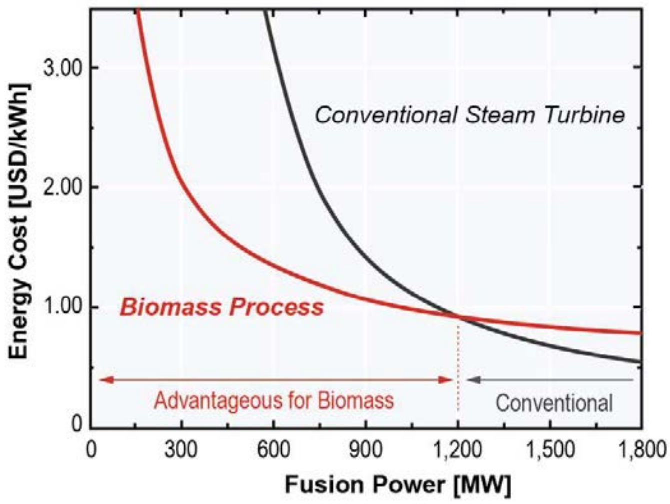

FIG. 2. Levelized Cost of Electricity of a Distributed Fusion Power Plant: Conventional vs. Fuel Production Process [5–6].

This calculation clearly indicates that smaller fusion reactors would benefit from the fuel production process. The levelized cost of electricity can be reduced by adopting the biomass process + fuel cell cycle for reactors with less than ~1,200 MW fusion power. This is a critical factor if the market demands a distributed fusion power source.

The fusion fuel production plant can be operated as a distributed, demand-following energy plant: the produced fuel can be stored on-site or be distributed to the customers. This makes the plant more market compatible as discussed in the previous sections.

Fuel production from biomass is an established technology: several similarly configured plants are already in operation around the globe, including the Osaki Cool Gen power plant in Japan (Ishida 2017). As such, the feasibility of the biomass gasification plant is already proven.

Many fusion startups are currently aiming for fusion reactors with a hundreds of MW output. Considering the anticipated future demands of the energy market (discussed in Section 2), high-temperature heat process application of fusion may be worth consideration.

REFERENCES

[1] TIJMENSEN, M. J. A., FAAIJ, A. P. C., HAMELINCK, C. N., Exploration of the Possibilities for Production of Fischer Tropsch Liquids and Power via Biomass Gasification, Biomass and Bioenergy **23** (2002) 129–152.

[2] TURN, S., KINOSHITA, C., ZHANG, Z., An Experimental Investigation of Hydrogen Production from Biomass Gasification. Int. J. Hydrog. **23** (1998) 64 –48.

[3] QUADER, M.A., AHMED, S., Bioenergy with Carbon Capture and Storage (BECCS): Prospects of Carbon-Negative Technologies, Energy. Sustain. Dev (2017) 91–140.

[4] HIROKI, K., TAKEUCHI, Y., YAMAMOTO, Y., Hydrogen Production from Biomass using Nuclear Fusion Energy. Fusion Sci. Technol. (2007) 756–760.

[5] IBANO, K., Design studies of innovatively small fusion reactor based on biomass-fusion hybrid concept: GNOME, Fusion Eng. Des. **86** (2011) 2779.

[6] KONISHI, S., TAKEDA, S., NAM, H., Future Possibility of Carbon Sequestration by Biomass Fusion Hybrid Systems, Preprints of IAEA FEC (2018), https://nucleus.iaea.org/sites/fusionportal/Shared%20Documents/FEC%202018/fec2018-preprints/preprint0274.pdf

SESSION III: FUSION POWER CORE DESIGN

FUSION LCOE: BASIS AND METHODOLOGY

R. MILLER
Co-Founder
Decysive Systems / Compact Fusion Systems, Santa Fe, U.S.

1. INTRODUCTION

Three criteria for successful fusion energy as commercial power stations have been identified, as follows [1]: economic competitiveness, regulatory simplicity, and public acceptance. Design choices made in furtherance of the second criterion (*e. g*., passive-safety features) and the third criterion (*e.g*., avoidance of emergency publicevacuation planning) can influence economic competitiveness under the first criterion. The prospects for mainline fusion concepts were reviewed in Refs [2–3]. The possibility of compact fusion systems at ~1-GWe was considered in Ref. [4].

Conceptual fusion power-plant studies often use Levelized Cost of Electricity (LCOE) as a figure of merit to project the future economic competitiveness of the approach. Starting with a comprehensive, hierarchical Cost Account Structure (CAS), the Total Direct Cost (TDC) is calculated, either as a top-down estimate or a more detailed bottom-up effort. The capital equipment costs represented by the TDC allow an estimate of the so-called overnight cost. Inclusion of additional Indirect Costs allows the estimate of the Total Capital Cost (TCC). Certain aspects of the costing methodology are discussed in Refs [5, 6].

2. LCOE CALCULATION

The LCOE (USD/kWh) is an energy cost; levelization is an amortization, using a Fixed Charge Rate (FCR) factor, of the dominant capital cost over a convenient analysis period (*e.g*., 30 years) that may be decoupled from the actual plant service life, called Life of Plant (LOP). Additional components of the LCOE include Scheduled Component Replacement (SCR), fixed and variable Operations and Maintenance (O&M), fuel (F) and other consumables, and a Decontamination and Decommissioning (D&D) allowance for radioactive waste disposal.

The LCOE (USD/kWh) is expressed by the equation:

$$LCOE=(C_{AC}+(C_{O\&M}+C_{SCR}+C_F)*(1+y)^Y)/(8760*P_E*p_f) + f_{D\&D} \quad (1)$$

where C_{AC} (USD/year) is the annual capital cost charge [entailing the Total Capital Cost (TCC (USD)) of the plant, multiplied by the Fixed Charge Rate (FCR (/year))], $C_{O\&M}$ (USD/year) is the annual operations and maintenance cost, C_{SCR} (USD/year) is the annual scheduled component replacement costs, C_F (USD/year) is the annual fuel costs, P_E (MWe) is the electric power output of the plant, p_f is the plant availability (typically 0.6–0.9). A small additional charge is imposed to build up a fund to cover end-of-life Decontamination and Decommissioning, $f_{D\&D}$ (USD/kWh). Over the life of the plant, f is accumulated to yield a fund, F ($), which can be applied to cover the costs of interim storage of radioactive waste and final D&D expenses. For a 1-Gwe-class plant, f at the level of a few 10^{-4} USD/kWh is thought to be sufficient; this value should be revisited for plants in the 100-MWe class. For f = 10^{-4} USD/kWh, a P_E = 100 MWe plant operating for 25 Full Power Years (FPY) will accumulate F = 21.9 million USD. The term 'y' is the annual inflation rate (e.g., 0.02/year) and 'Y (year)' is the construction lead time. The above LCOE definition is consistent with the methodology described in Ref. [7], subject to updating the historical financial factors that determine the FCR.

In comparison to mainline fusion concepts (*e.g.*, tokamak and stellarators) at the ~1-GWe plant size, concepts that have attracted the interest of enterprises often invoke smaller outputs, which might typically be thought to result in dis-economies of scale. Factory fabrication of a compact Fusion Power Core (FPC) might be expected to reduce construction lead times and the associated cost of Interest During Construction (IDC), benefitting the LCOE. While the economy of scale has been lost by making units smaller, it may be recovered by cost savings in centralized manufacture and modularization, together with shortened construction times, echoing recent developments anticipated for fission Small Modular Reactors (SMRs) [8, 9].

Simplified LCOE methods, assuming discount rates, allow convenient international estimates. More detailed procedures, linked to national circumstances including the cost of money and taxation rates, can also be considered. The USA historical experience is summarized in Refs [10–14], laying the groundwork for the multi-institutional ARIES studies [15].

An updated consideration of costs would include information from the Gen-IV fission studies [16] and SMRs. The scaling of Turbine-Generator to smaller sizes is considered in Ref. [17]. The capitalization structure of the potential utility customer is reflected in the Weighted Average Cost of Capital (WACC) [18]. The capital costs projections for competitive systems are summarized in Ref. [19].

The LCOE metric can be supplemented by consideration of external costs and the Levelized Avoided Cost of Electricity (LACE) to give a more complete picture to decision-makers. LACE reflects the cost of the electricity displaced by the new technology. A technology is generally considered economically competitive when its LACE exceeds its LCOE [20, 21].

3. OTHER FIGURES OF MERIT FOR FUSION

Other Figures of Merit (FOMs) of interest include energy payback time, FPC Mass Power Density [MPD, (kWe/tonne)], and Waste Disposal Rating (WDR). These FOMs can influence the estimated LCOE values as well as the regulatory simplicity and public acceptance criteria mentioned above.

A framework for the consideration of SMR-class Nuclear Power Plants [NPP, (fission)] has been proposed [22], which has applicability, under certain caveats, to the fusion approaches of interest here. This paper includes the reasonable, but unquantified, assertion that factory fabrication of modules can offset the traditional economies of scale that usually incentivize the selection of larger plant sizes. Lessons for compact fusion systems can perhaps be learned from the SMR fission experience, either projected [23] or from emerging experience.

4. CONCLUSION

In conclusion, LCOE and other FOMs can be used to steer and optimize the design of candidate fusion power plants of interest to enterprises. Tracking the competition and monitoring changing financial parameters requires effort, which is already ongoing in several contexts.

REFERENCES

[1] KASLOW, J., Criteria for Practical Fusion Power Systems: Report from the EPRI Fusion Panel, J. Fusion Energy **13** (1994) 181–182.

[2] MILLER, R. L., Economic Goals and Requirements for Competitive Fusion Energy, Proc. of the Fourth International Symposium on Fusion Nuclear Technology, Fusion Eng. Des. **41** (1998) 393–400.

[3] COOK, I., MILLER, R. L., WARD, D. J., Prospects for Economic Fusion Electricity, Proc. of the Sixth International Symposium on Fusion Nuclear Technology, Fusion Eng. Des. **25** (2002) 63–64.

[4] KRAKOWSKI, R. A., Small Fusion Reactors: Problems, Promise and Pathways, (1984), https://inis.iaea.org/search/searchsinglerecord.aspx?recordsFor=SingleRecord&RN=16062551

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Expansion Planning for Electrical Generating Systems–A Guidebook, Technical Reports Series No.241 (1984).

[6] NUCLEAR ENERGY AGENCY, Projected Costs of Generating Electricity (2015), https://www.oecd-nea.org/jcms/pl_14756/projected-costs-of-generating-electricity-2015-edition?details=true

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, Expansion Planning for Electrical Generating Systems, A Guidebook, Technical Reports Series No. 241 (1984).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Advances in Small Modular Reactor Technology Developments, Booklet (2014), https://aris.iaea.org/Publications/IAEA_SMR_Booklet_2014.pdf

[9] INGERSOLL, D. T., Small Modular Reactors: Nuclear Power Fad or Future?, Woodhead Publishing Series in Energy: Number 90, Elsevier (2016).

[10] SCHULTE, S. C., Fusion Reactor Design Studies–Standard Accounts for Cost Estimates, Battelle Pacific Northwest Laboratory report PNL-2648 (1978), https://www.osti.gov/biblio/6635206

[11] SCHULTE, S. C., Fusion Reactor Design Studies - Standard Unit Costs and Cost Scaling Rules, Pacific Northwest Laboratory report PNL-2987 (1979), https://www.osti.gov/biblio/5532719-fusion-reactor-design-studies-standard-unit-costs-cost-scaling-rules

[12] PHUNG, D. L., A Method for Estimating Escalation and Interest During Construction (EDC and IDC), in Proc. 2nd Miami Conf. on Alternative Energy Sources, Miami, FL (1979), https://www.osti.gov/biblio/5451750

[13] BAKER, C. C., STARFIRE – A Commercial Tokamak Fusion Power Plant Study, Argonne National Laboratory report ANL/FPP-80-1 (1980), https://www.osti.gov/biblio/6633213-starfire-commercial-tokamak-fusion-power-plant-study

[14] SHEFFIELD, J., DORY, R. A., COHN, S. M., Cost Assessment of a Generic Magnetic Fusion Reactor, Fusion Technology **9** (1986) 199–249.

[15] ARIES Program, Archival Information Site (2021), http://qedfusion.org/DOCS/bib.shtml

[16] THE ECONOMIC MODELING WORKING GROUP OF THE GENERATION IV INTERNATIONAL FORUM, Cost Estimating Guidelines for Generation IV Nuclear Energy Systems, Revision 4.2 (2007), https://www.gen-4.org/gif/upload/docs/application/pdf/2013-09/emwg_guidelines.pdf

[17] RABITI, C., Status Report on Modelling and Simulation Capabilities for Nuclear-Renewable Hybrid Energy Systems, Idaho National Laboratory report INL/EXT-17-43441 Revision 1 (2017), https://www.osti.gov/biblio/1408526-status-report-modelling-simulation-capabilities-nuclear-renewable-hybrid-energy-systems

[18] INVESTOPEDIA, Weighted Average Cost of Capital (WACC) (2021), https://www.investopedia.com/terms/w/wacc.asp

[19] ENERGY INFORMATION ADMINISTRATION, Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants (2013). https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/updated_capcost.pdf

[20] ENERGY INFORMATION ADMINISTRATION, Annual Energy Outlook 2016, DOE/EIA-0383 (2016), https://www.eia.gov/outlooks/aeo/

[21] ENERGY INFORMATION ADMINISTRATION, Annual Energy Outlook 2018, AEO2018 (2018),
https://www.eia.gov/outlooks/aeo/

[22] INTERNATIONAL ATOMIC ENERGY AGENCY, Deployment Indicators for Small Modular Reactors—Methodology, Analysis of Key Factors and Case Studies, IAEA-document-1854 (2018), https://www.iaea.org/publications/13404/deployment-indicators-for-small-modular-reactors

[23] LOCATELLI, G., BINGHAM, C., MANCINI, M., Small Modular Reactors: A Comprehensive Overview of their Economics and Strategic Aspects, Prog. Nucl. Energy **73** (2014) 75–85.

CONSTRAINTS PLACED ON RADIAL BUILD DEFINITION DUE TO TRITIUM BREEDING AND SHIELDING REQUIREMENTS

L. EL-GUEBALY
Distinguished Research Professor Emeritus
University of Wisconsin, Madison, U.S.

An integral nuclear assessment that considers the overall configuration, design requirements, criteria for attractive end products along with the overarching economics, safety, and environmental constraints is deemed necessary to deliver an optimal fusion design. In this regard, the nuclear analysis has been used as a design tool, focusing the majority of effort on the blanket and shielding systems to address key issues related to tritium breeding, radial/vertical build optimization and definition, magnet protection, shielding, survivability of structural materials in 14-MeV neutron environment, activation, and integral radwaste management strategy. The outcome of neutronics, shielding, and activation analyses was essential to the design process and called for measures to enhance the physics and engineering aspects of all US conceptual designs.

The blanket must breed all the tritium needed to sustain the operation of D-T fuelled plasmas. Several Li-based breeding systems were conceived and developed to some degree over the past 40 to 50 years. The PbLi breeder is the most popular liquid metal breeder worldwide and the dual coolant PbLi (DCLL) blanket is the preferred blanket concept for US fusion devices. There is a wide agreement in the fusion community that the tritium breeding ratio (TBR – a measure of T self-sufficiency) should be estimated with high fidelity as large deficiencies in the TBR prediction represent a significant burden on the operational cost. This requires a combination of the following two approaches: 1) performing state-of-the-art nuclear analyses using software (such as DAGMC) that couples the computer-aided-design (CAD) system directly with the 3-D MCNP code to preserve all geometrically complex design elements of the blanket and surroundings, and 2) experimenting on test blanket modules with fusion neutron sources. For recent ARIES designs employing the DCLL blanket, an ambitious goal for the calculated overall TBR is 1.05, which is achievable for advanced designs with dedicated R&D breeding programmes. Figure 1 displays the design elements that degrade the breeding significantly – from an ideal TBR value of 1.8, to 1.05 for a realistic design. The figure pinpoints the exact damaging conditions to the breeding (caused by the internal/external elements of the blanket) that have been puzzling the fusion community for decades. There will be several uncertainties during the facility’s operation that will determine the actual breeding level. To overcome this challenge, any blanket design should have a flexible approach and be able to accept a few necessary changes during operation in order to deliver a TBR greater than unity.

In summary:

- Breeding tritium is not a choice, but a mandate for all D-T fuelled fusion devices that consume kilograms of tritium annually.
- Breeding requirement is breeder and design dependent and should be established and tailored for each design separately.
- Estimating the TBR with high fidelity is not a simple proposition. Development of the sophisticated neutronics software (such as DAGMC) enables estimating the overall TBR with high fidelity.
- For advanced designs, a more ambitious goal for the overall TBR is 1.01, which is achievable with comprehensive R&D programme to curtail unknowns involving T production, storage, processing, etc. – far beyond what has been achieved so far.
- Any blanket design should have a flexible approach and be able to accept few necessary changes in order to deliver TBR > 1. A practical scheme for liquid breeders is to adjust the Li enrichment online during operation to compensate for unanticipated T production, usage, and/or losses.

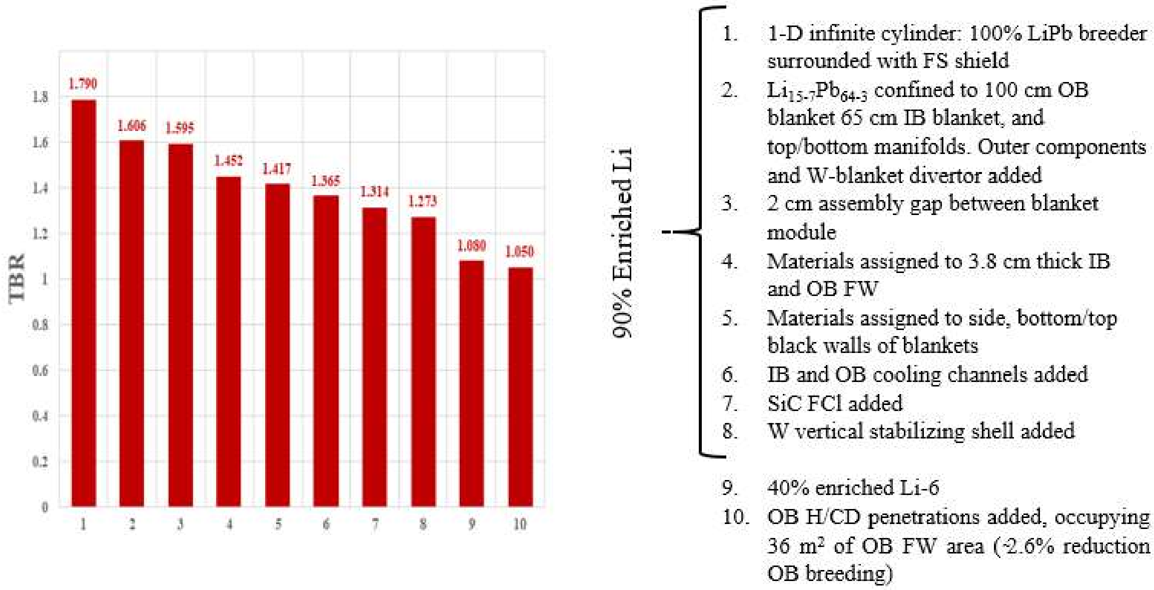

FIG. 1. Bar chart showing the reduction in TBR of ARIES-ACT2 as a result of including internals and externals of the DCLL blanket.

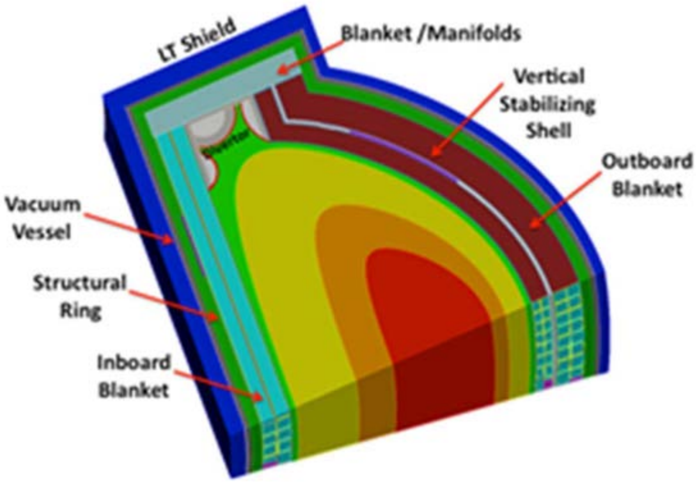

FIG. 2. Blanket Cross-cutting Diagram.

Behind the blanket, there is still significant flux to damage the outer components. A common theme between designs is that all specialized components (blanket, support structure, manifolds, vacuum vessel, etc., see Fig. 2) should provide a shielding function to collectively satisfy the radiation protection requirements and design limits with minimal radial/vertical standoffs. Well-optimized specialized components (blanket, vacuum vessel, and shield) not only define the most compact operational space of the machine, but also minimize the burden of generating unnecessary radioactive materials by a non-optimal radial build. The magnet radiation limits and neutron wall loading (NWL) determine the size of in-vessel components that, in turn, influence the radial build, machine size, and overall cost of electricity. Other shielding-related guidelines include:

- Each design has unique features that mandate changes in the shielding strategy.
- To reduce the cost, the skeleton of vacuum vessel and shield could be filled with fillers and then optimized to achieve the shielding requirements for magnet protection.
- A combination of WC (tungsten carbide) and H_2O is superior shielding material for the inboard constrained space in particular. However, the inherent high decay heat of W raises concern and may endanger the integrity of steel-based tokamaks during severe LOCA.
- Assembly gaps and large heating and current drive (H/CD) ports degrade the shielding functionality as neutrons stream through and enhance the damage behind the shield.
- With the economic advantages of compactness, emerge challenges of less blanket coverage and lower TBR, along with tight access to in-vessel components along with difficult design integration and challenging maintenance scheme.

There is some latitude in the selection of reduced-activation materials for fusion to generate only low level waste, but in very large quantities. The development of commercial fusion plants should demonstrate that the waste burden for future generations would be avoided in order to embrace the promise of fusion energy production with low environmental impact. This points the way to develop a new strategy to reshape the handling of the radioactive materials during and after the operation of a nuclear fusion power plant.

To conclude:

- The amount of low level waste (LLW) from fusion reactors is anticipated to be large (see Fig. 3). Fusion reactor designers should strive to minimize the amount of radioactive waste by improved designs and integrated recycling and clearance approaches at an early stage.
- Major rethinking, education, and R&D programmes need be pursued to explore waste disposal options for the large quantities of radioactive waste from fusion through the further development of fusion-specific recycling and clearance approaches.
- It's just a matter of time to develop recycling/clearance technologies and standards. The US Nuclear Regulatory Commission (NRC) will eventually need to issue official guidelines and standards to regulate the recycling/clearance processes for all nuclear systems, including fusion.
- In the meantime, national and international efforts should continue to convince industrial and environmental groups that risks to public health from the clearance of materials is trivial.

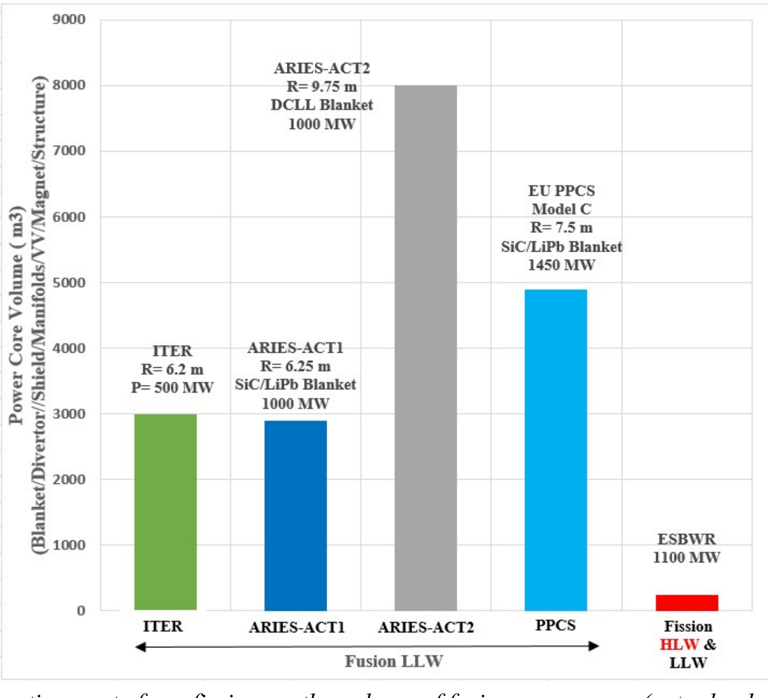

FIG 3. Comparison of radioactive waste from fission vs. the volume of fusion power core (actual volumes of components, not compacted, no replacements, no plasma chamber).

REFERENCES

[1] ARIES Project, Archival Information Site (2021), http://qedfusion.org/DOCS/bib.shtml

[2] EL-GUEBALY, L., MALANG, S., Toward the Ultimate Goal of Tritium Self-Sufficiency: Technical Issues and Requirements Imposed on ARIES Advanced Fusion Power Plants, Fusion Eng. Des. , **84**, 2072 (2009).

[3] EL-GUEBALY, L., Nuclear Assessment to Support ARIES Power Plants and Next Step Facilities: Emerging Challenges and Lessons Learned, Fusion Sci. Technol. **74** (2018) 340.

[4] EL-GUEBALY, L., MYNSBERGE, A., D'ANGELO, C., Design and Evaluation of Nuclear System for ARIES-ACT2 Power Plant with DCLL Blanket, Fusion Sci. Technol. **72**, (2017) 17–40.

[5] EL-GUEBALY, L., MALANG, S., Need for Online Adjustment of Tritium Bred in Blanket and Implications for ARIES Power Plants, Technology Institute Report UWFDM-1372 (2009), http://fti.neep.wisc.edu/pdf/fdm1372.pdf.

[6] UNIVERSITY OF WISCONSIN-MADISON, DAGMC Users Guide (2021), http://svalinn.github.io/DAGMC/usersguide/

[7] EL-GUEBALY, L., ZUCCHETTI, M., Progress and Challenges of Handling Fusion Radioactive Materials, Fusion Sci. Technol. **68** 3 (2015) 484–491.

[8] EL-GUEBALY, L., Goals, Challenges, and Successes of Managing Fusion Active Materials, Fusion Eng. Des. **83** (2008) 928–935.

SUMMARY OF ARPA-E’S 2017 FUSION COSTING STUDY

S. WOODRUFF
President/ Co-Founder
Woodruff Scientific / Compact Fusion Systems, Santa Fe, U.S.

In 2017, ARPA-E commissioned a costing analysis for four of the fusion energy concepts supported by the ALPHA programme [1]: this capital cost study was performed by Bechtel National’s power plant cost team, Woodruff Scientific and Decysive systems, extending prior work in fusion cost estimating [2–3]. The study was based upon four conceptual designs for a fusion core and present-day standard components for the balance of plant (BOP: heat exchanger, turbines, etc), but did not attempt LCOE calculations (although most of the contemporary thinking on the topic was summarized).

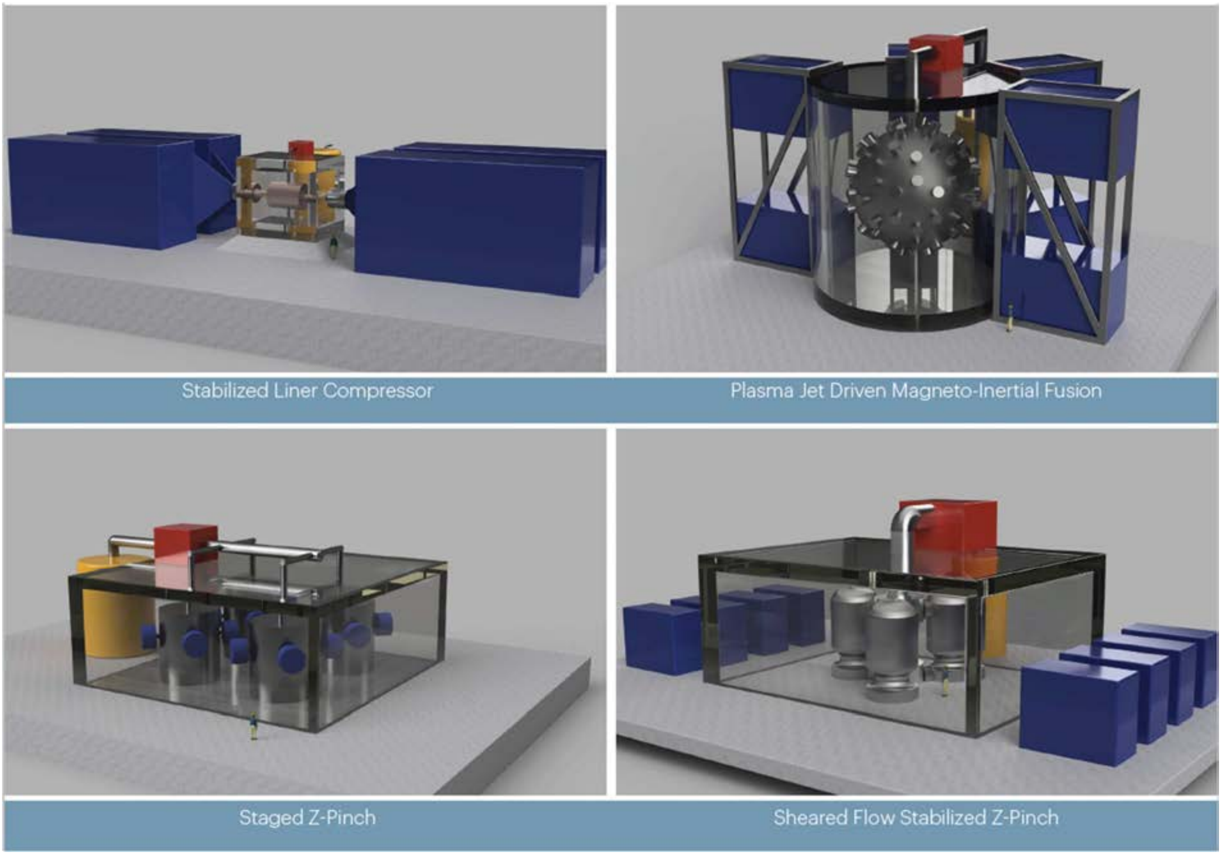

FIG. 1. Conceptual design points for four of the ARPA-E support fusion energy systems, currently supported by the ALPHA programme.

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. However, conceptual designs do not appropriately account for the effects of the high energy neutrons on various components, nor address tritium fuel extraction, transfer, and storage, among other considerations. The pulsed power system design and lifetime under power plant conditions (of ~1 Hz) also requires advancing to an engineering design stage. 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.). A principal cost saving, contrary to prior studies that found an economy of scale, is to utilize centralized manufacturing, which would allow these smaller systems to reach competitive LCOE for an nth of a kind power plant.

First, it can be concluded that 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.

Primary recommendations from this study were as follows:

- Physics modelling of the neutron-producing plasma should be increased in fidelity by use of advanced computational modelling.
- Neutronics analysis should be used to determine optimum component sizes.
- Electrical engineering of the primary power systems should be performed (at least to the conceptual level).
- Tritium handling systems should be advanced to conceptual level for each concept.
- Main heat exchanger costings should be 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').

REFERENCES

[1] WOODRUFF, S., Conceptual Cost Study for a Fusion Power Plant Based on Four Technologies from the DOE ARPA-E ALPHA Program, Bechtel National, Inc. Report No. 26029-000-30R-G01G-00001 (2017).

[2] WOODRUFF, S., BAERNY, J. K., MATTOR, N., Path to Market for Compact Modular Fusion Power Cores, J. Fusion Energy **31** 4 (2012) 305–316.

[3] WOODRUFF, S., MILLER L., Cost sensitivity analysis for a 100 MWe modular power plant and fusion neutron source, Fusion Eng. Des. **90** (2015) 7–16.

PRE-CONCEPTUAL FUSION POWER PLANT STUDIES – WHAT ARE THE PARTS?

C. KESSEL
Section Head, Fusion Nuclear Science, Technology, and Engineering
Oak Ridge National Laboratory, Tennessee, U.S.

The Fusion Energy Systems Studies are multi-institutional and multi-discipline activities providing integrated studies of issues in the US MFE programme with a focus on fusion energy [1–13]. Previous (recent) studies include the ARIES-Advanced Conservative Tokamak (ACT) power plant study, the Fusion Nuclear Science Facility (FNSF) study, and the present Liquid Metal Plasma Facing Component (LM PFC) study. These have quite different goals ranging from a 10th of a kind power plant to a first fusion nuclear facility to an organization and identification of R&D work to move LM PFCs forward.

It is important to understand that pre-conceptual designs (e.g. ARIES, SSTR, EU-DEMO, JA DEMO) are not equivalent to 'design to build' (ITER, TPX, CIT/BPX, NCSX), they are much less detailed and typically concentrate on critical components like the fusion core and some critical ex-core items. The difference is not just reflected in funding (1 million USD compared to 50–100 million USD) and manpower (10–15 compared to 50–100), but a 'design to build' activity can deliver designs for construction to vendors, while a pre-conceptual design does not. Pre-conceptual designs generally have a philosophy associated with them, such as minimizing the cost of electricity, or searching for strong leverages with advanced physics or technology or examining the first complete fusion nuclear device and its requirements. The typical outcome of such studies is a comprehensive design of the fusion core, with critical ex-core components described, and a list of required R&D for the fusion programme to pursue in plasma physics, engineering, enabling technologies, and maintenance/layout. Integration of disciplines all working on the same facility design is an important feature of these design studies since it is well known that interface issues are some of the most challenging and can present significant limitations.

Pre-conceptual design studies are analysis activities, and only rarely is there any experimental work done. The typical disciplines where analysis is performed in a pre-conceptual design study (tokamak, stellarator, or spherical tokamak) include:

- Thermo-mechanics and computational fluid mechanics for the blanket and divertor;
- Corrosion assessments in the blanket;
- Materials specification and property data;
- Nuclear analysis (neutronics) to determine heating and the tritium breeding ratio, as well as material damage and transmutations, decay heat, activation and waste rating;
- Liquid metal breeder thermo-fluids/MHD in the blanket, or solid breeder thermo-mechanics;
- Systems analysis;

- Accident scenarios and safety;
- Magnets;
- Tritium behaviour and processing in fusion core and ex-core;
- Core plasma;
- Edge/divertor plasma and plasma material interactions;
- Plasma transients;
- Thermohydraulics, power conversion;
- Radiofrequency and special plasma facing components;
- Tritium plant assessment;
- Plasma heating and current drive;
- Maintenance and layout.

Systems analysis involves using simpler models for plasma physics and engineering in order to explore the configuration space (geometry, plasma parameters, and engineering parameters). For example, one would determine the plasma major radius for a tokamak consistent with the required fusion power (or electric power) from fusion in the plasma, and consistent with the maximum plasma beta, toroidal field at the coil, peak heat flux in the divertor, and sufficiently low cost of electricity. Detailed analysis requires a specific design point, and so one can be derived from the systems analysis. Systems analysis can also depend on detailed information, and iterative processes between disciplines and between detailed and simpler analyses within the study are normal. Finally, recent systems studies have moved away from design point optimization solutions towards operating space solutions (multiple solutions) with similar COE's, which are more accommodating to the level of uncertainties that exist in virtually all the parameters that describe the system.

In order to explore the transition from experimental devices to the power plant regime for a fusion configuration there are some questions to consider, such as:

- What are new requirements that did not exist in experiments (e.g. breeding tritium, avoiding transients like disruptions, long life components and high duty cycle)?
- What is getting larger (e.g. magnets, fusion chamber, wall thickness, vacuum enclosure)?
- What is being pushed further away from the fusion core due to neutrons, gamma rays or plasma (e.g. magnets, heating systems, measurements)?
- What operating aspects are to fundamentally change (e.g. focus on one to a few plasmas, long duration on-time like 1-year, remote maintenance, more difficulty stabilizing plasma, materials used)?
- What components of the configuration are removable and what are permanent, the latter requiring protection by the former (e.g. fusion core versus vacuum vessel, magnets, cryostat)?

Systems studies activities are also focused on the design of numerous components inside the fusion core and outside. For example, the fusion core of a tokamak consists of a few primary elements, a breeding blanket (structure, coolant, breeder, functional materials), divertor (armour, structure, coolant, transition structure), and special plasma facing components like RF launchers (conductors, structures, coolant, plasma facing material). In addition, these core components are mounted to a structural member that also acts as a neutron shield, which is followed by a vacuum vessel, and a low temperature shield. These have multiple functions (heat capture, tritium containment, pressure, tritium breeding, disruption tolerance, maintenance access and so forth) that require design. Ex-core items include magnets, cryostat, tritium extraction, heat exchangers, clean up, tritium processing, etc.). The design process is important to evolving from ideas to more credible solutions, since they often involve unknowns, possibly in the area of loading (heat loads, electromagnetic loads, particle loads, corrosion) and properties (irradiated material properties).

Parametric analysis is often more important in the exploration of pre-conceptual designs, than are very detailed assessments of a very detailed design, for the basic reason that there is too high an uncertainty level in various aspects of the design, the loading environment, or property data. Establishing results over the range of uncertainty clarifies the importance of property choices, for example, and easily turns into R&D activities in the programme to provide greater certainty. Obviously as one moves to power plants, major changes are required, including simplification which translates directly into reliability, large piece maintenance to enhance speed and efficiency for higher availability, and a serious focus on safety, potential accident mitigation, and waste minimization.

Systems studies are critical to explore the power plant regime for any fusion configuration and can quickly identify critical R&D items that can build the concepts credibility. The act of design forces one to address the features of any configuration, and integrated design (multi-discipline) allows interfaces to be addressed as part of this. Iteration of systems studies as new experimental data, new material developments, and new enabling technologies are developed is a basic feature to evolve toward 'design to build' activities.

REFERENCES

[1] KESSEL, C. E., Overview of the Fusion Nuclear Science Facility, a Credible Break-in Step on the Path to Fusion Energy, Fusion Eng. Des. **135** (2018) 236.

[2] ZHAI, Y., Conceptual Magnet Design Study for Fusion Nuclear Science Facility, Fusion Eng. Des. **135** (2018) 324.

[3] WALLACE, G. M., Heating and Current Drive Actuators for the FNSF in the Ion Cyclotron and Lower Hybrid Frequency Range, Fusion Eng. Des. **135** (2018) 370.

[4] HUANG, Y., Multiphysics Modeling of the FW/Blanket of the U.S. Fusion Nuclear Science Facility, Fusion Eng. Des. **135** (2018) 279.

[5] KESSEL, C. E., Core Plasma Physics and its Impacts on the FNSF, Fusion Eng. Des. **135** (2018) 356.

[6] SMOLENTSEV S., MHD Thermohydraulics Analysis and Supporting R&D for DCLL Blanket in the FNSF, Fusion Eng. Des. **135** (2018) 314.

[7] ROWCLIFFE A. F., Materials Challenges for the Fusion Nuclear Science Facility, Fusion Eng. Des. **135** (2018) 290.

[8] HUANG Y., Tungsten Monoblock Concepts for the Fusion Nuclear Science Facility (FNSF) First Wall and Divertor, Fusion Eng. Des. **135** (2018) 346.

[9] DAVIS A., Neutronic Aspects of the FESS-FNSF, Fusion Eng. Des. **135** (2018) 271.

[10] ROGNLIEN T. D., Scrape-Off Layer Plasma and Neutral Characteristics and Their Interactions with Walls for FNSF, Fusion Eng. Des. **135** (2018) 380.

[11] HUMRICKHOUSE, P. W., MERRILL, B. J., Tritium Aspects of the Fusion Nuclear Science Facility, Fusion Eng. Des. **135** (2018) 302.

[12] BLANCHARD J. P., Effects of ELMs and Disruptions on FNSF Plasma Facing Components, Fusion Eng. Des. **135** (2018) 337.

[13] WAGANER L. M., The Examination of the FNSF Maintenance Approach, Fusion Eng. Des. **135** (2018) 394.

SESSION IV: CONSTRAINTS OF FUSION ENERGY SYSTEMS

TRITIUM FUEL CYCLE SAFETY

W. KIRK HOLLIS
Team Leader
LANL, Los Alamos, U.S.

Fusion research has traditionally been advanced by government funding, but with a view to commercialization, there has been an increase in development with private funds. A commercial fusion plant must address safety as well as technological hurdles. Stemming largely from radiological concerns, one area to address is the deuterium-tritium (DT) fuel cycle associated with fusion. In order to support a fusion reactor, the fuel cycle is an integral part of any designs. Safety should, of course, be incorporated into the DT fuel cycle from the beginning of design to develop controls to mitigate the hazards of this system. An overview of recent work at LANL, in support of ITER, to develop these controls using a hazard and operability process (HAZOP) is an example of this implementation process. By using this type of a hazard assessment, a fuel cycle system can be developed that addresses hazards and regulatory requirements, documents safety controls and develop operational requirements.

One of the first tritium fuel cycles to be designed and operated was developed at the LANL at the Tritium Station Test Assembly (TSTA). The design began in 1976 and operated until the late 1990's before being disassembled. The primary focus of TSTA was to serve as a flexible, full scale pilot plant to test components, show integrated operations and test environmental and personnel protective systems. The system studied performance, reliability, and response to off-normal conditions with the particular interest in the demonstration of the safe handling of tritium. Figure 1 below is a process diagram of the TSTA facility.

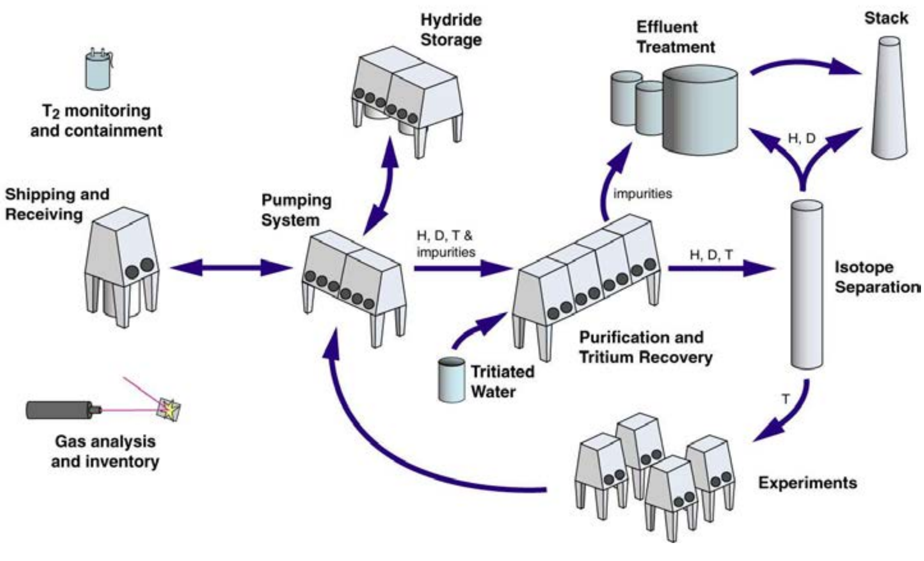

FIG. 1. Tritium Station Test Assembly (TSTA) Fuel Cycle.

TSTA integrated all major sub-systems of a tritium fuel cycle into its design with the exception of a fusion reactor. The process flow from the exhaust of a fusion reactor would follow the order of the sub-system above; Pumping System, Purification (hydrogen isotope separation for all other gases), Isotope Separation, Hydride Storage, and fuelling return to the reactor.

TSTA also integrated tritium monitoring, containment, analysis and inventory tracking, effluent treatment and environmental release systems.

This design has been further developed and is currently being fabricated in support of the ITER project in Saint-Paul-lès-Durance, France. The integrated process flow for ITER is shown in Fig. 2.

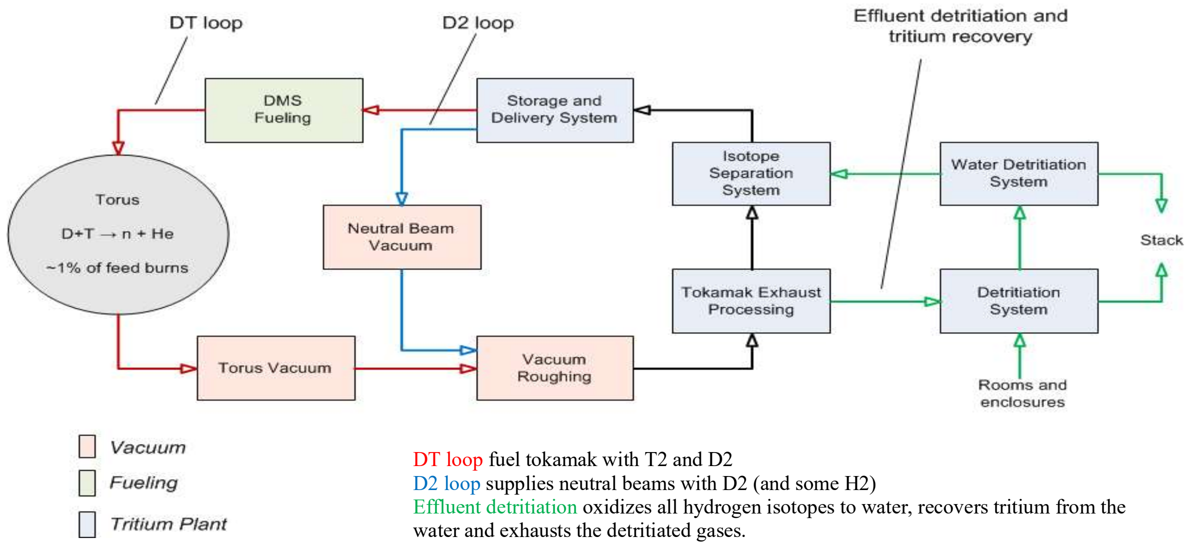

FIG. 2. ITER Fuel Cycle [1–2].

The technical aspects of a tritium fuel cycle are fairly mature but have limited fully integrated operational history. In addition, the safety documentation for this design has not been well documented. It was recognized that for the ITER systems this needed to be addressed. As a result, LANL and ITER collaborated to develop a process hazard analysis using the HAZOP methodology. The HAZOP method effectively addresses common hazard categories such as pressure, temperature, and flow. To ensure that tritium hazards are captured, new deviations were developed as shown in Table 1.

TABLE 1. HAZOP CONFINEMENT ADDITION

	GUIDE WORDS						
PROCESS VARIABLES	No, Not, None	Less, Low, Short	More, High, Long	Part of	As Well As Also	Other Than	Reverse
Confinement	Rapid failure	Slow leak	No overpressure relief				In-leakage

The addition of this deviation was helpful in documenting controls needed to address tritium safety to protect the workers, public and environment into the design of the systems. The controls identified assisted in regulatory documentation development and continue to be used to support preliminary and final design requirements for the fuel cycle.

As with all HAZOP processes, the team assembled to conduct the assessment is important. A limitation to correctly assess hazards and develop controls for tritium usage require personnel that have experience with tritium handling; this population is limited. Additionally, it is imperative to have representation of safety requirements that cover governing regulations and restrictions. These will bound release limitations and will drive the controls needed to address this hazard. It was understood that these regulations are not well defined for future private funded fusion reactors and will require all interested parties to begin to further define and develop what the governing requirements will be.

As privately funded fusion reactor programmes begin to be developed, the community should continue to be cognizant of current government funding programmes and use the experience and expertise of these projects to assist in the safety operations of these potential new reactors.

REFERENCES

[1] WILLMS, R. S., U.S. Tritium Plant Activities for ITER, Fusion Sci. Technol. **47** (2017) 979–982.

[2] WILLMS, R. S., Tritium Technology for ITER IAEA DEMO Workshop, Karlsruhe (2016), https://nucleus.iaea.org/sites/fusionportal/Technical%20Meeting%20Proceedings/4th%20DEMO/website/talks/November%2015%20Sessions/Willms.pdf

[3] HOLLIS, W. K., Self-assaying tritium accountability and containment unit for ITER (STACI), Review and Experimental Results from Initial Hydriding and Dehydriding (2015), https://www.osti.gov/servlets/purl/1225570.

COMMERCIALIZING FUSION: THE LEGAL PERSPECTIVE

A. ROMA
Partner
Hogan Lovells, London, U.K.

1. INTRODUCTION

This paper presents a few points of clarification focused on commercializing fusion. Bringing fusion out of the lab and to the marketplace can be a long process but engaging on aspects of the project outside the lab are necessary to move from one to the other. Outside engagement with the U.S. Nuclear Regulatory Commission (NRC), investors, US Department of Energy (DOE)/administration/congress all should be occurring now in order to support commercialization in the future. For any nuclear prototype or demonstration facility project to advance, policy issues need to be ironed out in advance. This section summarizes NRC engagement to highlight the present opportunity and realities; investment and customers (and why engagement with the NRC now matters); NRC/DOE jurisdiction; and engagement with the Administration/ DOE/Congress.

2. NRC ENGAGEMENT

For the fusion community, engaging the NRC at this stage does not likely to constitute a 'pre-application meeting'. Pre-application meeting is a term used at the NRC that describes meetings between the NRC and a company that intends to submit and is actively preparing an application to the NRC for a licence. The NRC charges for pre-applications meetings, and they tend to be highly technical in nature. Pre-application meetings can begin years before a submittal. In the case of NuScale, they engaged in pre-application meetings for 16 years before they submitted a design certification application to the NRC.

There is a level of NRC engagement before pre-application meetings, which can occur decades before an application is actually submitted. The NRC is interested to know who that is out there intends to come before the Commission so they can plan and begin policy discussions. And rulemakings, if necessary, can take a long time. As an example, when licensing an enrichment facility, the NRC ordered the staff to evaluate the disposal of large quantities of depleted uranium under its waste classification tables under 10 CFR Part 61 in 2003, during facility licensing. That rulemaking remains ongoing - and the NRC Commissioners just ordered the staff to go back and do substantial re-work on a proposed rule - a final rule in this case is still several years away. In other words, the waste classification for a unique waste stream in the enrichment case will likely take nearly 20 years to resolve, from the time it was first raised by an antinuclear group during the licensing process to the time it is resolved. And this example may be of huge importance to the parties because the outcome can cause the financial assurance the enrichment company must post for decommissioning funding to increase by potentially millions of dollars.

The NRC states in the NRC's 'Statement of Policy for the Regulation of Advanced Nuclear Power Plants' [1]:

> *"To provide for more timely and effective regulation of advanced reactors, the Commission encourages the earliest possible interaction of applicants, vendors, other government agencies, and the NRC to provide for early identification of regulatory requirements for advanced reactors and to provide all interested parties, including the public, with a timely, independent assessment of the safety and security characteristics of advanced reactor designs. Such licensing interaction and guidance early in the design process will contribute towards minimizing complexity and adding stability and predictability in the licensing and regulation of advanced reactors."*

And, if a legislative fix is needed to facilitate the NRC process, or provide greater access to national labs, or assist with waste streams (as it was needed for the medical isotope community) that can also take several more years to accomplish. In addition, rulemakings/policy discussions that are ongoing could significantly impact the fusion community. Some examples include: (1) the NRC's Greater-Than-Class C (GTCC) rulemaking [2] that is currently underway; (2) the new 'risk informed' rulemaking [3] that is currently being contemplated; and (3) the NRC is trying to figure out how to apply a 'phased' approach to licensing - that would significantly reduce regulatory risk, and upfront capital costs for applicants.

All of these discussions could be relevant and have a significant impact to the fusion community - not only regulatory, but financial and timing - on planned fusion projects. On GTCC, rulemaking, it could impact the disposal path for waste. On risk-informed regulations, this could significantly improve the NRC application process for new technologies because it's not prescriptive (e.g., prescriptive: "you must have x and y safety systems to protect against z" vs. risk informed: "you must demonstrate that you protect against z"; prescriptive regulations are hugely problematic for innovative technologies, and unfortunately most of the NRC's current regulatory framework is prescriptive). On the 'phased approach,' for example, the NRC has expressed a willingness to engage in review of a 'conceptual' design before a license application is submitted, including a review of portions of a design. That can further be worked into a company's schedule for NRC design review and future engagement and provides a huge leap forward for first-of-a kind projects. It can also significantly reduce regulatory risk, upfront costs, and facilitate investment. As an example, the NRC staff reviewed and generated pre-application safety evaluation reports (PSERs) for the General Electric Power Reactor Innovative Small Module (PRISM) sodium-cooled reactor. The review was conducted pursuant to the NRC's 'Statement of Policy for the Regulation of Advanced Nuclear Power Plants' [4] described in NUREG-1226, Development and Utilization of the NRC Policy Statement on the Regulation of Advanced Nuclear Power Plants [5]. NUREG-1226, the NRC explains, is intended to encourage the earliest possible interaction between the NRC and a future applicant.

The engagement with the NRC is and should be done by a private company if in pursuant of a private sector project. Even when DOE is providing funding. For the most part, DOE does not participate in Advanced Reactors' NRC meetings even though they receive DOE funding (even the UAMPS/NuScale meetings for a facility located at the INL site). If DOE funds are used, the only restriction is to ensure compliance with the terms of those funds.

It is far too early to meet with the NRC to walk through all the contents of an application, but NRC engagement is not a 'one-time deal.' It occurs over a very long time and gets more technical in nature as a company approaches licence submittal. But the first meetings should start to occur so the NRC can start to think about licensing and is aware of private fusion enterprises and, in fact, the NRC would be very surprised to hear there's an entirely new community of potential licensees out there with a new technology that plan to use the NRC, but doesn't want to go in and meet with them. Again, these would be high level, policy focused discussions that provides just an overview of the technology. They are not a detailed technical review of the technology.

3. INVESTORS AND CUSTOMERS

Understanding the regulatory path forward for a commercial project is absolutely critical for financing which is, in turn, absolutely critical for project survival. The three questions fusion companies will receive in diligence: (1) how is your facility licensed? (2) what about the waste? and (3) what about the nuclear liability? These are the questions that are discussed with investor clients during diligence and these are the questions that are answered for nuclear clients during diligence with investors. Each of these three matters requires NRC engagement to answer - and the last - nuclear liability - may require a legislative fix as well (e.g., if the Price Anderson Act [6] needs to be amended to expressly include Fusion).

Every fusion company is looking for private dollars if they intend to commercialize. Some investors - a very limited few, usually high-tech angel investors or a few limited funds, and in both cases usually because they are making a social impact investment - will invest without answers to these questions, but most will not. And the ongoing rulemakings noted above - licensing, phased licensing, waste disposal - are all questions an investor today will ask about in diligence. And to not have answers - even initial answers - very likely means not getting the investment.

And for customers - which are usually the facility 'operators' - they don't want to take on nuclear liability risk. Same with the supplier community - no US company will do business in India right now because its nuclear liability law is out of line with international norms. So, if you can't get a customer, and you can't get a supplier because of this risk, you cannot commercialize. Now, you may have a good explanation that this is not a risk that should be worried about - but even if the risk is low, and the consequences are low, if the perceived risk is an impediment to investment or customers, then being covered under the law may be better. With nuclear, the US established the Price-Anderson Act (the US nuclear liability law) to facilitate the commercial development of nuclear power - that is, to establish a liability regime to assure plant operators and suppliers that they would not be exposed to huge liability in the event of an accident - it was not established because the US was afraid there would be a large number of catastrophic accidents. The same type of law may be necessary here to promote commercialization of private fusion facilities - where the perceived risk and consequences may be more important than the actual risk and consequences.

And if there are plans to export technology to an overseas customer, the international nuclear liability regimes (e.g., the Paris and Vienna conventions) would need to be amended to reflect that the technology is covered. There are unique nuclear liability provisions in place for ITER with the understanding that the Paris Convention (the applicable nuclear liability regime in France) will be amended to include fusion. That is NOT a quick process (and in fact has been under discussion since before the ITER project started, and still hasn't happened yet). It requires amending the international convention, and then having each country amend their domestic nuclear liability laws (if necessary) to effectuate the change.

Customers will also want to know about the waste. If waste from private fusion facilities ends up as Greater-Than-Class C (GTCC), then waste may need to be disposed of in a high-level waste repository, and there's no commercial disposal path there at the moment. If there is no commercial disposal path for waste, then a statutory alternative will need to provide a waste disposal path (e.g., for medical isotopes, the American Medical Isotope Production Act [7] mandates that DOE do a lease/takeback for the high-assay LEU these facilities use - so their HLW stream is covered by statute). For enrichment, there is a legislative fix as well, DOE needs to take the waste if there's no commercial disposal path. Again, all this takes a lot of time to resolve.

And finally, unless there are plans to operate the facility, customers need to know that there is a regulatory path forward—as they would be the facility applicant. Again, while this is not a today issue, it will also be an initial question from a customer.

4. NRC/DOE JURISDICTION

This isn't really a grey area and has been extensively discussed in the fission space. And the fact that DOE is funding these ventures doesn't change the discussion. In fact, DOE has funded a large number of advanced reactor and medical isotope companies. It doesn't change the underlying fundamental law that delineates jurisdiction between the NRC and DOE in this area - the Atomic Energy Act. A private-sector facility is licensed by the NRC. For example, the UAMPS/NuScale project located at INL is going to be licensed by the NRC and UAMPS needed to negotiate a site use agreement with DOE to locate its facility at INL. Under the Atomic Energy Act (AEA), any private sector use of by-product, source, or special nuclear material, falls under the jurisdiction of the NRC. The NRC has extensive, publicly available guidance on this.

If fusion is licensed as a reactor (which is not unlikely, even if the requirements need to be adjusted), the NRC applies non-power reactor guidance to a 'prototype' or 'demonstration' reactor. A 'non-power reactor' refers to a research or test reactor licensed by the NRC pursuant to the provisions of 10 CFR

50.21(c) or 50.22 for research and development. Examples include a university research and teaching reactor licensed under Section 104c of the AEA pursuant to 10 CFR 50.21(c), and a commercial medical isotope production reactor licensed under AEA Section 103 pursuant to 10 CFR 50.22. A research reactor refers to a reactor licensed under AEA Section 104c pursuant to §50.21(c) for operation at 10 MWth or less and is not a testing facility.

A testing facility is licensed under AEA Section 104c pursuant to 10 CFR 50.21(c) for operation:

- In excess of 10 MWth (e.g., NIST facility); or
- In excess of 1 MWth if the reactor is to contain: a) a circulating loop through the core in which the applicant proposes to conduct fuel experiments; or b) a liquid fuel loading; or c) an experimental facility in the core in excess of 16 in x 2 in cross-section.

The AEA directs the NRC to impose under Section 104c "only such minimum amount of regulation of the licensee as the Commission finds will permit the Commission 93 fulfil its obligations".

NUREG-1537, 'Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors' [8] (the relevant NRC guidance document, and also the guidance document the NRC applies to medical isotope production facilities), provides both format and content guidance for an application and NRC staff review guidance.

A 'prototype plant' is defined in 10 CFR 50.2 as a reactor used to test design features, such as the testing required under §50.43(e). There is not a separate licensing process for a prototype plant. 10 CFR 50.43(e) describes provisions for a design differing significantly from light water designs licensed before 1997, and requires such designs to have demonstrated the performance of safety features through analysis, testing, experience, or a combination thereof, including sufficient test data, or the inclusion of additional requirements on siting, safety features, or operational conditions. A prototype plant may be considered a non-power facility if less than 50 percent of the annual cost of owning and operating is devoted to sale of materials, products, energy or services. Refer to Appendix B of the NRC staff's A Regulatory Review Roadmap for Non-Light Water Reactors (December 2017) for discussion of options for using a prototype plant to achieve a design certification or standard design approval.

5. ADMINISTRATION/DOE/CONGRESSIONAL ENGAGEMENT

Congressional delegations need to know about commercial fusion projects, key members of Congress should know about commercial fusion projects. Commercial fusion should be on the Administration's radar. This Administration is absolutely supportive of new nuclear technologies—fission or fusion. And does not want them to go overseas—especially ones that received DOE funding (e.g., TerraPower going to China), and really tries to bend over backwards to support the emerging nuclear technologies. Notably, unlike the NRC, DOE has an advocacy role to play here, so it would be useful to discuss with DOE how that advocacy role could be maximized.

There is much guidance about jurisdiction between the NRC and DOE—and a DOE/NRC Memorandum of Understanding on how to work together when there's some common interest. DOE maintains its authority to regulate activities conducted on its behalf, except for certain specific facilities. For a new DOE research or test reactor to be regulated by DOE and not NRC, it: (1) can't be operated for the purpose of demonstrating the suitability for commercial application of such a reactor and (2) can't be operated as part of the power generation facilities of an electric utility system. In Sept. 2015, the NRC-DOE held a Workshop on Advanced non-LWRs, and DOE did a presentation on DOE Roles & Responsibilities and walked through the jurisdiction issues [9].

Additionally, there were activities on fusion licensing during the ARIES project. G. Hofer et al. [10] reviewed the NRC documentation by Raytheon for DOE OFES in order to anticipate the role that the NRC might have with regard to fusion power systems constructed in the US. K. Rule et al. [11] and B. Merrill et al. [12] are white papers that were contributed to the 2017 National Academies of Science Fusion Study.

REFERENCES

[1] UNITED STATES NUCLEAR REGULATORY COMMISSION, NRC-2008-0237 Policy Statement on the Regulation of Advanced Reactors (2008), https://www.nrc.gov/docs/ML0827/ML082750370.pdf

[2] NUCLEAR REGULATORY COMMISSION, 10 CFR Part 61 [NRC–2017–0081] RIN 3150–AK00 Greater-Than-Class C and Transuranic Waste (2018), https://www.govinfo.gov/content/pkg/FR-2018-02-14/pdf/2018-03085.pdf

[3] UNITED STATES NUCLEAR REGULATORY COMMISSION, SECY-18-0060: Achieving Modern Risk-Informed Regulation Accession Number: ML18110A186 (2018), https://www.nrc.gov/docs/ML1811/ML18110A186.html

[4] UNITED STATES NUCLEAR REGULATORY COMMISSION, NRC-2008-0237 Policy Statement on the Regulation of Advanced Reactors (2008), https://www.nrc.gov/docs/ML0827/ML082750370.pdf

[5] UNITED STATES NUCLEAR REGULATORY COMMISSION, Development and Utilization of the NRC Policy Statement on the Regulation of Advanced Nuclear Power Plants NUREG-1226 (1988), https://www.nrc.gov/docs/ML1325/ML13253A431.pdf

[6] UNITED STATES GOVERNMENT, Energy Policy Act of 2005, Public Law 109–58 (2005), https://www.govinfo.gov/content/pkg/PLAW-109publ58/pdf/PLAW-109publ58.pdf

[7] 112th Congress, American Medical Isotopes Production Act of 2011 (2011), https://www.congress.gov/bill/112th-congress/senate-bill/99

[8] UNITED STATES NUCLEAR REGULATORY COMMISION, Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors NUREG-1537 (1996)

[9] UNITED STATES DEPARTMENT OF ENERGY, Workshop on Advanced non-LWRs DOE Roles & Responsibilities: DOE Roles & Responsibilities: Reactor Authorization (2015), https://www.nrc.gov/docs/ML1524/ML15245A685.pdf

[10] HOFER, G., NRC Regulations and Fusion Power, Report prepared for DOE OFES by Raytheon Nuclear Inc. (1995), http://aries.ucsd.edu/ARIES/DOCS/Hoffer9505/NRCregulations.pdf

[11] RULE, K., Development of a Licensing Framework and Roadmap for a Fusion Power Plant, white paper submitted to NAS Workshop at Madison, WI (2017).

[12] MERRILL, B., Trends in Reactor Licensing and the Computing Requirements Needed to Address Them, white paper submitted to NAS Workshop at Madison, WI (2017).

AN OVERVIEW ON THE SAFETY OF FUSION ENERGY FOCUSED ON THE U.S. FRAME

L. EL-GUEBALY
Distinguished Research Professor Emeritus
University of Wisconsin, Madison, U.S.

1. INTRODUCTION

There have been a number of studies on the safety of fusion. These studies generally agree that fusion power plants are envisioned to be safer than fission power plants. Notwithstanding, it is critical for fusion community to understand the answers to the critical questions of the safety aspects of fusion energy. This section is intended to provide an overview of three key safety-related questions on fusion energy, as well as highlighting some areas that requires further studies.

2. WHAT ARE THE RADIOACTIVE EMISSIONS AND WASTES GENERATED AT FUSION POWER PLANTS?

Fusion power plants are expected to emit small amount of radioactive substances annually, including very small amounts of tritium gas released up the stack and perhaps some small amounts of tritiated water in the plant's effluent water. However, a DOE supported fusion power plant can easily meet the DOE Federal limits of 10 mrem/year to the public for stack releases (40CFR61), and 4 mrem/year to the public for water releases (40CFR141). An NRC licensed fusion power plant would likely have to meet the airborne limit of 100 mrem/year for members of the public (10CFR20.1301). The NRC also requires plants to meet 40CFR141, the 4 mrem/y from drinking water. It is also expected that fusion power plant emissions of cryogens (helium and nitrogen) from cryo storage venting are small and warm quickly even in winter air, so they rise and disperse in the atmosphere with no effect at the site boundary. Magnetic and radiofrequency energy emissions will have no effect at the site boundary, these are localized in the fusion power plant buildings. A fusion power plant would utilize a steam cycle for producing electrical power. Therefore, the water treatment chemicals (e.g., acids and bases) released from a fusion power plant would be similar in quantity to those from a fission power plant. A fusion power plant would require emergency diesel generators like fission power plants. Therefore, diesel fuel combustion emissions from periodic testing of these units would be similar to those of a fission power plant. (For the low level waste, see Section 4.3).

3. FOR NUCLEAR FISSION, THERE IS A GENERAL PUBLIC UNEASINESS AROUND ACCIDENTS AND RADIOACTIVE WASTES. HOW DOES FUSION COMPARE WITH FISSION IN THESE REGARDS?

Fusion scientists and engineers have worked to include safety into power plant designs. Fusion has less at-risk fuel than fission. Fusion keeps the amount of fuel on-site as low as possible. At any given time, the kilogram amounts of tritium fuel in a fusion power plant are compartmentalized, and any at-risk amount (e.g., 70 grams or 700,000 Curies) is much lower than the ~100 tons of fuel in the core (more than 4 billion Curies of fission products, see NUREG-1228) of a large, 1000 MWe fission reactor, or the 20–30 tons in a small modular fission reactor. Fusion injects fuel in grams/minute timescales and can halt fuel injection to control a plant off-normal event. Unlike fission, fusion strives to recycle tritium fuel rather than hold previous spent fuel cores in canals or in dry casks on site. Fusion strives to breed new tritium fuel on an as-needed basis for plasma fuelling rather than mine and refine uranium fuel. Fusion has a lower level of activated materials than fission. Fusion has no chain reaction. Neutron economy concerns in materials selection and can use low-activation materials (e.g., silicon carbide, ferritic-martensitic stainless steels, vanadium, titanium, etc.) in plant design. A fusion plant would produce a higher volume of low level waste (LLW) than fission, but little or no high level waste (HLW[3]) that requires deep geologic disposal. The LLW volume can be minimised by design, recycling, and clearance. Fusion also controls neutron activated, tritiated dust in the vacuum vessel. The vacuum vessel has to be a robust, leaktight chamber; if not, the fusion plant cannot start up. Fusion has much lower radioactive decay heating than fission; fusion can select its materials to be low activation and low afterheat. Therefore, afterheat removal requirements are less for a fusion plant. Fusion also could use passive safety means whenever possible. We also believe the public will remain uneasy with new technology until the technology can prove itself with years or decades of safe operation.

Even in the most extreme case of plant blackout, fusion reactors are unlikely to lead to major incidents. This is because, even in case of blackout: there will be no energy and pressurization threats to confinement barriers (VV and cryostat) – no melting, no burning, no combustible gas generated; decay heat problem can be solved by design; stored magnet energy can be controlled by design; chemical energy can be controlled by design; an overpressure protection system can be implemented; chemical reaction can be avoided; plasma will be shutdown rapidly and benignly; there will be, minimal radioactive releases[4] both during normal and abnormal operations.

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[3] HLW legal definition: *spent fission fuel and residues of treatment of spent fission fuel. In fusion designs, HLW is used for components with Waste Disposal Rating* > *1.* This may include the Greater Than Class C (GTCC) waste – however, this is not formally defined yet by NRC.

[4] Such as T, volatile activated structure, corrosion products, and erosion dust. Or, from liquid and gas leaks.

4. DO FUSION POWER PLANTS REQUIRE EMERGENCY PLANS LIKE FISSION?

The Energy Reorganization Act of 1974 gives the US Nuclear Regulatory Commission jurisdiction over nuclear fission (and fusion) power generation facilities of an electric utility system. While the US Nuclear Regulatory Commission (NRC) asserts its jurisdiction to regulate commercial fusion power, there is no regulatory model in place at this time for a commercial fusion power plant. We assume the NRC would prudently require fusion to have an Emergency Plan (see 10CFR50.47) like fission power plants are required to have an Emergency Plan. This is a plan of actions that protect members of the public during off-normal events, such as shelter-in-place or evacuate from the path of a release plume from the plant. However, in fusion development, the aim of DOE-STD-6002 is to avoid requiring an evacuation plan in the Emergency Plan by keeping accident doses to the public below 1 rem[5]. Accident analyses of ARIES fusion power plant designs have shown that severe accident doses can be below 1 rem to members of the public.

5. WHAT TYPE OF REGULATORY APPROVALS ARE REQUIRED; WOULD FUSION POWER PLANTS BE GOVERNED BY THE EXISTING NRC?

If you follow the NuAB SMR model they are seeking pre-approval from the NRC. As stated above, the US NRC will regulate fusion power, but they have stated they will not develop a regulatory model for fusion power until fusion is closer to commercial application (NRC memorandum SRM-SECY-09-0064, July 2009). The NRC presently licenses companies that produce tritium (e.g., Schlumberger at Princeton Technology Centre). We also expect that a privately funded fusion experiment using tritium fuel would also be NRC licensed. The first fusion power plant may be a small Department of Energy governmental demonstration (DEMO) facility for testing the viability of commercial fusion power, but not be routinely connected to the electrical power grid. Or it might be a plant operated under a DOE and utility partnership.

It is not clear at the present time what the scope and mission of the first fusion power plant will be. It is possible that the first DEMO fusion power plant may have to meet both DOE and NRC rules. The DOE has Federal safety rules, e.g., 10CFR830, and Federal environmental rules, as mentioned in Q1, that must be met for the facility to be granted permission by DOE to operate. Later, fusion power plants, clearly operating as part of commercial power generation, would be licensed and regulated by the US NRC [1].

REFERENCES

[1] EL-GUEBALY, L., CADWALLADER, L., SOWDER, W., Challenges of Fusion Power Plant Licensing: Differences and Commonalities with Existing Systems, Fusion Science and Technology 60, Number 2 (2011) 751–759.

[5] 1 rem (= 10 mSv) accident dose stated in Fusion Safety Standards, DOE report, DOE-STD-6002-96 (1996).

SESSION V: TECHNOLOGIES OF FUSION ENTERPRISES

OVERVIEW OF MAGNETIC CONFINEMENT FUSION ENERGY CONCEPTS

D. BRUNNER
Chief Technology Officer
Commonwealth Fusion Systems, Cambridge, U.S.

The fields of nuclear fusion research have long been led by government-sponsored work done primarily in academic and national labs. However, over the last two decades, there has been a remarkable growth in the number of private companies in fusion energy R&D as well as the amount of funding supporting this work.

There are a variety of steady-state magnetic confinement concepts presently pursued by private industry. This paper presents a summary of the work being performed at companies pursuing fusion concepts that roughly fall under the categorization of steady-state magnetic confinement, extending into magneto-electrostatic confinement, see Fig. 1. (Companies pursuing pulsed inertial confinement and magnet-inertial confinement will be discussed in later papers.) Although these concepts span a wide range of technological readiness and feasibility/scalability under present scientific understanding, this work makes no attempt at comparing them by these important metrics. It is rather to serve as a compilation of the present state of each company, the near-term work, and challenges moving forward.

This paper was edited with the help of following experts: S. Cohen and M. Paluszek of Princeton Satellite Systems, R. Dinan of Applied Fusion Systems, M. Gryaznevich and D. Kingham of Tokamak Energy, T. McGuire of Lockheed Martin, J. Park of EMC2, D. Sutherland of CT Fusion, R. Volberg of Fusion One. Compilation of this information was supported by Commonwealth Fusion Systems.

FIG 1. Top left: Commonwealth Fusion Systems; Top right: Lockheed Martin; Bottom left: Tokamak Energy; Bottom right: TAE Technologies.

1. COMMONWEALTH FUSION SYSTEMS

Commonwealth Fusion Systems (CFS) is a recent spin out of the Massachusetts Institute of Technology Plasma Science and Fusion Center (PSFC) [1]. The basic concept CFS is pursuing is a compact, high-field, standard aspect ratio tokamak with high-temperature superconducting magnets. The major differentiations include: utilizing the proven confinement physics of tokamaks – the most studied fusion concept to date – resulting in minimal physics extrapolations; the major risk to demonstration of net energy is engineering of high-field magnets using new rare-earth barium copper oxide (REBCO) superconductors; and a major collaboration with an established leader in high-field fusion physics and magnet engineering (PSFC). The power plant vision for CFS is a compact D-T burning tokamak in the range of low 100's MWe, with simple maintenance due to demountable magnets and a liquid blanket [2].

The major challenge for CFS is the engineering, construction, and testing of a new class of large-bore, high-field superconducting magnets. The present status of CFS is that it is closing its first round of financing, ramping up business operations, and is beginning its research collaboration with MIT while preparing to extend it to the broader tokamak fusion research community. Near-term work includes the R&D of high-field superconducting magnets with MIT, establishing the physics basis for net energy in SPARC, and preliminary design of SPARC.

2. LOCKHEED MARTIN

Lockheed Martin is an aerospace, defence, security, and advanced technologies company that has been internally funding fusion energy R&D within their Skunk Works programme [3]. Their basic concept is a high-beta mirror/cusp hybrid, aiming to utilize diamagnetic sheath confinement, which they call a Compact Fusion Reactor (CFR). The major differentiators of Lockheed's CFR are a compact core with non-magnetized bulk plasma and good magnetic curvature stabilization. The vision for a CFR power plant is D-T at 100 MWe with a core that is ~200–1,000 metric tons and ~15.5 m long by ~6.5 m diameter.

Major challenges to getting to a reactor include a large parameter extrapolation from present experiments, a not-yet-demonstrated physics confinement regime, and radiation and plasma losses to internal superconducting coils. The present status of CFR research at Lockheed is plasma source testing and model benchmarking in their T4B device, commissioning of their T5 device, and examining plasma dynamics and confinement with PIC simulations [4]. Near-term goals on T5 include demonstrating plasma heating, high-density plasma source, and neutral beam particle confinement, as well as measuring sheath losses/size, cusp losses and instabilities.

3. TOKAMAK ENERGY

Tokamak Energy is a spin out of the spherical tokamak research performed in the UK (originally Tokamak Solutions) [5]. Their basic concept is a spherical tokamak (low aspect ratio) with high-temperature superconducting magnets. The major differentiation of low aspect ratio tokamaks over higher aspect ratio tokamaks are their ability to achieve higher beta (plasma pressure normalized to confining magnetic pressure) and a high fraction of plasma current driven by the plasma (bootstrap current) at the same time. Tokamak Energy's vision for a power plant are D-T burning compact, modular reactors at ~150 MW.

Major challenges for Tokamak Energy include reaching 100-million-degree plasma temperatures in their copper ST40 device (~10 keV), quench protection of their superconducting magnets, and extrapolation of plasma confinement in spherical tokamaks towards reactor-relevant conditions (low collisionality). Tokamak Energy's present status includes operation of ST40 to test spherical tokamak confinement extrapolations [6] and making progress with superconducting magnet design. Near-term work for Tokamak Energy includes further development of the ST40 spherical tokamak as well as design and prototyping of HTS magnets.

4. TAE TECHNOLOGIES

TAE Technologies (formerly Tri Alpha Energy) is a spin out of the field-reversed configuration research at the University of California, Irvine [7]. TAE's basic concept is injection of proton and boron-11 (p-11B) neutral beams into a field-reversed configuration, for a Colliding Beam Fusion Reactor (CBFR). Major differentiations of this concept include a linear system with simple maintenance, a primary fusion reaction that is largely aneutronic, and the potential for direct energy conversion of the charged fusion products. The vision for a power plant is p-11B at ~200–500 MW.

Major challenges for TAE include achieving the challenging conditions needed for p-11B energy confinement, the relatively thin margins for achieving net energy with p-11B, efficient systems for direct energy conversion and heating, and side nuclear issues for p-11B. The present status of TAE includes having achieved their goal of 'long enough' 10 ms plasma lifetime on C-2U [8] and commissioning their next device, Norman (formerly C-2W). Near-term work for TAE includes achieving their goal of 'hot enough' on Norman as well as spinning out their neutral beam technology for boron neutron capture cancer therapy.

5. APPLIED FUSION SYSTEMS

Applied Fusion Systems (AFS) grew out of its founder's 3D printer company [9]. AFS' concept and differentiation are that they are using computer simulation as well as design and manufacture of advanced, compact devices for the purposes of energy production and space propulsion. Their present status and near-term work include R&D of small, modular reactors and nuclear-enhanced air-breathing rockets [10].

6. CT FUSION

CT Fusion is a spin out of spheromak research done at the University of Washington (UW) [11]. Their concept is a spheromak plasma sustained with imposed-dynamo current drive, the 'Dynomak' fusion concept [12]. This is differentiated by its simply connected topology with no externally applied toroidal magnetic field and efficient plasma current drive. CT Fusion presently has a research collaboration with UW and rights to relevant IP. Near-term work includes executing a Phase I SBIR to build an advanced feedback control system to optimize spheromak performance in the current and next-generation Dynomak prototypes. CT Fusion plans to build and operate a next-generation Dynomak prototype to demonstrate their plasma driver technology sustaining higher temperature, longer pulse, spheromak plasmas.

7. ENERGY MATTER CONVERSION CORPORATION

Energy Matter Conversion Corporation (EMC2) is a company attempting to develop the Polywell concept [13]. Their concept forms an electrostatic potential well through electron confinement with an array of polyhedral magnets. The Polywell is differentiated by its simple, modular magnets and lower losses due to its gridless design. Their present status is somewhat dormant, after having completed a 20+ year R&D programme on 20 test devices with funding from DARPA, the US Navy, and others. EMC2 demonstrated confinement of 7 keV electrons [14]. If the funding becomes available, near-term work would aim to achieve steady-state operation with ~1–10 keV ion confinement.

8. FUSION ONE CORPORATION

Fusion One Corporation was founded to improve on the Polywell concept. Its major differentiation was the inclusion of electrostatic reflectors to improve electron confinement [15]. However, the project has been cancelled. Self-consistent analytic power balance simulations revealed that the power to maintain non-thermal ion distribution leads to poor efficiency. The best possible energy gain with D-T was ~3.5. Results similar to this have been found in the past [16] and apply to all electrostatic concepts.

9. PRINCETON SATELLITE SYSTEMS

Princeton Satellite Systems (PSS) is a spin out of and collaborator with the Princeton Plasma Physics Laboratory (PPPL) with the goal of providing efficient space propulsion [17, 18]. Their concept is a field-reversed configuration in a mirror with solenoidal coils and the major differentiation is heating with odd-parity rotating magnetic fields. PSS' is presently designing superconducting coils and high-efficiency heating systems. Near-term work includes increasing the RF drive to demonstrate 1 keV ion heating.

REFERENCES

[1] CHANDLER, D., MIT And Newly Formed Company Launch Novel Approach to Fusion Power (2018),
http://news.mit.edu/2018/mit-newly-formed-company-launch-novel-approach-fusion-power-0309

[2] SORBOM, B.N., ARC: A Compact, High-Field Fusion Nuclear Science Facility and Demonstration Power Plant With Demountable Magnets, Fusion Eng. Des. **100** (2015) 378–405.

[3] SHALAL, A., Lockheed Claims Breakthrough on Fusion Energy (2014),
https://www.scientificamerican.com/article/lockheed-claims-breakthrough-on-fusion-energy1/

[4] MCGUIRE, T.J., Compact Fusion Reactor – CFR, Concept Overview, Development Plan, Status, American Physical Society Division of Plasma Physics, Milwaukee, WI (2017).

[5] CZYZEWSKI, A. Super compact fusion reactor secures funding (2011),
https://www.theengineer.co.uk/issues/14-february-2011/super-compact-fusion-reactor-secures-funding/

[6] GRYAZNEVICH, M., Overview and status of construction of ST40, Fusion Eng. Des. **123** (2017) 177–180.

[7] ROSTOKER, N., Colliding Beam Fusion Reactor, Science **21** (1997) 1419–1422.

[8] BINDERBAUER, M.W., Recent Breakthroughs on C-2U: Norman's Legacy, AIP Conference Proceedings, **1721** (2016) 030003.

[9] INGHAM, L., Setting sights on fusion: entrepreneur to build prototype reactor within three years (2014),
http://factor-tech.com/green-energy/8991-setting-sights-on-fusion-entrepreneur-to-build-prototype-reactor-within-three-years/

[10] SCAMMELL, R., Applied Fusion Systems Targets Smaller Fusion Reactor For Interstellar Travel (2018),
https://www.aerospace-technology.com/news/applied-fusion-systems-targets-smaller-fusion-reactor-interstellar-travel/

[11] ACKERMAN, E., Inside the Dynomak: A Fusion Technology Cheaper Than Coal (2014),
https://spectrum.ieee.org/energy/nuclear/inside-the-dynomak-a-fusion-technology-cheaper-than-coal

[12] SUTHERLAND, D.A., The Dynomak: An Advanced Spheromak Reactor Concept With Imposed-Dynamo Current Drive And Next-Generation Nuclear Power Technologies, Fusion Eng. Des. **89** (2014) 412–425.

[13] KRALL, N.A., et al., Forming and Maintaining a Potential Well in a Quasispherical Magnetic Trap, Phys. Plasmas **2** (1995) 1–15.

[14] PARK, J., High-Energy Electron Confinement in a Magnetic Cusp Configuration, Phys. Rev. X 5 (2015) 021024.

[15] SIECK, P., VOLBERG, R., The F1 Reactor: An Evolution Of The Magneto-Electrostatic Fusion Concept To Achieve Economical Net Power, ALPHA Annual Meeting Presentation (2017), https://arpa-e.energy.gov/sites/default/files/3_VOLBERG.pdf

[16] RIDER, T.H., A General Critique Of Inertial-Electrostatic Confinement Fusion Systems, Phys. Plasmas **2** (1995) 1853–1872.

[17] CHOI, C.Q., Could Tiny Fusion Rockets Revolutionize Spaceflight? Scientific American (2017), https://www.scientificamerican.com/article/could-tiny-fusion-rockets-revolutionize-spaceflight/

[18] YOSEF, S.R., A Direct Fusion Drive For Rocket Propulsion, Acta Astronautica **105** (2014) 145–155.

OVERVIEW OF INERTIAL FUSION ENERGTY SYSTEM CONCEPTS

M. CAMPBELL
Director
University of Rochester - Laboratory for Laser Energetics, Rochester, U.S.

1. INTRODUCTION

Laser (or X ray)-induced ablation generates ultrahigh pressures that compress a fusion capsule to ignition conditions. In the first phase, the outer layer of a mm-sized DT target is irradiated either with laser light or X rays. In the second phase, the outer layer blows off, and the inner layers compress. In the third phase the compressed fuel is ignited. In hot-spot ignition, the core temperature must be at least 5keV and core fuel areal density must exceed 300mg/cm^2. Gains (fusion energy out over laser energy in) of 100 are anticipated for MJ laser systems.

NIF has achieved a fusion output of ~56kJ (G~3%) from X ray driven targets: alpha heating dominates compression work; fusion yield ~3x larger than that from pδV compression work; fuel gain (Fusion energy/ imploded fuel energy)>1; 'Real World (engineering features, 3D impact) are being explored; Fuel pressures >350Gbar have been inferred; 70% of that needed for ignition at capsule imploded energies achievable on NIF indirect drive (10–14 kJ). Omega implosion experiments when scaled to NIF energies have fusion outputs >400 kJ (G~25%). Ignition pressures for Direct Drive at NIF scale are ~120–140 Gbar; $P_{ign} \sim (E_{ign})^{-1/2}$

This paper was edited to cover the ICF technologies, Star-Driver^{TM} concept [1], commercial and spin-off technologies benefitting IFE lasers, examples of high average and peak-power lasers and applications of 'IFE relevant' lasers/systems. IFE will leverage technologies developed for inertial confinement fusion, see Fig. 1. Inertial confinement fusion (ICF) programmes developed many technologies that naturally extend to Inertial Fusion Energy (IFE), which include high-bandwidth/high-contrast pulse shaping, beam shaping, high-performance optical coatings; laser glass and optical technologies; and diode pumping and thermal management.

2. ICF TECHNOLOGIES

The total laser energy/power of an ICF laser is produced by a limited number of identical beams. In NIF there are 192 beams with 10 kJ of 0.35 µm light (>20 kJ of 1 µm light); total aperture: 300,000 cm^2. In LMJ (France) there are 220 beams; Omega has 60 beams; IFE concepts (e.g. LIFE) will require ~400 beams. The motivation is to minimize cost, provide alignment and controls.

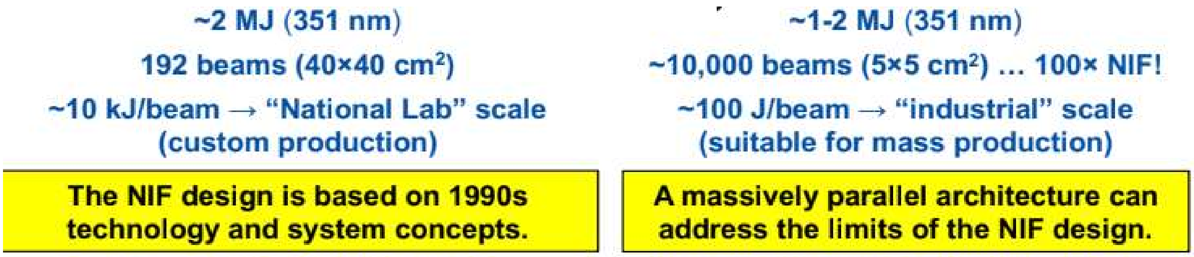

FIG 1. Beam Power Optimization for Commercial ICF Facilities.

Legacy laser drivers are large systems with large optics, with the intent of minimizing cost. NIF optics and Omega EP optics measure 42cm on a side — the laser beams are 36cm in aperture. StarDriver^{TM} optics are 5–10 cm in aperture, are much less expensive and much more widely available.

3. STARDRIVER^{TM} CONCEPT

StarDriver^{TM} is an IFE concept that builds on ICF technology and research, plus modern controls: Industrial-scale lasers – suitable for multiple purposes; Massively parallel architecture – enabled by modern controls. Spin-off IFE technologies can also expect to be applied to other fields: Extreme Ultraviolet (EUV) laser sources; Laser peening and other materials-processing techniques; and Laser accelerators, innovative surface processing.
StarDriver^{TM} offers a highly flexible architecture for laser-driven inertial fusion. A laser constructed from 10^4 to 10^5 individual beamlines using cm-scale apertures provides more flexibility to optimize the laser drive: compatible with high-volume manufacturing that can significantly reduce costs; a wider range of gain material options are possible; beamlines can operate differently to enable complex pulse shapes and focal spot zooming to optimize laser drive. A large number of independent beams effectively produces an 'incoherent source' to irradiate the target, and reduces (or even eliminates) laser−plasma instabilities; reduces laser nonuniformity that drives hydrodynamic instabilities. With a much smaller footprint, the development costs for a highly modular IFE design will be significantly reduced from that required for past ICF facilities.

Commercial and spin-off technologies benefiting IFE lasers are as follows:

- Time-multiplexed pulse−shaping systems can seed multiple laser systems with the required waveforms. Current Omega pulse shaping system (based on Techtronix AWG70001A) gives a time sample of 20ps, maximum waveform length of 2.5ms, resolution of 50ps, and jitter between two optical waveforms after a pulse-shaping system of 1ps over delays of up to 1us.
- Lithium niobate waveguide technology from telecommunications has been adapted for fusion lasers. Examples are high contrast amplitude modulators; three-stage phase modulators; and high contrast 1:8 demultiplexing switches.

- Time-multiplexed pulse shaping with long record lengths provides the performance required for IFE, e.g. Tektronix arbitrary waveform generators (24 Gsamples/sec, 11-GHz bandwidth, 1 V (p-p), 10-bit vertical resolution, 16 Gsample record, 1-ps (rms) jitter).
- A new class of polarizing (PZ) gain fibre was developed in collaboration with Fibercore (UK). PZ fibre eliminates the conversion of frequency modulation to amplitude modulation during laser pulse amplification.
- Display technology was adapted for laser beam shaping to optimize laser-output profiles. PSLIM uses a phase-only spatial light modulator: laser beam amplitude and phase can be simultaneously controlled using a carrier method; on-shot beam fluence profile data is used to specify the beam-shaping performed by PSLIM.
- Deterministic grinding and polishing for manufacturing fusion laser optics was transferred to industry.
- High-power and high-energy optical laser coatings are commercially available from a number of sources. Optimax Systems (Rochester, NY): Reactive evaporation; Plasma-ion-assisted deposition; Ion beam sputtering. Advanced Thin Films (Boulder, CO) + CVI Laser Optics (Albuquerque, NM): Ion beam sputtering; Magnetron Sputtering; Plasma ion-assisted deposition.
- Multichannel streak cameras required for diagnosing laser performance have been commercialized.
- Optical parametric amplification (OPA) developed for short pulses may be adapted broadband laser drivers. Collinear/degenerate OPA enables up to 80% efficiency using signal and idler waves; supports signal + idler bandwidth up to 100-nm ($D\lambda/\lambda \sim 10\%$); Nonlinear crystals are available for operating at high-average-powers

4. EXAMPLES OF HIGH AVERAGE AND PEAK POWER LASERS

Diode-pumped solid-state lasers (DPSSL) technology has advanced significantly. High energy (200 J), wall-plug efficiency (20% to 25%) and repetition rate (10 Hz) are suitable for IFE applications.

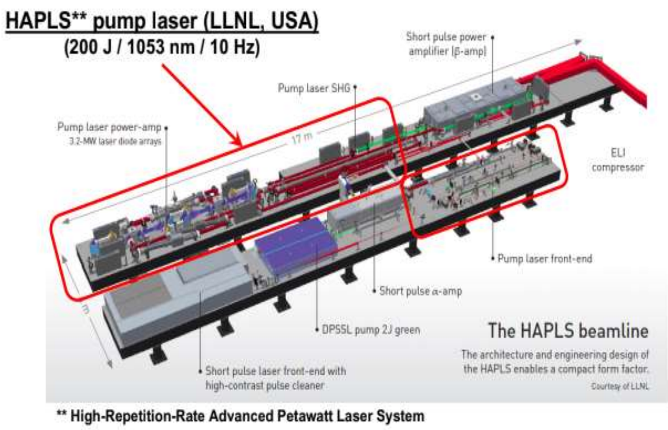

FIG 2. The HAPLS Beamline.

Leading multi-100 kWatt DEW laser systems have their origins in ICF and IFE will benefit from ongoing research. Programme focus: cost, efficiency, thermal management, beam quality, alignment and tracking, SW&P.

The ability to generate peak laser powers greater than 1 PW came out of the invention of chirped-pulse amplification (CPA) at the University of Rochester. CPA enables the amplification of a broad-bandwidth pulse to tens or hundreds of joules at intensities below the damage limits of laser gain materials, and the pulse's subsequent temporal recompression, by a factor of 10,000, to tens to hundreds of femtoseconds. When tightly focused, PW-peak-power lasers can generate intensities of greater than 1021 W/cm^2 and electromagnetic fields more than 100 times stronger than the field that binds electrons to atomic nuclei. The High-Repetition-Rate Advanced Petawatt Laser System (HAPLS), was developed to deliver PW pulses with durations of less than 30fs, at a 10-Hz repetition rate, see Fig. 2.

Diode-pumped solid-state laser (DPSSL) technology has advanced significantly. Laser cooling, diode lasers, and diode drivers are key technologies developed and delivered to operation.

5. APPLICATIONS OF 'IFE RELEVANT' LASERS/SYSTEMS

Spin-offs from fusion research benefit other fields, such as integrated circuit fabrication. R. Castellano, Information Network (2017) EUV stepper (ASML) at SUNY Polytechnic Institute (Albany) stated that:

> *"EUV is expected to enter the mainstream market in the next few years, implemented at GlobalFoundries, Intel, Samsung Electronics and TSMC. In fact, the latter three companies invested billions of dollars in ASML in 2012 to aid in the development of EUV systems".*

Laser peening leverages ICF technology for improving high-value metal parts, like jet engine turbine blades. A high-energy laser pulse strikes a coated surface that is covered by water, causing a localized high-pressure wave. A repetitive pattern of laser pulses results in an area of deep compressive stress that prevents crack formation and growth.

The future is peak- and average-power lasers. Most laser-based future applications will require average power lasers: laser-based accelerators; directed energy; THz sources; radiation sources (neutrons, gamma-rays); materials processing; high energy density physics.

Innovative commercial and national security applications are made possible by the development of high peak and average power broadband lasers, such as hydrophobic or hydrophilic surfaces, and by control of the optical and infra-red spectra of metal surfaces.

REFERENCES

[1] EIMERL, D., CAMPBELL, E. M., KRUPKE, W. F., A Flexible Laser Driver for Inertial Confinement Fusion and High Energy Density Physics, J. Fusion Energy **33** (2014).

OVERVIEW OF MAGNETO-INERTIAL FUSION AND OTHER INTERMEDIATE-DENSITY PULSED CONCEPTS

S. HSU
Programme Director
ARPA-E Department of Energy, Washington D.C., U.S.

1. INTRODUCTION

The Lawson criterion dictates that the product of the fuel density *n* and the energy confinement time τ_E must exceed a value of approximately 3×10^{14} cm^{-3} s (at around 10 keV) if the fusion power from DT-fusion α particles is to exceed power losses from the plasma. Exceeding Lawson conditions is likely required for any practical fusion power plant. Magneto-inertial fusion (MIF) and other intermediate-density pulsed concepts aim to achieve Lawson conditions at fuel densities between those of magnetic confinement fusion (MCF, $n\sim10^{14}$ cm^{-3}) and inertial confinement fusion (ICF, $n\sim10^{26}$ cm^{-3}). Studies suggest that intermediate-density fusion may constitute a low-cost minimum in the thermonuclear-fusion parameter space, due to an optimum in the required combination of stored energy and heating power to achieve Lawson conditions [1–2]. This is borne out by the recent achievement of fusion-relevant conditions on the 100 million USD-class Z machine at Sandia National Laboratories [3–4].

MIF and other intermediate-density fusion concepts must be pulsed because the pressure at Lawson conditions (at intermediate densities) exceeds the strength of materials (~1 Mbar), and thus such a plasma cannot be held in steady-state by physical structures such as magnetic coils. Using a strong magnetic field to reduce the rate of thermal transport and to enhance α-particle energy deposition within the fusion fuel, the Lawson criterion becomes achievable at intermediate densities [5]. Compared to ICF, the required implosion speed and instantaneous peak power are drastically reduced. Compared to MCF, the size and stored energy are drastically reduced. The density, pressure, power, size, and stored energy values for MIF are typically on the order of the geometric mean of the ICF and MCF values. This relaxes the technology and cost requirements compared to both ICF and MCF.

This paper was edited by Scott Hsu to provides an overview on the magneto-inertial fusion and other intermediate-density pulsed concepts. Pulsed, intermediate-density fusion concepts, including MIF and Z-pinch-based approaches, relax many of the technological challenges for fusion by optimizing the required combination of stored energy and heating power to reach Lawson conditions. However, as with any choice in fusion, there are trade-offs (advantages and disadvantages) compared to the more mature approaches of MCF and ICF. Scientific proof-of-principle for pulsed, intermediate-density fusion (i.e., thermonuclear conditions that can be scaled up further) was demonstrated via the MagLIF concept at Sandia National Laboratories within the past five years. A broad parameter space and many approaches with different combinations of drivers and plasmas are being explored by multiple private fusion ventures

(See Fig. 2); this diversifies and mitigates the overall risk. There is an opportunity to further develop many of the pulsed, intermediate-density concepts to see if they can realize their potential in delivering a lower-cost, faster development path toward commercial fusion energy.

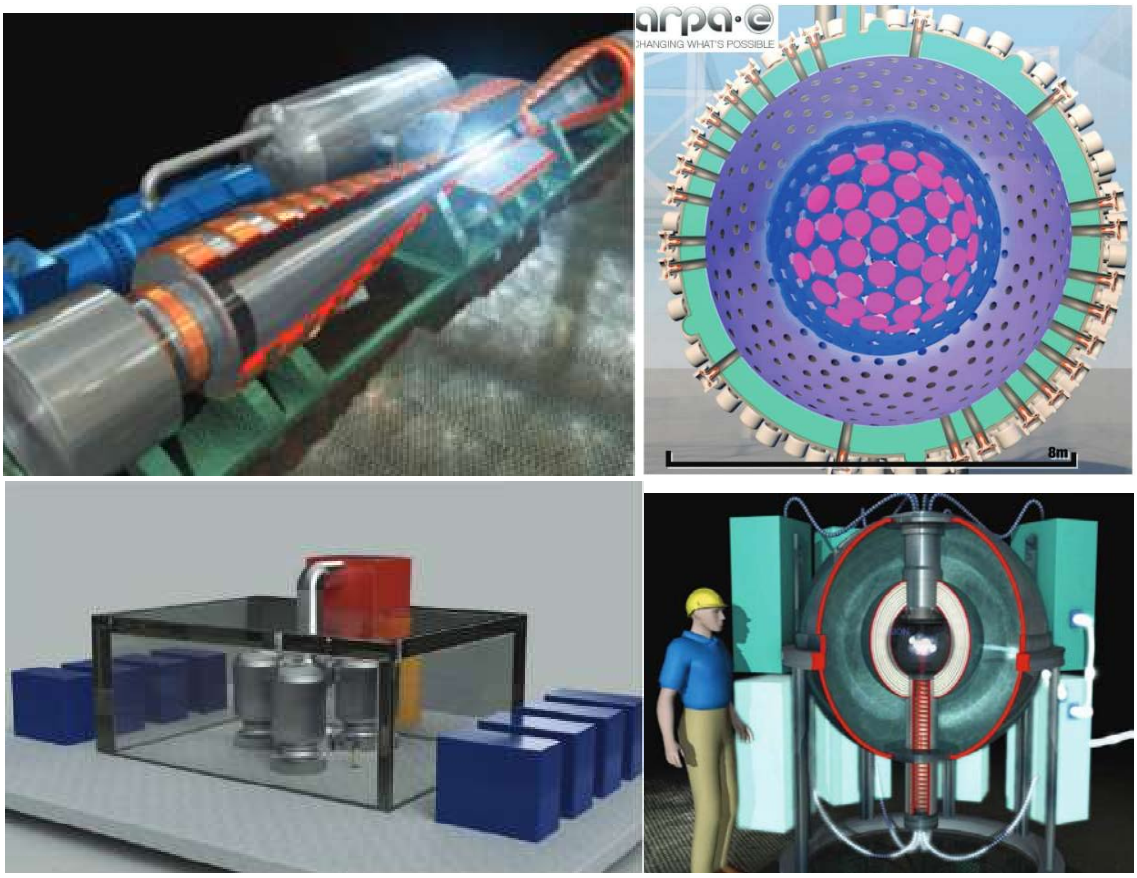

FIG. 1. Top left: Helion; Top right: HyperJet Fusion; Bottom left: Fuze; and Bottom right: Lawrenceville Plasma Physics.

2. ADVANTAGES AND DISADVANTAGES

Compressing a plasma is required to achieve Lawson conditions in the intermediate-density regime. MIF uses a liner (i.e., a pusher) to compress a magnetized plasma 'target.' Z-pinch-based approaches rely on an axial electrical current within the fusion fuel to generate an azimuthal field that 'self-compresses' the plasma. The lower densities compared to ICF reduces the required implosion speed, enabling the use of lower-cost, higher-efficiency pulsed-power drivers. In addition, there are no delicate front-end optics as compared to laser driven ICF systems. The higher efficiency of pulsed power enables a reduced repetition rate (compared to ICF) for an economically viable power plant. The pulsed, compressional heating eliminates the need for costly magnets and external heating systems, compared to MCF. Many MIF/Z-pinch designs are compatible with thick, flowing liquid first wall and blanket solutions, which de-emphasizes or eliminates the need for a costly, radiation-resistant-materials development programme.

Finally, the wide parameter space of intermediate-density fusion provides flexibility and room for optimization.

Of course, all choices in fusion involve trade-offs. MIF and intermediate-density fusion have disadvantages as well. Compared to ICF, the plasma physics has been more challenging, e.g., plasma formation, stability, and confinement. Compared to MCF, the lack of a strong applied magnetic field makes the required stability and confinement more difficult to achieve (though the requirements are relaxed in an absolute sense). Repetitively pulsed fusion systems present different technological challenges, e.g., the need for high-power, robust repetitive pulsed-power capacitors and switches, thermal-cycling fatigue of materials, and handling of very large amounts of liquid metal, etc. There is also a much wider parameter space to explore, which takes time and funds.

3. STATUS AND CHALLENGES

MIF, other pulsed, intermediate-density fusion concepts (e.g., Z pinches), and related technologies (e.g., flux compression using imploding liners) have been studied for more than fifty years, and in fact pre-date the advent of laser-driven ICF by at least a decade. For MIF, target-formation and liner technologies were pursued somewhat independently due to the extensive challenges of each; liner compression of a magnetized target plasma was only attempted within the past decade [6]. The scientific and technical challenges, coupled (historically) with the lack of a sustained, well-coordinated R&D programme, resulted in a definitive proof-of-concept being achieved only within the past several years in the MagLIF experiment at Sandia National Laboratories. The MagLIF experiments achieved multi-keV ion and electron temperatures, thermonuclear yields exceeding 10^{12} DD neutrons, and Lawson-relevant *BR* (product of magnetic field times fuel radius at stagnation) values. More recently, a laser-driven 'mini-MagLIF' platform [7] has been developed on the OMEGA facility at the Laboratory for Laser Energetics (LLE) at the University of Rochester, where important MIF physics issues can be studied at a high shot rate and low cost per shot. The launch of the ARPA-E ALPHA programme [8] in 2015 allowed for multiple fusion-energy-relevant (i.e., potentially scalable to high repetition rate and low cost per shot), intermediate-density fusion concepts to be explored and developed. However, all these approaches are in early stages of development, with fusion triple products that are orders of magnitude below that of Lawson. Continued, aggressive technical progress is needed to fulfil the promise of MIF and pulsed, intermediate-density fusion.

The challenges can be succinctly categorized as follows: (1) stability and confinement of the plasma fuel (2) formation of the fuel plasma, (3) liner/implosion technology and implosion speed capable of overcoming the rate of energy and magnetic flux loss from the target plasma during implosion, (4) mitigation and/or survival of asymmetries and/or mix of impurities into the fuel during implosion and at stagnation, and (5) compatibility of all the above with economical, repetitively pulsed operation.

4. PRIVATE ENTERPRISES PURSUING PULSED, INTERMEDIATE-DENSITY FUSION

There are at least seven private companies pursuing pulsed, intermediate-density fusion concepts (see Table 1). These include both MIF and Z-pinch-based approaches, spanning many orders of magnitude with respect to desired implosion time, peak density, and implosion method.

TABLE 1. SUMMARY OF PRIVATE FUSION COMPANIES PURSUING PULSED, INTERMEDIATE-DENSITY FUSION CONCEPTS.

Company	Approach	Contact
Compact Fusion Systems	Pistons driven by high-pressure gas cylindrically implode a rotating liquid liner on a field-reversed configuration (FRC) plasma	Simon Woodruff
General Fusion	Pistons driven by high-pressure gas spherically implode a liquid liner on a spherical tokamak	Michel Laberge
Helion Energy	Pulsed magnetic field cylindrically compresses FRC formed by pulsed-power-driven injectors	David Kirtley
HyperJet Fusion	Pulsed-power-driven plasma guns form plasma target and imploding plasma liner via merging hypersonic plasma jets	Francis Thio
LPPFusion	Dense plasma focus (DPF), a Z-pinch variant that radially collapses a high-energy plasma to generate high-energy ions	Eric Lerner
MIFTI	Staged Z pinch, where a gaseous shell ionized by electrical current is cylindrically imploded onto a shock-heated gaseous target	Hafiz Rahman
ZAP Energy	Pulsed-power-driven, flow-shear-stabilized Z-pinch, in which sheared axial flows stabilize well-known Z-pinch instabilities	Uri Shumlak

REFERENCES

[1] LINDEMUTH, I. R., SIEMON, R. E., The fundamental parameter space of controlled thermonuclear fusion, Amer. J. Phys. **77**, 407 (2009).
[2] TURCHI P. J., Stabilized Liner Compressor for Low-Cost Controlled Fusion at Megagauss Field Levels, IEEE Trans. Plasma Sci. **45**, 2800 (2017).
[3] GOMEZ M. R., Experimental Demonstration of Fusion-Relevant Conditions in Magnetized Liner Inertial Fusion, Phys. Rev. Lett. **113**, 155003 (2014).
[4] SCHMIT P. F., Understanding Fuel Magnetization and Mix Using Secondary Nuclear Reactions in Magneto-Inertial Fusion, Phys. Rev. Lett. **113**, 155004 (2014)
[5] BASKO M. M., Ignition conditions for magnetized target fusion in cylindrical geometry, Nucl. Fusion **40**, 59 (2000)

[6] DEGNAN J. H., Recent magneto-inertial fusion experiments on the field reversed configuration heating experiment, Nucl. Fusion **53**, 093003 (2013).
[7] DAVIES J. R., Laser-driven magnetized liner inertial fusion, Phys. Plasmas **24**, 062701 (2017).
[8] UNITED STATES DEPARTMENT OF ENERGY, Accelerating Low-cost Plasma Heating and Assembly (2015),
https://arpa-e.energy.gov/?q=arpa-e-programs/alpha

THREE CHALLENGES FOR LOW-COST MAGNETIC FUSION POWER

P. TURCHI
Co-Founder
Compact Fusion Systems, Santa Fe, U.S.

1. INTRODUCTION

With the notion that the apparent minimum cost of a fusion power system occurs at densities corresponding to magnetic fields of about a hundred tesla, and that such fields are attainable by magnetic flux compression, selection of paths forward can be guided by three challenges relating to stability, cost and neutrons.

2. STABILITY

Both the plasma target and the liner compression approach are included here. If the plasma target is unstable, either initially or during compression, clearly there is a problem. The present notions for low-cost fusion by compression to high density (e.g., several ALPHA schemes) have antecedents from forty, fifty and even sixty years ago, but may now achieve success due to various improvements in physics or engineering technique. For example, the flow-through z-pinch employs very clever physical understanding in stabilizing the plasma against the sausage and kink modes that ended earlier interest in the z-pinch (c. 1958). It also heats the plasma by magnetic flux compression instead of attempting to use resistive heating that was found previously to have fundamental limits. The use of very high current liner implosions (driven by explosive flux-compression generators, c. 1968) to compress plasma insulated by axial magnetic fields can now achieve success thanks to much higher power driving systems (i.e., Z-machine). The adverse magnetic field curvature for Field-Reversed Configurations (FRCs) that destroyed the plasma confinement (c. 1968) has apparently been overcome (c. 1977–90) for FRCs with adequate elongation (based on the finite number of ion gyro-radii in the separatrix radius).

Stability of the imploding liner during launch and plasma compression also has a long history of effort with both success and surprise. A basic difficulty is Rayleigh-Taylor instability and its magnetic version. Use of axial current through the outer surface of the liner creates an azimuthal magnetic field, the pressure of which accelerates the liner. Such acceleration is equivalent to gravity pointing from the high mass-density liner material toward the low (zero) density fluid represented by the magnetic field, so the amplitudes of initial perturbations of the outer surface will grow exponentially with time. Experiments with large-radius plasma liners (c. 1963) initiated the axial discharge in gas along the inner surface of a very smooth, cylindrical glass surface, which provided very small initial amplitudes. The implosion of the cylindrical plasma discharge therefore exhibited only minor perturbations. Similarly, the implosion of solid-density aluminium liners that had been machined with super-precision at LANL were successfully imploded (c. 2000) at 16 MA on the Shiva Star capacitor bank at AFRL (Kirtland AFB, NM). Subsequent experiments, however, on the Atlas bank at LANL (c. 2001), using the same precision liner 'cassette' (with a slight change in liner thickness for the higher current of 20 MA) were violently unstable, with perturbations rapidly distorting the initially smooth, inner surface of the liner.

The amplitude of perturbations on the inner surface of a liner implosion with any given mode number can grow simply to conserve mass as the surface radius decreases. Such 'secular' growth, which is not Rayleigh-Taylor instability, is worse for spherical vs cylindrical implosions, and furthermore becomes relatively more significant as it is compared to smaller radii during implosion. This places great importance on the quality of the implosion at earlier times, not merely in terms of variations in the radial position of the surface, but also variations in the liner momentum distribution.

Deceleration of a liquid liner surface in the last factor of two of plasma target diameter would be Rayleigh-Taylor unstable, providing a severe 'budget' for the allowable amplitudes of perturbations before deceleration starts. Of course, if the liner does not decelerate, Rayleigh-Taylor instability does not occur. The compression can still increase the plasma temperature, but the efficiency of utilization of liner kinetic energy will be poor and much higher nuclear gains would be required. The ability to recapture energy from the plasma target and make direct use of alpha particle work also is largely eliminated along with the opportunity to reduce the circulating power fraction.

Rotational stabilization of the inner surface of the liner and replacement of the free outer surface of the liquid by continual contact with free-pistons driven pneumatically (c.1977), can provide completely stable energy exchange with the plasma target, but only works with cylindrical implosions (for which the centrifugal term, v^2/r is present in the momentum equation to reverse the direction of the effective gravity). Axial compression would still be subject to Rayleigh-Taylor instability, but there is more space (and therefore a larger 'budget') available near the ends of a cylindrical plasma target. For an ideal FRC, axial compression is occurring due to self-contraction by magnetic forces. As the FRC radius r decreases, so does its length as $r^{0.4}$, so the elongation for stability improves with compression. Thus, cylindrical liner compression of a basically cylindrical plasma target is favoured over spherical implosion schemes.

To summarise, plasma must be stable during compression: Elongated FRC may work, but care is needed in the preparation of the initial state (e.g., temperature, azimuthal speed).

Liner perturbations can grow and penetrate the plasma: A very high-quality inner surface (position/speed) is needed or growth just by convergence will be too great; scaling as 1/r (cylindrical), 1/r2 (spherical). Rayleigh-Taylor growth can be avoided by rotation, but only for cylindrical implosions; 'polar' regions still unstable in spherical case.

3. COST

The sketch (Fig. 1) of cost vs plasma density was created for conditions of constant peak temperature and a nuclear gain Q = 1 relative to peak plasma energy. The cost of ITER, which is designed for Q = 5, was decreased accordingly from the presently estimated value of 20 B$. The log-log plot ameliorates the crudity of the modelling across so many technologies. For the so-called 'low-cost' fusion schemes (e.g., ALPHA projects), operation near fields of about a hundred tesla is indicated. In some schemes, however, the peak field near an inner conductor is much higher than the average field, so severe damage of the conductor surface at a hundred tesla would restrict the average field to lower values. Such restriction may then diminish the advantage of the scheme over conventional approaches that might employ super-conductors at 20–25 T. In this case, other advantages may persist, such as the use of strong adiabatic compression (radial ratio > 10:1) to attain fusion temperatures instead of the more complex techniques of neutral-beam and microwave heating (e.g., ICRH).

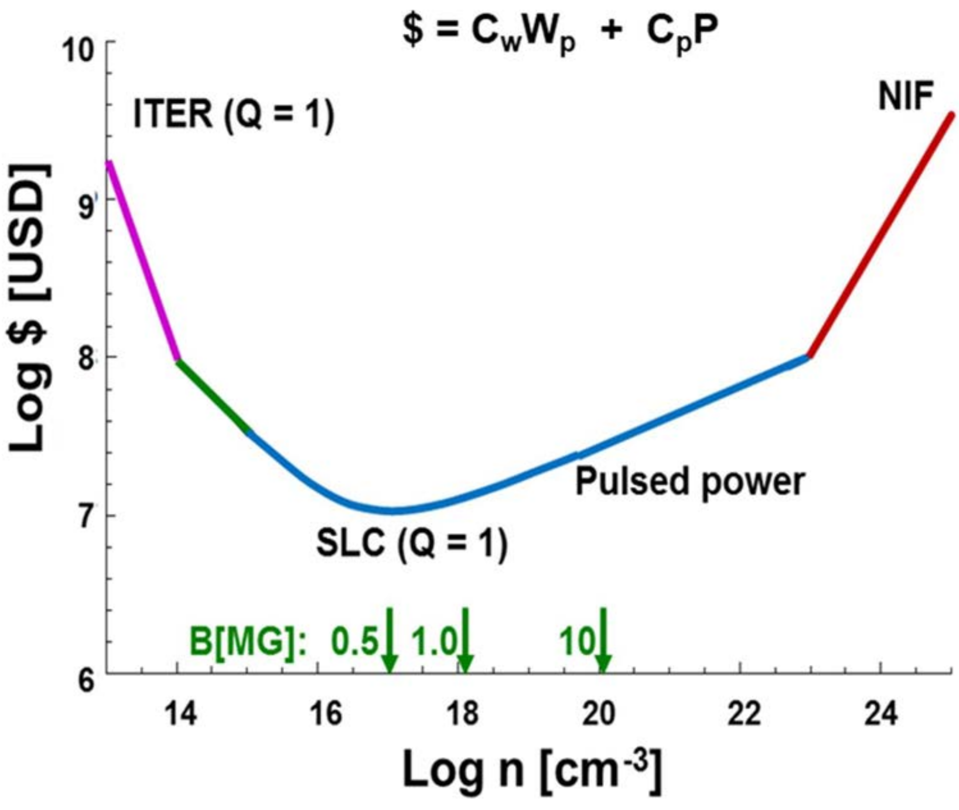

FIG. 1. Sketch of cost vs plasma density estimated across many technologies [1].

For inertial confinement schemes (MIF or ICF), simple scaling indicates that the characteristic size is proportional to the desired nuclear gain. The energy-related cost therefore increases as Q^3. Techniques that can retrieve energy from the plasma target, including work that may be done by trapped alpha-particles, demand less power circulated back after the thermo-electric generators, thereby reducing the necessary value of Q. Most schemes suffer from Rayleigh-Taylor instability or other issues and cannot capture energy efficiently with the plasma target after peak compression, so Q >>20. Rotational stabilization may accomplish this energy capture (but only for cylindrical implosions), reducing the needed gain to about Q = 6–7.

Concern with the total plasma energy required by a scheme also occurs less directly in terms of the cost for building and maintaining the pulsed power systems needed for the initial plasma production. While pneumatic techniques may supply the basic energy for liner implosion and adiabatic compression of the plasma, even an initial plasma energy of only a few percent of final energy can represent a costly burden because of the relatively low energy-density of capacitive energy storage (~10 kJ/m^3 vs ~85 MJ/m^3 pneumatically) and the large number of switches and connections required to handle high voltages and currents. The diameter of the 'cassette' for z-pinch liners, for example, scales as the total current required. At 60 MA (compared to the 10–20 MA used on the Shiva Star or Atlas banks, c. 2000), the diameter of the precision element that must be replaced each shot is about a metre. Damage (e.g., electrode and insulator erosion) in plasma switches and sources can require frequent maintenance, adding to the cost of electricity. Solid-state switching can avoid the problems of spark-gaps but must be operated in multi-element arrays to achieve the necessary low inductance and high power.

As a result, the challenge toward achieving low-cost fusion in this area is the significant improvement by reversible implosion (size/cost ~Q3) and strong adiabatic compression to reduce plasma source energy.

4. NEUTRONS

Damage to the several electrical systems of the fusion power plant can also result from the neutron fluence associated with operation using D-T. At 20 MeV/reaction, an electrical output of 100 MW(e) corresponds to 1.25 $x10^{20}$ n/s, largely independent of the fusion scheme. For plastic insulation used in high-voltage pulsed power systems, the damage threshold is about 10^{15} n/cm^2. Simple stand-off (< 100's meters) is quite inadequate to prevent the fusion system from killing itself in short times of operation (< weeks). Other insulator material (e.g., cyanate ester/epoxy, MgO) can increase the damage threshold by a few orders of magnitude, but merely offer a few years of operation, not 30–40. Instead, it is necessary to interpose shielding material between the plasma and the components of concern. Penetrations for access by neutral-particle beams, electromagnetic power, or high-speed plasma flows can defeat such shielding, unless some sort of convoluted channels are employed. This apparently is the approach for particle beams that are not neutralized until after they have been guided around obstructions that shield the accelerators. A similar scheme might protect other concepts, if the electromagnetic power is delivered to a plasma dynamic load after flowing around an obstructed channel in vacuum; (this has not yet been proposed, however, by advocates of such concepts.)

Production of tritium to sustain the D-T fusion power plant is closely related to the blanket design for neutron shielding. Thick blankets (> 1m) of homogeneous material in liquid form (e.g., Pb-Li) may be attractive solutions. Extraction of tritium from such liquid at output temperatures > 800 C can be relatively straightforward and not represent the major problem with tritium handling in terms of size and cost. Instead, safeguarding of tritium and its compounds in the basic production and reclamation associated with the pre- and post-shot plasma may be the principal issue. One can readily imagine tritium collecting almost everywhere, posing concerns, at least, for planned maintenance operations, let alone disruptions due to faults or accidents. Presumably, such concerns would affect licensing procedures.

Therefore, the challenge is that high-energy neutron fluence could kill reactor quickly unless very, very substantial (>> 104) shielding is provided.

Unless each of these challenges is successfully met, at least conceptually, it is unlikely that the investment will accomplish an economically viable fusion power plant. In some schemes, there may be actual data to establish the case for a concept. There may also be reasonably detailed and quantitative designs. In other schemes, however, it can be clear at very early stages that a concept may suffer intrinsically from problems that cannot be overcome, even with reasonable ingenuity. Sufficient due diligence may discern issues with various concepts, but the nature of most schemes can preclude proper considerations by non-experts. Some guidance may therefore be useful.

REFERENCES

[1] TURCHI, P.J., FRESE, S.D., FRESE, M.H., Stabilized liner compressor for low-cost controlled fusion at megagauss field levels, *IEEE Trans. on Plasma Science* 45 (2017) 10 2800.

ENABLING TECHNOLOGIES FOR FUSION POWER – A PERSPECTIVE FROM BERKELEY LAB

T. SCHENKEL
Group Leader Ion Beam Technology
Lawrence Berkeley National Laboratory, Berkeley, U.S.

1. INTRODUCTION

The development of fusion power concepts can benefit from enabling technologies, such as ion beams for plasma heating and fusion materials development. This section briefly reports on the development of ion accelerators based on micro-electromechanical systems (MEMS) and discusses requirements for plasma heating and fusion materials development.

A series of fusion power concepts currently being considered or developed can benefit from the development of emerging technologies, such as novel high temperature superconducting magnets and ion accelerators that can deliver more ions at lower cost [1–6]. Ion beams with ion energies in the 1 MeV range and currents of tens of Amperes can be used to form neutral deuterium beams for plasma heating of magnetic confinement devices, such as Tokamaks [7]. Magnetized target fusion approaches aim at confining plasmas for microseconds and ion beams might support plasma liner formation and compression complementing, e. g., plasma sources that can deliver high-mass particle pulses [8]. In inertial fusion approaches with heavy ion beams, GeV heavy ion pulses of nanosecond duration have been proposed as drivers for target heating to fusion conditions [9]. Table 1 lists the (order of magnitude) requirements on ion beam energy, peak current and pulse duration to deliver megajoules of driver energy for plasma heating in these three very different fusion concepts.

TABLE 1: ION BEAM REQUIREMENTS FOR FUSION POWER CONCEPTS

Fusion concept	Ion energy	Ion current	Pulse length	References
Magnetic confinement	20 keV to 1 MeV	10's of A	>1 s	[7]
Magnetized target fusion	20 keV to 1 MeV	10^6 A	microseconds	[8]
Heavy ion fusion	1 GeV	10^5 A	nanoseconds	[9]

Most current ion accelerators deliver ions in single beams. A concept of multi-beam ion accelerators was proposed by Maschke et al. and then compared to the performance of single beam RF linacs [10]. Dividing the total beam current into an array of smaller beams was shown to enable higher integrated beam currents in a more compact setup. The research team at the Lawrence Berkeley National

Laboratory have adapted this original MEQALAC (multiple electrostatic quadrupole accelerator) concept and the team are now forming ion beams in arrays using MEMS techniques (micro-electro-mechanical systems). This paper reports the status of this approach in relation to emerging fusion power concepts.

2. MEMS BASED RF LINAC DEVELOPMENT

The concept of a MEMS based radiofrequency (RF) driven linear accelerator (linac) was developed to address the question of ion accelerator technology that can deliver ion beams with high peak power for plasma heating at low enough cost to support the development of fusion power concepts with economic viability. Clearly, many problems have to be solved in order to reach this important goal, and low-cost ion beam drivers are one enabling technology. The approach that the research team at the Lawrence Berkeley National Laboratory took was to use MEMS based fabrication techniques to structure low cost wafers made of printed circuit board and silicon to form RF-acceleration modules and electrostatic quadrupoles (ESQ) as ion focusing elements in arrays. In our first prototype, the team designed and built an array of 3x3 beams with ~1 mm^2 beam apertures. Ions were extracted from a filament driven multi-cusp ion source and injected into the accelerator structure. A matching section formed from a lattice of ESQs matched the ion beam envelope from the ion source into the accelerator lattice. The latter consisted of RF accelerator units, formed from a stack of four wafers, alternating with ESQs for re-focusing. Ions were accelerated using RF high voltages generated with a compact RF amplifier operating in the 13 MHz range. The RF amplifier was mounted in a vacuum near the accelerator boards [6]. Figure 1 shows a photo of a prototype multi-beam ion accelerator based on stacks of wafers formed by MEMS.

MEMS fabrication was conducted at Cornell University in the laboratory of Prof. Amit Lal, while ion beam calculations and measurements were conducted at Lawrence Berkeley National Laboratory. To date, the team have accelerated ions by RF high voltages of 2.6 keV per acceleration gap, leading to a gradient of about 0.3 MV/m. This gradient is very modest compared to conventional RF accelerator technology with high Q cavities. Ion currents have been in the 0.1 mA range. Our MEMS based MEQALAC is massively scalable in both ion current and kinetic energy. Ion currents can be scaled by adding more beams. The team estimate that at least 15x15 beams on a 10 cm diameter wafer can be packed. Already in our first prototype, the effective current density matched that of high current linacs due to the small form factor of our multi-beam array compared to cavities in RFQs radio-frequency quadrupoles. RFQs are a proven technology that delivers ion beams with a high reliability and our approach is still far from that level of engineering development and maturity. Ion energies can be scaled by adding more acceleration modules. The team estimates that the RF amplifier technology can be improved to reach over 10 kV per gap with a gradient >1 MV/m. With ions extracted from an ion source with current density of ~100 mA/cm^2, the team estimates that amperes of beam current can be delivered with beam arrays packed densely on 15 cm diameter wafer modules. Clearly, many challenges remain, including demonstration of reliable operation at high beam power for extended times, as well as adaptation to specific requirements for plasma heating. For Tokamak heating, the use of multi-beam RF accelerators might have significant benefits for the integration of D- beams with neutralizers due to the absence of high voltages (>100 kV in current designs [7]). For short pulses in magnetized target fusion and heavy ion fusion, very high peak currents are required, e. g. through drift compression, where 200-fold longitudinal beam compression was recently demonstrated at the NDCX-II (Neutralized Drift Compression Experiment) at Berkeley Lab [11].

In parallel to plasma heating, ions have long been used for fusion materials testing and development of radiation hard materials. Ions can mimic the displacement damage effects of neutrons or also to drive neutron production. Here, advances in low cost, high power accelerators (e. g. with ion currents >>1 mA for multi-MeV protons and heavy ions) can replace older accelerators (which have a larger footprint and deliver much lower currents, typically <1 mA for multi-MeV protons and heavy ions) leading to much faster, lower cost fusion materials development.

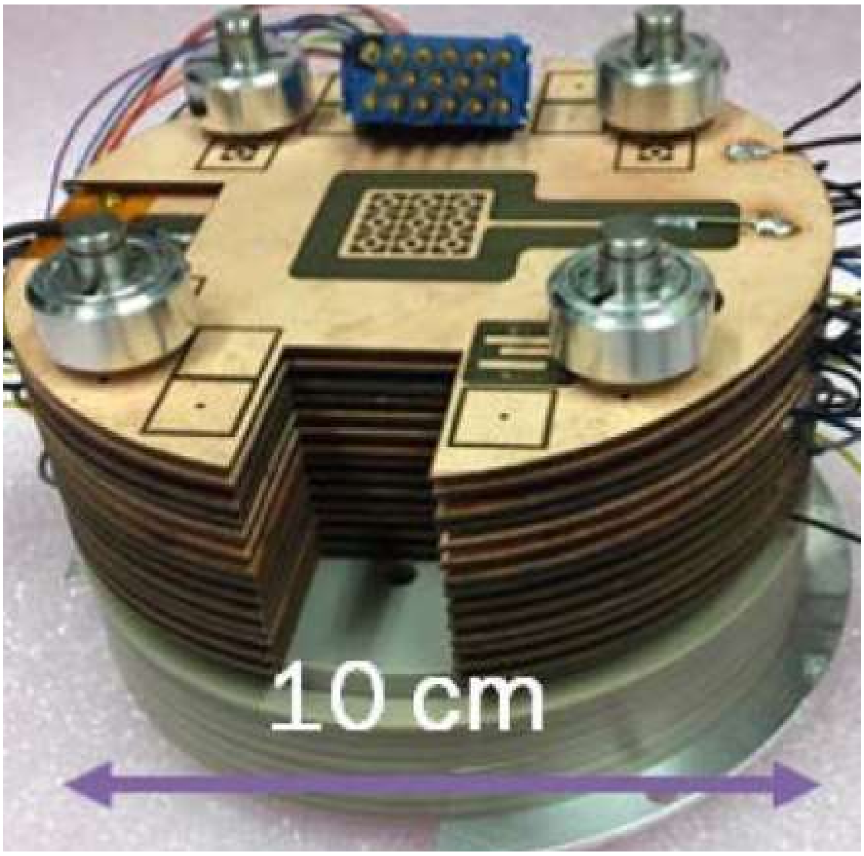

FIG. 1. Photo of a MEMS based multi-beam RF linac.

2. CONCLUSIONS

Ion beams are an enabling technology for a series of fusion power concepts. The research team at Lawrence Berkeley National Laboratory reports on the development of a low-cost multi-beam RF linac technology based on stacks of wafers that the team structured using MEMS techniques. While early in its development, proof-of-concept demonstrations show promise for massive scaling of ion beam power to deliver ion beams for fusion plasma heating.

ACKNOWLEDGEMENTS

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REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Santa Fe, Conference on Fusion Enterprises (2018),
https://nucleus.iaea.org/sites/fusionportal/Pages/Enterprises/2018/General-Info.aspx

[2] WANG, X. R., A Viable Dipole Magnet Concept with REBCO CORC (R) Wires and Further Development Needs for High-Field Magnet Applications, Supercond. Sci. Technol. **31**, 045007 (2018).

[3] SEIDL, P. A., Demonstration of a Compact Linear Accelerator (2018),
https://arxiv.org/abs/1802.00173

[4] PERSAUD, A., A compact linear accelerator based on a scalable microelectromechanical-system RF-structure, Rev. Sci. Instr. **88**, 063304 (2017)

[5] SEIDL, P. A., Multi-Beam RF Accelerators for Ion Implantation (2018),
https://arxiv.org/abs/1809.08525

[6] VINAYAKUMAR, K. B., Electrostatic Quadrupole Array for Multiple Ion Beam Manipulation (2018),
https://arxiv.org/abs/1802.02622

[7] HEMSWORTH, R. S., Overview of the Design of the ITER Heating Neutral Beam Injectors, J. Physics **19** 9 025005 (2017).

[8] HSU, S. C., Spherically Imploding Plasma Liners as a Standoff Driver for Magnetoinertial Fusion, IEEE Trans. Plasma Sci. 40 1287 (2012)

[9] BANGERTER, R. O., FALTENS A., SEIDL, P. A., Accelerators for Inertial Fusion Energy Production, Reviews of Accelerator Science and Technology **06** (2013) 85–116.

[10] URBANUS, W. H., Comparison of two types of low-β RF linacs: MEQALAC and RFQ, Nucl. Instr. Meth. A **290** (1990).

[11] SEIDL, P. A., Irradiation of materials with short, intense ion pulses at NDCX-II, Laser and Particle Beams **35** (2017) 373.

ABBREVIATIONS

ARPA-E	advanced research projects agency-energy
BOP	balance of plant
CAS	cost account structure
CPM	critical path method
CT	compact toroid
DCLL	dual coolant Pb-Li (blanket)
D&D	decontamination and decommissioning
DER	design electrical rating, net electrical power output
DOE	department of energy
EDC	escalation during construction
FDP	fusion demonstration plant
FOAK	first of a kind
FRC	field-reversed configuration
FCR	fixed charge rate
FPC	fusion power core
FPY	full power year
GDT	gas dynamic trap
GF	general fusion
HEDP	high energy density physics
IAEA	international atomic energy agency
ICF	inertial confinement fusion
ICT	information, communications and technology
IDC	interest during construction
IEC	inertial electrostatic confinement
IFE	inertial fusion energy
LACE	levelized avoided cost of electricity
LANL	los alamos national laboratory
LBNL	lawrence berkeley national laboratory
LCOE	levelized cost of electricity
LLE	laboratory for laser energetics (university of rochester)
LLNL	lawrence livermore national laboratory
LOP	life of plant
MCF	magnetic confinement fusion
MFE	magnetic fusion energy
MIF	magneto-inertial fusion
MPD	mass power density (kWe/tonne)
MTF	magnetized target fusion
NBI	neutral beam injection

NOAK	n_{th} of a kind (e.g., N = 10)
NPP	nuclear power plant
NRC	nuclear regulatory commission
NSSS	nuclear steam supply system
OECD	organisation for economic co-operation and development
O&M	operations and maintenance
POP	proof of principle
PNM	public service company of new mexico
R&D	research and development
SCR	scheduled component replacement
SMR	small modular reactor
SNL	sandia national laboratories
ST	spherical tokamak
TBR	tritium breeding ratio
TCC	total capital cost
TDC	total direct cost
TRL	technical readiness level
TSTA	tritium systems test assembly
VC	venture capital
WDR	waste disposal rating
WACC	Weighted Average Cost of Capital

ANNEX I: WORKSHOP PROGRAMME COMMITTEE

Sehila M. Gonzalez de Vicente	IAEA Scientific Secretary and chair of market session
Simon Woodruff	Chair, host
Ronald L. Miller	Co-Chair, host
Eric Ingersoll	Chair of commercialization session
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Thomas Weber	Chair of technologies session

ANNEX II: LIST OF PARTICIPANTS

Anderson, J.	University of Wisconsin, Madison, Wisconsin, USA
Barnes, D.	Tri-Alpha Energy, California, USA
Boyden, J.	Private Investor
Brunner, D	Commonwealth Fusion Systems Cambridge, Massachusetts, USA
Campbell, M.	University of Rochester Rochester, New York, USA
El-Guebaly, L.	University of Wisconsin Madison, Wisconsin, USA
Fallgren, T.	PNM, Albuquerque, New Mexico, USA
Gonzalez de Vicente, S. M.	International Atomic Energy Agency Vienna, Austria
Goodman, G.	ex-Du Pont Wilmington, Delaware, USA
Handley, M.	Strong Atomics San Francisco, California, USA
Hollis, K.	LANL New Mexico, USA
Holland, L.	General Atomics San Diego, California, USA
Hotchkiss, J.	Pegasus Fusion Strategies Concord, Massachusetts, USA
Hsu, S.	LANL New Mexico, USA
Hynes, V.	LANL New Mexico, USA
Ingersoll, E.	Lucid Strategy, California, USA
Johansson, L.	Element 8, Vienna, Austria

Kessel, C.	Princeton Plasma Physics Laboratory Princeton New Jersey, USA
Knapp, D.	Medical University of South Carolina Charleston, South Carolina, USA
Kowalczyk, J.	Southern Company Atlanta, Georgia, USA
Larochelle, P.	Breakthrough Energy Ventures Kirkland, Washington, USA
Miller, M.	Stellar Energy Foundation Princeton, New Jersey, USA
Miller, R.	Decysive Systems Santa Fe, New Mexico, USA
Minsheng, L.	ENN Energy Langfang, China
Plant, D.	General Fusion Burnaby, Canada
Renter, S.	Commonwealth Fusion Systems Cambridge, Massachusetts, USA
Roma, A.	Hogan Lovells London, UK
Schenkel, T.	Lawrence Berkeley National Laboratory Berkeley, California, USA
Sorbom, B.	Commonwealth Fusion Systems Cambridge, Massachusetts, USA
Thio, F.	Hyperjet Fusion Chantilly, Virginia, USA
Turchi, P.	Compact Fusion Systems Santa Fe, New Mexico, USA
Umstattd, R.	US DOE ARPA-E Washington D. C., USA
Wade, M.	General Atomics Burnaby, Canada

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