Commercialising Fusion Energy

How small businesses are transforming big science

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In memory of Stephen N P Smith

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Chapter 1

Introduction

William J Nuttall, Satoshi Konishi, Shutaro Takeda and David Webbe-Wood

1.1 Background

Nuclear fusion, the energy that makes the Sun shine, is regarded by many as the ultimate energy supply for humankind [1], and its promise of clean, safe, and virtually unlimited energy has driven global research and development for the last several decades. During this period, fusion research has sometimes met with criticism that the progress is too slow, or perhaps, stagnated. Today, however, there are indications that something is changing, the tide has turned. One can see that fusion energy makes headlines almost every day on major news outlets like Forbes[1] and Bloomberg[2]. The Economist, which ten years ago, observed 'Viable nuclear fusion has been only 30 years away since the idea was first mooted in the 1950s' [2] now reports with greater optimism: 'There is, then, no shortage of ideas about how a practical fusion reactor might be built…. Everyone talks a good story about this.' [3] This reinvigorated optimism was partly brought in by relatively new players in the fusion community: start-up companies.

Historically, fusion research has been the domain of large public institutions. These mainstream efforts seek to bring fusion to fruition as a source of energy and have been led initially by national governments and lately by international collaborations. The current international effort is focused on the ITER program—an international project with 36 nations participating directly or indirectly[3] at a cost of over €20 billion [4]. It is expected that the first deuterium-tritium operations of ITER will occur sometime after 2035.

[1] For example, 'Fusion Energy: Who Has The Courage To Take It To Market?' by Wal van Lierop on August 21, 2019.

[2] For example, 'Nuclear Fusion Could Rescue the Planet From Climate Catastrophe' by Jon Asmundsson and Will Wade on September 28, 2019.

[3] Members of the European Union are represented in this project via the Union. It is not clear at the time of writing what the position of the United Kingdom will be after Brexit.

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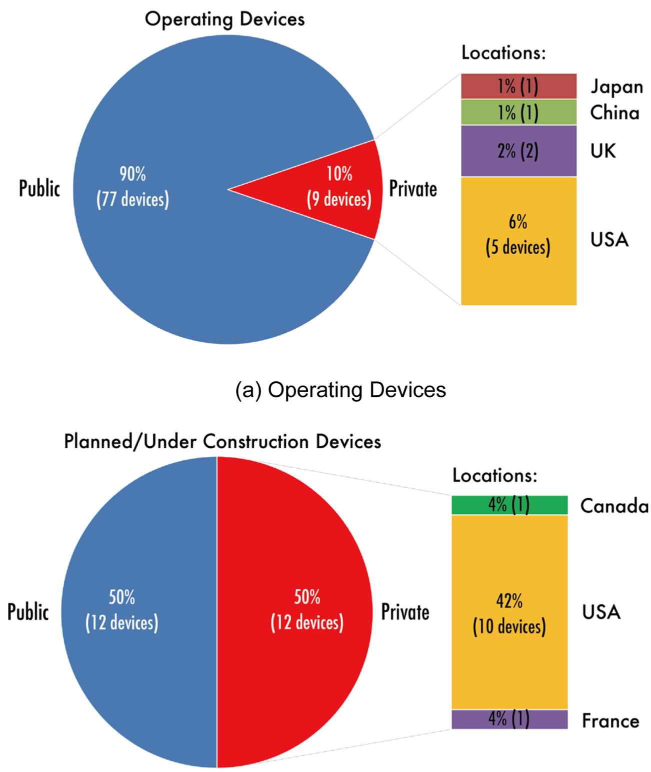
ITER will be followed by a set of DEMOs, an electricity-producing fusion power plant that is the last step to the commercial plants. It is anticipated that construction of DEMO, or set of DEMOs, will commence after 2040 [5, 6]. In this established sequence, the first demonstration fusion power plant would start supplying electricity around 2050 (see chapter 9). The start-up companies are striving to shortcut this path by 20 years using more innovative approaches. Some start-ups report on ambitions to start electricity generation even earlier, perhaps even as early as by 2025 (see chapters 5 and 7).

To illustrate how the landscape is changing in the global fusion community, the authors calculated the percentages of private versus public effort in terms of the number of devices[4] as shown in figure 1.1. This comparison shows that while only 10% of the currently operating fusion devices are owned by the private sector, half of



(a) Operating Devices

(b) Planned or Under Construction Devices

Figure 1.1. Percentages of fusion devices in the world in 2020: public versus private (based on [7]). (a) Operating devices (b) planned or under construction devices.

[4] Based on the IAEA Fusion Device Information System (FusDIS), a directory of fusion experimental facilities worldwide available online on https://nucleus.iaea.org/sites/fusionportal/Pages/FusDIS.aspx.

the planned or under construction fusion devices are already led by private entities. In fact, in the United States, the majority of fusion devices now belong to the private sector.

The rise of private fusion enterprises would have been inconceivable even a decade ago. Fusion research was once looked upon as being a synonym of 'big science'—*large-scale scientific research consisting of projects funded usually by a national government or group of governments*[5]. While it might still be appropriate to assess this global trend cautiously, such enterprises are gaining more and more support from investors. Prominent investors like Jeff Bezos and Bill Gates are among the supporters of this emerging sector. As a result, there are at least 40 private enterprises pursuing faster commercialization of fusion globally, with around $2 billion raised in total as of 2020 (chapter 7). These forward-thinking start-ups are competing to be the first to deliver on the long-overdue promise of virtually unlimited clean energy: they are transforming *big science*.

1.2 What is nuclear fusion?

But what is fusion? At its simplest, nuclear fusion is the application of Einstein's famous equation:

$$E = \Delta mc^2$$

When two light nuclei are fused together to form a heavier nucleus[6] (sometimes releasing other particles), the mass of the resulting nucleus and emitted particles slightly less than that of the two initial nuclei. This 'lost' mass is released as kinetic energy, as illustrated in figure 1.2. This is nuclear fusion.

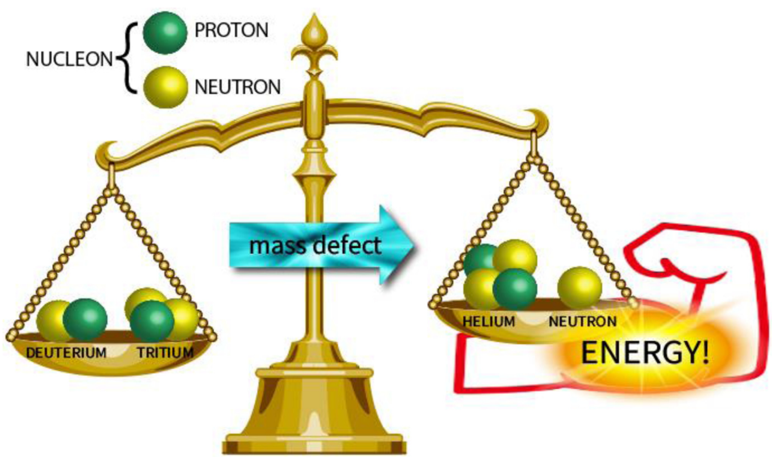


Figure 1.2. Fusion converts tiny amounts of mass into vast amounts of energy. Courtesy of Aya Kuretani.

[5] Marriam-Webster: https://www.merriam-webster.com/dictionary/big%20science
[6] In some cases, more than one nucleus is produced

Nuclear fusion is responsible for the production of energy in stars. At the core of stars, protons react with other protons to form deuterium nuclei[7] (^{2}H) and positrons. The deuterium nuclei can merge to form helium-4 nuclei (^{4}He), or they can interact with other protons to form helium-3 (^{3}He). Two helium-3 nuclei can fuse to form a nucleus of an unstable beryllium isotope (^{6}Be) that breaks apart to give ^{4}He and two protons. The energy released at each step causes stars to shine, including the Sun. As such, fusion can be regarded as the ultimate source of energy: life on earth would not be possible without fusion reaction.

In addition to the fusion processes briefly outlined above, a number of other fusion reactions exist. Examples include (where Q is the energy released in the reaction):

$^{2}\mathrm{H} + {}^{2}\mathrm{H} \rightarrow {}^{3}\mathrm{T} + {}^{1}\mathrm{H}$, $Q = 4.04$ MeV;
$^{2}\mathrm{H} + {}^{2}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \mathrm{n}$, $Q = 3.27$ MeV;
$^{2}\mathrm{H} + {}^{3}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \mathrm{n}$, $Q = 17.6$ MeV;
$^{1}\mathrm{H} + {}^{11}\mathrm{B} \rightarrow 3({}^{4}\mathrm{He})$; $Q = 8.68$ MeV;
$^{1}\mathrm{H} + {}^{6}\mathrm{Li} \rightarrow {}^{3}\mathrm{He} + {}^{4}\mathrm{He}$; $Q = 4.023$ MeV;
$^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2\mathrm{p}$; $Q = 12.9$ MeV;
$^{3}\mathrm{He} + {}^{6}\mathrm{Li} \rightarrow {}^{1}\mathrm{H} + 2({}^{4}\mathrm{He})$; $Q = 16.88$ MeV;
$^{3}\mathrm{He} + {}^{6}\mathrm{Li} \rightarrow {}^{2}\mathrm{H} + {}^{7}\mathrm{Be}$; $Q = 0.113$ MeV.

The reaction of principal interest to most commercial fusion developers is the deuterium (^{2}H or D)—tritium (^{3}H or T) reaction, as this 'D-T reaction' is regarded as the easiest to achieve [8]. However, a small number of companies, including TAE of the United States[8], are developing concepts based on other reactions (see chapter 7).

Unfortunately, the nuclei carry a positive electrostatic charge and repel each other before they can fuse. For fusion to occur, the plasma containing the fusion fuels must reach the thermal (kinetic) energy required, which requires both the containment and the heating of the plasma.

To use fusion as an energy source, the energy released by fusion reaction must be greater than the energy that is required to induce the reaction. The ratio of the energy output from nuclear fusion reactions in the plasma to the energy supplied to sustain the plasma is known as the fusion energy gain Q_{fus} [8]. $Q_{\mathrm{fus}} = 1$ is referred to as the break-even condition.

Q_{fus} is closely linked to the plasma density n, the plasma temperature T, and the efficiency of contained thermal energy (confinement time τ_{E}). The combination of these three factors $nT\tau_{\mathrm{E}}$ is known as the Lawson criterion, which is used to evaluate the performance of a fusion reactor. A higher performance for this combination of factors can be achieved in different ways, and this is where the ingenuities of the scientists are put to the real test. In magnetic confinement approaches, magnetic fields are applied to increase the confinement time, whereas in inertial confinement

[7] The ^{2}H species is often referred to a deuterium and the symbol D used. Similarly, the ^{3}H nuclei are referred to as tritium with the symbol T.
[8] Formerly known as Tri Alpha Energy

approaches, use is made of lasers or other techniques to compress targets to provide the high densities required. Both approaches are described in chapter 2.

When realized, fusion energy may have significant advantages over other low carbon energy sources: it does not suffer from the issues of variability that affect wind and solar; compared to nuclear fission, the issues of radioactive waste are much reduced. In addition, there are no risks of runaway accident; and above all, since the deuterium fuel can be extracted from seawater and lithium remains an abundant metal[9], fusion energy has almost unlimited fuel resources on earth—it is estimated that fusion could sustain humanity for the next one billion years [9]. That said, fusion is not without resource sustainability concerns, for example as regards helium as discussed in Chapter 11, section 11.7.1.

1.3 Purpose and structure of this book

This book aims to give readers, with or without a background in nuclear science or engineering, an appreciation of where the state of the art is and the future prospects for commercialization. This book is, in part, a follow up of a workshop organized jointly by the Open University (UK) and Kyoto University (Japan) under the auspices of the Anglo Japanese JUNO network (JUNO: A Network for Japan-UK Nuclear Opportunities) at Hughes Hall, Cambridge University in June 2019.

The book is organized into four sections. The first section, *Private Fusion Primer*, gives a brief overview of private fusion. In chapter 2, Dr Richard Pearson from Kyoto Fusioneering Ltd and Dr Shutaro Takeda from Kyushu University introduce the basics of fusion reactor engineering to the readers. Next, Dr Shutaro Takeda and Dr Sehila M Gozalez de Vicente from the International Atomic Energy Agency (IAEA) provide considerations for the commercialization of the technology in chapter 3. Subsequently, in chapter 4, Mr David Webbe-Wood summarizes possible funding schemes for future commercial fusion power plants.

The second section, *Progress in the Private Sector*, showcases the latest progress of the private fusion start-ups. First, Dr Melanie Windridge from Tokamak Energy Ltd. presents an argument for their approach, progress, and plans in chapter 5. Subsequently, in chapter 6, Professor Yoshitaka Mori from The Graduate School for the Creation of New Photonics Industries shares with the readers their public–private CANDY laser fusion concept. Chapter 7 provides an overview of the approaches of other private fusion companies by Dr Richard Pearson and Professor William Nuttall.

The third section, *Public Sector Push to Commercialization*, outlines the public sector's efforts toward commercialization. Professor Howard Wilson and his colleagues from the UK Atomic Energy Authority describes the UK's STEP programme in chapter 8. Next, in chapter 9, Professor Takuya Goto from National Institute for Fusion Science (NIFS) presents a technical overview of the Japanese public strategy for magnetically confined fusion energy.

[9] That is, notwithstanding the pressures placed on its supply by the burgeoning battery manufacturing industry.

The fourth section, *Challenges and Future Opportunities*, discusses the challenges and future opportunities of private fusion. In chapter 10, Dr Richard Pearson gives general observations on the challenges private fusion companies have to overcome. Professor William Nuttall provides the historical background of the private fusion and extrapolates the story to future opportunities in chapter 11. Professor Satoshi Konishi and Dr Shutaro Takeda then expand the idea to utilize nuclear fusion as a means of decarbonization in chapter 12. Finally, the book ends with the conclusions and thoughts of the editors.

Only time will tell when and how humanity realizes commercial fusion energy. It seems that the second decade of the 21st century represents the key moment that will determine the future of a concept that has been imagined for many decades. As the chapters that follow will discuss, the public sector efforts thus far have been essential in making the private sector initiatives possible. Whether the leadership in the field passes from the public to the private sector, or whether the relationship will be closer and more collaborative than that, will be something that we will see emerge in the coming years. What seems clear, however, is that fusion faces its best opportunity in many decades to find a bold and ambitious way ahead.

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