Barriers to Fusion Commercialization:

Understanding Innovation

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Outline

1. **What is innovation?**
2. **Fusion innovation**
   a) Innovation in government-led (public) fusion programmes
   b) The paradigm shift to privately funded fusion start-ups
3. **Commercial drivers:** key to successful innovation
4. **Technology barriers to fusion:** the commercialization perspective
5. **Towards commercial fusion:** a new approach to tackling the challenges ahead
6. **Summary**

The definition of innovation:

"THE EXPLOITATION OF INVENTION"

Reference: Pearson et al., 2020

What is Innovation?

- Innovation is often used erroneously to describe *an* "advanced" or *a* "promising" ***invention***.
- For an invention to constitute ***innovation***, it must have a useful ***application***, i.e. the invention must provide some kind of usefulness.
- ***Technological innovation*** refers to an invention that provides a new or improved technical use.
- ***Inventions*** – *even remarkable ones* – which constitute technological innovation, do not automatically result in ***commercial success*** in and of themselves.

Until now, fusion has predominantly been focused on ***technological innovation*** *and not on* ***commercialisation***

References: Kline & Rosenberg, 1986; Park, 2005; Bonvillian & Weiss, 2015

Innovation is a process

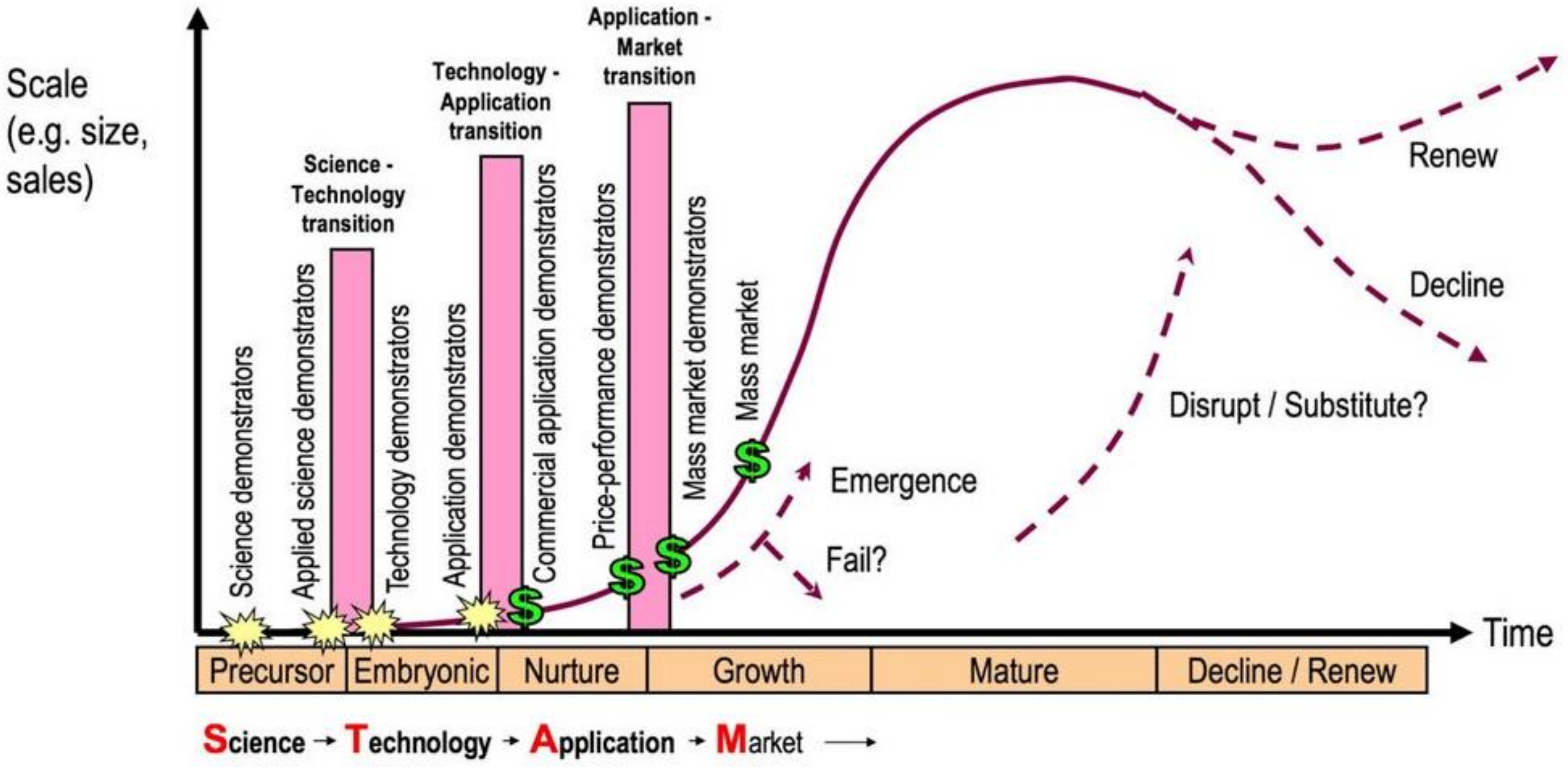


Image: Phaal et al., 2011

Fusion & the Linear Model of Innovation

Historically, advanced technology missions – endeavors with a **high degree of technical risk, but with potentially high (often societal) reward** – have been developed on a linear model. Such missions require **significant investment** (money and time) and are thus, typically, shouldered by **governments.** Key examples are *the development of **nuclear fission**, the **Apollo moon landings**, and **the internet***.

The linear model places scientific understanding (**technological innovation**) as the first goal.

Science → Technology → Application (product) → Market

The linear model perpetuates a "***technology push***" approach in which technology is developed in an "R&D vacuum". The mechanisms to deploy the technology in the market are not explored until later – i.e. until **after** a promising invention is realised/discovered.

The majority of fusion development has been via **publicly funded programmes** at **government laboratories** (and international collaboration – currently **ITER**) on a **linear innovation model**.

References: Fitzgerald et al., 2011; Bonvillian & Weiss, 2015; Pearson et al., 2020; Godin, 2006

A Paradigm Shift: Private Fusion Start-ups

Funded by **private capital**, fusion start-ups are pursuing reactor concepts that may **accelerate development**, **increase** the **performance**, and/or **reduce the cost** of commercial fusion.

Pursuing an agile innovation model, they are upending the existing **fusion innovation paradigm**.

Agile Fusion Start-ups:
Have **limited resources**, which forces them to proceed with risk (without full technical know-how or understanding). In fact, they view **technical risk (and failure)** as **acceptable** and **necessary** for innovation.
Develop on **rapid, iterative cycles** in which they **build-test-learn**, often through those failures. These cycles:
➢ Necessitate **simple design** (*complex designs cost time and money*). ➢ Avoid the development of technology not related to mission (i.e. they **reduce waste**). ➢ **No late changes**, as changes create delays or cost overruns. ➢ Promote the generation of **new ideas**, which are integrated into the next iteration (to **speed up** the **testing cycle**).
Are focused on **returning investment to their backers**, and explore potential **routes to market**, angling technology development towards those **commercialisation pathways**.
Have a workforce with a high degree of **autonomy**, **led by entrepreneurs** and **guided by a vision** to commercialize fusion.

References: Pearson et al., 2020; McCurdy, 2001; Rigby et al., 2016; Ries, 2011

Towards commercial fusion

Going beyond technological innovation

Technology Barriers to Commercial Fusion

Despite an inherent focus on commercialisation – *like public programmes* – start-ups are mostly focused on **developing core systems and demonstrating technical viability of their inventions**.

Whilst these core systems vary across reactor concepts, typically, they include:

- The **reactor chamber/vessel**
- **Magnets** (MCF), **lasers** (ICF), or **drivers** (MIF)
- **Fuelling systems** (as well as heating & current drive)
- **Exhaust systems** (for both heat and fuel)
- **Diagnostics**

Several **next-step engineering and technology challenges** – which *are not fundamental to demonstrate proof of principle, but crucial for commercialisation* – have not been centre stage.

These challenges are here distilled into the following categories:

- **Materials**
- **Tritium Breeding Blankets & Tritium Handling**
- **Waste & Remote Handling**
- **Balance of Plant Systems**

Commercial Drivers: Key to Innovation Success

The technical challenges (and drivers) – *required for successful technological innovation* – are well understood.

However, fusion developers must consider what is needed to take **technology to market**, i.e. the **commercial drivers**, defined here as: **anything that impacts the development of technology into a product for market**.

For successful **commercialisation**, fusion developers must consider **both** technical and market drivers.

This requires a shift from **technology and R&D management** to **innovation management**.

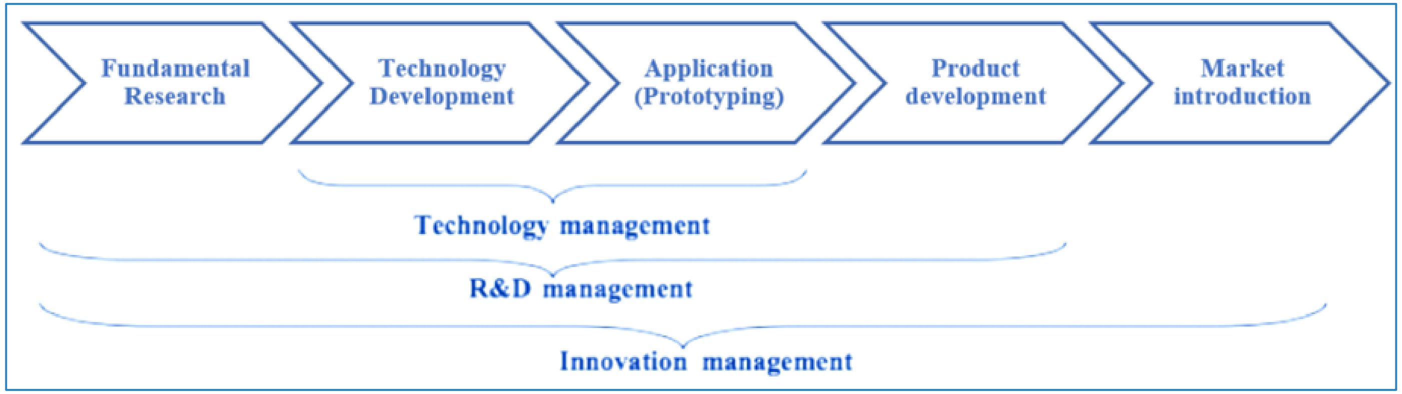


Image:
Brem & Voigt, 2009;
Pearson, 2020

Also see: Marechal, 2019

Commercial Drivers for Fusion (PESTLE Analysis)

Political

- Taxes (or tax relief)
- Government policy (ever-changing)
- Regulation
- Geopolitics
- Limits on international trade (incl. trade wars)
- Conflict & war

Economic

- Movement of capital
- Alternative applications/ markets
- Competition
- Economic growth
- Cost of borrowing (interest rates)
- Investment
- Labour supply

Social

- Social & cultural change
- Advertising
- Media (and PR)
- Health
- Education
- Consumer attitudes
- Workforce demographics (aging workforce, skills shortages etc.)

Technological

- Artificial intelligence
- Other computing advances, e.g. modelling & simulation
- Smart materials
- Nanotechnology
- Automation
- Internet of Things

Legal

- Domestic and international law
- Employment law
- Nuclear regulation
- Health & safety
- Copyright law, IP law & patenting
- Codes & standards

Environmental

- Climate change
- Carbon tax
- Siting
- Pollution and emissions
- Local ecology
- Natural disasters
- Sustainable mining & supply chains
- Competition (e.g. renewables)

Image: adapted from Pearson, PhD Thesis, 2020

Barriers to Fusion

Understanding the challenges from the commercialization perspective

Fusion Materials

Technical description:

Fusion materials must withstand very *high temperatures* and *neutron loads*.

Materials issues overlap heavily with – *and often underpin* – the challenges associated with *all* reactor systems, from plasma-facing components (*e.g. the first wall*) and breeding blankets, to magnets (or lasers/drivers).

Fusion materials is thus a multifaceted challenge. It also directly impacts the technological and commercial viability of fusion as an energy source.

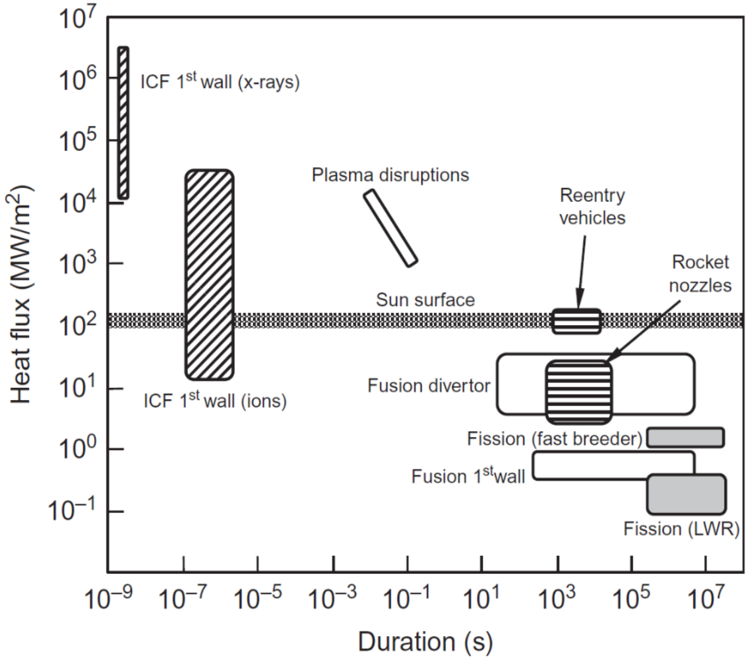


Image: Perlado & Sanz, 1993

Potential commercial challenges:

- Regarding the lifecycle of, for example, mining isotopes for advanced materials:
  - Do **supply chains** exist?
  - What is the **environmental** impact?
  - What is the **carbon** footprint?
  - Are there limits on **international trade**?
- What will it **cost** to **qualify** a **new material** for operation in a fusion reactor?
- Will the material be able to withstand **accident scenario** conditions? (relates to the *safety case and regulation*)

Tritium Breeding & Tritium Handling

Technical description:

Commercial D-T reactors require tritium breeding blankets, which perform two key functions:

1. To **breed tritium** (not available as a natural resource) through interaction of neutrons with lithium.
2. To capture and transfer the **kinetic energy** of fusion neutrons as **heat**.

Tritium is a **radioactive** isotope. All tritium in the reactor, including from the blanket, must be accounted for and managed by tritium handling systems.

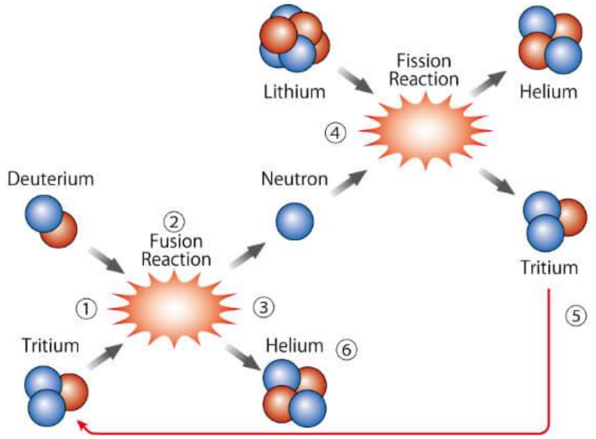


Image: kyotofusioneering.com

Potential commercial challenges:

- **Blanket lifetime** (due to material damage) dictates **reactor downtime** for *replacement/maintenance* and drives **cost**.
- The **enrichment of lithium-6** – a critical isotope for breeding – is **restricted** (and regulated). Further, **no supply** of lithium-6 **available**.
- Similarly, **beryllium** – a key material in some tritium breeding blanket designs – is **ultra-scarce** and **expensive**.
- **Tritium supply and use** is **regulated**, e.g. max limits for tritium stored on-site, embedded in materials, and for environmental release (tritium handling).

Waste & Remote Handling

Technical description:

Many materials that can withstand the D-T fusion reactor environment (e.g. existing high-temp steels) may **produce radioactive waste**. Unless judiciously chosen, this waste may remain radioactive such that it cannot be disposed of for *decades* or perhaps even *millennia*.

Radioactive waste will be produced in two main forms:

1. Materials that become **activated** through fusion neutrons.
2. Components that become **tritiated** (*contaminated with embedded tritium*).

During reactor operation, **damaged components** (due to, e.g. irradiation or mechanical failure) must be **replaced**. This requires maintenance by **remote handling** (robotic) technology.

Potential commercial challenges:

- Waste from fusion presents a **PR challenge**: do the public know that there will be radioactive waste from "*clean*" fusion?
- **Lead** – required in certain breeding blanket designs – produces **long-lived radioisotopes** (mercury & polonium).
- What are the regulations on **waste storage**, and how much does it **cost**? Will this affect **siting**?
- What is the **cost** of **remote handling** equipment, and the **opportunity cost** of **downtime** for maintenance/replacement?
- Flowing **liquid metal walls** may reduce the quantity of activated materials, but what is the **cost** and are there associated **regulatory constraints**?

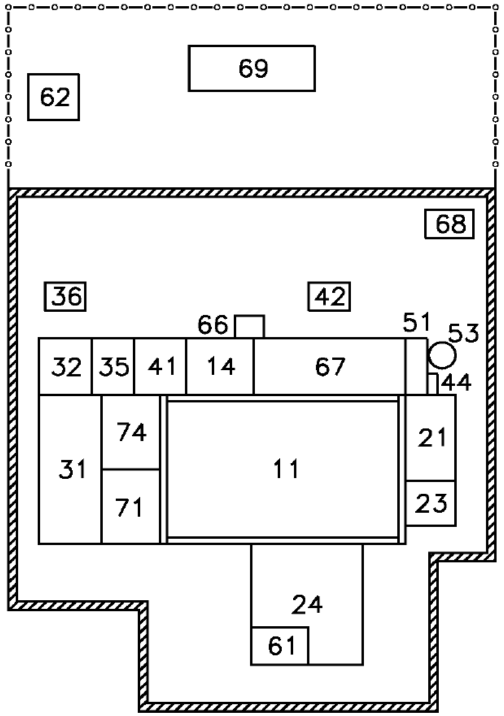
Balance of Plant (BoP) Systems

Technical description:

The Balance of Plant (BoP) refers to **all auxiliary systems** and buildings for the operation of a fusion reactor. They include:

- Energy conversion systems (incl. turbines)
- Electrical power supply
- Radiation monitoring systems
- Cryoplant
- Emergency power
- Containment building
- Control room and administrative buildings

Whilst BoP systems for a fusion power plant have been conceptualised (*based on existing power plants – mainly fission*), there are commercial challenges specific to fusion that haven't yet been fully considered.



KEY BUILDING STRUCTURE PLOT PLAN

Image: Bechtel, 2017

Potential commercial challenges:

- What is the **cost** of the **BoP systems** for a fusion reactor?*
- What are the **safety and security standards**, **codes** and **regulations** that must be followed?
- Are all BoP systems developed and ready to purchase, i.e. is the **supply chain** in place?
- How does pursuing a commercial application such as **hydrogen production** change the requirements for the BoP systems?

**dependent on scale, these could be multiple $B (see Meier et al., 2009)*

A way forward: a new approach to innovation

For private developers to flourish and to commercialize fusion, a **new innovation ecosystem** is required.

Private companies do not have **resources** or **capabilities** – *financial, expertise, equipment* – to go it alone.

Government laboratories and **research institutions** (universities) must move to provide **world-class scientific R&D** and **support** to plug these gaps – in the same way that national laboratories support the development of advanced nuclear fission.

The relationship needs to allow both parties to do what they do best:

- **Private companies** – led by **entrepreneurs** – can focus on **developing technologies** that present the most promise for the **commercialization of fusion**.
- **Government-funded laboratories (and research institutions)** – housing the world's leading **scientists and engineers** – can provide **technical support and expertise** to private fusion developers, i.e. *they can fully focus on technological innovation!*

Summary

- Innovation is the ***exploitation of invention***.
- **Public** and **private** fusion programmes are pursuing **different approaches to innovation**:
  - **Public fusion programmes** mostly follow a **linear model** in which **technological innovation** is the primary focus.
  - **Private fusion programmes** mostly follow an **agile innovation model** in which **commercialization** is the primary focus.
- Several **next-step engineering challenges** – *materials, tritium breeding and handling, waste and remote handling, and Balance of Plant* – present significant hurdles that are **not yet being addressed** substantively by fusion developers.
- Solutions must be developed that are simultaneously **technologically advanced** and **commercially viable** – if **commercialization** is the goal.
- **PESTLE analysis** is a useful tool to characterize **commercial drivers** for fusion – it can support plans to develop technology towards commercialization.
- Public and private fusion entities have different roles in **delivering commercial fusion** – but cohesion is needed!

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