

Path to Market for Compact Modular Fusion Power Cores

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Abstract The benefits of an energy source whose reactants are plentiful and whose products are benign is hard to measure, but at no time in history has this energy source been more needed. Nuclear fusion continues to promise to be this energy source. However, the path to market for fusion systems is still regularly a matter for long-term (20 + year) plans. This white paper is intended to stimulate discussion of faster commercialization paths, distilling guidance from investors, utilities, and the wider energy research community (including from ARPA-E). There is great interest in a small modular fusion system that can be developed quickly and inexpensively. A simple model shows how compact modular fusion can produce a low cost development path by optimizing traditional systems that burn deuterium and tritium, operating not only at high magnetic field strength, but also by omitting some

components that allow for the core to become more compact and easier to maintain. The dominant hurdles to the development of low cost, practical fusion systems are discussed, primarily in terms of the constraints placed on the cost of development stages in the private sector. The main finding presented here is that the bridge from DOE Office of Science to the energy market can come at the Proof of Principle development stage, providing the concept is sufficiently compact and inexpensive that its development allows for a normal technology commercialization path.

Keywords Commercial fusion systems · Compact fusion power cores · Spheromak · Compact torus · Deuterium-tritium fusion

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Introduction

While the day of fusion systems designed for net power production is dawning, follow-on devices are being proposed that require large capital outlays which inhibits both their development and commercial deployment. The Department of Energy (DOE) Office of Science supports fundamental research which could potentially lead to the future deployment of commercial systems, and while this research is comprehensive, it is also primarily directed at the most developed and usually the largest systems. DOE Office of Science programs will therefore have an inherent time-line that is longer than industry typically tolerates, and a preference towards systems carrying the lowest scientific risk. Within the commercial sector, time-lines for demonstrating critical milestones are short and resources scarce, requiring a very different approach in the design of commercial systems.

This white paper summarizes a commercialization plan for compact modular fusion power cores that is constrained by private sector development. Following a standard development path for new energy technology, it becomes apparent that high-risk concepts could be developed by private companies with equity investment from venture capitalists (VCs), followed by sale to a capable multi-industry company for subsequent pilot plant development. The DOE Office of Science Proof of Principle development stage can serve as a natural bridge to market. There are constraints on the size, cost, and timeline for concepts that can make it across this bridge, set by the limit and financial risk tolerance of equity investors. While some investors can tolerate risk, the onus remains on the scientist to demonstrate not only a full knowledge of the risks and means for mitigating them, but also the constraints placed on technology development.

The thesis presented here is that low-risk fusion systems burning deuterium and tritium can be optimized for development and market entry by making them compact and modular. A costing model is used to compare costs of compact fusion power cores with leading lowest-risk designs. The comprehensive reactor studies of the past all point to the economy of scale, particularly Galambos et al. [1], Sheffield et al. [2] and Perkins [3], which is still true for tokamaks (Najmabadi et al. [4]). However, by omission of the toroidal field coil, central solenoid and inner blanket sections a much lower-cost fusion power core for the same power is obtained (shown also by Krakowski [5], and recently by Woodruff et al. [6]), and the opportunity for making the system even more compact at the expense of the \$/W ratio exists. Here the argument is presented that this system will still be competitive with larger systems that take advantage of economy of scale and integrated costs to a demonstration reactor (DEMO) would be small; fitting into standard technology commercialization paths.

This whitepaper is therefore structured as follows: in the section titled “[World Energy Market and the Challenge to Meet it](#)”, the context of the international energy market is discussed, underlining the need for an accelerated program. In the section titled “[Context of US DOE Office of Fusion Energy Sciences](#)” the development stages in the DOE fusion program are translated into Technical Readiness Levels discussed in other agencies (such as ARPA-E). It becomes clear that some of these development stages are compatible with the constraints of private development both in time and cost, discussed in the section titled “[Private Sector Development](#)”. In the section titled “[Characteristics of Systems that Could Fit Into a Standard Development Path](#)” the characteristics of compact fusion systems that could be a good candidate for private fusion development are outlined, with reference to a costing model. Other issues relating to fusion development are

presented in the section titled “[A Commercialization Plan for Compact Modular Systems](#)”.

World Energy Market and the Challenge to Meet it

The world energy market is currently a bit over 500 Quads (1E15 BTUs) and is expected to grow to almost 740 Quads by 2035. Historically, the US consumes about 25% of the entire global energy production. However, by 2035, the US percentage is expected to decrease to 15% and China is expected to consume 25% and India 5%. The developing world countries energy consumption equaled the developed world countries in 2007 and will double it by 2035. The majority of this energy is produced through heat generated by the combustion of fossil fuels. Table 1 provides an approximate breakdown of the current global source of energy (in Quads) and the projected values for 2035.

Table 1 clearly shows the challenge of reducing the global carbon footprint. Currently, less than 16% of energy is of the low carbon emission variety. The low carbon portion is predicted to increase to slightly over 20% in 2035. Increasing concerns over global climate change result from the 35% increase in the annual consumption of fossil fuels. In order to meet the seemingly insoluble dilemma of meeting the increased energy demands of a more populous planet and reduce the emissions of greenhouse gases (GHGs), disciplined regime needs to be followed, by: (1) using energy more efficiently, (2) reducing the cost and increase the deployment of low emission energy technologies (renewables and nuclear energy) and (3) developing new, innovative energy sources, including clean coal. Most of the liquid hydrocarbon fuels cited in the table are used as transportation fuels, including gasoline, diesel and jet fuel. One means to reduce dependency on fossil liquids is to convert the global fleets of cars and small trucks to plugged hybrid or straight electric technology. While this will require a major change out of capital stock, it must be done to increase energy supply security and manage climate change. About 37% of all manmade CO₂ emissions are attributable to the production, refining and consumption of transportation fuels. The transition to plugged hybrid and electric drive technologies will further increase the demand for electricity. Producing the

Table 1 Global energy sources projected to 2035 (units in Quads)

Year	Liquid hydrocarbons	Coal	Natural gas	Renewables	Uranium
2010	180	135	120	55	25
2035	220	205	160	100	50

electricity with conventional coal-fired power plants makes no sense, if we are truly serious about climate change.

What really is needed is a non-emitting source of energy that is not dependent on wind or sunshine or rainfall as a resource, but does not produce the long-term radioactive waste concerns as do conventional nuclear power plants. A very promising candidate energy source (amongst a needed portfolio of options) is nuclear fusion, the process that generates the solar energy we use for heating and electricity generation. Fusion uses water as a source of its fuel, so sustainability is not an issue. Fusion is a difficult and elusive technology. Historically, governments have pursued very expensive, very large fusion programs that almost preclude conventional paths to commercialization. A more desirable fusion technology is one that produces energy (and electricity) in the quantities that most utilities can accommodate and at costs that are comparable with competitive low-emission electric generation technologies. Such a fusion technology would be the ‘ultimate renewable energy’ resource. This is exactly what a number of small, entrepreneurial fusion companies, including Woodruff Scientific Inc., are pursuing.

Context of US DOE Office of Fusion Energy Sciences

In the US, fusion energy development is sponsored only by the DOE Office of Fusion Energy Sciences (OFES). In the OFES, fusion energy research is supported by a process of answering calls for proposals to address high priority programmatic issues usually defined in planning activities lead by the field, or from direction from expert panels such as the Fusion Energy Sciences Advisory Committee (FESAC).

Funds are also made available in the Small Business Innovation Research (SBIR) program. Its solicitation contains technical topics in such research areas as: Energy Production (Fossil Energy, Nuclear Energy, Renewable Energy, and Fusion Energy), Energy Use (in buildings, vehicles, and industry), Fundamental Energy Sciences (Materials Sciences, Life Sciences, Environmental Sciences, and Computational Sciences, Nuclear and High Energy Physics) Environmental Management and Nuclear Nonproliferation. The SBIR programs at DOE have three distinct phases with the third phase being a commercialization phase.

The Advanced Research Projects Agency for Energy (ARPA-E) is a new organization within the DOE, created specifically to foster research and development of transformational energy-related technologies. ARPA-E operates within a framework of nine “technology readiness levels” (TRL). (See Table 2 below). ARPA-E is expected to operate mainly within the range of TRL-2 through TRL-7.

Once it has been determined through R&D that the apparent barriers can be overcome and how they may be overcome, then additional investment from many other sources causes a new field of technology options to open up. In 2008, the Advanced Research Projects Agency for Energy (ARPA-E) opened a solicitation that also included a category for fusion energy systems.

Fusion Energy Development Stages (CE, POP, PE, BPX, DEMO)

In the DOE OFES, there are several well-defined stages of fusion development. These are the Concept Exploration (CE), Proof of Principle (POP), Performance Extension (PE), Burning Plasma Experiment (BPX) and Demo. Table 2 summarizes the levels of development (from [7]). An example of a POP device is MST at the University of Wisconsin, and an example of a PE device is the DIII-D tokamak at General Atomics. Two experiments aim to produce scientific break-even in a controlled manner in the coming decade: the National Ignition Facility (NIF) at LLNL in California, and the International Thermonuclear Experimental Reactor (ITER), which is currently under construction in Cadarache in France. Both are considered BPX (other possible BPXs that have been taken through design iterations are FIRE and IGNITOR (which is currently under construction)).

Of primary interest here are the higher risk, and less developed, CE and POP level concepts, since the development costs for the tokamak are already largely known for later development stages: Table 2 shows the tokamak development stage cost estimates from the IPPA Report [8]. Also according to this community consensus report, a CE experiment “is typically at <\$5 M/year and involves the investigation of basic characteristics. “Concepts” should be interpreted to include experiments designed to test important basic fusion-relevant science “concepts” as well as potential reactor “concepts”. Experiments cover a smaller range of plasma parameters (e.g., at <1 keV) and have fewer controls and diagnostics than a PoP level experiment. However, sufficient diagnostics are required to carry out high quality, scientific investigations.” POP experiment “is the lowest cost program (\$5 M–\$30 M/year) to develop an integrated understanding of the basic science of a concept. Well-diagnosed and controlled experiments are large enough to cover a fairly wide range of plasma parameters, with temperatures of a few kilo-electron volts, and some dimensionless parameters in the power plant range.”

It is concepts at the CE and POP level that could potentially give much lower-cost development paths in the private sector. The characteristics of these systems are discussed below.

Table 2 TRL and OFES usual definitions of technology maturity

TRL	Description	Equiv. stage	Constr. cost*	Op. Cost*
1	Scientific research begins with a systematic study directed toward greater knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications or products in mind. The knowledge or understanding will later be translated into applied R&D	Pre-concept exploration	200 k/yr	
2	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions	Concept exploration	1 M	750 k/yr
3	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate predictions of separate elements of the technology	Concept exploration	10 M	10 M/yr
4	Basic technological components are integrated to establish that they will work together. This is relatively “low fidelity” compared to the eventual system. Examples include integration of hardware in the lab	Concept exploration	10 M	10 M/yr
5	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.	Proof of principle	10–100 M	10–50 M/yr
6	Representative model or prototype system, which is well beyond that of RL-5, is tested in a relevant environment. This represents a major step up in a technology’s demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment	Performance extension	100–500 M	50–100 M/yr
7	This represents a major step up from RL-6. It requires the demonstration of an actual system prototype in an operational environment	Burning plasma experiment	0.5–3 Bn	100–300 M/yr
8	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this RL-8 represents the end of true system development	Demo	0.5–3 Bn	100–300 M/yr
9	The technology is applied and operated in its final form and under real life conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last “bug fixing” aspects of system development	Pilot plant		

* Costs are estimated for the tokamak development stages, published in the IPPA Report [7]. Compact modular systems would have lower development costs at stages beyond the POP

Private Sector Development

The Need for Private Sector Development

The government is not mandated to develop commercially viable products—this is the role of private industry. The need for private sector development is therefore given by the need for commercial deployment of an energy technology. As soon as a technology developed by the government matures to the point of selling aspects of it (arguably any aspect that could return a profit), then the technology is ready for private sector development. However, the government continues to assist some technologies towards commercial viability. In Fig. 1, derived from a presentation given by Dr Majumdar, Director of ARPA-E to the Committee on Science and Technology of the U.S. House of Representatives [9], the various organizations are mapped out to show how technologies can make a path towards commercialization. The shading in ARPA-E and the Applied Offices is omitted here to emphasize that there is a gap for fusion development—ARPA-E has not

supported fusion, recent solicitations are not encouraging of fusion systems, and there is no Applied Office for systems that burn deuterium and tritium as fuel. Next we consider in detail the funding possibilities for taking the technology to market.

Constraints on any Commercialization Plan

The most practical constraint on technology development is *cost*, and to meet the cost of development, investment of some sort is usually required. It is often possible to bring a new technology to market without requiring any investment (by growing a company organically), however, investment can expedite the commercial deployment. Table 3 shows the typical deal size for various kinds of investors. Usually the investment is obtained to reach a significant technical milestone that makes an obvious increase in the company value. The constraints are discussed in reverse order: latest stages before market (or biggest dollar amount) first.

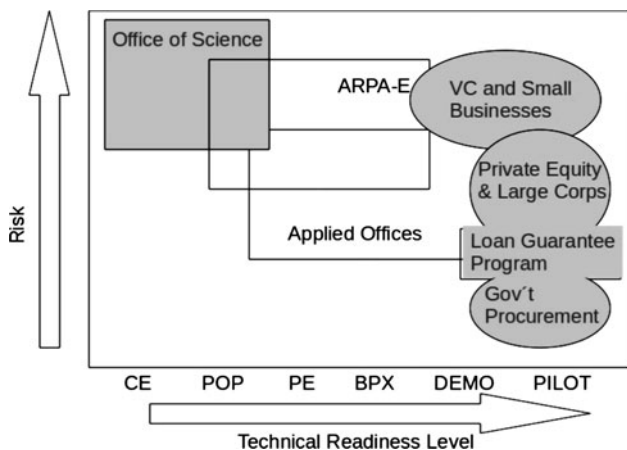


Fig. 1 Technology Readiness Levels versus Risk and the map of various organizations in the commercialization path of a new energy technology (cf Majumdar 2010). Note that there is a gap for fusion development—neither ARPA-E nor the Applied Offices support fusion development

Table 3 Typical investments for each type of investor

To \$1 M	Angel investors	Pre-CE
To \$150 M	VC investors	Proof of principle
To \$500 M	Large corporations, institutional	Pilot
To \$10 Bn	Loan guarantee program	Commercialization

DOE Loan guarantee program The mission of the DOE Loan Program Office (LPO) is to accelerate the domestic commercial deployment of innovative and advanced clean energy technologies at a scale sufficient to contribute meaningfully to the achievement of our national clean energy objectives: including job creation; reducing dependency on foreign oil; improving our environmental legacy; and enhancing American competitiveness.

LPO executes this mission by guaranteeing loans to eligible clean energy projects (i.e., agreeing to repay the borrower’s debt obligation in the event of a default), and by providing direct loans to eligible manufacturers of advanced technology vehicles and components. Loans can vary in amount from a tens of millions to ten billion dollars.

Institutional investors are organizations which pool large sums of money and invest those sums in securities, real property and other investment assets. They can also include operating companies which decide to invest its profits to some degree in these types of assets. Types of typical investors include banks, insurance companies, retirement or pension funds, hedge funds, investment advisors and mutual funds. Their role in the economy is to act as highly specialized investors on behalf of others. For instance, an ordinary person will have a pension from his employer. The employer gives that person’s pension

contributions to a fund. The fund will buy shares in a company, or some other financial product. Funds are useful because they will hold a broad portfolio of investments in many companies. This spreads risk, so if one company fails, it will be only a small part of the whole fund’s investment. Currently there are precedents for institutional investment in a fusion company.

Venture capital (VC) is financial capital provided to early-stage, high-potential, growth startup companies. The venture capital fund makes money by owning equity in the companies it invests in, which usually have a novel technology or business model in high technology industries, such as biotechnology, IT, software, etc. The typical venture capital investment occurs after the seed funding round as growth funding round (also referred as Series A round) in the interest of generating a return through an eventual realization event, such as an IPO or trade sale of the company.

Presently there are several examples of VC investments in fusion companies. From discussions with VCs, it appears that their first concern is determining if the power source competes economically with other sources—the argument for investment seems straightforward: if the source can be shown to provide a cost of electricity (COE) that is half that of competing sources then it becomes an attractive investment. Another parameter discussed is the cost per Watt of the constructed system, where \$1/Watt is a rule-of-thumb cost to better (which takes no account of plant life-time, operating costs, availability, safety and maintainability, etc.). Discerning VCs are generally very wary, and need to see a future stage development partner involved at the earliest stage.

Angel investors typically invest their own funds, unlike VCs, who manage the money of others. The actual entity that provides the funding may be a trust, business, limited liability company, investment fund, etc. Angel-funded startup companies are less likely to fail than companies that rely on other forms of initial financing. Angel investments vary from a few thousand to millions of dollars, and investors can become involved in the operation of the company. Initial involvement of angels, or high net worth individuals, has been important for some fusion companies to obtain subsequent VC investment. Angels though will very typically not see an exit in a time-frame for their investments for a fusion technology, unless the deal involves other aspects, such as tax breaks. For angels, the emphasis is near term, and so there might be investment interest in a particular item of technology that could be spun out from the company which would require clear definition at an early stage.

In summary, the cost constraints on development to market have been presented for the standard angel, VC, institutional investor and government loan program. Next, the system that could be developing in this context is discussed.

Characteristics of Systems that Could Fit into a Standard Development Path

The cost model for the fusion power core was developed previously [6], and is included in full in the Appendix. The cost of the core is determined from the mass, applying a cost factor of \$1 M/tonne and mass factor of 10 tonnes per m^3 . Knowing the volume of the chamber, coils, shield and blanket from geometrical approximations, it is possible to determine the cost. Power is determined by assuming that the first wall will tolerate a neutron flux of 5 MW/m^2 in steady state, and so knowing the surface area, the power is specified. Power to cost ratio and power to mass ratio (or mass power density, MPD) are then further derived trivially.

Figure 2 shows the three configurations considered in the costing model: tokamak, compact torus (CT), and the ‘ultra-compact torus’ (UCT). The systems all burn deuterium and tritium as fuel, so included are the usual blanket and shield, and poloidal field coils to keep the plasma isolated from the wall. For the model, a 1 m blanket thickness is used.

Running the scripted code, the parameters in Table 4 are obtained. The output power of the CT and tokamak are set in the model to be equal by appropriate choice of first wall radius (to give $\sim 200 \text{ MWe}$), and the UCT power is approximately an order less (at $\sim 30 \text{ MWe}$). While the plasmas in the CT and tokamak have similar volumes, the UCT’s is smaller by over factor of ten, however, the volume of the CT power core differs from that of the tokamak by a factor of ~ 2 , and the UCT by a factor of ~ 10 . The

MPD of the CT is 160 kWe/tonne and that of the tokamak is 65 kWe/tonne (agreeing roughly with the previous work of Hagenson and Krakowski [10]), whereas the MPD of the UCT is intermediate. The total cost for the power core of the tokamak is estimated at \$3 Bn and that of the CT at \$1.5 Bn, the difference being given by the omission of the TF and OH coils and central blanket (for calibration, ITER coils account for half of the cost of the power core). However, the cost of the UCT core is an order of magnitude lower—at under \$100 M. Finally, the cost per unit power for the CT is lowest, but the UCT and tokamak are nearly the same, expected due to the reduction in power for the UCT system.

In order to accurately define the COE for these systems (or even the \$/W value), it would be necessary to complete a comprehensive systems study that includes ancillary systems, and the components that make up the Balance of Plant (including hot cells, remote handling). However, from the basic arguments presented here, and from work previously performed by others, from the engineering considerations alone the projected COE will not much differ from that of conventional tokamak designs, i.e. competitive with other existing systems, with a COE of 60–80 mill/kWh. However, the integrated cost to a pilot could be less than a hundredth of that of the larger systems (considering the sum of all of the development stages, which e.g. for ITER alone is $\sim \$20\text{Bn}$). A cost of $\sim \$500\text{M}$ for a Demo stage that entails also remote handling, massive shielding, hot cells and waste disposal, seems reasonable, although will require further detailed analysis.

Fig. 2 Tokamaks, compact tori and ultra compact tori

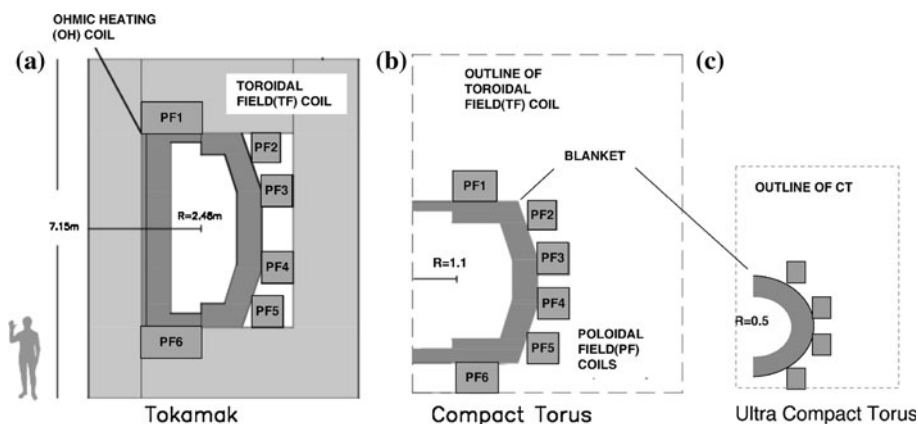


Table 4 Parameters obtained from costing model

Plasma volume (m^3)	Machine volume (m^3)	Power (MWe)	MPD (kWe/tonne)	Cost (\$M)	Cost/power (\$/We)
28.2	318.2	205.9	64.7	3,182.2	15.5
69.5	126.3	204.3	161.7	1,263.1	6.2
4.2	34	31.4	92.3	31.4	10.8

A Commercialization Plan for Compact Modular Systems

Compact modular power cores could be developed aggressively in three phases over a 9–15 year period, following the development roadmap depicted in Fig. 3. Each phase includes a series of technological, business, marketing, and funding goals over a 3–5 year time-frame. The first phase should achieve a Proof of Principle within a 3–5 year horizon. The second phase will develop a commercially viable prototype over an additional 3–5 years. The third phase will lead to initial commercial application to compete in the utility market, finalizing the production and marketing arrangements needed to fully commercialize the product. These phases are discussed as follows.

The first phase of development will consist of completing buildup and access to scientific, industry, and business resources along with the technological goal of achieving a proof of concept within a 3–5 year horizon with a total budget of <\$50 M. Scientific and business advisory boards need to be established to assist in this effort. While pursuing Proof of Principle technology, partnering with other research efforts will be needed. Intellectual property rights associated with the technology will be defined and appropriate protective action taken. Marketing efforts will focus on identifying initial customer base and defining system capabilities and features needed to best suit customer needs. Initial customer commitments will be sought and potentially those commitments will be used as security for equity funding.

The second phase of development will focus on creating a commercially viable prototype facility over 3–5 years after completion of the first phase with a total anticipated

budget of <\$500 M million. During this phase the technical goal will be to integrate the power core with other components and systems to construct energy generating system and successfully demonstrate its operating capabilities. Business goals will include establishing initial customer and supplier contacts and operating/partnering agreements. Marketing efforts will focus on continued public education on fusion energy and coordination of customer requirements.

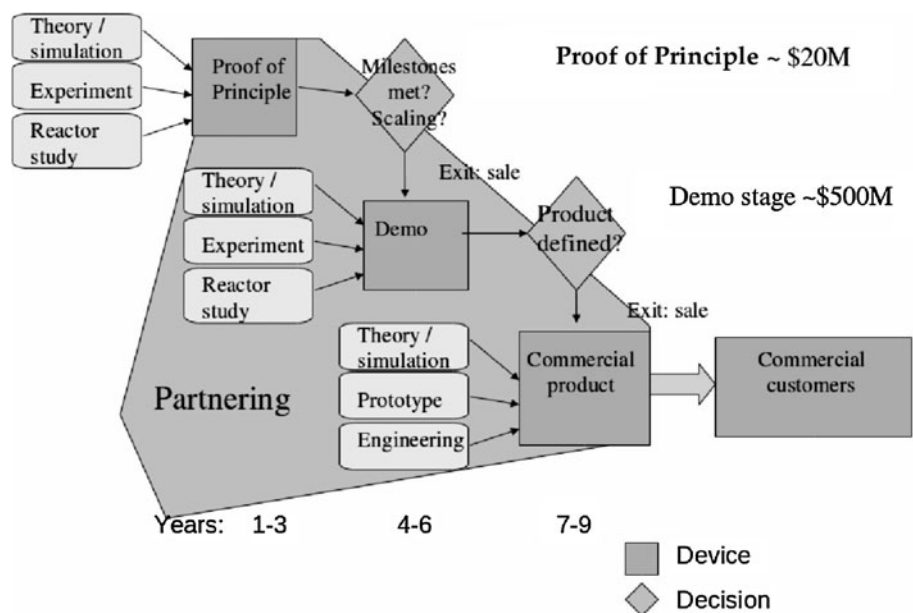
During *the third phase of development* the goal is to complete the commercialization of the technology over a period of 3–5 years. Technical goals are to design a base production model and initial customer options and to initiate work toward subsequent products and markets. After demonstrating commercial viability in initial markets, arrangements with production partners will be pursued, allowing the licensing of the technology and focus on technical support, product improvement and marketing.

Lessons from Compact Modular Nuclear Fission Systems

The status of fission Small Modular Reactors (SMRs) is summarized by the Nuclear Energy Institute (NEI) [11]. A preliminary regulatory perspective from the viewpoint of a member of the US Nuclear Regulatory Commission (NRC). Certain generic features of the SMR, including factory fabrication and possible reduction of the construction lead time may well carry over to fusion applications.

For fusion, there is limited information on tokamak power-plant designs in the regime below 1 GWe(net), but there is a sense that dis-economies of scale are discouraging. Compact toroids (CTs) may provide some

Fig. 3 Development roadmap for private sector fusion systems



advantages in this regime, resulting from higher plasma beta values, certain configurational differences in the fusion power core, and possible maintenance advantages leading to better availability. The working hypothesis that CTs are particularly well suited to take advantage of the SMR regime remains to be demonstrated. Additionally, claims that the SMR regime as a commercial end-product would allow a faster or less expensive development path or easier market penetration would have to be fortified.

The power-generation playing field embraces issues of public acceptance, regulatory simplicity (safety and waste disposal), and economic competitiveness. A CT fusion system tuned to the SMR regime may prove to be advantageous.

Lessons from Mainline Systems

Integrated into the commercialization path are concepts being developed as part of the international fusion program. For example, diagnostics, remote handling, blanket and tritium systems are being investigated as part of the international fusion program, and the database will be available soon after initial operations.

Discussion of Other Issues

Regulatory issues: time and costs To date, the Nuclear Regulatory Commission (NRC), has not: exercised regulatory jurisdiction over fusion devices, developed regulations or actively participated in the licensing and/or oversight of construction or operation of existing fusion research facilities, and regulated exports of fusion reactors and equipment specially designed for use in fusion devices. In July of 2009, the NRC Commission did vote to assert jurisdiction over fusion energy devices but have decided to wait before further evaluating the technical or addressing the legal issues associated with their regulation of fusion devices. Due to the NRC's decision to assert jurisdiction and a lack of previous fusion devices going through the process, time estimates and associated licenses are based on current nuclear fission device requirements, despite enormous fundamental differences in the nature of the technologies (see for example Holdren [12]).

Risk mitigation in technology development Diversifying portfolio—very much like investment strategy of mutual funds vs single stocks: while each individual 'stock' is risk in and of itself, there's a reduced risk by investment in a broad portfolio. Other factors affecting risk include the development of risk mitigation plans, oversight by scientific experts, and review by a wider scientific community. A standard method in technology development entails a design review procedure, whereby much scientific risk is

taken out of the project at the Concept Design phase, before progressing to an Engineering Design phase (there are many available textbooks on this subject). Feasibility studies may even precede a full Concept Design Review.

Export control There are existing regulations and guidelines that prohibit the export of certain technologies with direct impact on nuclear weapons, and export to a short list of countries is explicitly prohibited. The export controls guidelines also cover dual use technologies, and so it is critical to be aware of what can and cannot be exported beyond the US.

Virtues of ideal fusion systems There are many papers published, almost routinely, on the optimum characteristics of a fusion system. From the 1994 EPRI report 'Criteria for practical fusion power', the commercial power plant top-level requirements are:

1. No public evacuation plan required: total dose <1 rem at site boundary;
2. Generate no radioactive waste greater than Class C;
3. Must not disturb public's day-to-day activities;
4. Must not expose workers to a higher risk than other power plants;
5. Closed tritium fuel cycle;
6. Must provide for operation at partial load conditions (50%);
7. Maintainability of power core;
8. Must operate routinely with less than 0.1 unscheduled shut-down per year, including disruptions;
9. Cost of electricity must be competitive (in 1995 mill kWh): Goal 65 mill kWh, Requirement 80 mill kWh.

Don't underestimate the problem of 14 MeV neutrons Without the production of neutrons, fusion systems would not activate, there would not be need for hot cells, and direct energy convertors could be used to harness power, doing away with costly blankets, reducing shielding, and allowing coils to be even more compact. Novel formation schemes that would otherwise require large distances between burn chamber and formation region could be moved closer. The use of advanced fuels has often been discussed (see e.g. DD [13] and P-B¹¹ [14]), and while specific concepts exist to burn advanced fuels, the general approach taken by international fusion activities is to address deuterium and tritium systems first. This needn't be.

Pulsed systems are not considered here There are various concepts that rely on a batch burn of a target plasma that undergoes a compression, limited by the dwell of the liner. The analysis for this paper pertains only to systems in steady-state, with continuous power loading on the first wall.

Materials development time and cost The argument is currently made that a strong material science program is necessary in order to determine which materials will be

used in a future Demo reactor. The time line for the development of radiation resistant materials for commercial operation and to qualify all components to establish a database on reliability and maintainability could be decadal. This information will be needed for systems of any size, however, compact modular systems require lower capital costs, and so materials could be developed during the commercialization phase, and subsequently by the private sector. An example of this type of development is the internal combustion engine: Diesel wasn't troubled by refractory surface coatings for his piston, his aim was to demonstrate first that the engine system could drive a belt. There are great advantages to starting small, particularly since it is very unlikely that we'll get it right the first time.

Maturity of compact systems: timeline for POP-level devices In the US OFES program, there have only been a handful of Concept Exploration level devices (in comparison with the >100 tokamaks investigated worldwide), so the database on performance is small. Summary reviews are available, however, with published confinement similar to early-stage tokamaks. There could be a wide range of specific technical issues to address at the POP level. For example, the MST device at the University of Wisconsin became a POP-level system in 1999, and a vibrant scientific program continues today.

Discussion

Venture capital could spur on compact modular system development It seems clear that the development path for compact modular concepts meshes well with the private sector—at the early stages of development, CE and POP, it is possible to make progress towards substantial milestones entirely with equity investment. Initial discussions with VCs suggests that there is interest in being more involved, and some already have made investments in compact modular fusion. There are some interesting parallels with the space program, where for a few decades, the government was the dominant contractor and contractee, but since the advent of private space companies, there is a transition to small-scale companies offering performance at considerably reduced costs. A broad portfolio of concepts could be envisaged in the private sector with therefore a possibility of the reduction of risk.

DOE FESP could engage a wider set of concept, particularly compact modular ones A discussion that engages the government would be worthwhile—while the push to make ITER and NIF work is still the primary focus, there ought still be a discussion of other possible routes that consider also compact modular ones.

ARPA-E could help bridge the gap The most natural bridge to the private sector could be through ARPA-E,

although the policy seems to be to adopt concepts that are much closer to commercialization (no fusion concepts were funded by ARPA-E, and new solicitations have not included fusion).

Science of compact modular systems: strong field, high beta Though not dwelled on here, the science of these systems differs markedly in many respects from that of the mainline tokamak systems, in that confinement scaling at small system sizes and strong magnetic fields is not mapped out. However, the proposed use of high field-strength concepts has been considered at length by proponents of the tokamak, and is gaining some acceptance, with for example the decision to build IGNITOR—a high field strength burning plasma device. Other devices such as CIT and LITE also considered the use of strong magnetic fields.

Summary

The present context for fusion concept development has been presented: set primarily by the DOE OFES. The commonly-used development stages have been translated into Technical Readiness Levels. Traditional commercialization paths for new technologies have been outlined: that there is a support gap for developing fusion systems, which however, could be bridged by VC investment at the Proof of Principle stage. It was shown by use of a geometric model that the POP device needs to be compact, otherwise it will not be possible to develop it privately. A costing model showed that more compact systems are inherently less costly to develop than their larger higher power counterparts, and while there is some loss of power per mass, they would still be competitive with larger systems exploiting economies of scale if ganged together. Finally, a commercialization path is presented that is quite standard that entails the development of a concept under OFES sponsorship at the CE level and transfer to the private sector at the Proof of Principle, and fully fits into the context and capabilities of large multi-industry companies.

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Appendix

```

%Matlab code for the comparison of major parameters for the tokamak (tok),
%compact torus (ct), and ultra-compact torus (uct)
. Also runs with Octave.
%

%INPUT PARAMETERS-----

%

P_wn =5;           %Neutron wall loading power [MW/m^2]

d    =1;           %Thickness of blanket [m]

k    =1;           %Cost factor [$M/Tonne]

m    =10;          %Mass factor [Tonne/m^3]

eff  =0.4;         %Efficiency of plant

L_pf =0.25;        %Length of PF coil side [m]

%Tokamak: approximate as a cylinder with axis along magnetic axis

a_tok =0.7;        %Radius of first wall [m]

r_tf  =1.08;       %Radius of inner toroidal field leg [m]

d_sol =0.2;        %Radial thickness of solenoid [m]

L     =2*pi*(a_tok + d + r_tf + d_sol); %Length of first wall

%Compact torus and Ultra compact torus: approximate as a sphere

a_ct  =2.55;       %Radius of 1st wall [m]

a_uct =1;          %Major radius of 1st wall [m]

%OUTPUT PARAMETERS-----

%SURFACE AREA OF 1st WALL, A [m^2]

A_tok  =2*pi*a_tok*L;

A_ct   =4*pi*a_ct^2;

A_uct  =4*pi*a_uct^2;

%POWER, P [MWe]

P_tok  = eff * A_tok*1.25*P_wn;

P_ct   = eff * A_ct*1.25*P_wn;

P_uct  = eff * A_uct*1.25*P_wn;

%VOLUME OF PLASMA [m^3]

V_tok_p =pi*a_tok^2*L;

V_ct_p  =4/3*pi*a_ct^3;

V_uct_p =4/3*pi*a_uct^3;

```

%VOLUME OF BLANKET [m³]

$$V_{\text{tok_b}} = \pi * L * (a_{\text{tok}} + d)^2 - V_{\text{tok_p}};$$

$$V_{\text{ct_b}} = 4/3 * \pi * (a_{\text{ct}} + d)^3 - V_{\text{ct_p}};$$

$$V_{\text{uct_b}} = 4/3 * \pi * (a_{\text{uct}} + d)^3 - V_{\text{uct_p}};$$

%VOLUME OF PF COILS [m³]

$$V_{\text{tok_pf}} = 6 * L_{\text{pf}}^2 * 2 * \pi * (2 * r_{\text{tf}} + d_{\text{sol}} + 2 * d + 2 * a_{\text{tok}});$$

$$V_{\text{ct_pf}} = 6 * L_{\text{pf}}^2 * 2 * \pi * (d + a_{\text{ct}});$$

$$V_{\text{uct_pf}} = 6 * L_{\text{pf}}^2 * 2 * \pi * (d + a_{\text{uct}});$$

%VOLUME OF TF COIL FOR TOKAMAK ONLY [m³]

$$V_{\text{tok_tf}} = 0.5 * (\pi * L * (a_{\text{tok}} + d + r_{\text{tf}})^2 - V_{\text{tok_b}});$$

%VOLUME OF OH SOLENOID FOR TOKAMAK ONLY [m³]

$$V_{\text{tok_oh}} = \pi * ((r_{\text{tf}} + d_{\text{sol}})^2 - r_{\text{tf}}^2) * (2 * a_{\text{tok}} + d + 2 * r_{\text{tf}});$$

%TOTAL VOLUME OF POWER CORE [m³]

$$V_{\text{tok_m}} = V_{\text{tok_b}} + V_{\text{tok_pf}} + V_{\text{tok_tf}} + V_{\text{tok_oh}};$$

$$V_{\text{ct_m}} = V_{\text{ct_b}} + V_{\text{ct_pf}};$$

$$V_{\text{uct_m}} = V_{\text{uct_b}} + V_{\text{uct_pf}};$$

%MASS OF POWER CORE [Tonnes]

$$M_{\text{tok}} = m * V_{\text{tok_m}};$$

$$M_{\text{ct}} = m * V_{\text{ct_m}};$$

$$M_{\text{uct}} = m * V_{\text{uct_m}};$$

%MASS POWER DENSITY, MPD [kWe/Tonne]

$$\text{MPD}_{\text{tok}} = (P_{\text{tok}} * 1000) / M_{\text{tok}};$$

$$\text{MPD}_{\text{ct}} = (P_{\text{ct}} * 1000) / M_{\text{ct}};$$

$$\text{MPD}_{\text{uct}} = (P_{\text{uct}} * 1000) / M_{\text{uct}};$$

%CAPITAL COST [\$M]

$$C_{\text{tok}} = k * M_{\text{tok}};$$

$$C_{\text{ct}} = k * M_{\text{ct}};$$

$$C_{\text{uct}} = k * M_{\text{uct}};$$

%COST PER UNIT POWER [\$/We]

$$\text{CP}_{\text{tok}} = C_{\text{tok}} / P_{\text{tok}};$$

$$\text{CP}_{\text{ct}} = C_{\text{ct}} / P_{\text{ct}};$$

$$\text{CP}_{\text{uct}} = C_{\text{uct}} / P_{\text{uct}};$$

%WRITE OUT PARAMETERS-----

disp('Plasma Volume [m3] Machine Volume [m3] Power [MWe] MPD [kWe/Tonne] Cost [\$M]
Cost/Power [\$W)')

Out = [V_tok_p V_tok_m P_tok MPD_tok C_tok CP_tok; V_ct_p V_ct_m P_ct MPD_ct C_ct CP_ct;

V_uct_p V_uct_m P_uct MPD_uct P_uct CP_uct]

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