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CRITICAL TECHNOLOGY ISSUES AND DEVELOPMENT REQUIREMENTS FOR A FUSION DEVELOPMENT FACILITY

by
J.C. WESLEY AND R.D. STAMBAUGH

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ABSTRACT

Parameters and physics and technology performance attributes of the Fusion Development Facility (FDF), a 13-MA volume neutron source and fusion materials and component testing facility are described and the resulting plasma and nuclear technology development requirements summarized. The programmatic means by which these mostly not-yet-available 'critical technologies' can be realized by 2015 when high-performance FDF operation may first commence are suggested. Given these enabling technologies for initial operation, a 15-year iterative component and material test and development program for taking the final step to 'reactor-qualified' technologies becomes possible.

I. INTRODUCTION

The Fusion Development Facility, a 13-MA DT-burning 'next-step' fusion experiment (Fig. 1), can give the world fusion program a first-of-kind capability for 'reactor-relevant' fusion materials and prototype component testing.[1] This testing capability can complement the physics study and plasma optimization capabilities of lower-fluence DT-burning next-step experiments such as the International Thermonuclear Experimental Reactor (ITER)[2] or the Fusion Ignition Research Experiment (FIRE).[3,4] The FDF can also provide a means to conserve and even modestly increase the 'tritium patrimony' that fusion inherits from the Canadian CANDU fission reactors.[5] Finally, FDF can also provide a high-flux, high-fluence, high-duty-factor neutron source for a fusion-based fission waste transmutation demonstration.[6] Table 1 summarizes FDF design parameters and attributes and projected operation capabilities.

But all of this promise is contingent on having 'near-term' fusion technologies and materials that will allow FDF to operate in a 2015 time period at its anticipated plasma performance levels. Neutron flux and fluence are 'reactor-like', i.e, 5 MW/m^2 and 5 MWa/m^2 per calendar year of operation, so technologies with reactor-like performance

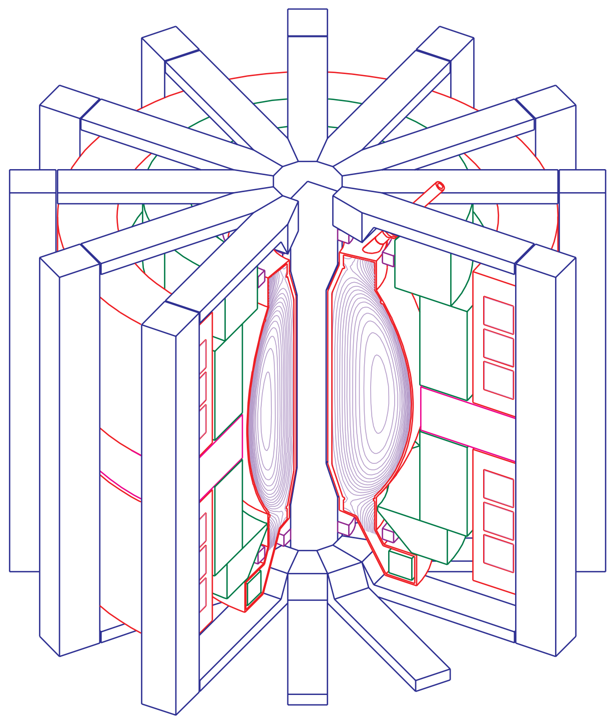

Fig. 1. The FDF device. Overall dimensions are about 9.5 m diameter x 7 m high. Plasma current is 13 MA. Additional parameters and capabilities are summarized in Table 1

and service lifetimes will be needed. Also, in contrast to less-ambitious 'next-step' fusion device proposals such as ITER and FIRE, FDF will need full remote handling capability, wherein any or all parts of the device can be maintained or replaced in a timely manner. These requirements collectively pose great fusion material and technology challenges. This paper identifies these challenges and suggests how they can begin to be met within the near-term capabilities of the world fusion program. The feasibility of using a 'bootstrap' operational approach, wherein an initial cycle of materials testing in FDF itself yields results and experience that can then be incorporated in subsequent testing cycles and/or upgrades of the FDF device components or the whole device is examined. We believe that this incremental

TABLE 1: FDF Device and Performance Parameters	
Attribute or Parameter (Symbol)	Key Features or Value
Device configuration (all components modular and fully maintainable/ replaceable in radioactivated state by remote handling means)	ST plasma with DN divertor; resistive demountable TF coil; resistive/superconducting PF coils; modular breeding blanket and shield; 12 test and plasma access ports
Plasma current (I_p)	13 MA
Toroidal field at plasma axis (B_o)	2.90 T
Aspect ratio ($A = R_o/a$) ---	1.60
Major radius (R_o)	1.12 m
Minor radius (a)	0.70 m
Vertical full height	4.2 m
Plasma edge safety factor (q_{95})	≅ 7
Volume-average beta ($\langle\beta_T\rangle$)	≅ 0.55 (55%)
Fusion power (P_{fus})	500 MW
Plasma/fusion operation	Continuous
Current sustainment and profile control	Bootstrap current + NBI + rf current drive
Heating + current-drive power	20 MW
Fusion energy gain (Q) ---	25
Plasma/fusion availability (duty factor, annual basis)	0.8 (80%)
Neutron wall loading test port)	≅ 8 MW/m^2
Neutron fluence(at test module first-wall, 80% availability)	≅ 6 MWa/m^2
Tritium burnup (with 80% avail.)	21.4 kg/yr
Tritium breeding (80% avail., TBR = 1.1)	≅ 2
Plasma/fusion thermal output (plasma heating, n-2n nuclear multiplication included)	600 MWth
Blanket/shield thermal output	480 MWth
TF and resistive PF coil power	210 MWth
NBI/rf line power demand	50 MWe
Total line power demand	270 MWe
Dimensions (TF coil)	7 m high x 9.5 m dia.
Mass (TF and in-TF systems)	1800 metric tonnes

‘bootstrap’ approach may provide the most credible means for fusion to address developing fusion reactor materials and technologies in a time and cost effective manner. We also believe that technology and materials development in FDF are and should be a necessary complement to the ‘burning plasma’ physics development proposed for the next generation of toroidal fusion science experiments. Both FDF and at least one other more-conventional burning plasma physics-oriented experiement are needed for timely world-wide progress to a future fusion reactor system.

II. TECHNOLOGY ISSUES FOR FUSION REACTORS

Projections of future magnetic fusion energy (MFE) power reactors find that operation at a peak plasma-facing first wall (FW) neutron flux of at least 5 MW/m^2 is needed for economic feasibility. At this ‘reactor-relevant’ FW flux, surfaces will accumulate 14 MeV neutron fluence at a rate of about 5 MWa/m^2, and this fluence will in turn result in material lattice perturbations of about 50 dpa (displacements per atom) per year. Since 50 dpa already exceeds the level at which lower-energy fission neutrons cause dramatic modification of the structural, thermal and electrical properties of candidate fusion reactor plasma-facing materials, the problem of identifying materials with neutron irradiation tolerance and service lifetimes adequate for MFE or IFE (inertial fusion energy) reactors is acknowledged to be a serious enabling issue for the feasibility of fusion energy.

The import this issue is compounded by a present world-wide lack of large-scale 14 MeV neutron irradiation capabilities. The present amount of 14 MeV irradiation data in the reactor-fluence regime is very limited, and what data exist have been obtained on small-scale material samples that may not be fully relevant to the much larger article sizes and complexities needed for an MFE or IFE reactor. Furthermore, proposals to employ next-step ‘burning plasma’ magnetic fusion experiments (e.g., ITER-FDR) for materials testing founder owing to limited flux or fluence capabilities. At least 5 calendar years of continuous operation of ITER (8-m FDR design) would be required to conduct a single ‘reactor-relevant’ test. A similar limitation applies to Volume Neutron Source (VNS) concepts[6], where fluxes are also limited to about 1 MW/m^2. It is debatable whether the testing pace that 1 MW/m^2 wall loading allows is rapid enough for fusion’s needs.

III. TECHNOLOGY TESTING IN FDF

In contrast, the FDF concept will make it possible to conduct 5 MWa/m^2 testing on a time- and cost-effective basis. The FDF concept employs a spherical torus (ST) plasma to achieve up to 8 MW/m^2 wall loading in a device that is relatively small in overall size (1.1-m plasma major radius, see Fig. 2) and low in construction cost. The high wall loading, comparable to that needed for a commercial reactor, is obtained on a continuous operation basis, and hence test article fluences of ~5 MWa/m^2 can be reached in one year of operation. Up to 10 test modules, each with about 1 m^2 of plasma facing surface area are provided, so testing of both large-scale material samples and prototype reactor first wall and breeding blanket components will be possible. The testing pace will be rapid: test time and cycle rate will yield progress and materials development data within a reasonable period. The high-flux and annual fluence of FDF also make it a candidate neutron source for a demonstration of fusion-based fission waste transmutation.[5]

The plasma physics and operation feasibility of the high-performance ST plasma needed for FDF are the present focus of a world-wide plasma science study effort. Present theoretical and experimental indications of the 'physics feasibility' of FDF (see Ref. 1 and Section 3 below) are positive but by no means yet definitive. In what follows in this paper we presume that the physics outcome will be positive, and ask the further question: if projected FDF plasma operation is achieved, what materials and technology developments and FDF device and facility design features are necessary to be able to exploit the 5 MWa/m^2 per year materials testing capabilities of an FDF plasma?

3. FDF DESIGN FEATURES AND ISSUES

Figure 2 illustrates the plasma core region of the FDF device. The design is based upon a spherical-torus plasma equilibrium that is produced by the poloidal field (PF) coil set shown. This set comprises two up/down symmetric pairs of resistive copper 'divertor-forming' PF coils supplemented with 3 pairs of superconducting NbSn outboard PF coils. A 0.32-m diameter single-turn copper centerpost (CP) fills the center of the 3:1 elongated plasma. The CP has axial cooling channels for once-through water cooling. Resistive (ohmic) power dissipation in the central 4-m high plasma-facing portion of the centerpost is approximately 70 MW.

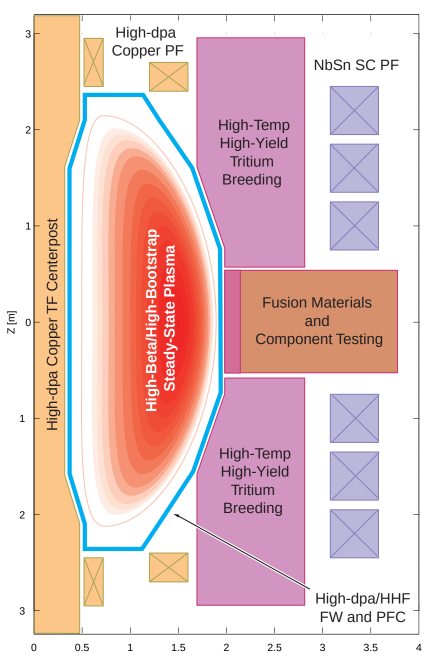

Fig. 2. Semi-schematic cross-section of the FDF device. Major device components and corresponding performance requirements are indicated

A 12-conductor 'picture-frame' TF outer conductor set (Fig. 1) completes the TF circuit and provides the 16.3-MA total current needed in the CP. Separate rectifier sets supply the 1.35-MA current needed in each outer TF circuit. Iindividual TF currents are regulated (equalized) to ±0.01% to provide a correspondingly low toroidal field ripple. A 1.3-m thick tritium breeding blanket and shield imposed between the plasma and the outer PF cryostat reduces coil heating and radiation doses to acceptable levels. The blanket/shield assembly has penetrations at the midplane at 12 equally-spaced azimuths for 1 m x 1 m x 1 m materials test modules, or, at two azimuths, access ports for neutral beam injection current drive.

The device configuration and coil locations and cross-sections illustrated in Fig. 2 satisfy requirements for plasma to first-wall clearance, CP current-carrying capability, water flow for CP and divertor PF cooling, adequateblanket/shield thickness for tritium breeding and superconducting coil shielding, space for the outer PF cryostat and access gaps for test modules and NBI. The plasma equilibrium is MHD stable in the presence of a conducting wall at a toroidal β (ratio of plasma pressure to magnetic field pressure) in excess of 55%, and the NBI ports allow the remaining 10% of the 13-MA plasma current not directly driven by the plasma pressure (owing to the neoclassical bootstrap current) to be supplied by two 7-MW 100 keV neutral beam injectors.

Resistive power dissipation in the TFCP and the external TF circuit (including rectifier losses) falls in the range of 150 to 192 MW. This is for a CP with expanded 0.48-m radius end sections as illustrated in Figs. 1 and 2. The exact value depends on the amount of material (cross-section) incorporated in the external 'picture frame' circuit and in the TF-to-rectifier bus system. For a straight (without end expansion) CP, resistive power is 200-240 MW.

Resistive power dissipation in the upper/lower divertor coils depends on the details of the plasma profiles but is typically ≤20 MW. Nuclear and ac heating in the outboard PF system is ≤ 1 kWth; PF system cryorefrigeration power input is ≤ 1 MWe.

Figure 3 shows the torus vessel surface-average neutron wall loading calculated for the reference plasma equilibrium. A 2-D quasi-optical model is used. For 500 MW fusion power (400 MW neutron power), the peak wall loading at the outboard midplane, where test modules will be located, is 8 MW/m^2. Approximately 84% of the total plasma neutron power falls on the outboard section of the torus vessel and hence is potentially usable for tritium breeding and/or the generation of high-temperature process heat. The remaining 16% neutron power falls on the copper centerpost (11%) and the divertor target regions (5%). There may be a possibility of incorporating breeding capability into (behind) the divertor targets

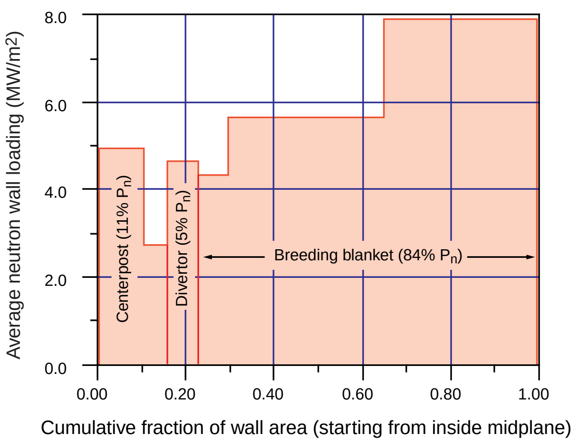

Fig. 3. FDF first-wall neutron wall loading distribution

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While many of the details of the design remain to be determined, the concept illustrated in Figs. 1 and 2 is complete and self-consistent enough to provide a basis for quantifying the many materials and technology application challenges that FDF will entail. In many ways, these challenges are the same as those for a MFE reactor, since FDF and MFE reactor flux, fluence and overall operation lifetimes are similar. Some, but not all, of these challenges also apply to VNS. The discussion below defines the major challenges for FDF, and, where applicable, overlap with VNS.

A. Plasma

Achievement of full FDF testing capability requires operation with a high-performance spherical-torus plasma having a normalized beta $\beta_N \cong 8.3$, a normalized energy confinement $H_{89P} \cong 5$ and a bootstrap current fraction $f_{bs} \geq 90\%$. In addition, the plasma pressure profile (variation of pressure with plasma minor radius) must yield a bootstrap current profile that closely matches the profile required for optimal ideal MHD stability at the 55% toroidal beta needed for rated fusion power. To obtain steady-state operation, the remaining 10% plasma current must be supplied, again with a prescribed profile, by non-inductive means. Finally, the so-called resistive wall mode MHD instability must be stabilized by means of actively-controlled helical coils.

Discussion of the physics and plasma current drive and profile and MHD stability control technology challenges associated with attainment of this optimized ST plasma operation state are beyond the scope of this paper. The issues and prospects for positive resolution are discussed in Ref. 1. We note here, however, that these challenges are essentially the same as those which are already receiving extensive on-going study in world-wide fusion research activities that seek to optimize the performance of ‘conventional’ high-aspect-ratio ($3 \leq A \leq 5$) tokamaks (to attain so-called ‘advanced tokamak’ performance). And the same generic challenges will also apply to future experiments that seek to exploit the higher β_N capabilities that low-aspect-ratio (A = 1.4-2) spherical tori offer. Finally, we note that while attainment of full FDF performance (i.e., 8 MW/m^2 peak wall load) does require simultaneous achievement of the design basis β_N, H_{89P} and f_{bs} and also near-optimal bootstrap current alignment and resistive-wall-mode stabilization, there are ‘fall-back’ scenarios with reduced β_N and/or reduced f_{bs} or alignment and without wall-stabilization that yield steady-state operation at 3-4 MW/m^2 peak wall loading. There are also scenarios with lower H_{89P} ($\cong 2$) that yield VNS-like 1-2 MW/m^2 wall loadings. So we anticipate that likelihood that FDF plasmas can achieve significant neutron wall loading will be high and not contingent on the attainment of a fully optimal physics outcome.

B. Centerpost and Inboard Vacuum Vessel and PFCs

Scoping studies of FDF and of other ST-based VNS devices have identified a consistent design approach: use of a resistive copper toroidal field magnet with a solid copper centerpost (CP). This CP is separated from the inboard side of the plasma by only the minimum first-wall/plasma-facing-components (FW/PFCs) needed to sustain the torus vacuum and exhaust the plasma power and particles incident on the inboard PFCs. There is no nuclear shielding or tritium breeding. This makes for a high-performance plasma, but also subjects the CP and inboard FW/PFCs to high levels of neutron flux and fluence, plus, for the PFCs, additional high levels of surface heat flux from plasma radiation and particles.

The combination of challenging plasma operation and nuclear irradiation tolerance requirements needed for FDF (and also for VNS) makes the selection of materials for this region and the development of design concepts that satisfy the complex combination of thermal, structural, and radiation tolerance requirements key critical FDF and VNS technology feasibility issues. Reliable bonding of the materials needed and service lifetime of the CP/VV/PFC and design concepts that allow for ready maintenance and replacement of the CP and/or the inboard VV also pose additional material and technology issues. Finally, the PFCs must not retain large unrecoverable inventories of tritium.

Assessements of the effects of neutron irradiation of the CP indicate that early onset of material embrittlement is will likely constitute the most serious operation limitation. Fission reactor data for low-temperature (400-500 K) irradiation of copper indicates loss of ductility and onset of appreciable embrittlement at ≤ 1 dpa exposure. Higher temperature during irradiation delays onset of embrittlement, but is not consistent with the attainment of the highest possible centerpost conductivity during operation. In contrast, direct transmutation-produced increase in copper resistivity becomes an issue only for irradiation approaching 100 dpa. This corresponds to a CP service lifetime of greater than 1 year. So the immediate problem is to find structural design and/or material optimization means (external structure and preloading, demountable joint design, composite reinforcement) and operation strategies (periodic annealing) to cope with the embrittlement issue that is common to both FDF and VNS toroidal field system centerposts.

B. Outboard PFC and Breeding Blanket

Similar materials feasibility issues apply for the PFCs and tritium breeding blanket that surround the outboard regions of the FDF plasma. At rated 500-MW power and 80% availability, FDF will burn about 21 kg of tritium per calendar year, so in-situ tritium breeding with a total device tritium breeding ratio (TBR) of at least 0.9 is essential (Fig. 4). Furthermore, given that the breeding blanket will intercept only 84% of the neutrons, high local breeding efficiency is essential. If a device TBR of 1.1 can be achieved, then FDF will become a net producer rather than consumer of tritium. So development of a high-performance breeding blanket and a FW design with fully reactor-relevant characteristics and high neutron transparency and reliability is needed for the testing phase of FDF operation. Again, there are significant material and technology questions that apply, and being able to quantify a fully-adequate design concept is not yet a foregone conclusion. Here the benefits of incorporating 'developmental' materials such as HT-9 ferritic steel or vanadium into the first FDF blanket may prove important.

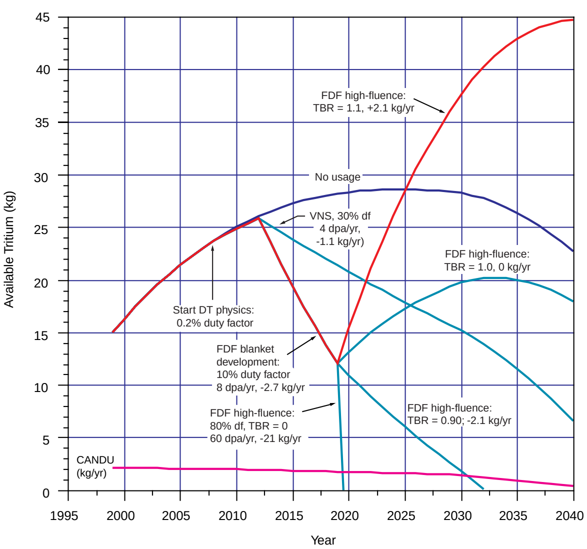

Fig. 4. Tritium availability from CANDU fission reactors and use/production by VNS and FDF fusion exporiments

C. Radiation-Tolerant Internal Coils.

Multi-turn copper coils carrying several MA of current are needed in FDF and VNS to form the plasma-defining separatrix and divertor configuration (or 'natural divertor' in VNS) and lower current (~100 kA) axisymmetric control coils will be needed in to stabilize the plasma vertical position in either device. In FDF, helical coils carrying ~20 kA will be needed to stabilize external kink MHD modes, which manifest themselves in the presence of a resistive wall as the resistive wall mode. Neutron exposure for these divertor and control coils will be similar to that of the solid-copper CP. Mineral-insulated conductors are a likely solution, but design details and confirmation of the ability of mineral-insulated coils to operate reliably in FDF for service lifetimes ≥ 1 full-power year require study.

D. Device Maintenance Concept.

FDF irradiation levels and overall device scale are such that all components of the device plus most of the ancillary systems (neutral beam injectors, rf launcher and transmission systems, plasma diagnostics, control systems, etc.) in the device test cell will have to be fully maintainable and replaceable on a remote handling (RH) basis. A similar full-RH need will likely apply for VNS. Hands-on access and appreciable human presence within the FDF or VNS test cell in periods between operation after DT-burning operation commences will be limited or non-existent. Consequently, the entire FDF or VNS device must be designed to be maintainable by RH means, and presently envisioned operation scenarios for the FDF device will include replacement of the CP and other highly-irradiated components on a near-annual basis. Hence the FDF device, ancillary systems and facility must be designed and configured with full RH capability. This is a 'first-of-kind' requirement for a near-term fusion experiment/facility, and the device component configuration and attachments and utility services (heating, cooling, electric, control and diagnostics) require careful study to ensure that a credible solution with 'real-world' RH capabilities exists.

E. Facility Concept and Capabilities.

The facility that supports the FDF device must incorporate both a nuclear-shielded test cell for the device itself plus several nearby nuclear-shielded maintenance and component system disassembly/reassembly cells. A remotely-controlled lifting and millimeter-accuracy positioning capability of several hundred tonnes will be required in the test cell, and provisions to remotely disassemble the entire FDF device and then move all device components in an activated and/or tritium-contaminated state must be provided. On-site storage and reprocessing of kilogram quantities of tritium will be required. Finally, provision must be made to locate the device power, plasma heating and device cooling systems in nearby hands-on accessible areas.

The combination of requirements and the intimate interaction that applies between the FDF device concept and the capabilities of the facility that will be required to operate and maintain it—and to upgrade it as needed—make design of the FDF facility (or a VNS facility) another 'first-of-kind' critical feasibility challenge. We believe that it will prove critically important to near-term study efforts to involve fusion and fission-cognizant personnel in identifying facility layout and operation concepts that confront this challenge.

4. STRATEGIC PLAN

Figure 5 below illustrates the broad outline of a 25-year strategic plan for constructing FDF and bringing the device and facility into a fully operational state. There are three phases:'physics' operation and optimization in Phase I (~6 years); blanket system testing and operations optimization in Phase II (~7 years) and, following installation of a full-coverage breeding blanket and the achievement of tritium self-sufficiency (or at least near self-sufficiency), concerted materials and component testing operation in Phase III (7 years or for as long as needed). Cumulative tritium consumption or production and cumulative first-wall fluence for each phase of the plan are given in Table 2.

The plan outlined in Figure 5 and Table 2 is success-oriented and presumes achievement on a timely basis of the plasma performance attributes identified in Section 3A and also the availability by the beginning of Phase II of the critical enabling technology and material requirements outlined

TABLE 2: FDF Strategic Plan and Operation Parameters

Phase	Years	Duty Factor (average)	Φ_n MWa/m^2	T burnup (kg)
Physics	1(DD) 5(DT)	0.002	---- 0.1	--- 0.25
Blanket development	7	0.1	5	19
Test ops + breeding	7	0.8	45	150 -14[a]

[a] With global tritium breeding ratio = 1.1

in Sections 3B-3D. In addition, availability of a suitable fusion and tritium-qualified experimental site and facility as outlined in Section 3F is required. In this latter regard, while we recognize that the nuclear and tritium attributes of an FDF-class experiment make it unlikely that such an experiment can be sited at any presently operating fusion experiment site within the United States, we also believe that there are a number of well-qualified sites — with already existing electrical, thermal disposition and nuclear infrastructures and in some cases, even on-site tritium — available both within the United States and elsewhere around the world. So we anticipate that finding a site for FDF will not pose any major technical or environmental issues. But we are concerned about the present near-term availability of the critical enabling technologies that we have identified above as being necessary for FDF to proceed beyond Phase I.

5. NEAR-TERM DEVELOPMENT

We believe that it is time to carefully evaluate the availability of the 'near-term' fusion materials and technologies needed to realize the type of FDF or high-performance VNS concept proposed herein. Here, near-term refers to materials and technologies that can be expected —

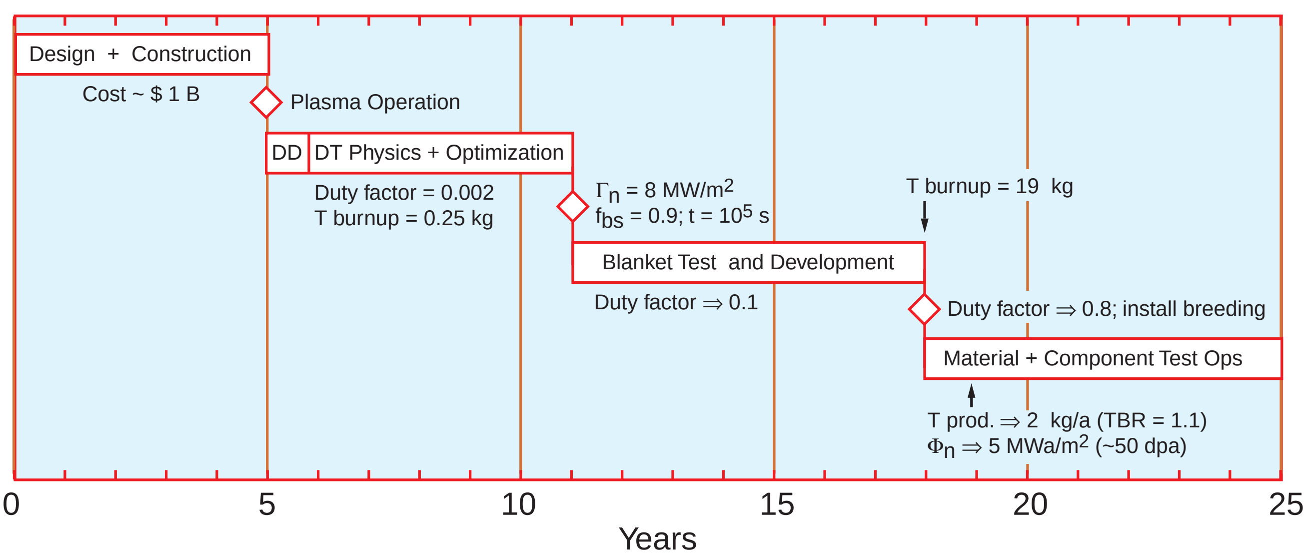

Fig. 5. Fusion Development Facility stategic plan to attain full operation capability. Cost estimates are approximate

with some intermediate R&D — in the '10-years from now' time-frame when high-fluence FDF operation may first commence. We anticipate that most of the findings obtained from this evaluation will also be applicable to a VNS. Work can be organized into four tasks that progress from initial identification of issues to development of R&D strategies and FDF and VNS design optimizations to mitigate the most limiting issues identified.

Task 1. Identify key enabling technology and materials issues. The strawman FDF concept shown in Fig. 1 and the associated device and facility operation parameters can be used as a basis to quantify the material and design requirements for the various critical device systems and regions identified in Section 3. Focus should be on identifying candidate materials, design concepts and assembly methods and on quantifying the associated structural, thermal, electrical and nuclear-irradiation-tolerance requirements. Lifetime and/or reliability estimates should be made and used as a basis for assessing maintenance schedules and device assembly and disassembly requirements. The emphasis in this phase should be on identifying material and design requirements. Specific or detailed designs should be developed or modified only to the extent that they are needed to self-consistently define requirements.

Task 2. Evaluate prospects for resolving these issues. Here the focus shifts to evaluating the prospects for being able to successfully achieve the requirements identified in Task 1. Initial work should focus on assessing presently available materials data and technology status. Subsequent work should shift to assessing foreseeable progress and improvements that can be expected before the final FDF design needs to be completed. Juxtaposition of the status and anticipated progress data obtained here with requirements compiled in Task 1 yields the basis for Task 3.

Task 3. Identify near-term materials and technology development strategies. Tasks 1 and 2 will identify an number of materials and/or technology development areas where present or projected status will likely be inadequate for initial FDF high-fluence operation. Possibilities for focused near-term R&D that can address these inadequacies need to be examined. Facilities both within the US and world-wide should be considered. The desired result is an R&D plan, like that developed for ITER, that is consistent with R&D resources and facilities available world-wide.

Task 4. Identify FDF design and facility optimizations and operation program strategies. In concert with Task 3, the FDF concept and facility used for Task 1 should be re-examined and optimized to increase the likelihood of timely attainment of testing capabilities. The initial focus here should be to configure the device concept and facility configuration so as to minimize materials and technology development requirements. But as a second and perhaps most important part of this task, the feasibility of a 'bootstrap' FDF operational approach, wherein an initial cycle of materials testing yields results and experience that can be incorporated in subsequent testing cycles and/or upgrades of the FDF device components or the whole device should be critically examined.

We believe that pursuing this type of incremental bootstrap approach may provide the most credible scenario for using FDF to address the challenging problems of developing fusion reactor materials and technologies in a time- and cost-effective manner. If this strategy proves to be viable and if the near-term technologies needed for the start of FDF Phase II operation are provided, then we can anticipate that fusion will for the first time have a credible means to confront the materials and component development issues that may otherwise prove to be the ultimate stumbling block for successful application of fusion for electrical power generation and other socially beneficial uses.

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