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PROGRESS OF THE ST-VNS STUDY

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ABSTRACT

Progress is given on the investigation of a low cost, scientifically attractive, and technologically feasible volumetric neutron source (VNS) based on the spherical torus (ST) concept. The ST-VNS has a major radius of 1.07 m, an aspect ratio of 1.4, and a plasma elongation 3. It can produce a neutron wall loading ultimately up to 5 MW/m^2 averaged over the outboard test section when the fusion power reaches 380 MW. Initial operation of this device can be at a level of 1 MW/m^2 or lower. Higher performance blanket components can be developed to raised the neutron wall loading. Using staged high wall loading operation scheme and optimistic availability projected for the VNS device, a neutron fluence of more than 30 MW-y/m^2 can be expected to accumulate within 20 years of operation. Assessments of lifetime and reliability of fusion core components will thus be allowed in a power reactor relevant environment. A full-function testing of fusion core components may also become possible because of the high neutron wall loading capability. Integrated testing of tritium breeding in such a full scale power reactor relevant VNS device can be very useful to verify the self-sufficiency of fuel cycle in candidate power blanket concepts.

I. INTRODUCTION

A plasma based volumetric neutron source (VNS) has been considered as an intermediate facility to support the development of the demonstration fusion power reactor (DEMO).[1] It can be used to test and develop necessary fusion blanket and divertor components and provide sufficient database, particularly those that are relevant to the reliability of nuclear components necessary for DEMO.

The spherical torus (ST) confinement concept is an emerging innovative approach to fusion energy development. Because of its attractive features such as small size and high beta, the ST device can be an ideal VNS facility.[2-5] A cost-effective, scientifically feasible design of such a ST-VNS, VNS-I, was conceived during Phase I of a study sponsored by the U.S. Department of Energy Small Business Innovative Research (SBIR) Program.[5] It satisfies all requirements specified in Ref. 1 as a VNS for nuclear technology testing. VNS-I has a major radius of 0.8 m, aspect ratio of 1.33, and an on-axis magnetic field strength of 1.8 tesla. It is operated with a single-turn toroidal field copper magnet and can produce 38 MW fusion power when driven and heated by 21 MW of 500 keV neutral particles. The neutron wall loading at the 10 m^2 test section reaches 1 MW/m^2.

Research continues during Phase II of the SBIR study, and focuses, however, on the optimization and technological feasibility of the VNS with higher neutron wall loads. The motivation in the Phase II study is to design a VNS that can be used to test nuclear technologies at a neutron wall load anticipated in future power reactors up to 5 MW/m^2 averaged over the outboard blanket component (6.5 MW/m^2 peak at the midplane). A second goal is to test the component in a power reactor relevant environment with a neutron fluence exceeding the expected component lifetime.

II. VNS CONFIGURATION AND PHYSICS DESIGN

The configuration of the Phase II ST-VNS, VNS-II, was determined based on conservative physics assumptions.[6] VNS-II has a major radius of 1.07 m, minor radius 0.76 m, aspect ratio 1.4, and plasma elongation 3. Figure 1 displays schematically the configuration of the ST-VNS design. A top view of the device ports is given in Fig. 2 showing the two neutral beam injectors (NBI), two maintenance ports, and 8 test ports. Note that each port has a width of 1.05 m at the midplane location. With a module height of 2 m, the 8 test ports will provide a total testing area of 16.8 m^2.

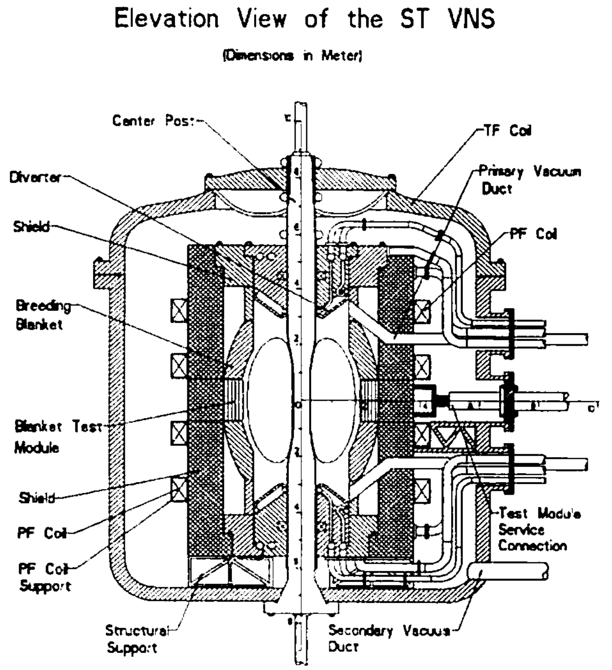

Fig. 1. Side view of the ST-VNS.

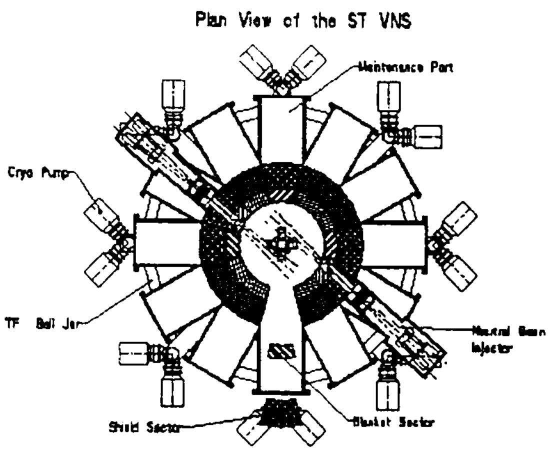

Fig. 2. Top view of the ST-VNS.

The physics design has considered two cases. One is a device using neutral beams for heating and driving the plasma current, and the other device is heated and driven by ICRF. Note that both devices are designed to have the identical physical configuration as described above. Table I displays plasma and power performance parameters for both NBI and ICRF driven cases at 2 MW/m^2 neutron wall loading and 151 MW fusion power. The average toroidal beta is 37% and 27%, respectively, for the NBI and ICRF cases. Due to the lower beta in the ICRF case, the on-axis toroidal field (B_t) is higher in the ICRF case (2.55 tesla) than in the NBI case (2.13 tesla). The Von-Mises stresses in the center-post copper magnet in the NBI and ICRF devices were estimated to be 96 MPa and 136 MPa, respectively, pushing the ICRF device beyond the presently recommended limit of 100 MPa.[7] The parameters of NBI driven cases other than the 2 MW/m^2 case are also shown in Table I.

III. THERMAL AND MECHANICAL DESIGN

The mechanical design of this device[8] is similar to the smaller size Phase I device as described in detail in Ref. 2. The centerpost is an unshielded single-turn normal conducting copper magnet, made of dispersion oxide strengthened copper alloy, Glidcop. As described in Refs. 2 and 5, it has three sectors with the top and bottom sectors tapered to increase the radius of the conductor in order to minimize the ohmic heat loss. Using the ICRF heated and driven, 151 MW fusion power device (2 MW/m^2 wall load) as the reference design, the thermal-mechanical aspect of the centerpost was analyzed.[8] Due to primarily nuclear transmutation of copper into nickel, the resistivity of copper in the centerpost will increase during operation. Figure 3 display the contour profile of the nickel concentration in the centerpost after 2.5 full power years at 2 MW/m^2 average wall loading at the outboard. The maximum nickel concentration is about 10,000 ppm, as shown in Fig.3, and corresponds to about 55% increase in the local resistivity. An overall of five percent increase in ohmic heating loss for each full power year operation in the 2 MW/m^2 device can be obtained from a detailed resistivity change profile in the centerpost.

Table II summarizes the thermal hydraulic parameters of the centerpost for up to 3 full power years (FPY) of operation. To minimize the ohmic heating, it is necessary to maintain a low copper temperature during operation. One way to accommodate this is by increasing the water mass flow rate, as done in this study. Fortunately, the resultant water pressure drop and increase in water pumping power are not excessive. The centerpost resistive ohmic power was estimated to be 153 MW at start, 161 MW after one full power year, and 178 MW after 3 FPYs. The total supply power needed to operate the reference VNS was estimated to be 313 MWe. The operating cost figure of merit can thus be calculated to be about 180 $M/y, assuming an availability of 60%

Table I
Summary of Key Operating Parameters for NBI-driven VNS Fusion Core Systems
VNS Device: Major Radius - 1.07 m; Aspect Ratio - 1.4; Plasma Elongation - 3

Average Wall Load (MW/m^2)	0.5 (NBI)	1.0 (NBI)	2.0 (ICRF)	2.0 (NBI)	3.0 (NBI)	4.0 (NBI)	5.0 (NBI)
Plasma current (MA)	9.7	10.0	13.2	11.1	12.8	13.4	14.3
Toroidal field (T)	1.9	1.91	2.55	2.13	2.44	2.52	2.67
Average toroidal beta $<\beta_t>$	0.24	0.32	0.27	0.37	0.36	0.38	0.39
Poloidal beta β_p	0.61	0.80	0.68	0.94	0.87	0.92	0.91
Normalized beta β_N (Tm/MA)	0.035	0.047	0.040	0.055	0.052	0.055	0.055
Average n_e ($10^{20}/m^3$)	0.91	1.53	2.59	2.16	2.63	3.50	4.57
Average n_i ($10^{20}/m^3$)	0.81	1.40	2.37	1.98	2.40	3.20	4.19
Greenwald n_e limit ($10^{20}/m^3$)	5.31	5.43	7.17	6.03	6.99	7.31	7.79
Borrass n_e limit ($10^{20}/m^3$)	1.62	2.15	2.85	2.96	3.37	3.80	4.14
Central temperature (keV)	15.7	14.1	14.0	14.9	15.7	14.0	12.4
Fusion power P_{fusion} (MW)	37.8	75.6	151	151	227	302	377
Fusion amplification Q	1.59	2.04	3.32	2.67	3.96	4.53	5.25
Heating power, P_{aux} (MW)	23.8	37.0	45.5	56.7	57.2	66.7	71.9
Bootstrap current fraction	0.60	0.68	0.79	0.66	0.76	0.81	0.87
TFC total current (MA)	10.2	10.2	13.6	11.4	13.1	13.5	14.3
Mid-plane TFC average J_{tf} (kA/cm^2)+	6.36	6.36	8.48	7.11	8.17	8.42	8.92
Centerpost von-Mises Stress (MPa)	75.7	76.5	136	95.6	118	126	141
Inner leg resistive power, P_{tfi} (MW)	86	86	153	107	141	150	168
Fusion core supply power P_{supply} (MW)*	168	192	313	261	320	355	398
Operating cost figure of merit ($M/yr)#	82 (44)	126 (51)	234 (83)	220 (69)	312 (84)	396 (94)	483 (105)

+ Estimated based on 30% water and 70% copper. * P_{supply} (MW) = [1.5 (P_{aux} + P_{tfi}) + 0.1 P_{fusion}] is assumed.

Operating cost figure of merit ($M/yr) = 0.6 [1.67 (1-TBR) P_{fusion} + 0.44 P_{supply}], TBR = 0. Numbers in the brackets are those with TBR=1.0. Assumptions: Tritium cost = $30,000/g; electricity cost = $0.060/KWh; VNS availability = 60%.

Table II
Thermal Hydraulic Parameters of the Centerpost at 2 MW/m2 Neutron Wall Loading (ICRF Driven Device)

	At Start	1 FPY	3 FPY
Ohmic Heating, MW	153	161	178
Nuclear Heating, MW	11	11	11
Water Mass Flow Rate, kg/s	675	766	937
Maximum Cu Temp., C	150	151	156
Water Pressure Drop, MPa	0.189	0.255	0.369
Water Pumping Power, kW	128	196	346

Design analyses were extrapolated from the reference design to the NBI driven designs and the results are also given in Table I. Note that as shown in Table I, the NBI heated and driven device shows lower stresses in the centerpost due to the lower applied magnetic field. At a higher magnetic field of 2.7 tesla, the fusion power can be increased to 377 MW providing a neutron wall loading of more than 5 MW/m^2 at the outboard. The VNS-II produces 151 MW fusion power and the neutron wall load is 2 MW/m^2 at the midplane.

IV. FUSION TECHNOLOGY DEVELOPMENT AND DEMONSTRATION

Due to the capability of high neutron wall loading in a given device configuration, the ST-VNS can be used to obtain (1) lifetime limiting factors for power core components including the first wall, divertor and blanket, and (2) operating experience of reactor components at increasing levels of neutron wall loading. In other words, the unique capability of the ST-VNS allows the development of needed fusion core components and related technologies for the DEMO in a reactor relevant environment.[9] An illustrative demonstration of such an operational scenario is shown in Fig.4.

The initial operation is at a very low wall loading, such as 0.5 MW/m^2 as shown in Fig. 4, to gain the first experience of significant 14 MeV neutron flux level in an engineering component. The availability can be very low due to lack of knowledge and experience in operating such a device. The ITER developed SS316 based shielding blanket materials can be used for all components except the test blanket section. Feasible core component concepts can be tested and selected. Tritium breeding in the shielding blanket region may not be needed at this stage because the needed tritium consumption is only 640 g/y if the availability is 30%. The total tritium consumption in the initial stage is no more than 2.13 kg to accumulate to a fluence of 0.5 MW-y/m^2.

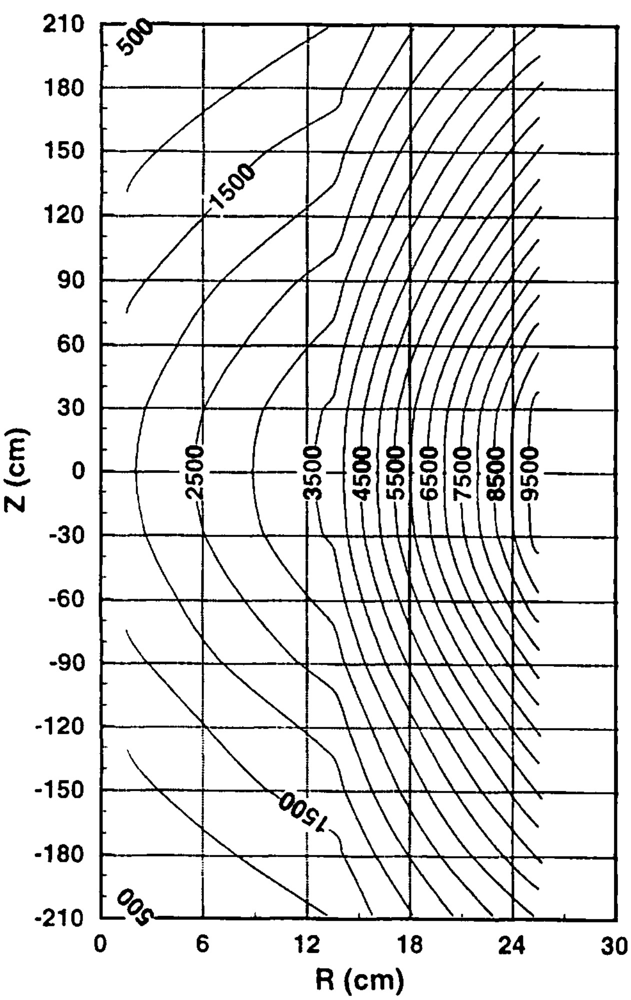

Fig. 3. The contour profile of nickel (appm) in the copper magnet after 2.5 full power years at 2 MW/m^2.

Higher wall loading operations can continue after the initial stage operation, as shown in Fig. 5. At the higher wall loading stages, the outboard shielding blanket region other than the test section can begin to incorporate power reactor relevant core components already tested and qualified in the test section. The availability can be increased to 60% after significant experience learned from the initial operation.

During these stages, the power blankets and divertor components will begin to undergo mean-time-to-failure testing. Reliability information of the fusion core components start to accumulate.[1] Tritium breeding will be available during these stages. Since the power blanket segment can be employed in the entire outboard region, an overall tritium breeding can be assessed. The self-sufficiency of tritium can thus be demonstrated for the relevant blanket concept.

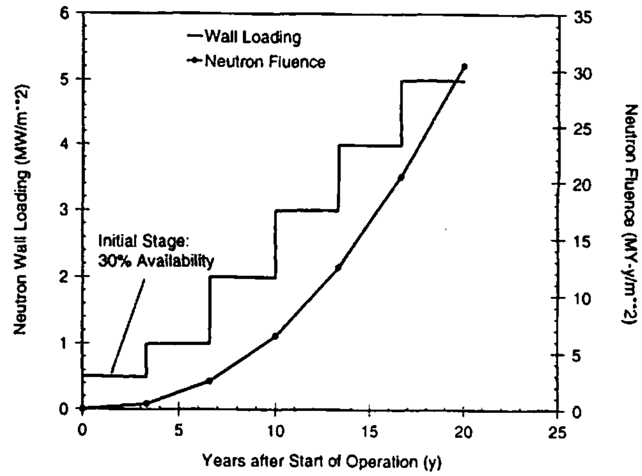

Fig. 4. A staged ST-VNS operational scenario with a neutron wall loading ranging from 0.5 to 5 MW/m2. The availability is 60% except at the initial stage.

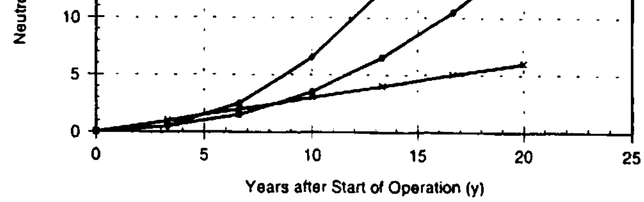

Fig. 5. Comparison of accumulated neutron fluence for several operational scenarios.

With the above assumptions, the staged high wall loading operation of an ST-VNS can provide an accumulated neutron fluence of more than 30 MW-y/m^2 in a power reactor relevant environment within about 20 years, as shown in Fig. 4. Compared to a fixed neutron wall load device, as shown in Fig. 5, the staged high wall loading device offers a very attractive scenario for the development of power reactor relevant fusion technology.

The ST-VNS can provide a reactor relevant environment for the power core components to demonstrate all functions required for a power plant or DEMO through the start-up, transition, and steady-state operation at the designated power levels. Ultimate performance capability of promising power core components can thus be developed and demonstrated for the power plant application.

V. SCALED VNS COSTS

Scaled capital cost analysis was performed as part of the systems study leading to the current VNS configuration and physics parameters.[10] It was found that the total construction cost of the ST-VNS ranges from $1.36 to $1.62B (in 1989$). The fusion core including the centerpost, the outer return TF legs, divertor, shielding blanket and radiation shield (see Fig. 1) is about $260M. The NBI heated and driven system for the 2 MW/m^2 (151 MW fusion power) operation is about $380M. Note that the beam power delivered to the plasma in this case is 56.7 MW. When the heating power increases the NBI cost goes up too. The NBI cost for the highest wall loading case, 5 MW/m^2, is about $480M because the needed heating power is 72 MW. The remaining cost items include the site ($440M), instrumentation and control for power supplies ($79M), diagnostics ($148M), remote handling systems ($123M), tooling and assembly ($89M), etc., adding to about $880M.

The operating costs were estimated and also given in Table I. As shown in Table I, for the 2 MW/m^2 NBI driven device it is $105M/y (60% availability) when a self-sufficienct tritium breeding is provided. Tritium breeding is essential in this case, other wise the operating cost will exceed $480M/y.

VI. CONCLUSIONS

A low cost, scientifically attractive, and technologically feasible volumetric neutron source based on the spherical torus concept has been conceived. The ST-VNS has a major radius of 1.07 m, an aspect ratio of 1.4, and a plasma elongation 3. It can produce a neutron wall loading ultimately up to 5 MW/m^2 averaged over the test section when the fusion power reaches a modest level of 380 MW. Initial operation of this device can be at a level of 1 MW/m^2 or lower, utilizing the fusion core components developed during the ITER EDA. Higher performance components can be developed and implemented to raise the neutron wall loading. Using staged high wall loading operation scheme and optimistic availability projected for the VNS device, a neutron fluence of more than 30 MW-y/m^2 can be expected to accumulate within 20 years. Assessments of lifetime and reliability of promising fusion core components will thus be allowed. A full-function testing of power reactor fusion core may become possible because of the high neutron wall loading capability. Integrated testing of tritium breeding in such a full-scale power reactor relevant VNS can be very useful to verify the self-sufficiency of D-T fuel cycle in the candidate power blanket concepts.

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