Vision and Requirements for VNS

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BLANKET ENGINEERING

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RESULTS OF AN INTERNATIONAL STUDY ON A HIGH-VOLUME PLASMA-BASED NEUTRON SOURCE FOR FUSION BLANKET DEVELOPMENT

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Outline

1) VNS for Fusion Nuclear Technology Testing

Summary of IEA Study Requirements

2) Tradeoffs in VNS Design as a Function of Aspect Ratio

3) A Volumetric Neutron Source For Fusion Engineering Feasibility

– Preliminary Thoughts

VNS for FNT Testing

VNS Mission

To serve as a test facility for fusion nuclear technology and to provide a database sufficient to construct FNT components for DEMO.

Testing Requirements

VNS must satisfy the following FNT testing requirements:

Wall Load: 1-2 MW/m^2

Neutron Fluence: $\geq$ 6 MW•y/m^2

Plasma Mode of Operation: steady state, or long plasma burn with duty cycle > 80%

Minimum Test Area per Test Article: 0.36 m^2

Total Test Area: > 10m^2 (up to ~ 20m^2)
(however, test devices that can satisfy part of the total testing area requirements should be considered in a cost/benefit/risk analysis)

Device Availability: > 25%

Minimum Continuous Operating Time: 1-2 weeks
(periods with 100% availability)

Magnetic Field at the Test Region: > 2T

VNS Design Features/Constraints

VNS design should be consistent with the following features/constraints:

- Configuration, remote maintenance and other design features must emphasize the reliability of basic device components and rapid replacement of device components and test articles.

- Device must be able to test all candidate blanket concepts for DEMO including liquid metal and beryllium.

- The fusion power must be low enough that the tritium consumption does not exceed that available from external sources (e.g., the fusion power should be <150 MW with 30% of the first wall occupied by test modules).

- The capital cost of VNS should be kept as low as possible (e.g., less than 25% of that for ITER).

- The power consumption of the VNS site (e.g., from normal copper coils, current drive, etc.) should be kept reasonably low (e.g., < 700 MW).

Figures of Merit

In determining an attractive design envelope for VNS, cost/benefit/risk analysis and tradeoff studies should be conducted.

Suggested figures of merit include the following:

- extent of meeting FNT requirements (wall load, fluence, test area, etc.)
- total capital and operating costs
- contribution to nuclear testing for DEMO components
- additional contributions to satisfying DEMO database requirements other than testing
- minimal R&D to construct VNS
- confidence in achieving VNS goals
- contributions to ITER (e.g. reduced technological burden and possible cost savings)
- contributions to improvements in the development schedule to DEMO

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Exploration and assesment of design windows for a Tokamak-based volumetric neutron source

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N·H
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Table 1. Major Physics and Engineering Assumptions

Physics Constraint/Parameter	Value
normalized plasma beta, β_N (%)	≤ 3.5
confinement enhancement factor, H	≤ 2.0
plasma elongation, κ_{95}	≤ 2.0
plasma triangularity, δ_{95}	≤ 0.3
plasma MHD-q, q_{95}	3.0
Radial Build	
OH coil bore (m)	0.2
inboard shield (m)	0.3
inner scrape-off layer (m)	0.08
outer scrape-off layer (m)	0.10
outboard radial build (m)	1.7
Power Constraint	
fusion power (MW)	≤ 150
site power consumption (MW)	≤ 700

Table 2. Design Options with Various Aspect Ratio A

	A=2.5*	A=3.0	Min cost A=3.45	A=4.0	A=5.0
average wall load (MW/m^2)	1.0	1.0	1.0	1.0	1.0
major radius (m)	1.77	1.63	1.58	1.73	1.99
minor radius (m)	0.71	0.54	0.46	0.43	0.40
plasma current (MA)	7.4	5.2	4.2	3.7	3.0
toroidal field (T)	4.4	5.3	6.0	6.6	7.7
average density (10^{20} m^{-3})	1.4	1.7	2.0	2.2	2.3
average temperature (keV)	10.0	8.9	8.2	8.0	8.2
drive power (MW)	53	48	44	46	48
fusion power (MW)	108	80	66	70	75
power consumption (MW)	627	593	589	605	682
plasma Q	2.0	1.7	1.5	1.5	1.6
plasma volume (m^3)	34.1	18.9	12.8	12.7	12.3
plasma surface area (m^2)	74.5	53.6	43.4	45.4	48.1
first wall surface area (m^2)	76.6	56.5	46.9	49.3	52.7
relative cost (wrt A=3.45)	1.17	1.04	1.00	1.05	1.19

* minimum A obtained for the specified wall load

Table 3. Reference VNS Design Candidates

Major design parameter	1-MW/m^2 case	1.5-MW/m^2 case
average wall load (MW/m^2)	1.0	1.5
peak wall load (MW/m^2)	1.4	2.2
major radius (m)	1.58	1.64
minor radius (m)	0.46	0.46
aspect ratio	3.45	3.58
plasma current (MA)	4.2	4.5
toroidal field (T)	6.0	6.8
average density (10^{20} m^{-3})	2.0	2.4
average temperature (keV)	8.2	8.6
drive power (MW)	44	52
fusion power (MW)	66	103
power consumption (MW)	589	698
plasma Q	1.5	2.0
plasma volume (m^3)	12.8	13.3
plasma surface area (m^2)	43.4	45.2
first wall surface area (m^2)	46.9	48.7
relative cost (wrt A=3.45)	1.00	1.17

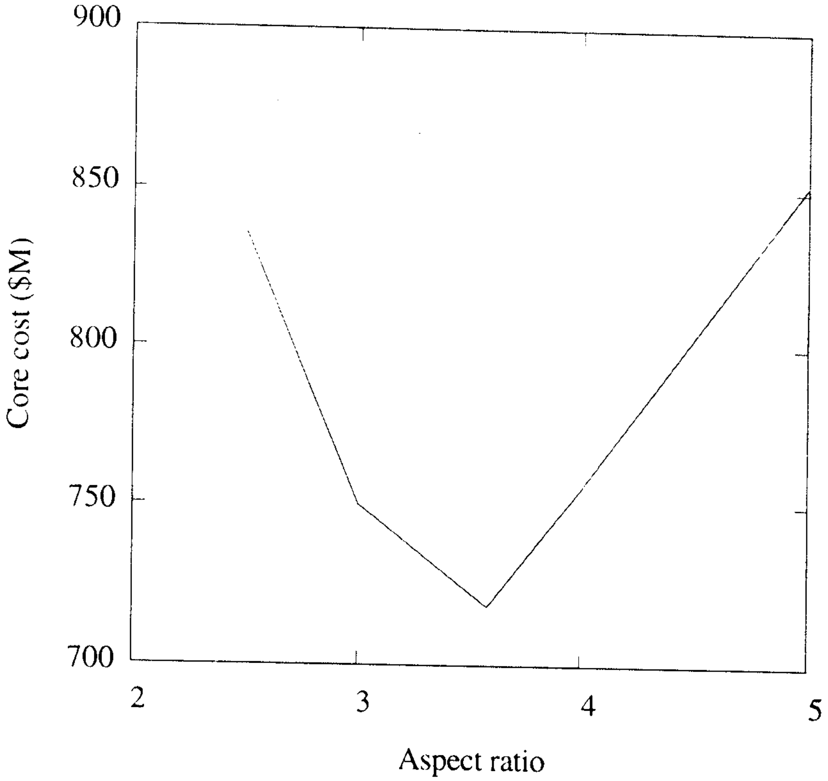

Fig. 1. VNS tokamak core cost versus aspect ratio.

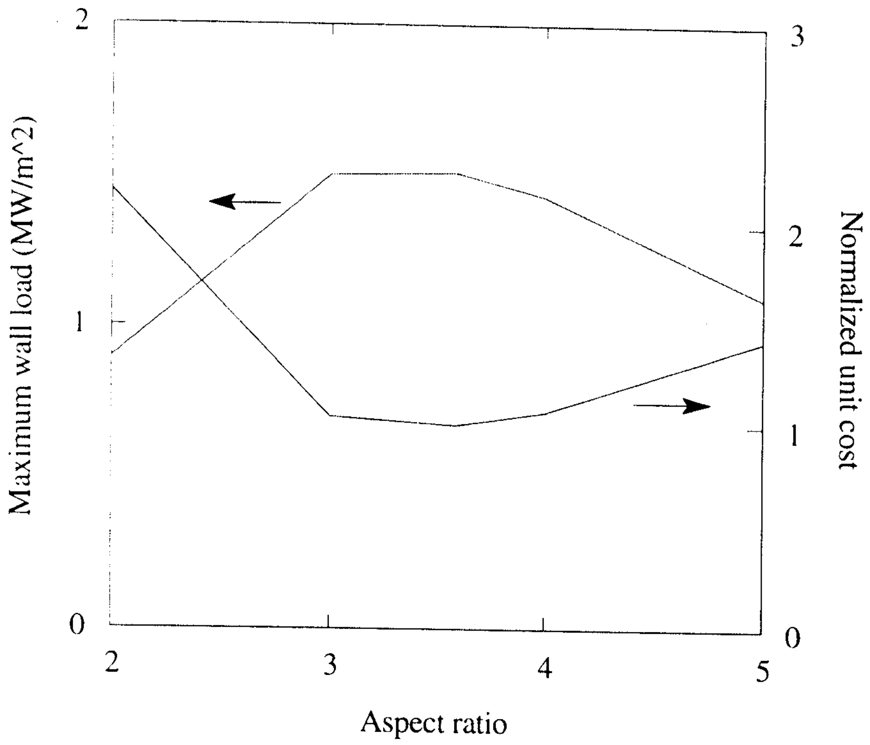

Fig. 2. Variations of maximum neutron wall load and normalized unit cost with aspect ratio.

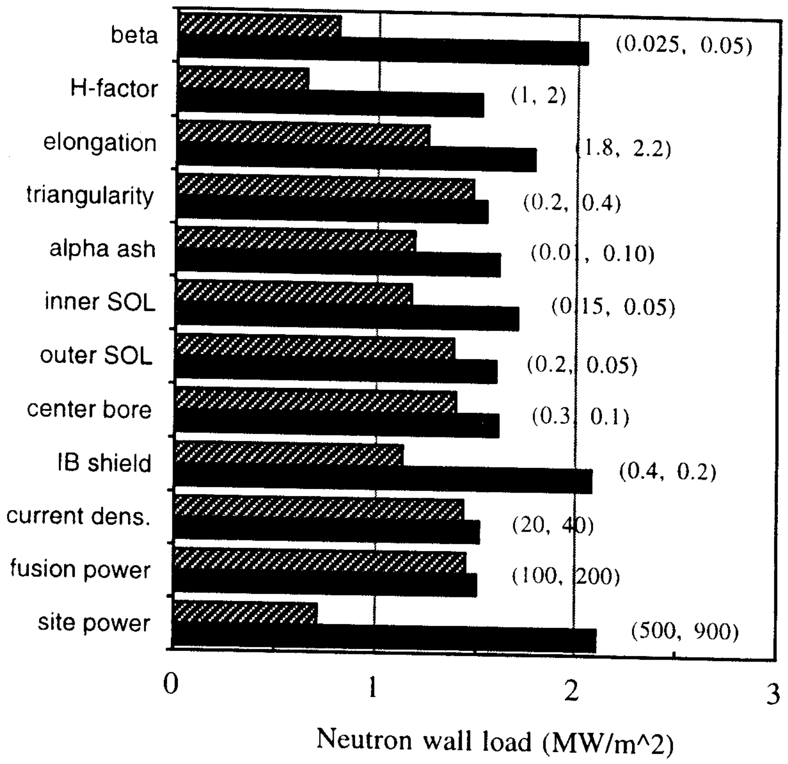

Fig. 3. Maximum average neutron wall load at bounding limits of design parameters.

Thoughts Behind Engineering Feasibility Device

Key Issues For Fusion

1. Ignition
   - Net Power

2. Engineering Feasibility
   - Tritium self-sufficiency
   - Heat extraction at elevated temperature
   - Reasonable Mean-Time-Between-Failures (MTBF) in early life
   - Basic safety

3. Long Term Issues
   - Incorporating and improving known technologies (e.g. superconducting magnets)
   - Economic competitiveness
   - Striving for "Inherent Safety"
   - Striving to enhance environmental attractiveness

History of Fusion

- Focused on Ignition as the top priority (for the last 20 years)
  - We discovered that the device is very large and the cost is very high

- We insisted on using Superconducting magnets in the same device that tests for Ignition
  - Size and cost became even larger (because of the much thicker inboard shield)

- The World Fusion Program is facing major difficulties in securing funds for Ignition/ Superconducting device

- We hope we succeed in securing these funds

- But, whether we succeed or not, there is a lot of equally critical and exciting R&D we can do by pursuing a device aimed at establishing fusion engineering feasibility

Observations and Comments

1) In the development of a product, **feasibility** comes *before* **attractiveness**

   - *Feasibility* must be demonstrated on <u>a reasonable time scale</u>. *Attractiveness* will come from continuous hard work and experience plus occasional breakthroughs for which the time scale is much harder to predict.

   - Work on Feasibility Goals, while keeping an eye on attractiveness

   - Avoid *"Working on attractiveness and forgetting about feasibility"* (There are examples of this)

2) *Engineering feasibility* can **not** be addressed unless we have a device that burns tritium and deals with the physics and engineering issues of DT

Comments Contd.

3) Progress in fusion is NOW hindered by limitations of available technology

e.g.

- ITER has to keep the power density low (i.e. neutron wall load of 1MW/m^2) because of the limitations of available divertor/first wall/blanket technology

- Even at low power density, 25% of the plasma chamber volume in ITER has to be used for non-productive gaseous regions because the solid plate divertor can not handle the power

- ITER did NOT incorporate **a tritium breeding blanket** because of a lack of sufficient scientific and technological data base (Thus, the basic feasibility issue of tritium self sufficiency can NOT be directly addressed)

Comments Contd.

4) The Mean-Time-Between-Failure (**MTBF**) for components in a DT fusion system is a serious **feasibility** issue

- The first wall/blanket for a machine the size of ITER is predicted to have

MTBF = 1 hour
MTTR ~ Weeks to Months

- **MTBF** is a **feasibility** issue that deals with many interactions in a system in the fusion environment

- In contrast, **Lifetime** is an **attractiveness** issue

- Dealing with **MTBF** MUST be a higher priority than the **lifetime**

  - Determining the **MTBF** requires an operating fusion device

Engineering Feasibility Strategy

- Focus on **Engineering Feasibility** as a goal. Show that a DT fusion system can operate with:
  - A steady state or long burn DT plasma
  - 1 MW/m^2 neutron wall load capability
  - Closed DT cycle
  - MTBF (in vessel components) > 1 week
  - MTTR from a failure < 1 month
- A DT burning device is needed and the Tokamak is the only viable option now
- The device will have to be used as a test facility FIRST to find **options that will work**, and second to explore options that may be attractive

- To keep the device cost relatively low (~ \$2 B to \$3 B)
  - Use **normal** conducting magnets
  - Settle for **low Q** (~1-3)
  - Keep the fusion power low (<150 MW)

- This device will have parameters similar to those of a VNS for FNT Testing

How to Achieve Fusion Attractiveness

- We should explore options now that can make fusion attractive. We need technology and materials options with high power density, capability and attractive environmental and safety features.

e.g.

- High Neutron Wall Load (> 5 MW/m^2)
- Large design margins, especially for tritium self sufficiency
- Low decay heat
- Low chemical reactivity
- Low tritium permeation
- Low long-term radioactivity
- etc.

- We need to develop innovative concepts

- Serious evaluation of high-risk, high pay-off options for advanced technology and materials require some "screening tests" in the complex fusion environment
  - This environment can be provided by the same small size, low Q, DT device used for engineering feasibility