Motivation, Scope, and Preliminary Approach for APEX

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The Motivation for Conducting APEX Emerged from the New Vision for Fusion Restructured Program

<u>New Vision</u>

- Take the long term view
- Emphasize science (including engineering sciences) as basis for innovation
- Key is Improving Fusion
  - Make the ultimate product more attractive
  - Have more effective R&D pathways

How to Improve Fusion

1) Plasma Physics Innovation
2) Technology Innovation
   - can make product more competitive
   - can define the limits
     - provide boundary conditions to physics research
     - better evaluation of fusion's potential

APEX

Ultimate Goal

Significant contributions to making the (long-term) fusion energy system more competitive through exploring and developing more attractive concepts for Fusion Power Technology (FPT)

FPT: Region from the edge of the plasma to the inner surface of the magnets

Near-Term Objective

Explore new (and possibly revolutionary) concepts that can provide the capability to efficiently extract heat from systems with high neutron and surface heat loads while satisfying all FPT functional requirements and maximizing reliability, maintainability, safety and environmental attractiveness

A Conceptual FPT Design

1. Must satisfy functional requirements

2. Strive to be attractive

   - There are many attractiveness criteria. It is probably impossible to satisfy (or win) all of them

   - Ultimately, the best choice is based on trade-offs among the various criteria

Functional Requirements of Fusion Power Technology

1) provision of VACUUM environment

2) EXHAUST of plasma burn products

3) POWER EXTRACTION from plasma particles and radiation (surface heat loads)

4) POWER EXTRACTION from energy deposition of neutrons and secondary gamma rays

5) TRITIUM BREEDING at the rate required to satisfy tritium self sufficiency

6) TRITIUM EXTRACTION and processing

7) RADIATION PROTECTION

General Criteria for Attractiveness of (Fusion) Energy System

1. ECONOMICS
    a) cost per unit thermal power
    b) thermal conversion efficiency
    c) mean time between failure (MTBF)
    d) mean time to repair (MTTR)
    e) lifetime
2. SAFETY
    a) chemical reactivity
    b) decay heat
    c) tritium inventory
    d) dose
    e) etc.
3. ENVIRONMENTAL
    a) waste disposal
    b) routine releases (e.g. tritium)
    c) material resources utilization
    d) etc.

APEX (initial) focus:	Economics
APEX (initial) DRIVER:	Capability for High Neutron Wall Load and Associated Surface Heat Flux

Most Challenging Issues for FPT

1. Heat removal at high temperature and high wall load

2. Failure rate

3. Time to recover from a failure

4. Tritium fuel self sufficiency

- A brief summary of these issues follows
- This provides critical framework for:
  - understanding the motivation for APEX
  - evolving the APEX approach

Power Density and Heat Flux in Fission Reactors

	PWR	BWR	HTGR	LMFBR	ITER-Type
Equivalent Core Diameter(m) **Core Length (m)**	3.6 3.8	4.6 3.8	8.4 6.3	2.1 0.9	30 15
Average Core Power Density (MW/m^3)	**96**	**56**	**9**	**240**	**0.4**
Peak-to-Average Heat Flux Coolant (MW/m2)	2.8	2.6	12.8	1.43	50

Suggested Fusion Goals

- Neutron Wall Load > 10 MW/m^2
- Minimize Peak - to - Average Power Density

Current Design Concepts and Materials for First Wall / Blanket Do NOT Have the Capability to Meet the Fusion Challenge

Concept	**Wall Load Capability MW/m^2**	**Other Observations**
Ferritic / He / Breeder **Ferritic / H_20 / Li Pb**	2	• Magnetic material • Fracture toughness
Vanadium Alloy / Lithium	2.5	• V works only with lithium • Is lithium acceptable? • Not feasible until a self healing coating is found
SiC / SiC / He / Breeder	1.5	• Serious feasibility issues • Do <u>NOT</u> know how to design • Poor thermal conductivity

Goals for MTBF & MTTR
Can be Easily Derived

<u>Availability = A</u>
A (Plant) = 75%
A (BOP) = 85%
A (Reactor) = 88%

<u>Reactor</u>
Assume 6 major components with equal outage risk
An example of such a component is FW / Blanket
A (Blanket) = 97.8 %

<u>A (FW / Blanket)</u>

$$A = \frac{MTBF}{MTBF + MTTR}$$

$$\boxed{\frac{MTBF}{MTTR} = 43.8}$$

<u>Note</u>: It is the Mean Time Between Failure which is the issue.
It is NOT lifetime

What MTBF Can Be Achieved?

Several Studies

- R. Bünde et al. (several articles, 1990-95)
- Abdou & Ying (1994)
- Detailed EU Blanket Evaluation (1994)

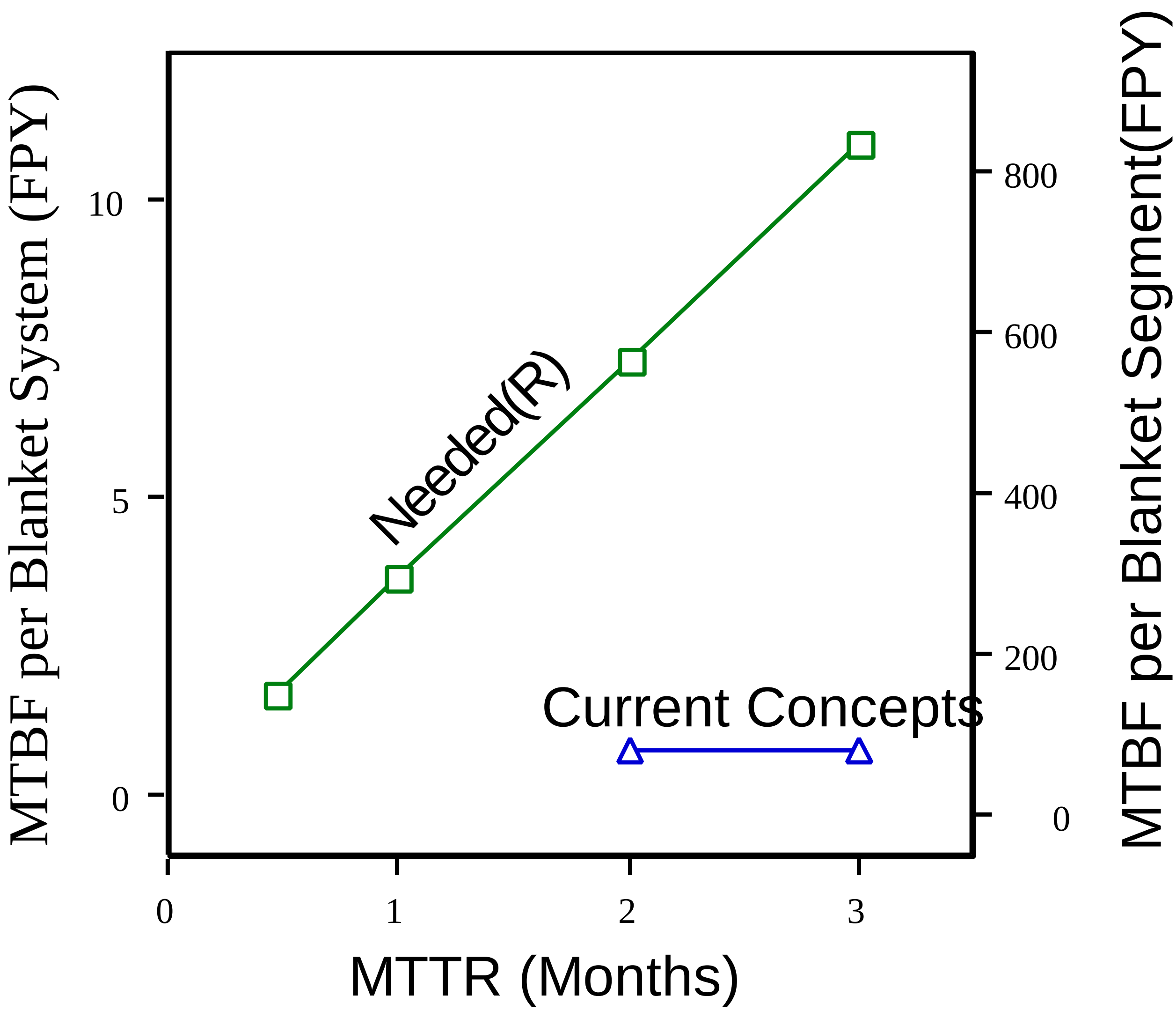
Methodology

- Compile Relevant Failure Rate from Mature Technologies (e.g. fission)
- Estimate Failure Frequency For the Best FW/Blanket Designs Available
    - ◊ Include Failures for Pipes and Welds
    - ◊ IGNORE (DO NOT Include) Fusion Specific Failure Modes

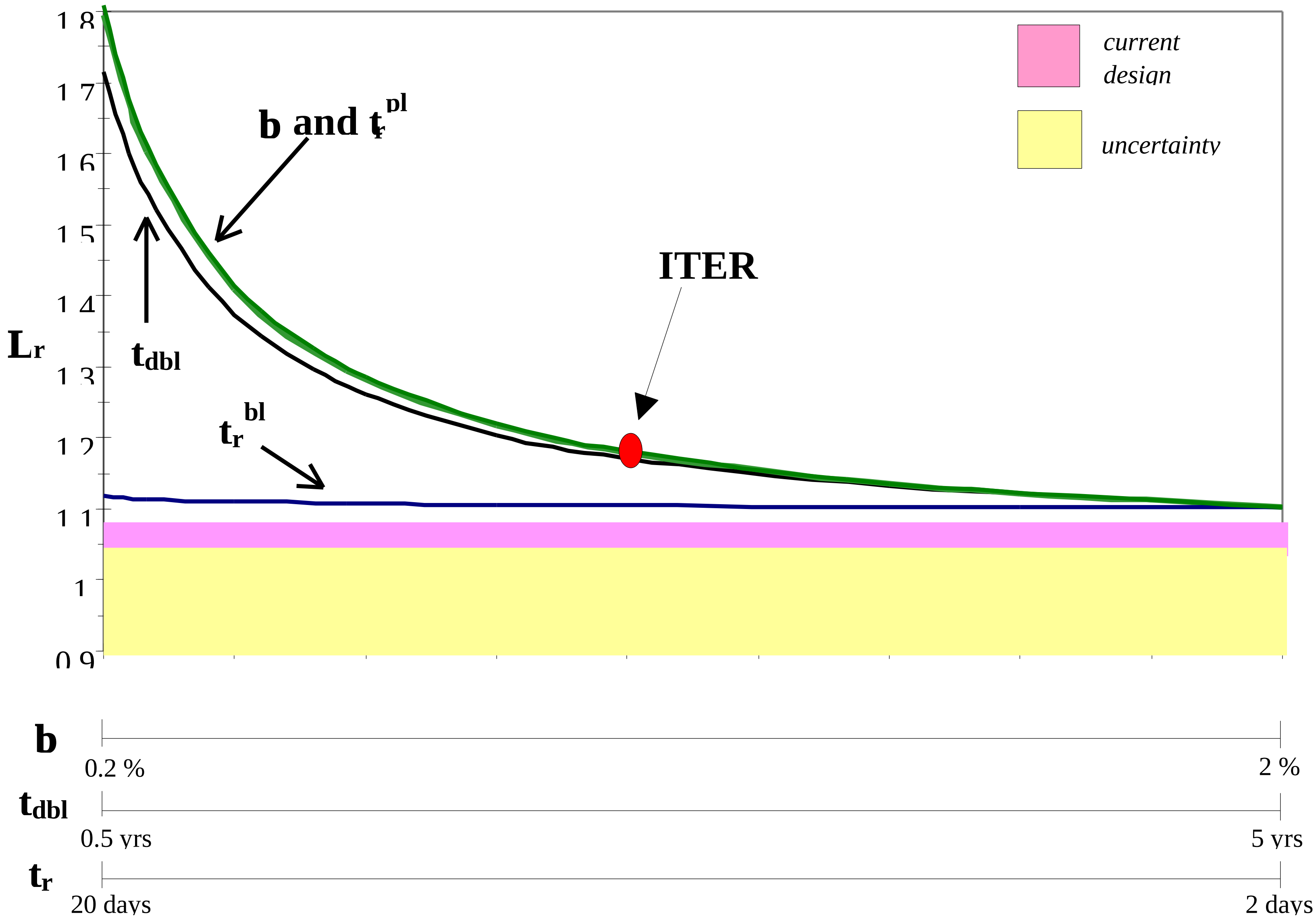
Failure Modes (FW)	**Failure Rate $hr^{-1}.m^{-1}$**	**Length**
Diffusion weld	1×10^{-9}	4.56 km
EB Weld	1×10^{-8}	2.93 km
Longitudinal weld	1×10^{-9}	19 km

Failure Modes (BLKT)	**Failure Rate $hr^{-1}.m^{-1}$**	**Length**
Longitudinal weld	1×10^{-9}	4.8 km
Butt weld	1×10^{-9}	2.58 km
Pipe bend (90°)	5×10^{-9}	1152 bends
Straight pipe	1×10^{-10}	2.9 km

Current FW/B Design Concepts are NOT Capable of Meeting the Challenging Reliability and Maintenance Requirements



Tritium Self Sufficiency is a Serious Issue



Summary of FPT most challenging issues

1) Economic competitiveness requires much higher power density than we have been working on. Current first wall/blanket concepts are limited to about 2 or 2.5 MW/m^2 neutron wall load. Comparison to fission reactors reveals that much more higher neutron wall loads should be the goal for fusion R & D.
2) Tritium self-sufficiency is highly uncertain with present concepts.
3) Failure rates as extrapolated from current technologies are too high with present first wall/blanket concepts (and due to the nature of present magnetic confinement schemes)
4) Maintainability is a serious issue with current concepts. Specifically, MTTR (mean time to recover from failure) is very long. Such long MTTR (>2 months) seriously reduces reactor availability and make requirements on MTBF impractical.

Path to Improving Fusion

- All the above four issues need to be addressed (ultimately).
- We need concepts that
    1) can handle much higher wall loads than we have been working on,
    2) can provide better margins for insuring self-sufficiency,
    3) have lower failure rate (longer MTBF), and
    4) faster maintenance (shorter MTTR)

APEX Focus

- APEX is only the first leg along the path toward improving fusion
- APEX will focus specifically on simulating new design concepts for in-vessel components that are capable of handling high neutron wall loads and the associated surface heat flux

The Driver for APEX (at least initially) will be the high wall load requirement

- Of course, we should keep an eye on maintainability, failure rate, and tritium self sufficiency plus many other criteria (low decay heat, low activation, etc.)
- However, we should not overconstrain the problem from the beginning. If we succeed in finding high power density concepts, we can work later on making them better for other issues.

We invite comments on this

Proposed Goals for Neutron Wall Load and Surface Heat Flux at the First Wall

1) Average Neutron Wall Load = 5 MW/m^2
Peaking Factor = 1.4
Peak Neutron Wall Load = 7.0 MW/m^2

Reasons

- High enough to improve economics
- Not overly ambitious: we probably can find a concept or two that meet the goal

2) Surface Heat Flux

A good approach to reducing the divertor problem to a more manageable level is to radiate most of the $\propto$- power to the first wall

- first wall surface area is more than ten times the divertor area
- this also allows useful (sensible) heat recovery for the $\propto$- power

Suggested Peak Surface Heat Flux ~ .85 x 0.25 x 7 ~ 1.5 MW/m^2

Design goals that must be met in a concept to be considered suitable for APEX
Neutron Wall Load = 7 Surface Heat Flux = 1.5

APEX Phases

APEX will be conducted in three phases that are mostly sequential but with some overlap

1. Planning Phase lasting for about 4 months
   Start: October 15, 1997
   Report Due: February 15, 1998
2. Evaluation and Supporting R & D Phase lasting for approximately 3 years
   Start: October 15, 1997
   End: September 30, 2000
3. R & D Phase beginning after the Evaluation Phase (Beginning FY 2001)

Notes:

- The planning phase is the responsibility of the Planning Group
- The evaluation phase is the responsibility of the APEX Team
- By starting the evaluation phase early, we can learn about the range of concepts and issues. This makes the planning more realistic

The APEX Planning Group

- This group will initially (the first four months) prepare a planning report (due Feb. 15, 1998)

- Recommendation: This group should continue as the core of the APEX Team for the evaluation phase. Some members can be very active in actual design conceptualization and analysis. Others with limited time and limited resources can provide advise, guidance and resource of knowledge

APEX Tasks

Task 1: Delineate function requirements and develop evaluation Approach (criteria)

A. Special driver criteria (high wall load)
B. General Criteria (economics, safety, environmental)
C. R & D and potential success criteria

Task 2: Determine the key limiting factors on high power density

- understand the limits to learn how to extend them

Task 3: Explore concepts with high power density capability

- A primary task
- Primary sources of new concepts:
  - A) concepts previously proposed in literature
  - B) "Innovation through analogy" to other technologies (e.g. rocket engine)
  - C) "Innovation through pursuit of engineering science logic" (building on what we learn from Task 2)

Task 4: Preliminary conceptual designs for new concepts

- Approach:
  - Concepts identified in Task 3 will be carefully analyzed and evaluated
  - Initially, examine the scientific foundation of the concept
  - If a concept has sound scientific basis, a preliminary conceptual design will be attempted to satisfy all functional requirements of FPT
  - Only if such effort is successful for a concept, will we attempt to improve and optimize it using the evaluation criteria as a guide

- Please note that some concepts require new models and methods of analysis to predict behavior. This can be a major effort

- Initially, we will not constrain conceptualization too much. For example, low activation will not be an initial requirement.

- Output of this task
  a) a set of preliminary conceptual designs for a number of promising concepts
  b) preliminary evaluation of each concept
  c) a set of key issues for each concept

Task 5: Comparative evaluation and selection of most promising concepts

– The magnitude of this effort will strongly depend on the outcome of Task 4, i.e. how many concepts (There may be none, or only one, or many)
– If there are several concepts, then the evaluation criteria developed in Task 1 will be utilized to select the most promising concepts that are worthy of further detailed studies

Task 6: Detailed analysis and evaluation of most promising concepts

– The most promising new concepts selected in Task 5 will be subjected to more comprehensive analysis and detailed evaluation
– Key issues will be identified and key R & D items will be recommended

Task 7: Study conclusions and report

Suggested Project Groups

(1) Design Conceptualization and Analysis

1. This is the core of the project
2. We encourage all individuals and organizations to contribute to this effort
3. We can have several subgroups around various concepts
4. Suggestions for such subgroups should be discussed in the meeting
   (or forwarded later to M. Abdou)

(2) Mechanical Design Group

This group will be responsible for assisting all design conceptualization groups in developing mechanical design and integration. The group has responsibility for:

1. Vacuum boundary concept
   (separate vacuum vessel, resistive shield, or other approaches)
2. Mechanical configuration
3. Maintenance approach

Chair: Brad Nelson, ORNL
Others from ORNL? (Brad to provide names)
Mark Tillack, UCSD
Other Volunteers?

(3) Materials Group

1. Suggest Materials for High Power Density Applications
2. Provide Basic Material Properties for Design,
   Assemble Database
3. Suggest Operating Limits
   -Minimum and maximum temperature limits
   (with justification)
   -Stress limits
4. (Later) Evaluate compatibility of proposed combinations of materials.

Chair: Steve Zinkle, ORNL
Members: N. Ghoniem, A. El-Azab, Zi Lu, Mike Billone,
Rick Mattas, M. Ulrickson

(4) Power Conversion

1. Evaluate/suggest advanced energy conversion cycles suitable for proposed high power density concepts
2. Delineate operating temperature, materials, and technology requirements and issues. Also estimate efficiency as a function of blanket/first wall outlet coolant temperature

Chair: Mark Tillack, UCSD
Members: D. Sze, C. Wong.
Others?

(5) Physics Interface Group

Provide physics boundary conditions for FPT design (some issues may require interface with the physics community to get the best input)

a) Operating temperature limits for liquids on the plasma-side of the first wall for lithium, LiPb, Pb (vapor pressure is one of the considerations)
Also, how can impurity control and exhaust scheme relax these requirements
b) What is reasonable to assume about the fraction of alpha power that could be radiated to the first wall?
c) Spatial distribution of the alpha power on the first wall (peak-to-average ratio may be good enough)
d) Transients conditions for (long-term best) plasma to beassumed for power reactors
e) Evaluate dependence of physics boundary conditions on reactor confinement scheme

Members: Robert Woolley, Mike Ulrickson, Ralph Moir
Others?
(Need Physicists?)

(6) Safety Group

a) Summarize and provide "fresh"guidance on how to improve safety

(cover all key issues: chemical reactivity, toxicity, tritium, dose, etc.)

b) What are the real limits on decay heat
(keeping in mind recent lessons from ITER)?

c) If there is a trade off between passive safety and low long-term
activation, which direction is preferred?

d) Reevaluate low activation requirements considering recycling
and also for the small volume of the first wall

Chair: Kathy McCarthy, INEL
Others from INEL?
Other Volunteers?