APPENDIX C

Key Tables and Figures from: 1) FINESSE (1984-87), and 2) IEA Study on VNS (1994-95) that deal with FNT issues and testing requirements in non-fusion and fusion facilities

Table 3. Worldwide Blanket Options for DEMO

Breeder	Coolant	Structural Material
A. Solid Breeders Li_2O, Li_4SiO_4, Li_2ZrO_3, Li_2TiO_3	He or H_2O	FS†, V alloy, SiC Composites
B. Self Cooled Liquid Metal Breeders Li, LiPb	Li, LiPb	FS, V alloy with Electric Insulator, SiC Composites with LiPb only
C. Separately Cooled Liquid Metal Breeders Li LiPb	He He or H_2O	FS, V alloy FS, V alloy, SiC Composites

* almost all concepts use beryllium as neutron multiplier
† FS = Ferritic Steel

For solid breeder blankets, the major classes of issues include:

1. Tritium self sufficiency
2. Breeder/multiplier/structure interactive effects under nuclear heating and irradiation
3. Tritium inventory, recovery and control; development of tritium permeation barriers
4. Thermal control
5. Allowable operating temperature window for breeder
6. Failure modes, effects, and rates
7. Mass transfer
8. Temperature limits for structural materials and coolants
9. Mechanical loads caused by major plasma disruption
10. Response to off-normal conditions

TABLE I

Fusion Program Guidelines for DEMO Major Parameters and Features

Parameter of Feature	European Union	Japan	Russian Federation	United States
Plasma mode of operation	Aim for steady state; determine whether long-burn pulsed operation can be tolerated	Steady state	Both pulsed and steady state are being considered	Steady state
Tritium fuel cycle: global	Self-sufficient	Self-sufficient	Self-sufficient	Self-sufficient
Tritium breeding ratio (TBR)	TBR > 1.0	TBR > 1.0	TBR: 1.05 to 1.1	TBR > 1.0+ addition for doubling time
Power output	Significant amounts of electricity	3 GW fusion power	<1.5 GW(electric)	Hundreds of megawatts(electric)
Neutron wall loading (MW/m^2)	2 to 3	Up to 5.0	2 to 3	2 to 3 average 3 to 4 peak
Availability	Depends on DEMO mission; could be >50% for reactor island	70%	>60%	50% net plant goal[a]
Thermal efficiency	Unspecified	30 to 40% net	>40%	>30% net
Blanket lifetime goal (MW·yr/m^2)	Depends on specific DEMO goals; could be 5 for first blanket and >10 long term	Up to 7	15 to 20	10 to 20
Environmental consideration	Due account of environmental constraints	Low-activation materials	Low-activation materials; recycling and refabrication of DEMO materials	Low-activation materials; recycling and refabrication of DEMO materials

[a] An initial stage of lower availability is acceptable provided the goal availability is reached and sustained for several years.

century. According to this plan, if the research and development (R&D) in the experimental reactor stage (e.g., ITER) progresses well, the operation of the DEMO can be expected in the 2020 to 2030 period, and commercialization of fusion power can be expected by the middle of the next century. A recent draft pamphlet[3] showing the annual progress of fusion research at the Japan Atomic Energy Research Institute (JAERI) reports the operation of DEMO to be around 2030.

Reference 2 indicates that the mission of the DEMO phase of fusion R&D is to demonstrate in a plant scale the technological feasibility of realizing a high-energy multiplication steady-state plasma, of extracting energy generated from the plasma, and of converting the energy into electricity. A DEMO would demonstrate all the technologies necessary for a commercial fusion power reactor but would not necessarily be economically competitive. The DEMO technologies would be sufficient to achieve tritium breeding and power generation, reliable operation and maintainability, and benign environmental and safety aspects.

In the PROTO reactor phase of fusion R&D (i.e., a prototype commercial fusion power plant), the reactor load and utilization factors would be enhanced, and by the efficient utilization of the reactor power, the overall plant energy efficiency should be improved with the aim of demonstrating that a fusion reactor has a sufficient economic capability as an energy generation plant.

Table I provides examples of DEMO major parameters and features based on the foregoing discussion.

II.B.3. Russian Federation Perspective

The Russian Federation strategy for developing fusion on the path toward the practical use of fusion energy is based on three sequential basic steps: an experimental reactor (e.g., ITER), DEMO, and a commercial power reactor. The engineering foundation of DEMO must be based on ITER and its testing program. The proposed start of DEMO operation is 2025.

A conceptual study of a DEMO was begun in 1992 with the goals of choosing key parameters for DEMO based on the database from ITER, of performing a conceptual design of main DEMO systems, of specifying requirements for the ITER testing program, and of

Table 5. Summary of Critical R&D Issues for Fusion Nuclear Technology

1. D-T fuel cycle **self sufficiency**
2. **Thermomechanical** loadings and response of blanket components under normal and off-normal operation
3. Materials **compatibility**
4. Identification and characterization of **failure modes, effects, and rates**
5. Effect of imperfections in electric (MHD) **insulators** in self cooled liquid metal blanket under thermal/mechanical/electrical/nuclear loading
6. **Tritium inventory** and recovery in the solid breeder under actual operating conditions
7. **Tritium permeation** and inventory in the structure
8. Radiation Shielding: accuracy of prediction and quantification of radiation production requirements
9. Plasma-facing component thermomechanical response and lifetime
10. **Lifetime** of first wall and blanket components
11. Remote maintenance with acceptable machine shutdown time.

Table 6. Key Fusion Environmental Conditions for Testing Fusion Nuclear Components

- **Neutrons** (fluence, spectrum, spatial and temporal gradient)
  - Radiation Effects
    (at relevant temperatures, stresses, loading conditions)
  - Bulk Heating
  - Tritium Production
  - Activation

- **Heat Sources** (magnitude, gradient)
  - Bulk (from neutrons)
  - Surface

- **Particle Flux**

- **Magnetic Field**
  - Steady Field
  - Time-Varying Field

- **Mechanical Forces**
  - Normal
  - Off-Normal

- **Thermal/Chemical/Mechanical/Electrical/Magnetic Interactions**

- **Synergistic Effects**
  - Combined environmental loading conditions
  - Interactions among physical elements of components

Table 7. Test Categories for Blanket R&D

Basic test

- Basic or intrinsic property data
- Single material specimen
- Examples: thermal conductivity; neutron absorption cross section

Single-effect test

- Explore a single effect, a single phenomenon, or the interaction of a limited number of phenomena, in order to develop understanding and models
- Generally a single environmental condition and a "clean" geometry
- Examples: (a) pellet-in-can test of the thermal stress/creep interaction between solid breeder and clad; (b) electromagnetic response of bonded materials to a transient magnetic field; (c) tritium production rate in a slab of heterogeneous materials exposed to a point neutron source

Multiple-effect/multiple interaction test

- Explores multiple environmental conditions and multiple interactions among physical elements in order to develop understanding and prediction capabilities
- Includes identifying unknown interactions, and directly measuring specific global parameters that cannot be calculated
- Two or more environmental conditions; more realistic geometry
- Example: testing of an internally cooled first-wall section under a steady surface heat load and a time-dependent magnetic field

Partially integrated test

- Partial "integration test" information, but without some important environmental condition to permit large cost savings
- All key physical elements of the component; not necessarily full scale
- Example: liquid-metal blanket test facility without neutrons if insulators are not required. (For concepts requiring insulators, tests without neutrons are limited to multiple effect.)

Integrated test

- Concept verification and identification of unknowns
- All key environmental conditions and physical elements, although often not full scale
- Example: blanket module test in a fusion test device

Component test

- Design verification and reliability data
- Full-size component under prototypical operating conditions
- Examples: (a) an isolated blanket module with its own cooling system in a fusion test reactor; (b) a complete integrated blanket in an experimental power reactor

TABLE IV

List of B/FW Testing Issues

- Structure
  - Changes in properties and behavior of materials
  - Deformation and/or breach of components
    - Effect of first-wall heat flux and cycling on fatigue or crack growth–related failure
    - Magnetic forces within the structure (including disruptions)
    - Premature failure at welds and discontinuities
    - Failures due to hot spots
    - Interaction of primary and secondary stresses and deformation
    - Effect of swelling, creep, and thermal gradients on stress concentrations (e.g., in grooved surfaces)
    - Failure due to shutdown residual stress
    - Interaction between surface effects and first-wall failures
    - Self-welding of similar and dissimilar metals
  - Tritium permeation through the structure
    - Effectiveness of tritium permeation barriers
    - Effect of radiation on tritium permeation
  - Structural activation product inventory and volatility
  - Hermiticity of SiC

- Coolant
  - MHD pressure drop and pressure stresses
  - MHD and geometric effects on flow distribution
  - MHD insulating coating fabrication, integrity, and in situ self-healing
  - Stability/kinetics of tritium oxidation in the coolant
  - Helium bubble formation leading to hot spots
  - Coolant/purge stream containment and leakage
  - Activation products in Pb-Li
  - Liquid-metal purification

- Breeder and purge
  - Tritium recovery and inventory in solid breeder materials
  - Liquid breeder tritium extraction
  - Temperature limits and variability in solid breeder materials
    - Temperature limits
    - Thermal conductivity changes under irradiation
    - Effect of cracking
    - Effect of LiOT mass transfer
  - Breeder behavior at high burnup/high dpa

- Coolant/structure interactions
  - Mechanical and materials interactions
    - Corrosion
    - Mechanical wear and fatigue from flow-induced vibrations
    - Failure of coolant wall due to stress corrosion cracking
    - Failure of coolant wall due to liquid-metal embrittlement
  - Thermal interactions
    - MHD effects on first-wall cooling and hot spots
    - Response to cooling system transients
    - Flow sensitivity to dimensional changes
  - Coolant/coatings/structure interactions

- Solid breeder/multiplier/structure interactions
  - Solid breeder mechanical and materials interactions
    - Clad corrosion from breeder burnup products
    - Strain accommodation by creep and plastic flow
    - Swelling driving force
    - Stress concentrations at cracks and discontinuities
    - Thermal expansion driving force
  - Neutron multiplier mechanical interactions
    - Beryllium swelling (swelling driving force in beryllium)
    - Strain accommodation by creep in beryllium
    - Mechanical integrity of unclad beryllium
  - Thermal interactions
    - Breeder-structure and multiplier-structure interface heat transfer (gap conductance)

- General blanket
  - D-T fuel self-sufficiency
    - Uncertainties in achievable breeding ratio
    - Uncertainties in required breeding ratio
  - Tritium permeation
    - Permeation from breeder to blanket coolant
    - Permeation from beryllium to coolant
    - Permeation characteristics at low pressure
  - Chemical reactions
  - Tritium inventory
  - Failure modes and frequencies
  - Nuclear heating rate predictions
  - Time constant for magnetic field penetration for plasma control
  - Blanket response to near blanket failures
  - Assembly and fabrication of blankets
  - Recycling of irradiated lithium and beryllium
  - Prediction and control of normal effluents associated with fluid radioactivity
  - Liquid-metal blanket insulator fabrication, effectiveness, and lifetime
  - Tritium trapping in beryllium

Table 14. Capabilities of Non-fusion Facilities for Simulation of Key Conditions for Fusion Nuclear Components Experiments

	Neutron Effects(1)	Bulk Heating(2)	Non-Nuclear(3)	Thermal/ Mechanical/ Chemical/ Electrical(4)	Integrated Synergistic
Non-Neutron Test Stands	no	no	partial	no	no
Fission Reactor	partial	partial	no	no	no
Accelerator-Based Neutron Source	partial	no	no	no	no

(1) radiation damage, tritium and helium production

(2) nuclear heating in a significant volume

(3) magnetic field, surface heat flux, particle flux, mechanical forces

(4) thermal-mechanical-chemical-electrical interactions (normal and off normal)

TABLE VIII

Capabilities of Available Fission Reactors for Blanket Tests

Reactor	Location	Reactor Power (MW)	Fast Flux (n/cm^2·s)	Thermal Flux (n/cm^2·s)	Dimension of Irradiation Channel (cm)	Effective Core Height (cm)
EBR-II	United States	62	2.0×10^{15}		7.4 (circular)	36
HFIR	United States	100	1.5×10^{15}	2.3×10^{15}	3.7 (circular)	51
ATR	United States	250	1.9×10^{14}	8.8×10^{14}	6.05 (seven flux traps)	122
RBT-10	Russia	10	4.4×10^{13}	2.3×10^{13}	15.8 × 23.7	35
SM-3	Russia	100	2.2×10^{14}	8.8×10^{13}	6 and 16 (circular)	35
IVV-2M	Russia	20	9.3×10^{13}	5.5×10^{13}	14.7 × 25.5	50
Phénix	France	250	1.3×10^{15}		12.67 (hexagonal)	85
OSIRIS	France	70	5.0×10^{14}	1×10^{14}	8.4 (circular)	60
SILOE	France	35	5.0×10^{14}	4.0×10^{14}	8.0 (circular)	60
BR-2	Belgium	60	6.0×10^{14}	1.0×10^{15}	20 (circular)	96
HFR	The Netherlands	20	5.0×10^{14}		14.5 (circular)	60
JRR-2	Japan	10	1.0×10^{14}	1.0×10^{14}		
NRU	Canada	125	4×10^{13}	2.4×10^{14}	10 (circular)	300

Most serious is the small test volume. For example, there is no fission reactor now operating anywhere in the world that can provide a test location with a ≥15-cm equivalent circular diameter at a fast neutron flux equivalent to 1 MW/m^2 wall loading ($\geq 1 \times 10^{15}$ n/cm^2·s). This limitation, together with some safety aspects of fission reactors, also makes the simulation of nonnuclear effects such as magnetic field and mechanical forces very difficult or impossible. Another set of problems arises from the difference between the fission and fusion reactor neutron and secondary gamma-ray spectra. These differences lead to difficulties in simulating the magnitude, profile, and time-dependent behavior of reaction rates such as helium and tritium production, as well as power density and atomic displacements.

TABLE IX

Key Limitations of Fission Reactors

- Small test volume
  - Small size per location
  - Small number of existing locations
- Lack of fusion-related (nonneutron) conditions
  - Magnetic field
  - Surface heat
  - Particle flux
  - Mechanical forces
  - Accessibility
- Lack of fusion-related radiation damage parameters
  - Neutron spectra
  - Helium-to-dpa ratio
  - Types and rates
- Lack of fusion-related power density
  - Magnitude
  - Spatial profile
- Lack of fusion-related lithium burnup rate
  - Magnitude
  - Spatial profile
- Reactivity considerations limits on size and type of experiments
- Availability of fission test reactors for testing (rapid downward trend)

Despite these limitations, fission reactor testing is extremely useful for near-term FNT experiments. It is suited for some multiple-effect tests that depend on nuclear effects and are less sensitive to nonnuclear effects. Examples are tests of a unit cell of a solid breeder blanket to investigate tritium release behavior and some aspects of breeder/structure interactions.

IV.C. Accelerator-Based Neutron Sources

Accelerator-based neutron sources produce neutrons in such a small volume that they are normally called point neutron sources. Deuterium-tritium point sources produce 14-MeV neutrons, hence the correct fusion spectra, but their yield in existing facilities is limited technologically to $\sim 10^{13}$ n/s. Such a yield results in a very low neutron flux. Even at a small distance as close as 5 cm to the target, the neutron flux is more than five orders of magnitude lower than that in a fusion reactor with a 1 MW/m^2 wall load. Furthermore, the life of the target is limited to a <100-h irradiation. Therefore, the usefulness of D-T point neutron sources is limited to neutronics experiments, e.g., measurements of tritium production rates (TPRs).

Contribution of Non-Fusion Facilities to Resolving Critical Issues for Fusion Nuclear Technology Component Performance Demonstration[a]

Critical Issue	Non-neutron Test Stands	Fission Reactors	Accelerator Based Neutron Sources	
			D-T	D-Li
1. D-T fuel cycle self sufficiency	none	small	partial[b]	none
2. Thermomechanical loadings and response of blanket components under normal and off-normal operation	small	small	none	none
3. Materials compatibility	some	some	none	small
4. Identification and characterizations of failure modes, effects and rates	none	none	none	none
5. Effect of imperfections in electric (MHD) insulators in self cooled liquid metal blanket under thermal/mechanical/electrical/nuclear loading	small	small	none	small
6. Tritium inventory and recovery in the solid breeder under actual operating conditions	none	partial	none	none
7. Tritium permeation and inventory in the structure	some	partial	none	small
8. Radiation shielding: accuracy of prediction and quantification of radiation protection requirements	none	small	partial	small
9. Plasma-facing component thermomechanical response and lifetime	some	some	none	some
10. Lifetime of first wall and blanket components	none	partial	none	partial[b]
11. Remote Maintenance with acceptable shutdown time	none	none	none	none

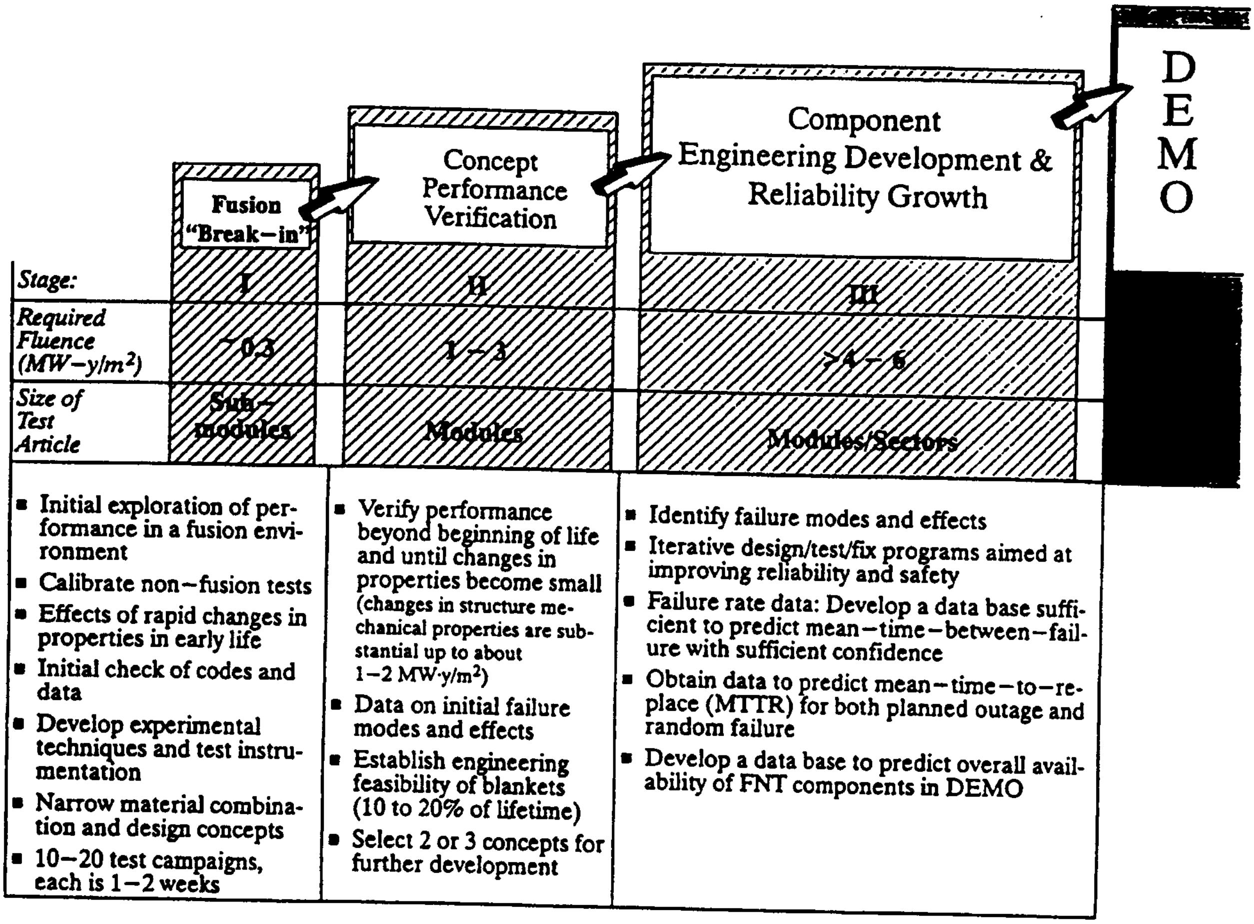
Table 22. Major R&D Tasks To Be Accomplished Prior to DEMO

1) **Plasma**
    - Confinement
    - Impurity control and exhaust (divertor)
    - Disruption control
    - Current drive

2) **System Integration**

3) **Plasma Support Systems**
    - Magnets
    - Heating

4) **Fusion Nuclear Technology Components and Materials**
    [Blanket, First Wall, High Performance Divertors]
    - Materials combination selection
    - Performance verification and concept validation
    - Show that the fuel cycle can be closed
    - Failure modes and effects
    - Remote maintenance demonstration
    - Reliability growth
    - Component lifetime
    - Mean time to recover from failure



- Initial exploration of performance in a fusion environment
- Calibrate non−fusion tests
- Effects of rapid changes in properties in early life
- Initial check of codes and data
- Develop experimental techniques and test instrumentation
- Narrow material combination and design concepts
- 10−20 test campaigns, each is 1−2 weeks

- Verify performance beyond beginning of life and until changes in properties become small (changes in structure mechanical properties are substantial up to about 1−2 MW·y/m²)
- Data on initial failure modes and effects
- Establish engineering feasibility of blankets (10 to 20% of lifetime)
- Select 2 or 3 concepts for further development

- Identify failure modes and effects
- Iterative design/test/fix programs aimed at improving reliability and safety
- Failure rate data: Develop a data base sufficient to predict mean−time−between−failure with sufficient confidence
- Obtain data to predict mean−time−to−replace (MTTR) for both planned outage and random failure
- Develop a data base to predict overall availability of FNT components in DEMO

Fig. 3. Stages of FNT testing in fusion facilities.

There are other important requirements that are not given in Table XVII, such as the value of the magnetic field in the blanket test region (e.g., to test liquid-metal blankets or the effects of ferritic steel on magnetic performance), surface heat flux, and minimum test area per module. We limited Table XVII to those requirements that appear to be major discriminating factors in the selection among options for fusion testing facilities. Other parameters not given in Table XVII are either implied or can be deduced from those already given or do not appear to be crucial discriminating factors in the selection among options for fusion testing facilities. The technical basis for the values given in Table XVII are briefly summarized in Secs. V.B.1, V.B.2, and V.B.3.

V.B.1. Neutron Wall Load

The minimum acceptable neutron wall load is derived from two factors: (a) engineering scaling considerations and (b) trade-offs between device availability and wall load for a given testing fluence and testing time.

Volumetric heating in the blanket is directly proportional to the wall load. Most thermomechanical and tritium-related phenomena in the blanket strongly depend on the temperature and stress profiles, which in turn are directly dependent on the heating rates. Since the wall load in a fusion test facility is likely to be much lower than that in DEMO (~3 MW/m^2) and commercial plants (~4 to 5 MW/m^2), engineering scaling considerations[6,7,31] are crucial. Useful testing at a reduced wall load, relative to DEMO and reactor conditions, is possible by altering the design and operating parameters of the test modules. Test modules must "act like" rather than "look like" a DEMO module. Generally, the coolant bulk average temperatures are easy to maintain by varying the coolant speed and flow rate. Temperature distributions within components are much more difficult to maintain. Some control over temperature distributions can be obtained by changing the thickness of blanket elements within the blanket as well as the overall dimensions of the test module. However, very large changes in sizes lead to new effects and an

Table A. 3 Estimated Failure Rate for Typical Blanket Based on Data from Non-fusion Technologies. Failure rates given here do not include fusion-specific failure modes.

Blanket Element	No. or Length of Elements per Blanket Module	(Unit) Failure Rate(1)		Failure Rate per Blanket Module (1/h)	
		Mean	High	Mean	High
Longitudinal Welds	66 m	5.0e-8 /h-m	5.0 e-7/h-m	3.3125e-6	3.3125e-5
Butt Welds of Pipe	462	5e-9 /h-weld	1e-7/h-weld	2.31e-6	4.62e-5
Pipes (straight)	2.75 km	5e-10/h-m	1e-8/h-m	1.375e-6	2.75e-5
Pipe Bend	28	1e-8/h-bend	3.5e-7/h-bend	2.8e-7	9.8e-6
Overall Failure Rate per Module (1/h)		$7x10^{-6}$ - $1x10^{-4}$			
Calculated MTBF per module (years)		1 - 16			
Calculated MTBF for blanket system (years)- 80 modules		0.01 - 0.2			

(1) R. Bünde, et. al., 16(1991) 59-72 (Fus. Eng. & Design 1991) [failure rates are based on experience from non-fusion technologies]

Table A-5. Examples of possible Failure Modes in Blanket/First Wall (for solid and liquid breeder blanket concepts)

- Cracking around a discontinuity/weld
- Crack on shutdown (with cooling)
- Solid breeder loses functional capability due to extensive cracking
- Cracks in electrical insulators (for liquid metal blankets)
- Cracks, thermal shock, vaporization, and melting during disruptions
- First wall/breeder structure swelling and creep leading to excessive deformation or first wall/coolant tube failure
- Environmentally assisted cracking
- Excessive tritium permeation to worker or public areas
- Cracks in electrical connections between modules

Our concern is that failure rates may be much higher in fusion blankets because they appear to be much more complex than steam generators and the core of fission reactors because of the following points:

- Larger numbers of subcomponents and interactions (tubes, welds, breeder, multiplier, coolant, structure, insulators, tritium recovery, etc.).
- More damaging, higher energy neutrons.
- Other environmental conditions: magnetic field, vacuum, tritium, etc. (for example, a leak from the first wall or blanket module walls into the vacuum system results in failure, while in steam generators and fission reactors, continued operation with leaks is often possible).
- Reactor components must penetrate each other; many penetrations have to be provided through the blanket for plasma heating, fueling, exhaust, etc.
- Ability to have redundancy inside the blanket / first wall system is practically impossible.

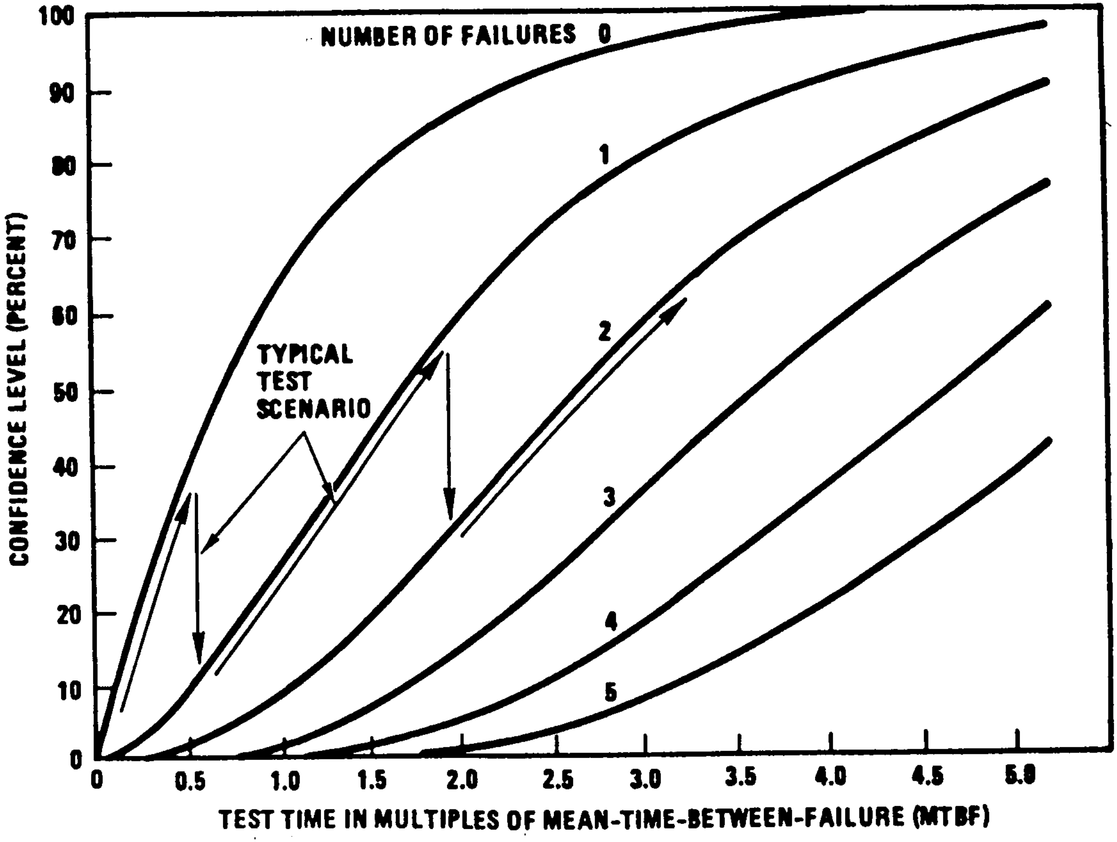


Fig. 8. Confidence level as a function of test time in multiples of MTBF and the number of failures that occur during the tests.