TECHNICAL REQUIREMENTS OF EXPERIMENTS AND FACILITIES FOR FUSION BLANKET DEVELOPMENT*

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ABSTRACT

The technical issues, development problems, and required experiments and facilities for both solid and liquid breeder blankets have been investigated. The results have been used to develop a technical framework for a test plan that identifies the role, timing, and characteristics of major experiments and facilities. A major feature of this framework is the utilization of non-fusion facilities over the next 15 years, followed by testing in fusion devices beyond about the year 2000. Basic, separate-effect and multiple-interaction experiments in non-fusion facilities will provide property data, explore phenomena and provide input to theory and analytic modeling. Experiments in fusion facilities can proceed in two phases: 1) concept verification and 2) component reliability growth. Integrated testing imposes certain requirements on fusion testing device parameters; these requirements have been quantified.

I. INTRODUCTION

The first wall/blanket is a particularly important fusion nuclear component that has a number of critical feasibility and attractiveness concerns. Blanket concepts can be divided into liquid breeders and solid breeders. Within each class, there are a number of distinct material and design options, as shown in Figure 1. Although the functional requirements (e.g., tritium breeding) and reactor operating conditions (e.g., neutron wall load) are similar for both classes of blankets, the critical issues are generally not. Consequently, the issues and associated experiments are discussed separately.

Within the uncertainties, it is not possible to determine whether solid or liquid breeder blankets are more attractive. Consequently, it appears prudent for the fusion program to retain both options, although a selection could be made at some point in the future when more information is available. In the test plans considered here, this selection is not explicitly made. Rather, separate test plans are presented that could develop solid and liquid breeder blanket concepts to the point of integrated fusion testing.

In general, the overall strategies of fusion development have been carried out in the U.S. as part of the Technical Planning Activity for fusion(1); and as part of the FINESSE program for the nuclear technology.(2) The work reported here is summarized from the FINESSE work, but is generally consistent with the recommendations of TPA.

II. SOLID BREEDER BLANKETS

The general classes of issues for solid breeder blanket are given in Table 1. These are based on the characteristics of solid breeder concepts from recent studies such as the Blanket Comparison and Selection Study (BCSS).(3) Some of the design uncertainties resulting from these issues are large enough to make the blankets potentially impractical. The most important uncertainties are related to tritium breeding, tritium recovery, and breeder thermomechanical behavior.

TABLE 1. Solid Breeder Blanket Issues

Tritium self-sufficiency
Breeder/multiplier tritium inventory and recovery
Breeder/multiplier thermomechanical behavior
Corrosion and mass transfer
Structural response and failure modes in fusion environment
Tritium permeation and processing from blanket

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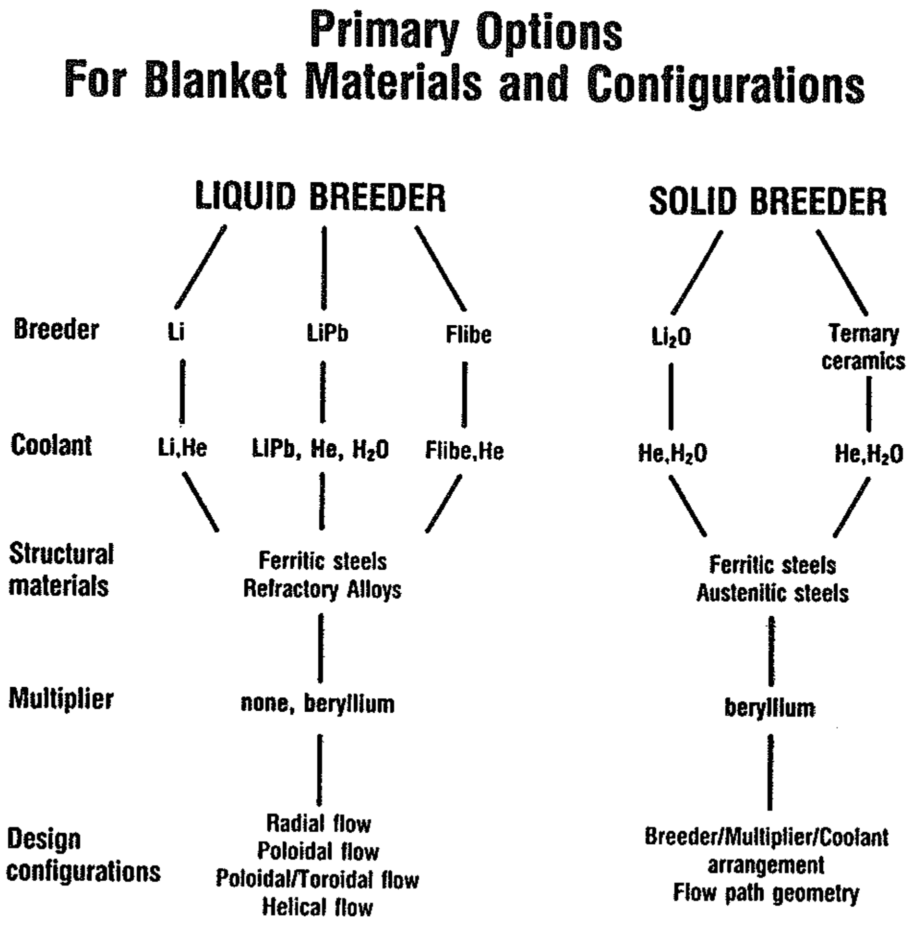

—Further experimental work is required prior to selection.

Figure 1. Primary blanket options

The issues can be addressed by a range of possible experiments as summarized in Figure 2. The actual experiments will depend on particular test program assumptions and funding constraints. These tests are organized according to their level of integration, from basic properties, to phenomena exploration in separate and multiple effect tests, to concept verification in integrated fusion tests.

The basic material in solid breeder blankets can be tailored to some degree to provide specific properties. The objective of these experiments is to fabricate, characterize, and improve the properties of candidate breeder materials. The measurement of tritium recovery and thermal behavior in closed and open capsule irradiation of material specimens is an integral part of this task. Various completed and active irradiation experiments to characterize and understand material parameters are summarized in Table 2. The immediate goal is to provide basic data for candidate breeder materials to support blanket designs and provide a basis for the selection of materials (e.g., Li_2O or $LiAlO_2$) and material parameters (e.g., grain size, sintered versus sphere-pac). In the long-term, this task will seek to optimize the properties of selected materials, and to develop fabrication techniques that can be extrapolated to commercial operation.

A test program for the development of solid breeder (and liquid breeder) blankets can proceed with the four overlapping phases outlined in Table 3. The nature of the information sought in each phase gradually shifts from fundamental, scientific data to empirical, design-related data which will ultimately be requried to support testing in a fusion environment. The phasing is important due to our present inability to demonstrate a clearly superior blanket design, and because some of the required types of experiments vary widely between different blanket options.

Figure 3 illustrates a solid breeder test sequence that structures the experiments according to the test program phases described in Table 3, with initial emphasis on understanding material behavior and blanket phenomena and a 15-year objective of concept verification in a non-fusion environment.

III. LIQUID BREEDER BLANKETS

A number of large uncertainties also exist in the behavior of liquid breeder blankets, leading to uncertainties in their feasibility and attractiveness. Generic issues have been defined to encompass the most promising blanket designs. These issues are listed in Table 4 and are discussed below. Issues relating to safety and/or transient effects are not listed separately, as they are considered an integral part of each issue.

Liquid breeder blankets encompass a variety of generic design variations and material combinations. Current designs include a number of self-cooled and separately cooled options with widely varying geometries. Table 5 indicates the effect of material choices on the dominant near-term issues. The existence and seriousness of the major issues depend not only on the particular blanket concept, but also on the operating conditions such as power density, magnetic field, surface heat flux, temperature, and duct length.

Through examination of the key issues and test requirements, a complete matrix of needed experiments and test facilities has been identified. Figure 4 shows this matrix of tests for liquid breeder blankets, including some experiments which are already in progress.

The objectives of the liquid breeder blanket test plan are similar to those of solid breeder blankets. However, the experiments are quite different in several ways. For liquid breeder blankets, most of the key issues can be resolved in non-neutron test facilities. These include, for example, fluid flow, heat transfer, structural response, and material interaction test stands. Another important difference is the greater uncertainty in material behavior for solid breeders as opposed to liquid breeder blankets. While the issues for liquid breeder blankets are very dependent on the choice of materials, the material properties themselves are generally not considered key uncertainties.

Figure 5 shows greater detail in the test program for liquid breeder blankets.(1) The figure indicates specific experiments and classes of experiments which should be performed in each task area such that the milestones and objectives can be met. The initial years of the plan are dedicated to a large number of small experiments in the task areas of MHD effects, material compatibility, tritium recovery, and tritium breeding. Since magnetic field effects are expected to be a dominant influence on self-cooled blanket behavior, a number of second generation facilities and experiments are indicated to explore advanced MHD effects, including MHD mass transfer and MHD heat transfer/fluid flow using elements of actual blanket geometries. After approximately 10 years, a small number of large scale experiments will be required for concept verification to the maximum extent possible in non-fusion facilities. For liquid breeder blankets, two different options for concept verification are indicated. A Thermomechanics Integration Facility (TMIF) is needed to explore MHD and material compatibility issues in a large system with prototypical designs. A non-neutron Partially

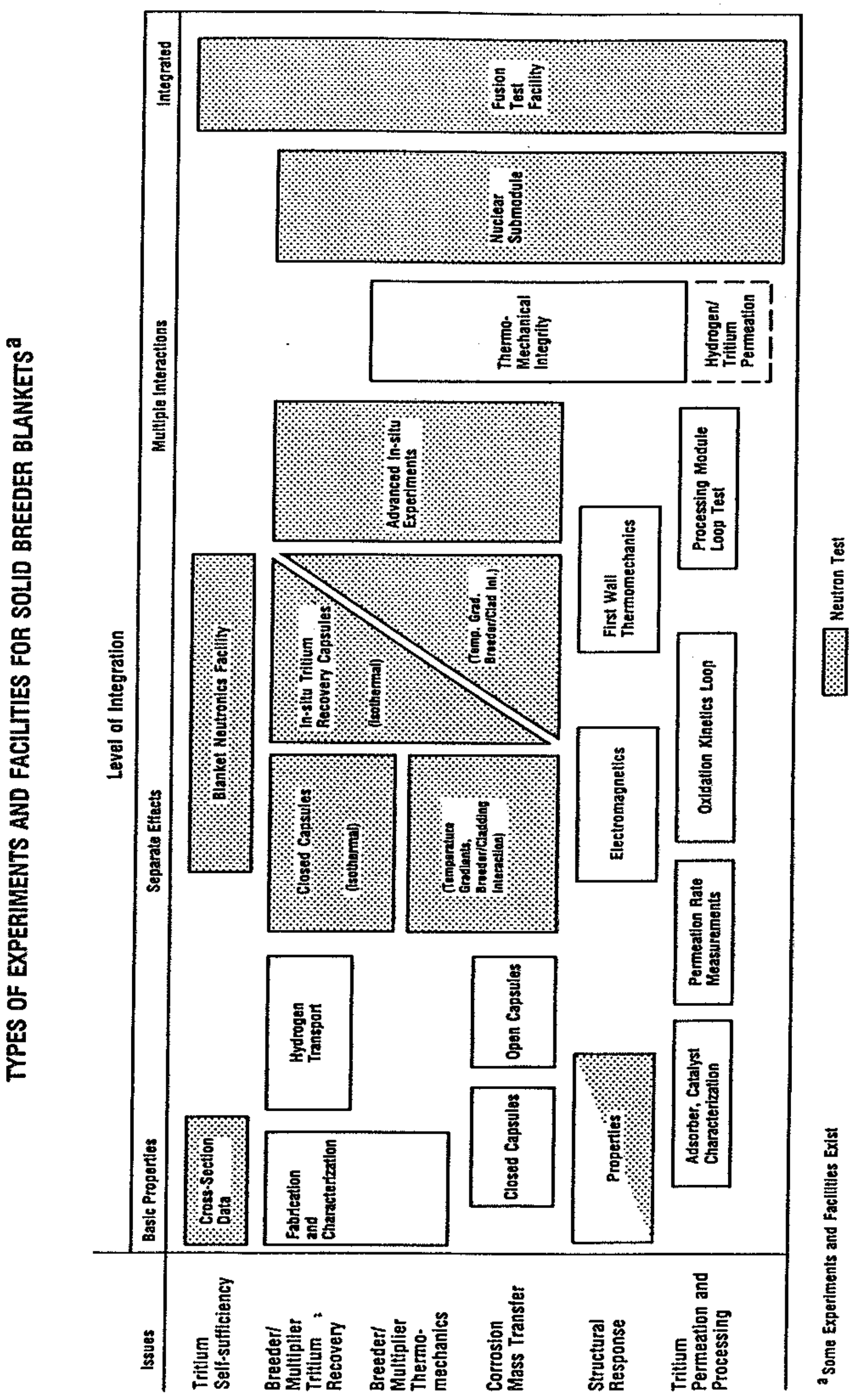

Figure 2. Types of experiments and facilities for solid breeder blankets[a]

Table 2. Completed and Active Solid Breeder Material Irradiation Experiments

Experiment	Ceramic	Grain size (μm)	Density (%TD)	Temperature (°C)	Li burnup (Max at.%)	Time Frame
Closed Capsule						
ORR (US)	Li_2O	< 47	70	750,850,1000	0.05	84
TULIP (US)	Li_2O	50	87	600	3	84
FUBR-1A (US)	Li_2O	6	85	500,700,900	1.5	84/85
	$LiAlO_2$	< 1	85,95	500,700,900	3	84/85
	Li_4SiO_4	2	85	500,700,900	2	84/85
	Li_2ZrO_3	2	85	500,700,900	2	84/85
FUBR-1B (US)	Li_2O	< 5	60,80	500,700,900	5	85/89
	Li_2O	< 5	80	500-700/1000		
	$LiAlO_2$	< 5-10	80	500,700,900	9	85/89
	(sphere-pac)		80	500-700/1000		
	Li_4SiO_4	< 5	80	400-500	9	85/89
	Li_8ZrO_6	< 5	80	600-700	7	85/89
	Li_2ZrO_3	< 5	85	520-620	7	85/89
ALICE (France)	$LiAlO_2$	0.35-13	71-84	400,600	-	85/86
DELICE (Germany)	Li_2SiO_3 (Li_4SiO_4)	-	65,85,95	400,600,700	< 0.02	85/86
EXOTIC-1,-2 (Neth./UK/ Belgium)	Li_2SiO_3	1,10	80,95	400,600	-	85/86
	Li_2O	5-10	80,90	400,600	-	85/86
	$LiAlO_2$	1,8	80	400,600	-	85/86
CREATE (Canada)	$LiAlO_2$	-	60-90	100	<0.05	85/86
	Li_2O	-				
In-situ Tritium Recovery						
TRIO (US)	$LiAlO_2$	0.2 (50 μm particles in pellets)	65	400,...,700	0.2	84/85
VOM-15H (Japan)	Li_2O	< 10	86	480,...,760	0.24	84
VOM 22/23 (Japan)	Li_2O	- (4 mm dia. pellets)	-	400-900	0.04	86
	$LiAlO_2$	0.5 (4 mm dia. pellets)	77	400-900	0.1	86
LILA-1 (France)	$LiAlO_2$	0.4-13 (1 cm dia. pellet)	78	375-600	< 0.02	86
LISA-1 (Germany)	Li_2SiO_3	30-80 (1 cm dia. pellet)	86,93	550,600	< 0.02	86
EXOTIC-1 (Neth./UK/ Belgium)	$LiAlO_2$	1,8 (1 cm thick annular pellet)	80	400,600	< 0.4	86
	Li_2SiO_3	1,10 (1 cm thick annular pellet)	80,95	400,600	< 0.4	86
CRITIC-1 (Canada)	Li_2O	20 (1 cm thick annular pellet)	80	400-950	0.15	86
	$LiAlO_2$	1 (sphere-pac)	85	400-1000	0.15	87

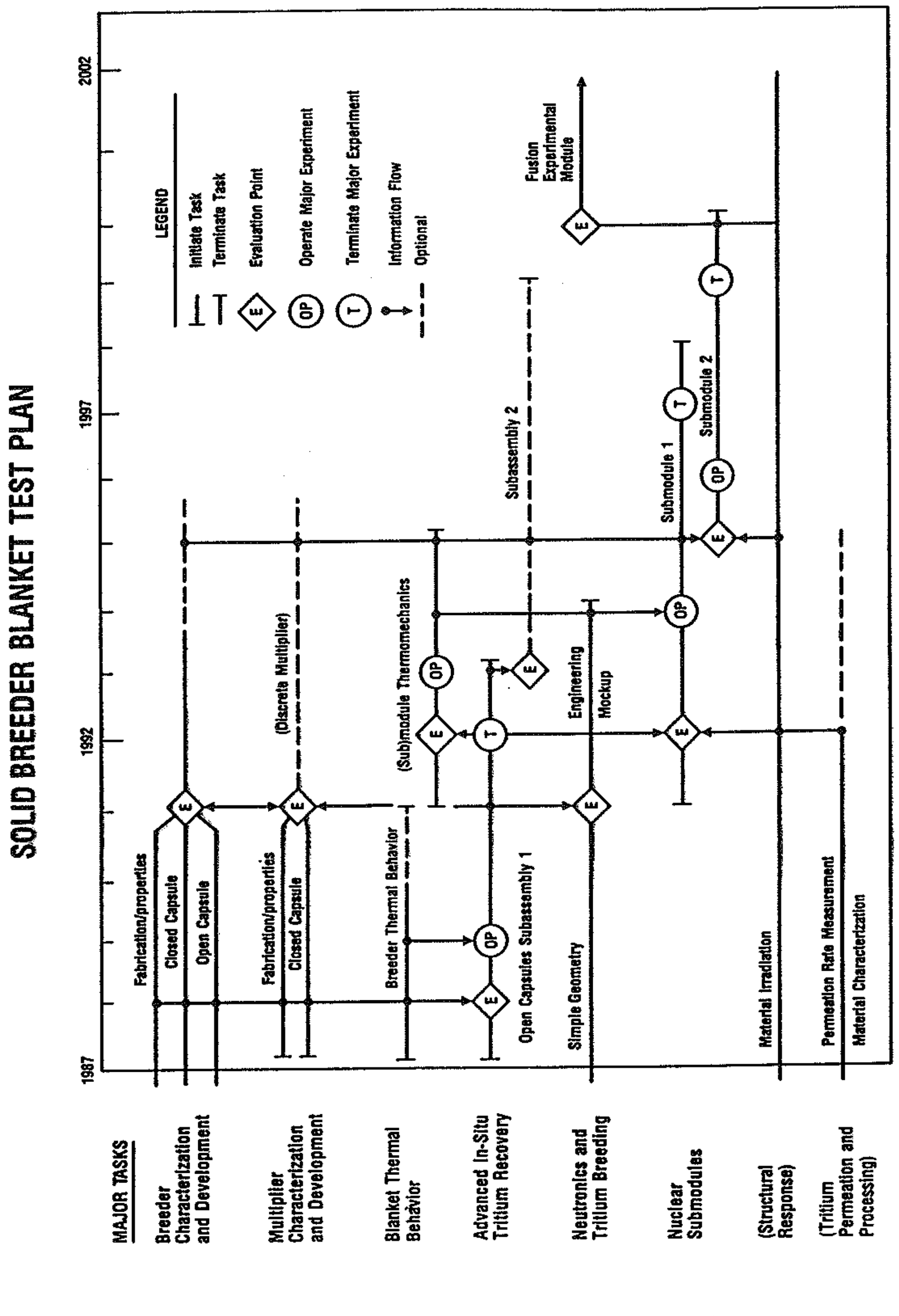

Figure 3. Test sequence for major solid breeder blanket tasks

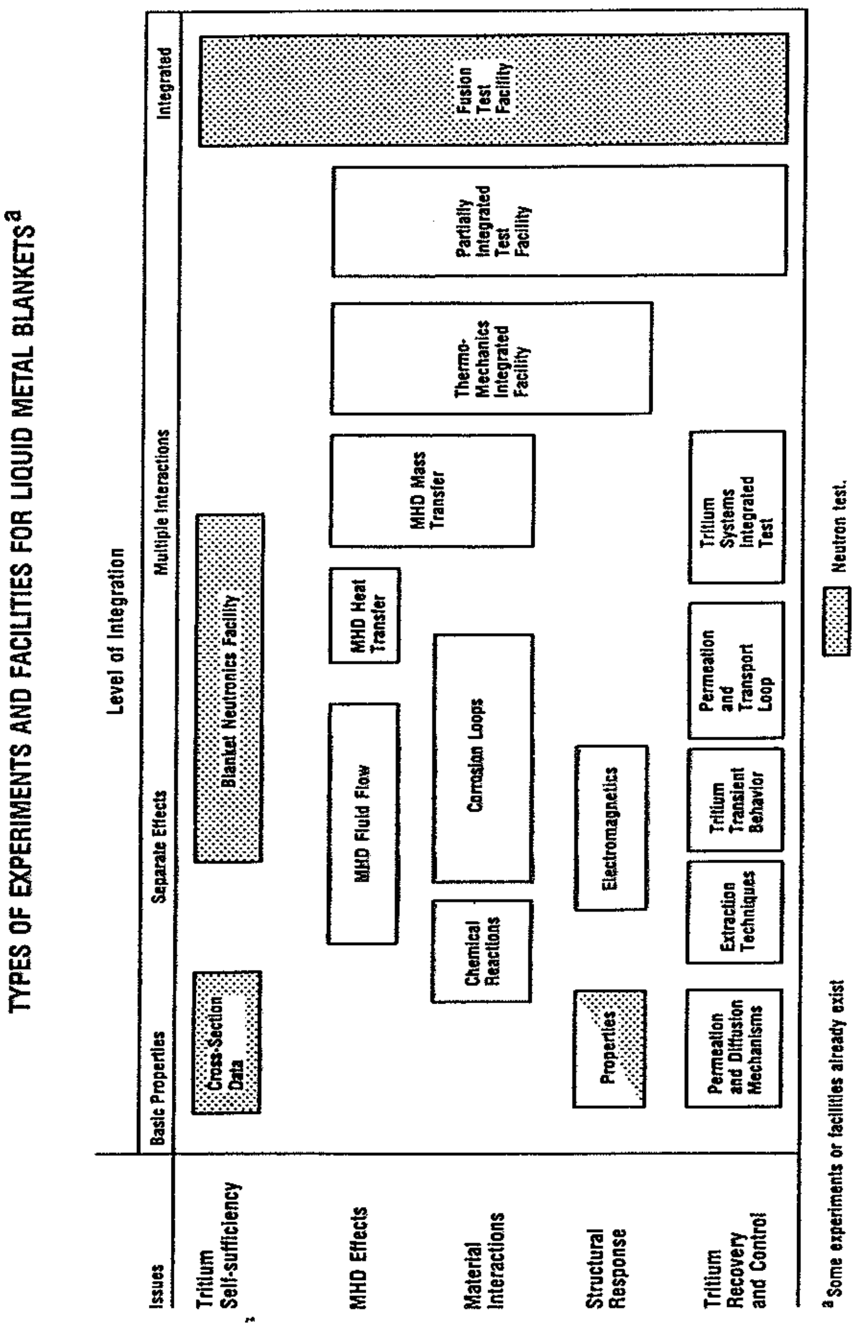

Figure 4. Types of experiments and facilities for liquid breeder blankets

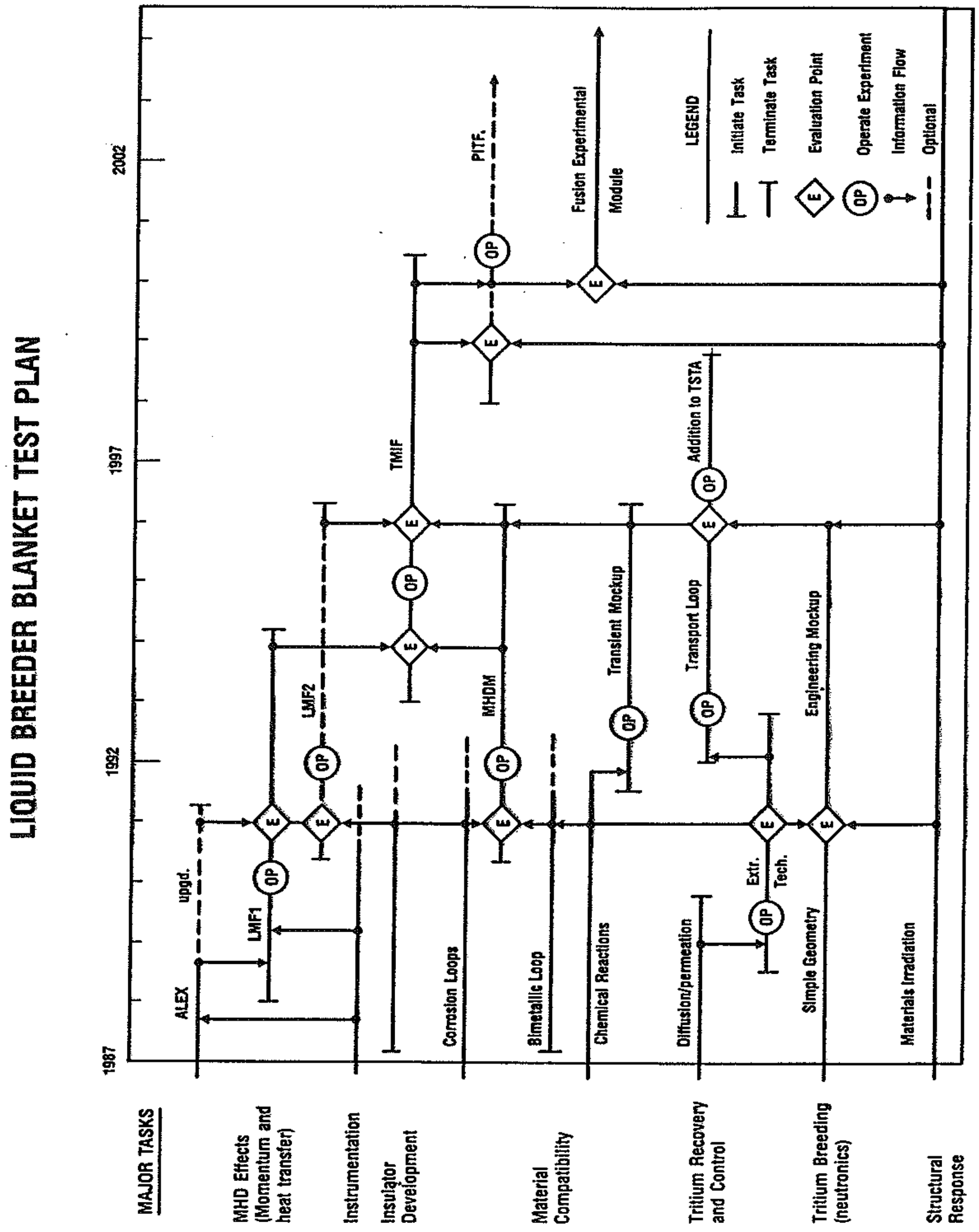

Figure 5. Test sequence for major liquid breeder blanket tasks

Integrated Test Facility (PITF) may additionally be required to supply reliability data in near full-scale components. The need for experiments in this facility are uncertain, depending on prior experimental results. In addition, the experiments may be possible to perform as an upgrade to TMIF.

IV. ACKNOWLEDGEMENTS

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Table 3. Objectives and Milestones of the Four Phases of Blanket Testing

	Approximate Time Frame	Level of Integration	Primary Objectives	Milestones
Phase I	0-10 yrs	properties, separate effects	develop understanding of material behavior and blanket phenomena	select material combinations[a]
Phase II	5-15 yrs	multiple effects	understand phenomena, develop predictive capabilities for complex configurations	select blanket configurations
Phase III	10-20 yrs	partially integrated (non-fusion)	design concept verification in non-fusion environment	select primary blanket design options for fusion testing
Phase IV	15-25 yrs	integrated	design concept verification in fusion facility	successfully operate test modules

[a] To the extent possible with limited high fluence irradiation data

TABLE 4. Liquid Breeder Blanket Issues

- Tritium self-sufficiency
- Magnetohydrodynamic (MHD) effects
  - Fluid flow (including pressure drop)
  - Heat transfer
- Material interactions (e.g., corrosion)
- Structural response in the fusion environment
  - Irradiation effects on material properties
  - Response to complex loading conditions
  - Failure modes
- Tritium recovery and control

TABLE 5. Effect of Coolant, Breeder, and Structural Material Choices on the Dominant Issues for Liquid Breeder Blankets

Liquid Metal Cooling	
Li or 17Li-83Pb	MHD effects (including viability of insulators) corrosion (including viability of inhibitors)
Coolant or Breeder	
Lithium	chemical reactivity
17Li-83Pb	tritium containment
Flibe	tritium containment
Helium	tritium containment
Structural Material	
Vanadium alloys	bimetallic mass transfer DBTT[a]
Ferritic steels	DBTT[a]

[a] Ductile-to-brittle transition temperature (changes due to impurities, radiation, H, and He)