Evaluation of Fusion Reactor Structural Failure Modes by Subscale Interactive Testing

D.S. Zuckerman
*McDonnell Douglas Astronautics Company, St. Louis Division, P.O. Box 516,
St. Louis, Missouri 63166, U.S.A.*

R.J. Puigh
*Hanford Engineering Development Laboratory, Westinghouse Hanford Company,
P.O. Box 1970, Hanford, Washington 99352, U.S.A.*

Abstract

This paper describes an assessment of failure modes and testing requirements for a magnetic confinement fusion reactor first wall and blanket. The study was performed for the Electric Power Research Institute. The primary failure modes are presented in rank order as to their likelihood of occurrence in various reactor and blanket types. In addition, an interactive effects test progression is presented and material and subscale interactive effects tests described.

1. Introduction

McDonnell Douglas Astronautics Company, in conjunction with the Hanford Engineering Development Laboratory, the University of Illinois and Purdue University, has recently completed an Assessment of Neutron Requirements and Potential Sources for Fusion Development. During this study, we identified the anticipated failure modes for a Fusion Engineering Research Facility (FERF) and took the first steps in identifying the interactive effects which can be expected to occur in FERF modules and components. In order to perform this analysis, we concentrated our efforts on four main reactor types: (1) Steady-state tokamaks ($t_{burn} > 1$ hr, $I_w \sim 5$ MW/m^2); (2) steady-state tandem mirrors ($t_{burn} > 1$ hr, $I_w \sim 5$ MW/m^2); (3) pulsed tokamaks ($t_{burn} < 1$ hr, $I_w \sim 5$ MW/m^2); and (4) pulsed high-wall load toroidal devices ($t_{burn} < 1$ hr, $I_w \sim 20$ MW/m^2). We also restricted our effects to four of the more popular blanket combinations presently under consideration: (1) $LiAl_2O_3$ breeder/Be multiplier/PCA first wall/H_2O coolant; (2) Li_2O breeder/HT-9 first wall/He coolant; (3) liquid Li self-cooled breeder/HT-9 first wall; and (4) liquid Li-Pb self-cooled breeder/V-15Cr-5Ti first wall. Work was focussed only on those design aspects of a fusion reactor which are impacted by neutron radiation.

2. First Wall/Blanket Failure Modes

Eleven major failure modes for magnetic confinement fusion were identified. These failure modes were then ranked as to their likelihood of occurrence for each of the 16 combinations of reactor type and blanket configuration. Figure 1 shows the composite ranking of these failure modes.

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One of the difficulties encountered during the course of the rankings was that many of the failure modes were considered to have a "high" likelihood of occurrence. Therefore, a secondary ranking of the "high's" was undertaken: for each reactor concept, the failure modes with "high" rankings were further ordered from 1 (most likely) to 4 (less likely). Even so, it was in some cases impossible to differentiate between failure modes, and several received the same numerical rank.

3. Materials Testing

The next step in the project was to identify the appropriate material properties and testing requirements for these failure modes. Fourteen properties were identified as important and the top five were selected for further study. There are: tensile properties; fracture toughness; irradiation creep; swelling; and creep fatigue. The testing performed to date on the three first wall and four breeder materials was then researched, and a set of material testing requirements for a FERF identified. Table I presents the overall material testing requirements identified during the project. The dpa requirement was restricted to 55 dpa ($\sim$5 MW-yr/m^2) because a FERF is not expected to operate to first wall/blanket end-of-life. Irradiation environments include inert gas, hydrogen, He^3, lithium and impurities (e.g. C or O).

Most sample irradiations can be accomplished in fission reactors (low energy specturm), but some small number of tests should be performed in accelerator-based sources in order to determine the effect of neutron energy spectrum on material property changes. PCA is expected to behave similarly to 316 SS, which has received extensive testing. Therefore, PCA requires relatively few tests. HT-9 is less well characterized, particularly with respect to irradiation effects on brittle failure. It, therefore, has a larger number of tests. V-15Cr-5Ti is anticipated to be the least likely of the three materials to be used in a near-term fusion reactor. Therefore, although very little testing has been done on this material, a smaller test matrix is proposed.

4. Interactive Effects Testing

Once the basic material property changes as a function of irradiation are known, it becomes important to understand how different materials will function together within a module or component. For instance, welded structures will show differences in creep and swelling between the base metal, weld metal and heat-affected zone. The proximity of different materials will produce a complex set of interactions and loads which might cause failure in ways not predicted by the foregoing material tests.

During the project, we attempted to identify a set of relatively generic material interactions which could be expected to have significant impact on the operation of a FERF. The failure modes listed above were broken down into simple interactions. Combinations of these simple interactions produce more complex phenomena, leading eventually to a complete interactive effects model of the first wall and breeder. A flow diagram showing the progression of these interactions from the simplest (Basic Material Interactive Tests) to the most complex (Complex Material Interactions) is shown in Figure 2. As the simplest interactions become better understood through analysis and testing, the bottom of the chart will be defined in more detail. New entries will undoubtedly be added and some of the existing ones removed.

Two specific interactions were selected for initial investigation: (1) the creep-swelling interaction of the first wall or structure, and (2) the creep-swelling interaction between the first wall and breeder.

Creep-Swelling Interaction in the First Wall. Swelling in the first wall will lead to dynamic loading. This loading arises from:

Differential swelling due to temperature and flux gradients
Differential swelling associated with different materials
Mechanical constraints which oppose swelling-induced dimensional changes.

Creep deformation will act to relieve these stresses. Reliable design requires the ability to predict the residual stresses in a component and its deformation with service time. Based upon fission reactor experience, the main materials of interest here are 316 SS and PCA. Other candidate fusion first-wall materials (e.g. HT-9 or vanadium-based alloys) are not expected to swell significantly in the relatively low fluxes anticipated in a FERF. The major environmental parameters associated with this issue are temperature, neutron flux and externally applied stress (all potentially time-dependent).

Three specimen geometries have been chosen for use in the investigation of the creep-swelling interaction (see Figure 3). These are: (1) a right circular cylinder, (2) a circular rod and (3) a rectangular bar. These geometries were chosen primarily for their simplicity. The right circular cylinder and rectangular bar can be used to investigate the creep-swelling interaction due to radial temperature gradients or dissimilar materials. The solid rod can be used for the investigation of the interaction of uniform (isothermal) restrained swelling with creep.

Mechanical Interaction Between Solid Breeder and Structure. Many solid breeder blanket designs have the breeder in close contact with the first wall and structure. Differences in the swelling rates and thermal expansion coefficients of the various materials will create dynamic loading of both, and can lead to breeder cracking. This, in turn, can alter loading and temperature gradients throughout the blanket. These loads can only be relieved by creep and deformation. The following two interaction tests bear on this problem:

Unrestrained, and radially and axially restrained solid breeder dimensional changes
Radial and axial thin-wall interaction between breeder and structure

Figure 4 shows schematics of these tests. In the first three, a thick-walled, nonswelling capsule is used to restrain the breeder material. In the last test, a thin-walled capsule is used to examine the breeder/structure interaction. The unrestrained swelling test provides basic information on solid breeder swelling and cracking. The axially- and radially-restrained specimens provide further information on swelling and cracking, plus data on breeder creep. The interaction test is designed to examine the balance between breeder swelling and creep/deformation of the entire module. Failure modes, stress and temperature distributions, and crack morphology as a function of the various environmental parameters (temperature, neutron flux, and externally applied stress) can also be examined. Two materials combinations are recommended: Li_2O breeder with HT-9 structure, and $LiAlO_2O_3$ breeder with PCA structure.

Table I

MATERIAL IRRADIATION AND TESTING REQUIREMENTS

	FIRST WALL/STRUCTURE			BREEDERS	
	PCA	HT-9	V-15Cr-5Ti	SOLID	LIQUID
No. of Specimens (min/max)	382/3048	458/4008	406/3048	288/432	192/288
Temperature Range (^{0}C)	400-600	275-550	300-600	300-700	300-700
Fluence Range (dpa)	0-55	0-55	0-55	0-55	0-55
Energy Level (MeV)	<1, 14	<1, 14	<1, 14	<1, 14	<1, 14
Flux Range (dpa/yr)	10-55	10-55	10-55	10-55	10-55

LIKELIHOOD OF OCCURRENCE FOR VARIOUS FAILURE MODES

FWB FAILURE MODES[a]	STEADY STATE								PULSED TOROIDAL							
	TOKAMAK				TMR				MOD.WALL LOAD				HIGH WALL LOAD			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Cracking Around a Discontinuity/Weld	H^1	H^2	H^1	H^1	H^1	H^2	H^1	H^1	H^1	H^1	H^1	H^1	H^1	H^1	H^1	H^1
Crack on Shutdown (with cooling)	H^2	L	H^3	H^2	H^2	L	H^3	H^2	H^2	H^2	H^2	H^2	H^1	H^1	H^1	H^1
Breeder Disintegrates/Cracks	H^3	H^3	N/A	N/A	H^3	H^3	N/A	N/A	H^4	H^4	N/A	N/A	H^3	H^4	N/A	N/A
FW/Breeder/Structure Swelling & Creep Leading to Excessive Deformation or FW/Coolant Tube Failure	H^1	H^2	H^3	H^3	M-H	M-H	M-H	M-H	M	M	M	M	M	M	M	M
Crack During Operation (FW/Breeder/Structure)	M	H^{1b}	M	M	M	H^1	M	M	H^3	H^3	H^3	H^3	H^2	H^2	H^2	H^2
Environmentally Assisted Cracking	M	H^{1c}	H^1	H^1	M	H^1	H^1	H^1	M	H^2	H^2	H^2	M	H^2	H^2	H^2
Crack on Start-up (FW/Breeder/Structure)	H^2	L	H^2	H^2	H^2	L	H^2	H^2	H^2	L	H^2	H^2	H^1	L	H^1	H^1
Excessive Tritium Permeation of Coolant Tubes	M	M	N/A	N/A	M	M	N/A	N/A	M	M	N/A	N/A	M	M	N/A	N/A
FW/Breeder/Structure Melting	L	L	L	L	L	M	L	L	L	M	L	L	L	M	L	L
Manifold Tube Breaks	L	L	L	L	L	L	L	M^d	L	L	L	L	L	L	L	L
Insufficient Tritium Diffusion Through Breeder	L	L	N/A	N/A	L	L	N/A	N/A	L	L	N/A	N/A	L	L	N/A	N/A

A - Li_2O/He/HT-9	H - Highest Likelihood of Failure
B - H_2O/$LiAlO_2$/PCA	M - Medium Likelihood of Failure
C - Li/V Self Cooled	L - Lowest Likelihood of Failure
D - LiPb/HT-9 Self Cooled	N/A - Not Applicable Failure Mode for That Blanket Concept

[a] Failure Modes Ranked with Most Likely First

[b] High Pressure

[c] H_2O Corrosion

[d] Based on MARS Constrained Header Design

[1] Superscript indicates relative ranking of H's by column

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Figure 1. Likelihood of Occurrence for Various Failure Modes

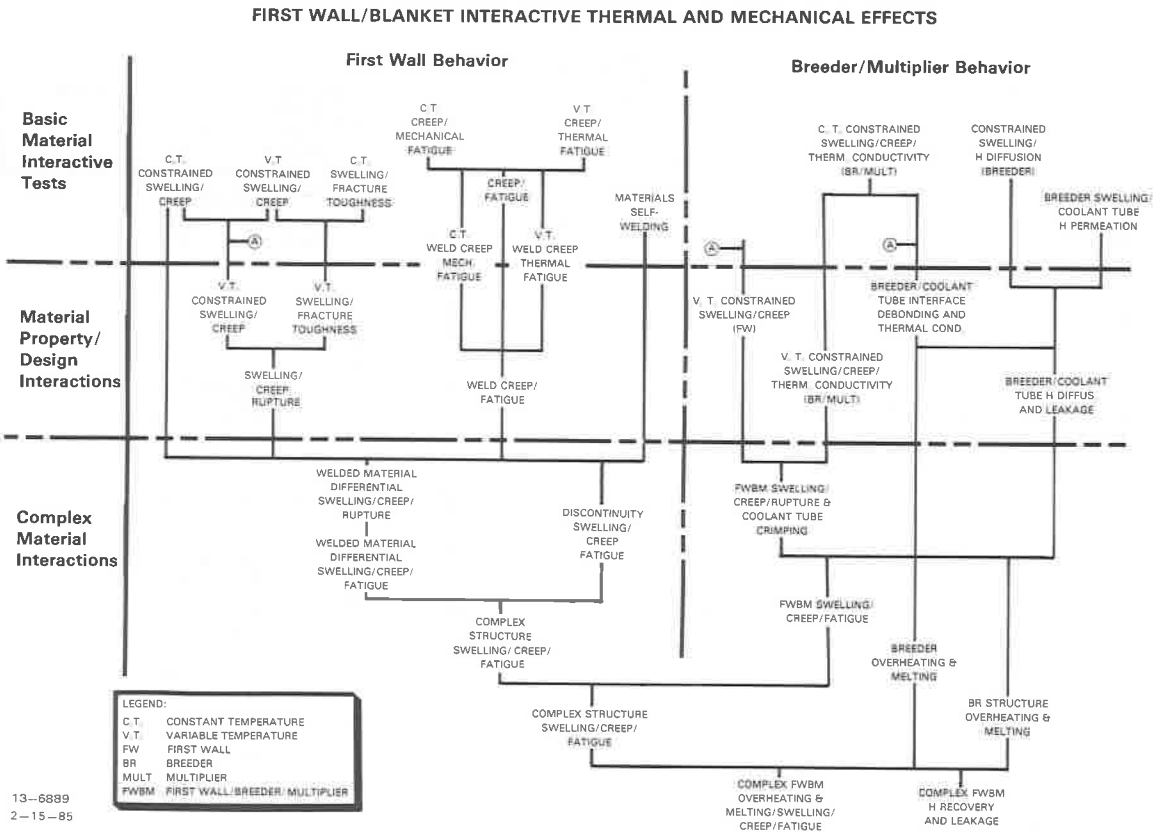

Figure 2. First Wall/Blanket Interactive Thermal and Mechanical Effects

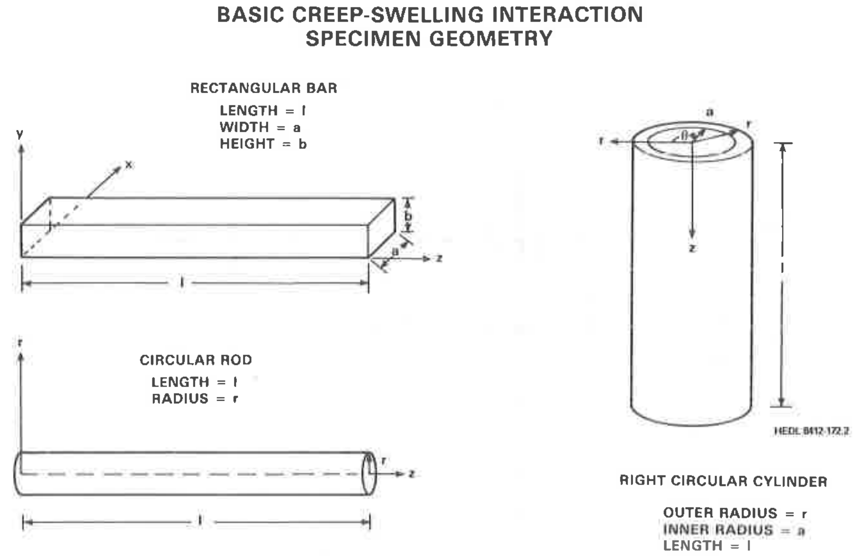

Figure 3. Basic Creep-Swelling Interaction Specimen Geometry

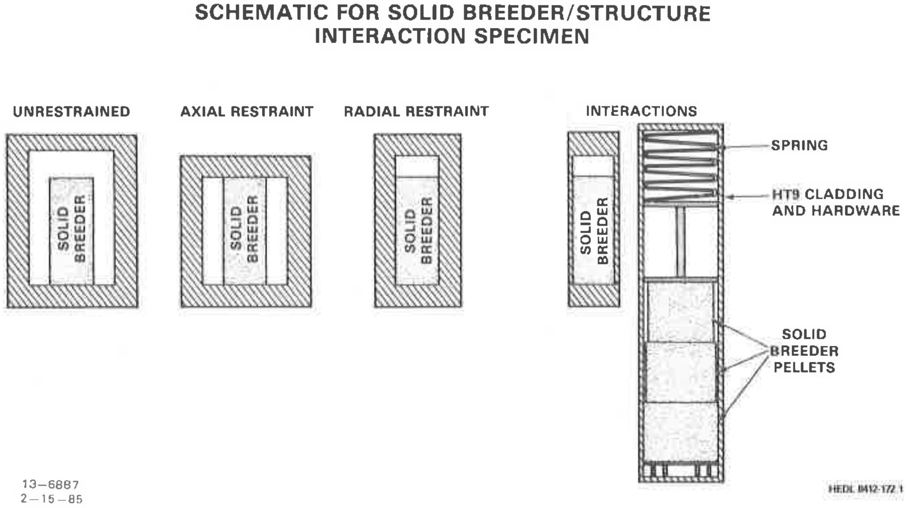

Figure 4. Schematic for Solid Breeder/Structure Interaction Test