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UCRL - 73673
PREPRINT

Conf-720110--1

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**CONSIDERATIONS IN THE DESIGN OF FUSION
REACTOR BLANKET STRUCTURES**

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January 20, 1972

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This paper was prepared for presentation at
Fusion Vacuum Wall Meeting,
Germantown, A.E.C., Washington D.C., January 27-28, 1972

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CONSIDERATIONS IN THE DESIGN OF FUSION
REACTOR BLANKET STRUCTURES*

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ABSTRACT

In the design of moderating blankets surrounding plasmas it is often assumed that the first wall of the blanket is a "vacuum vessel". The consequence of this assumption is that a structure is created which is subjected to buckling instability problems because it is compressively loaded. It is the contention of the author that if this "vacuum vessel" approach is followed that structural, neutronic and heat transfer requirements cannot be satisfied simultaneously for the blanket. An alternate design is proposed in which the vacuum vessel is relocated on the magnet side of the blanket.

* This work was performed under the auspices of the United States Atomic Energy Commission.

INTRODUCTION

In the Controlled Thermonuclear Reactor engineering and technology studies on blanket surrounding plasmas one problem consistently appears. Perhaps the problem is only one of semantics, and if this is the case, then it is trivial and of little concern. However, the problem may be one which centers on a fundamental principle of engineering design in which case it is far from trivial and must be considered rigorously. The problem is the manner in which a substantial number of authors^{1 2 3 4 5} refer to the first surface between plasma and moderator of a fusion reactor as a "vacuum wall". As a matter of fact, this meeting bears the title, "Fusion Vacuum Wall Meeting", and the title prompts this paper. If the terminology is to be interpreted literally, it would mean a vacuum wall consisting of a continuous surface, a thin cylindrical shell perhaps, separating a vacuum region from one which exerts a positive pressure. The consequence of employing this concept is that a vessel is created which is subjected to compressive loads at elevated temperatures for long time periods; time periods that are probably in excess of 10,000 hours and temperatures that are not less than 1000°K. This vessel, in addition to satisfying structural requirements, must also satisfy requirements of neutronics and heat transfer. It is my contention that if the vessel is truly a "vacuum vessel" the three requirements for structure, neutronics and heat transfer cannot be satisfied simultaneously. Either the structure will buckle, or convective heat transfer limits will be reached or the blanket will contain such a high volume fraction of structure that the tritium breeding ratio

will be less than one.

COMPRESSIVE BUCKLING

Let us first consider the probability of buckling of this vessel and what will cause buckling to be initiated. It may be recalled that when a relatively short column is subjected to a gradually increasing compressive load, the column will fail by crushing. If the column is relatively long, however, it will buckle sideways at a load that is very much smaller than that which would crush the material. Buckling is defined as a runaway deflection. This sideways deflection of the column increases greatly even when the load increases a very minor amount. The column will fail by bending in the middle in its simplest mode. Everyone has observed this phenomena by bending a meter stick. The equation for the lateral buckling of long columns was developed by Euler in 1744. Euler's column buckling equation may be expressed as follows:

$$P_{cr} = \pi^2 \frac{EI}{L^2} \quad (1)$$

This equation is appropriate to a perfectly straight, slender column of length L subjected to a longitudinal force P . The elastic modulus is E and the minimum moment of inertia is I . The critical load that will cause buckling is P_{cr} . The point to observe about this equation is that it is independent of material strength. Mild steels and high strength steels will both fail at the same buckling load. What is required for high buckling resistance is high stiffness or moment of inertia and a high modulus of elasticity.

We can write an equivalent instability equation for the buckling of a long, thin cylindrical shell subjected to lateral external pressure. The critical pressure in this case is as follows:

$$q_{cr} = \frac{E}{4(1 - \nu^2)} \left(\frac{t}{r}\right)^3 \quad (2)$$

where : ν = Poisson ratio, t = vessel thickness, r = vessel radius

Both of these equations are limited to the elastic region of the stress strain curve.

Using equation 2 it can be seen that the assumption of a "vacuum wall" as being a thin-walled cylinder with very high ratios of diameter-to-thickness, is limited strictly to neutronic calculations and not applicable when structural or heat transfer considerations must ultimately enter.

A simple calculation will demonstrate this. Let us assume that the wall thickness is one centimeter and the shell radius is 100 centimeters. These are dimensions typically used in blanket design studies. Then for a material such as niobium, where $E = 15. \times 10^6$ psi, at 1000°K , the critical pressure is :

$$q_{cr} = \frac{25 \times 10^6}{4(1 - .3^2)} \left(\frac{1}{100} \right)^3 = 4. \text{ psi}$$

Hydrostatic pressures from the coolant and moderating fluid would exceed this pressure by more than an order of magnitude. To meet this design pressure load would require a wall not less than 2 centimeters thick. In fact, the wall thickness required must be even greater because of creep problems.* It must be noted that the buckling equation as it was just used applies to short time (instantaneous) behavior of materials within the elastic limit. Since operation of the reactor must be carried on at elevated temperatures structural creep must be considered and the equation must be modified to include the degrading effect of long term creep buckling. This effect is discussed in detail by Corum of ORNL⁶. For our purposes here it is sufficient to say that the equation must be modified by substitution of a reduced modulus of elasticity. The value of the reduced modulus is determined from creep data for the particular material of interest by development of what is termed an isochronous stress strain curve. The curve generated depicts the total strain ϵ_t , (elastic, plus short time plastic, plus time dependent plastic) versus stress for a time period of T_t hours. For instance, if 10,000 hour creep strain data were known for a set of compressive stress, an isochronous curve could be generated. If an isochronous stress-strain curve for T_t hours is used then

* See Data Sheets in Appendix

the predictions will be those that produce collapse at the end of T_t hours. The general idea is illustrated in Figure 1 which depicts an isochronous curve for a time T_0 representing ordinary short time behavior and a time T_t representing the long time creep behavior.

Fig. 1. Isochronous curve showing the effect of creep on the modulus of elasticity.

By definition, the modulus of elasticity is

$$E = \frac{d\sigma}{d\epsilon} \quad (3)$$

It can be seen from Figure 1 that the modulus for the material in creep can be degraded markedly compared to the elastic modulus since it is the slope of the stress strain curve. It is conceivable the degradation could be one or more orders of magnitude. This new modulus is called the reduced modulus or time dependent tangent modulus and can be used in Equation 2 for predicting collapse pressure under conditions of creep. If in our previous calculation E were reduced by a factor of 100 then the wall thickness would have to be ~ 10 centimeters to resist the 70 psi pressure load. Furthermore as the slope of the isochronous stress strain curve decreases it can be appreciated that the uncertainty in the usable value of E increases so that design in this regime of fundamentally unstable structure is an uncertain science and large safety factors would have to be used.

HEAT TRANSFER

If we use the normal wall loading (neutron energy flux) of 10 Mw/m^2 it can be shown that the internal heat generation in the niobium due to neutron heating is approximately 250 w/cm^3 .⁷⁻⁸ If we assume lithium as a coolant, then convective heat transfer limits are substantially less than 250 w/cm^2 (probably $< 100 \text{ w/cm}^2$ in a magnetic field) so on a heat transfer basis the wall thickness per unit area of heat transfer surface must be $< 100/250$ centimeters or approximately .4 of a centimeter. Inclusion of bremsstrahlung heating and synchrotron radiation would decrease this allowable thickness further. Clearly the requirements for structural strength and heat transfer are divergent since the structural requirements dictate a wall whose thickness t is at least of the order of 10 centimeters and heat transfer limits the wall to less than one centimeter.

A POSSIBLE SUBSTITUTE FOR THE THIN SHELL

To get the necessary structural rigidity and integrity which the simple thin shell cylinder can not have because of the foregoing con-

siderations, it can be replaced by an open, ribbed, convectively cooled structure with a higher moment of inertia and greater stiffness, as illustrated in Figure 2. This would still be a cylindrical shell compressively loaded and subjected to the same buckling criteria. In effect, the thin shell has been replaced by a continuous, webbed thick shell of relatively high porosity which effectively forms the total blanket moderating structure.

Fig.2 Section through a cellular structure for the vacuum wall

When one investigates this approach, it is found that the web thicknesses that are necessary to provide structural integrity using the reduced modulus are thicker than is desirable both from a neutronic and from a heat transfer standpoint. Fraas, for instance found that web thicknesses would be approximately 0.6 cm in a design he considered⁹ Hopkins and d'Hospital used thicknesses of 0.5 cm¹⁰ when the vessel radius was 10 meters. Neither investigator, to my knowledge, considered the creep buckling instability problem.

The reason the webbed shell does not provide an adequate solution to the buckling problem is somewhat analogous to the effect on buckling of the reduced modulus E_r due to creep. That is, a shell with high porosity will have an effective modulus of elasticity E^* approximately defined by

$$E^* = E_r \frac{\rho_p}{\rho_s}$$

where ρ_p = effective density of the porous shell.

ρ_s = density of the shell as a solid.

Since ρ_p/ρ_s is really the volume fraction of structure in the blanket it is limited neutronically to values of about five or ten percent. Thus the modulus of elasticity to be used in Equation 2 has decreased another order of magnitude. The moment of inertia or stiffness has increased by the use of this structural approach but is a function of porosity and t^* , the effective thickness of the shell which gages stiffness is inversely proportional to porosity. Finally, a porous shell of this type is difficult and costly to fabricate and probably cannot be replaced except as a unit.

NEUTRONIC CONSIDERATIONS

Figure 3 shows a plot of tritium breeding versus volume fraction of structure in a representative blanket.¹¹ It can be shown that at structural volumes greater than about 20% the tritium breeding is less than unity. This sets the upper limit on the amount of structure that can be used and it is likely the webbed structures of Fraas or Hopkins would approach or exceed that limit when buckling stability is considered.

A NEW CONCEPT

It seems evident that the minimum structure required for neutronics and heat transfer which must be realized in practice for a blanket surrounding a plasma must be based on a different design approach than the compressively loaded cylinder. The solution to the problem is to load the structure in tension in some way.

Fig. 3. Tritium breeding in natural Lithium Blankets. Sixty-six energy groups 14 MeV. Five batches of 500 neutrons each. Monte Carlo system.

The solution takes form with recognition of the fact that the first surface between plasma and moderator need not and should not be a vacuum vessel. I have proposed that the necessary vacuum vessel be located on the other side of the moderating blanket (i.e. between blanket and magnet)¹¹. In this location it can run at low temperatures without creep buckling problems and not be subjected to neutron damage since the neutrons are slowed down before they reach this wall. It can be as

thick as required for buckling stability since it does not interfere with neutronics and has virtually no heat transfer load. A cross section of a reactor using this approach is shown in Figure 4.

Fig. 4. Cross section through a blanket using tube bank arrangement for moderating and with vacuum vessel on magnet side of the blanket.

When this relocation of the vacuum vessel has taken place the blanket structure itself, in which the neutron moderation will be accomplished, can be designed similar in arrangement to a tube bank heat exchanger. Each tube in this heat exchanger is independent of all other tubes. Because of this individual tube approach the design requirements are based simply on hoop stresses arising from the pressurized liquid metal flow in small diameter tubes, and all compressive loads are eliminated. A sample calculation will yield some feeling for tube sizes. Hoop stresses created in pressurized tubes are determined as follows:

$$\sigma = \frac{Pr}{2t} \quad (4)$$

where

σ = stress

P = internal pressure

r = tube radius

t = tube thickness

For niobium, a reasonable stress for 10,000 hour, one percent creep is $\sim 5,000$ psi. If we use this value and a 100 psi internal tube pressure then the ratio of tube thickness to radius is

$$\frac{t}{r} = \frac{P}{2\sigma} = \frac{1}{100}$$

With a suitable safety factor this ratio might reduce to $\sim 1/25$. Clearly we are not stress limited. Because of the thin walls loaded in tension with no instability problems, convective heat transfer is not limiting and total structural volume in the blanket can be reduced to as low as 5%, enhancing the tritium breeding ratio. Individual tubes can be changed without changing the entire structure. With this arrangement of a large number of independent tubes surrounding the plasma it is also possible (but not essential to the concept) to create modules of tube banks incorporating heat pipes¹¹ or similar latent heat of vaporization techniques for averaging and flattening radial energy distribution.

CONCLUSIONS

It appears highly desirable, probably essential, to remove the large compressively loaded vacuum vessel from the first wall facing the plasma. The wall of the vacuum vessel should be placed outside the moderator blanket where it can operate at relatively low temperature and where the neutron energy disposition is minimal. This elimination of the vacuum wall requirements from the moderator blanket can greatly facilitate the design of a blanket to meet the other structural, neutronic and heat transfer requirements of a fusion reactor.

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APPENDIX

MISCELLANEOUS MATERIAL PROPERTIES ON NIOBIUM ALLOY Nb-1%Zr

- A-1 Stress-Rupture Data
- A-2 Elastic Modulus vs. Temperature
- A-3 Short Time Tensile Properties vs. Temperature
- A-4 Mean Coefficient of Thermal Expansion vs. Temperature
- A-5 Rupture of $\frac{1}{2}\%$ Creep Data for Nb-1%Zr at 2200°F

MASTER RUPTURE CHART

PC 32

A-1

Alloy		Temp. (°F)		Stress (ksi)		Time (hours)	
Cb-1% Zr		2000	2260	20	5	100	3.3
Prepared by	Checked by	2000	2200	27	2.5	10	10
Collins		1800	2200	36	3.5	78	1.2
Subject	Date of test	1800		28		350	
	1-18-61	2200		5		2.2	

Treatment: Electron beam melt - Arc cast - 4:1 Extrusion
 Remarks: Coated specimens in air & uncoated in vacuum

TEMPERATURE (°F)

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○ = Westinghouse & Fansteel data - vacuum

□ = LRL data - air

△ = LRL 1% Creep data - air

Stress - Rupture

1% Creep

cb-1% Zr alloy
Elastic Modulus
vs. Temperature

Modulus of Elasticity
PSI $\times 10^{-6}$

Modulus of Elasticity
PSI $\times 10^{-6}$

TEMPERATURE - °F

0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300

Cb-190 Zr alloy

Short time tensile
properties vs Temp

Union Carbide data

Argon atmosphere

A-4

Cb-10%Zr alloy

Mean coefficient of thermal expansion vs Temp.

Mean Coefficient of Thermal Expansion
in/in/°F x 10⁶

TEMPERATURE OF

Collins 1-18-61