FWLTB — A COMPUTER PROGRAM FOR PREDICTING THE LIFETIME OF A FUSION REACTOR FIRST WALL

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Abstract

FWLTB is a computer program for simulating the First Wall Long Term Behaviour in a fusion reactor environment. It combines nonstationary thermoelastic and long-term inelastic analysis, thus providing a basis for life prediction by comparing the results with a set of constraints on the properties of the material. The present status of program development is briefly summarized and the main features and limitations are outlined. For the reference case already used in earlier publications those results are reported which are subjected to certain limitations. The procedures to be used for life prediction are discussed. It is emphasized that the program, when completed, is expected to be applicable for trend analyses but not yet for accurate prediction of the real wall life.

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1. Introduction

The useful life of the first wall has a significant influence on the economic and environmental characteristics of a fusion power plant. It determines the necessary replacement frequency of wall or blanket modules and therefore has a strong bearing on the power plant availability, on the one hand, and on the amounts of structural material consumed and radioactive waste produced, on the other hand. For these reasons the wall lifetime is considered as a key figure in fusion reactor systems analyses.

Undoubtedly, the only way to obtain reliable information about the wall life would be to conduct a performance test under realistic load conditions. Since, however, it is not possible today to verify these conditions even for the purpose of material testing, we have to look for other ways in order to obtain an early answer to the important question of wall lifetime. The approach adopted in the course of fusion reactor systems studies at IPP Garching is to prepare a computer program for numerically simulating the long-term behaviour of the first wall on the basis of the latest knowledge about the material properties. By combining structural analysis and an appropriate description of the long-term variation of the material properties it will, in principle, be possible to predict the lifetime.

2. Status of program development

The present program, which is schematically shown in Fig. 1, was developed in several steps. Development started with computerizing analytical expressions for the temperature, stress, and strain distributions, $\vartheta(x)$, $\sigma(x)$, and $\varepsilon(x)$, under steady-state conditions [1]. Both pressure stresses σ_m and thermal stresses σ_{th} resulting from an external heat flux density Q_s (delivered by the plasma) and from internal heat sources $q_n(x)$ have been taken into account. The power density distribution $q_n(x)$ inside the wall is taken from the results of neutronics/photonics calculations [2].

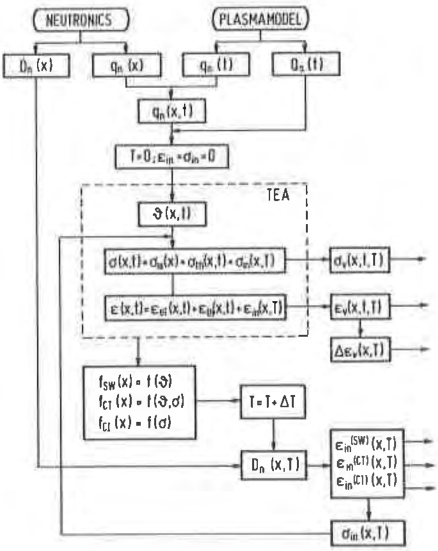

Fig. 1: Flow diagram of the long-term model.

The second step was to include the time variation of the quantities mentioned above during a single operation cycle [3]. This was done by solving the nonstationary heat conduction problem by means of Fourier series. This procedure allows of introducing arbitrary shapes of periodic time functions for both the internal power density $q_n(t)$ and the external heat flux density $Q_s(t)$. It is therefore not necessary to assume idealized pulse shapes. In fact, the analysis was based directly on the results of plasma physics calculations [4] which yield the neutron wall loading $P_{wn}(t)$ and the radiation and heat wall loading $P_{ws}(t)$ as functions of time t. The stress/strain analysis is done in a quasi-steady-state manner for a series of time instants within a single operation cycle of duration t_c.

The third step in the program development, now being completed, was to superimpose on the non-stationary thermoelastic analysis (TEA) a procedure which allows the First Wall Long Term Behaviour (FWLTB) to be followed. The main feature of this long-term model is that it includes the calculation of the inelastic strains $\varepsilon_{in}^{(SW)}$, $\varepsilon_{in}^{(CT)}$, and $\varepsilon_{in}^{(CI)}$ due to swelling,thermal creep, and irradiation creep, and feedback of stresses σ_{in} caused by the differential strains. The inelastic material's response is followed on a macro time scale labelled "T" using a finite difference scheme. The macro time scale and micro time scale are related by the equation

$$T = t + n \cdot t_c, \tag{1}$$

where n is the number of operation cycles completed. As compared with other methods like that of the viscoelastic-elastic analogy [5], the procedure used here allows of introducing arbitrary functions to describe the inelastic strains. Thermal and irradiation creep strains, for instance, thus do not have to be restricted to a linear dependence on stress.

The inelastic material's response (i.e. the inelastic strains and the stresses produced by them) calculated at the end of a macro time interval ΔT which may comprise a large number n of operation cycles is fed back to the thermoelastic analysis. At the end of a macro time step the stress and strain fields are thus corrected for the inelastic response and the new results become the basis for calculating the response during the next step ΔT.

Four main features of the FWLTB program may be emphasized:

- The calculation of the nonstationary temperature fields and hence that of thermal stresses is done in such a way that it can be consistently based on the results of plasma physics and of neutronics/photonics calculations.
- For calculating the inelastic strains an averaging procedure with respect to the micro time scale is applied which yields effective values for the temperature and stress functions determining the strain rates.
- The method of calculating the stresses σ_{in} due to inelastic strains is able to cope with anisotropic behaviour.
- The macro time scale T may be subdivided into an arbitrary number of ranges with different sizes of the time interval ΔT. A high degree of time resolution can thus be achieved wherever necessary.

On the other hand, two features of the program which help to illustrate the limits of the present version should be emphasized:

- As far as the data of the material are concerned, the present version of FWLTB is restricted to German type 1.4970 stainless steel. For the inelastic effects empirical equations are used which are based on experimental results from the fast breeder reactor development program. No attempt has so far been made to include modifications to be exptected from typical characteristics of the fusion reactor radiation environment [6].
- In FWLTB, the geometry options are restricted to cylindrical and spherical shells

which may be impinged on by particle and energy radiation either at the inside or the outside surface. In both cases, however, symmetrical loading is assumed. Although both types of geometry have a certain relevance to a modular blanket design, symmetric loading is by no means assured. In this respect the present version of FWLTB should be regarded as a tool for developing a methodology and for understanding the interaction of the processes involved rather than a means of accurately predicting the real behaviour. To approach real geometries more closely, it is intended for the future to replace analytical thermoelastic analysis by finite element methods.

3. Typical results for a reference case

Preliminary results from the FWLTB computer program have already been published [7, 8, 9], the emphasis being placed on various items of concern. In [7], for instance, the very first results for a reference case were reported, these demonstrating that inelastic response is indeed not negligible. Imperfections in the program at this time have prevented us, however, from completely understanding the results. The introduction of a non-equidistant time interval structure on the macro time scale led to a more flexible time resolution and allowed determination of specific characteristics in the build-up of "inelastic" stresses and their dependence on external load and design conditions [8]. By improving the averaging procedures on the micro time scale more precise and, in fact, more unfavourable results were obtained for the reference case already mentioned [9]. Variations in the equations for swelling and creep, finally, resulted in a better understanding of the interaction of the two effects and gave indications of their relative importance [9]. In this paper more emphasis will be placed on the long-term behaviour of those quantities which are considered significant for the wall life.

The reference case considered is again a cylindrical shell with an outer radius of 30 cm and a wall thickness of 0.2 cm which is allowed to expand freely in the axial direction. Its interior temperature is assumed to be kept constant at 500^{o} C by appropriate coolant flow at a pressure level of 1 MPa. The outside of the cylinder is assumed to be exposed to a periodic sequence of operation cycles of 150 s duration including a burn period of 110 s. The time variations of both the neutron and radiation wall loadings, P_{wn} and P_{ws}, resulting from plasma physics calculations [4] are shown in Fig. 2. The response of the van Mises stress σ_V to this plasma burn during the first operation cycle is shown in Fig. 3 for the hot (H) and cold (C) surfaces of the wall. The maximum stress gradient across the wall occurs at the time instant of maximum temperature difference, which in this case amounts to about 43^{o} C. The stress level reached during the down-time

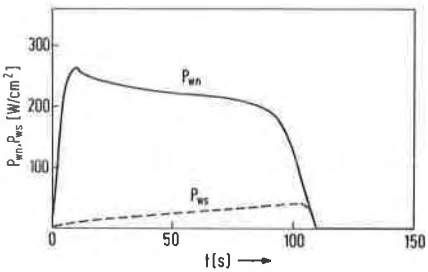

Fig. 2: Time variation of the neutron wall loading P_{wn} and the radiation wall loading P_{ws} .

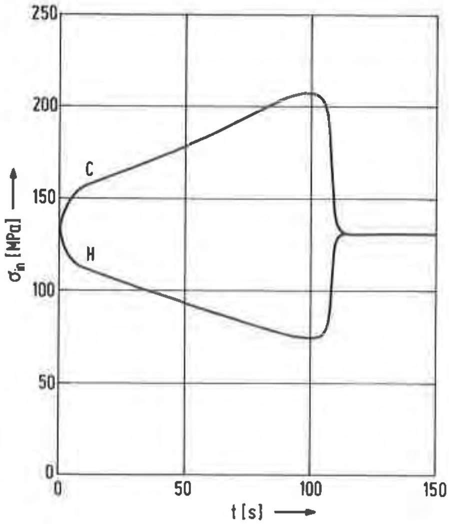

Fig. 3: Time variation of the van Mises stress σ_v during the first operation cycle.

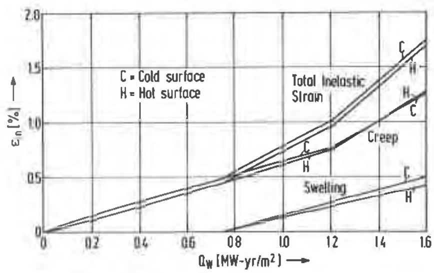

Fig. 4: Long-term variation of the inelastic strains ε_{in} as a function of the time integrated wall loading Q_w.

period results from the coolant pressure.

During long-term operation swelling and creep strains develop, as shown in Fig. 4, as functions of the time-integrated wall loading Q_w. The total inelastic strain gives rise to the build-up of irreversible stresses σ_{in}, as shown in Fig. 5. The first level of saturation is reached when the creep rates in the absence of swelling become uniform across the entire cross-section of the wall. Its height is determined by the average thermal stress during the burn period. The further increase of the stress level is due to the onset of swelling. This level saturates when the total inelastic strain rates balance at a level determined by the ratio of the swelling and creep rates [9]. A lower level is reached later when, as can be seen from Fig. 4, the creep rate is enhanced. The peak stress in between these two ranges is a consequence of the creep acceleration in the presence of a dose profile across the wall. For further details the reader is referred to the literature [8 , 9].

It is important to note that there are two types of stresses that differ in their time behaviour on the macro time scale: the rapidly oscillating thermal stresses and the slowly increasing sum of pressure and irreversible stresses. As indicated in Fig. 6, the latter lead to a change in the stress profiles across the wall. The left side of Fig. 6 shows the initial situation ($T = Q_w = 0$), the right side that at the end of the macro time range considered here ($Q_w \approx 1.6$ MW-yr/m^2). In both cases the solid lines represent the profile at the instant of maximum temperature difference, the dashed lines that existing during the down phase of an operation cycle. It can clearly be seen that the stresses relax at the cold surface at the expense of an increase at the hot surface.

Fig. 7 shows the entire history of the van Mises stress σ_v, which reflects, as is to be expected, that of the "inelastic" stress σ_{in} shown in Fig. 5. Similar behaviour is also exhibited by the van Mises strain [7]. In Fig. 8 we show the history of the strain range $\Delta\varepsilon_v$, which is the difference between the absolute amounts of the van Mises strain at the

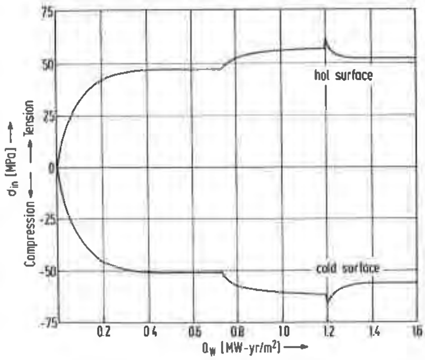

Fig. 5: Long-term variation of the stresses σ_{in} due to inelastic strains as a function of the time integrated wall loading Q_W.

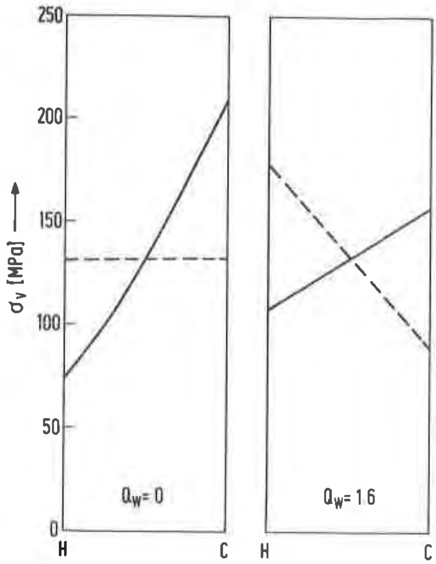

Fig. 6: Stress profiles across the wall at the initial stage (left side) and the final stage (right side).

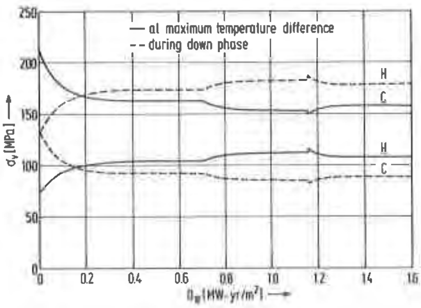

Fig. 7: Long-term variation of the van Mises stress σ_V as a function of the time integrated wall loading Q_W.

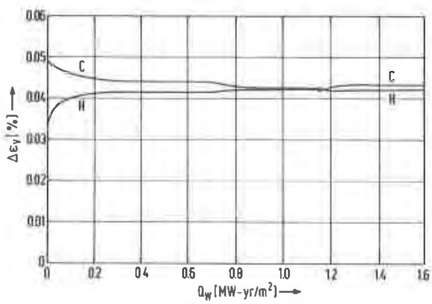

Fig. 8: Long-term variation of the strain range $\Delta\varepsilon_V$ as a function of the time integrated wall loading Q_W.

instants of maximum and minimum temperature difference across the wall. Whereas there exists a larger difference between the hot and cold surfaces at the beginning of operation, the strain ranges become nearly equal in the long term.

4. Anticipated procedures for life prediction

As indicated by the open arrows in Fig. 1, the FWLTB computer program is not yet completed. The results obtainable so far are intended to be correlated with a set of data on the material's properties in order to arrive at an estimation of the lifetime to be expected.

In the absence of a complete concept some preliminary ideas indicating how we wish to proceed are discussed.

As shown in Fig. 4, the program yields information about the absolute amount of swelling. Other than in the field of fission reactor technology, where this kind of dimensional instability is of major concern because of the tiny geometry, the situation should be much more relaxed in a fusion reactor blanket. Limitations can, however, only be defined by detailed design studies. At present, an amount of about 5 % in volume increase, corresponding to about 1.6 % in linear swelling strain, is considered acceptable.

A second life criterion will be the absolute amount of creep strain, which also follows from Fig. 4. Limitations to this quantity will be set by the ductility of the material. It is well known that this property is strongly dependent on the amount of helium accumulated and, therefore, a function of time T. Unlike in the case of swelling, not a fixed but a moving limit will have to be evaluated. Unfortunately, there is still much uncertainty today about the amount of ductility remaining after the formation of some hundred ppm He, which is characteristic of a fusion reactor first wall after about one year of operation. The life prediction will be totally different, depending on whether we base it on the results of post-irradiation experiments [10] suggesting a residual ductility of about 0.5 % or on measurements during irradiation, from which higher values are reported [11, 12].

There is another class of criteria requiring a larger amount of calculational layout as compared with swelling and creep. One example is the history of the van Mises stress σ_V, which has to be compared with the time rupture strength. To find an effective value of σ_V, we have to use averaging over each operation cycle and subsequent averaging of the mean values over one macro time step. The resulting value has to be evaluated by means of a Larsen-Miller representation of experimental results which must include a dependence of the irradiation dose. Together with an effective temperature also averaged over an operation cycle we shall gain an estimated lifetime T_{rm} for this special situation. The ratio α_m

$$\alpha_m = \frac{T}{T_{rm}} \tag{2}$$

will thus give us the fraction of life "consumed" during a single macro time interval.

In a similar way we shall proceed with the information about the strain ranges $\Delta\varepsilon$, shown in Fig. 8. Fatigue data are required from which the number of cycles to failure N_f can be derived, depending on temperature, irradiation dose, and - if possible - mean strain or stress. For each macro time interval ΔT, again a life fraction β_m can be determined from the equation

$$\beta_m = \frac{N}{N_{fm}} , \tag{3}$$

where N is the actual number of cycles performed during ΔT.

It will have to be examined whether the simple life fraction rule

$$\sum_m (\alpha_m + \beta_m) = C ; \quad C \approx 1 \tag{4}$$

will be appropriate to predict the lifetime due to creep-fatigue interaction or whether more sophisticated models will have to be used.

In addition to the criteria mentioned above, we shall check for situations where the yield stress is exceeded. This may be of importance during the onset of enhanced creep. As outlined in [9], however, parameter constellations where other effects force the stresses up to this limit may also occur. We shall also examine the possibilities afforded by experimental data on the time yield limit and by the field of fracture mechanics.

As far as practical utilization of all these criteria is concerned, we intend to check each of them on completion of every macro time step. This procedure will not only yield information about the lifetime "consumed" but also some kind of forecast being revised step by step.

5. Conclusions

The development of the FWLTB program has proceeded to a point where the long-term behaviour of the first wall with respect to stresses and strains can be simulated at least for simple geometries. The next step is the inclusion of a number of material's properties on which a procedure for the life prediction can be based.

In pursuing this goal it is fully recognized that an accurate prediction of the lifetime will not be possible. There are a number of obstacles preventing the adopted method from being perfect. Firstly, there are still appreciable gaps in the available data base. Secondly, in spite of a steadily increasing knowledge in the field of radiation damage just first indications can be made for some few properties in which direction changes in the behaviour will occur when going from a fission to a fusion reactor environment. Thirdly, the accuracy of life prediction is very strongly impaired by the appreciable scatter in the experimental data and by a partly high sensitivity with respect to little changes in the parameters.

In spite of this unfavourable situation, the attempt will be made to provide a consistent methodology by which at least trend analyses can be made. These are necessary both to identify the quantities of major importance and to point to those items which should earn special attention in future experimental programs.

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References

[1] Daenner W., "The mechanical performance of the fusion reactor first wall. Part I: Steady state analysis without irradiation effects", IPP 4/143 (Oct. 1976)

[2] Daenner W., "Some nuclear characteristics of liquid lithium/stainless steel fusion reactor blankets", IPP report (to be published)

[3] Daenner W., Raeder J., "The mechanical performance of the fusion reactor first wall. Part II: Behaviour under pulsed load conditions", IPP 4/149 (March 1977)

[4] Borrass K., "A zero-dimensional Tokamak transport model. Part I: General description", IPP 4/146 (Aug. 1977)

[5] Lamkin D.E., Brehm R.L., "Analytical stress analysis solution for a simplified model of a reactor fuel element", Nucl. Technol. 27 (1975), 273-285

[6] see: Proc. of the 1st Top. Meet, on Fus. React. Mat., Miami Beach, Florida, 29.-31.1.1979, J. Nucl. Mat. (special issue to be published)

[7] Daenner W., Raeder J., "FWLTB - A mathematical model to calculate the lifetime of the fusion reactor first wall", Proc. 3rd Top. Meet. on the Technol. of Contr.Nucl.Fus., Santa Fé, New Mexico, USA (May 1978), (to be published)

[8] Daenner W., Raeder J., "FWLTB - A mathematical model to calculate the lifetime of the fusion reactor first wall", Proc. 10th Symp. on Fus. Technol., Padua, Italy (Sept. 1978) (to be published)

[9] Daenner W., Raeder J., "Latest results from the FWLTB computer code: The influence of swelling and irradiation creep on the stainless steel first wall of a fusion reactor", for reference see [6]

[10] Ehrlich K., "Werkstoffe für die erste Wand von Fusionsreaktoren", published in KfK 2590 (March 1978)

[11] Jung P., Schwaiger C., Ullmaier H., "Irradiation creep in deuteron-bombarded stainless steel", for reference see [6]

[12] Ehrlich K., private communication