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EVALUATION OF MATERIALS FOR EPR POWER GENERATION*

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The blanket materials employed for heat generation in the Argonne Experimental Power Reactor (EPR) are evaluated. The EPR blanket consists of annealed Type 316 stainless steel sections cooled by pressurized water and Inconel 718 sections cooled by steam. The predicted life-times of the two different blanket sections is approximately 2 years of normal operation. The lifetime of annealed Type 316 stainless steel is limited by swelling considerations, while the lifetime of Inconel 718 is limited by ductility considerations.

1. INTRODUCTION

Future development of fusion power includes the construction of an Experimental Power Reactor (EPR) that will test engineering concepts for electrical power generation. The reactor is expected to operate at a high plant capacity factor and to produce heat capable of generating electricity at efficiencies similar to those in present power stations. Recent work at Argonne National Laboratory (ANL) has been aimed at the design of heat generating blankets for tokamak-type fusion reactors capable of achieving high thermal efficiencies. Successful operation of such a blanket requires a thorough understanding of the materials limitations. The severe temperature, stress, and irradiation conditions will limit the lifetimes of the blanket materials. This paper presents an evaluation of the lifetime of the ANL-EPR blanket, based upon presently available bulk property data.

The evaluation of the blanket begins by working backward from the desired thermal efficiency for electrical energy production. This efficiency sets the coolant outlet temperatures from the reactor. The blanket temperatures can then be calculated from a computer code for specific coolant channel configurations and neutron flux conditions. The lifetimes of the blanket materials are then evaluated for the calculated temperatures and stresses. The analysis considers only neutron heating since the first wall will receive the particle and photon flux from the plasma.

2. BLANKET DESIGN

The ANL-EPR is designed to operate at a nominal neutron wall loading of 0.75 MW/m^2 and has a three minute burn cycle with a 15 second dwell time between cycles. The blanket employs a dual cooling system of pressurized water and steam which is capable of producing at thermodynamic efficiency of approximately 40%. The water inlet and outlet temperatures are 191°C and 340°C respectively, while the steam inlet and outlet temperatures are 300°C and 500°C , respectively.

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The EPR blanket design is shown in Figs. 1 and 2 [1]. The blanket is composed of 28 cm thick segments which surround the plasma. The inner and outer blanket segments are made of annealed 316 stainless steel and are cooled by pressurized water, while the horizontal upper and lower blanket blocks are made of Inconel 718 and are cooled by steam. Higher steam coolant temperatures, approaching steam conditions in modern fossil plants, are possible in the Inconel 718 blanket regions because of its high temperature strength and creep resistance. The coolant channel layout is shown in Fig. 2. Six layers of holes radial to the plasma on 3 cm centers form the grid pattern for the coolant channels. Each channel extends across the block in the poloidal direction. All channels are 1.5 cm in diameter and filler rods are placed within the channels to adjust the coolant velocity with the given mass flow in each of the six coolant layers.

3. TEMPERATURE CALCULATIONS

A computer code capable of solving a set of three-dimensional thermal-hydraulic equations was used to establish the transient and quasi-steady state temperature distributions within the blanket blocks. The temperature gradients within the blanket were minimized by an iterative process of changing the coolant channel distribution and the coolant flow rates. The

Fig. 1. Schematic of EPR blanket.

Fig. 2. Blanket block manifold layout

thermal strains within the blanket were then calculated from the temperature distribution. Details of the calculations are given elsewhere [1].

The highest temperatures in both the Type 316 stainless steel and Inconel 718 segments are located at the surface of the blanket nearest the plasma. These temperatures are 498°C for Type 316 stainless steel and 629°C for Inconel 718. The coolest temperatures are located near the surface furthest from other plasma and are 326°C for Type 316 stainless steel and 433°C for Inconel 718. This represents maximum temperature differences of 172°C and 196°C, respectively, which translates into temperature gradients across the blanket thickness of 6 and 7°C/cm. The temperature gradients between coolant channels are significantly greater. The temperature differences between the midpoint between channels and the channel surfaces are a maximum of 30°C for the Type 316 stainless steel segments and 40°C for the Inconel 718 segments. The temperature gradients are 40°C/cm and 53°C/cm, respectively.

The time variation of these temperatures is relatively mild due to the thermal inertia of the blanket blocks as well as the fact that only neutron heating is taking place. Quasi-steady state temperatures are not reached until after 10 complete burn cycles. During the dwell period the temperatures in the blanket decrease by only 20–40°C, while the temperature gradients are approximately the same as during the burn cycle.

A summary of the operating temperatures in the blanket is shown in Table 1.

4. STRESSES IN THE BLANKET

The stresses and strains in the blanket originate from temperature differences, coolant

Table 1. Operating Conditions in EPR - Blanket

Condition	SA 316	Inconel 718
Nominal wall loading	0.75 MW/m ²	0.75 MW/m ²
Burn cycle	3 min burn - 15 s dwell	3 min burn - 15 s dwell
Coolant inlet temp.	191°C (water)	300°C (steam)
Coolant outlet temp.	340°C	500°C
Maximum blanket temp.	498°C	629°C
Blanket temp. range	326–498°C	433–629°C
Maximum temp. gradient	40°C/cm	53°C/cm

pressure, and radiation swelling gradients. The thermal strains can be calculated from the results of the last section. The nonuniform thermal strain is 0.31% in the Type 316 stainless steel segments and 0.29% in the Inconel 718 segments. The stresses generated in the blanket by these strains depends upon whether the thermal expansion is restrained or unrestrained. The ANL/EPR blanket structure has been designed to accommodate the thermal strains in an unrestrained manner, and thus the stresses will be low. Any stresses which occur due to a non-linear temperature gradient are expected to decrease in a short time due to relaxation. The strains produced by thermal gradients between channels are expected to result in restrained stresses. The maximum stresses that are reached due to these temperature differences are 115 MPa in the Type 316 stainless steel segments and 120 MPa in the Inconel 718 segments. These stresses are also expected to decrease during reactor operation due to relaxation.

The stresses due to coolant pressure are low. The pressurized water in the Type 316 stainless steel sections operates at a pressure of 14 MPa while the steam in the Inconel 718 segments operates at 8.6 MPa. Using a stress calculation for a thick wall tube (considered the worst case approximation), these coolant pressures result in hoop stresses at the coolant channel surfaces of 23.2 MPa and 14.3 MPa.

A potential source of high stresses is the swelling gradient that is produced during irradiation. The amount of swelling will decrease non-linearly (usually exponentially) from the surface nearest the plasma to the rear of the blanket due to the decreasing damage level with thickness. For the case of stainless steel and Inconel 718, the damage level drops by approximately a factor of 10 for every 20 cm of thickness [2]. If the swelling nearest the plasma reaches 5%, a simple elastic analysis, using

a thin plate approximation, predicts stress levels of ~ 500 MPa [3]. The actual stresses in the blanket will be reduced by relaxation during reactor operation, but they are likely to remain at a relatively high level.

5. MATERIALS EVALUATION

The evaluation of the blanket materials depends not only on the materials properties for the reactor operating conditions, but also on the lifetime criteria used in the analysis. These are the values at which the material is considered to fail due to fracture or excessive dimensional instability. The life limiting parameters are expected to vary with component geometry, function, and location in the reactor. The criteria chosen here are not necessarily the most suitable, but they provide an acceptable means for comparing and evaluating the materials.

Swelling in the blanket is undesirable for two reasons. First, excessive geometric changes could make the removal of a defective component difficult or impossible, and second, the differential swelling described in the last section could result in high stresses which could adversely affect other properties. The effect of irradiation on swelling is shown in Fig. 3. Peak swelling rates are assumed to account for the potential peak widening effect of helium [4]. Inconel 718 exhibits reduced swelling compared with annealed Type 316 stainless steel. Low swelling is typical of high nickel (≥ 40 wt %) alloys. A life limiting value of 5% has been set for swelling. This is a value that can be accommodated into the design without seriously affecting reactor performance. Annealed 316 stainless steel has a predicted lifetime of 29 DPA, while Inconel 718 has an indefinite lifetime.

Irradiation will reduce the ductility of the blanket materials. The loss of ductility reduces the ability of the material to withstand short term stresses and strains that could result during off normal conditions. Figure 4 compares the change in uniform elongation with irradiation for the maximum operating temperatures of the blanket [4-7]. The ductility is reduced more rapidly in the Inconel 718. In addition, helium embrittlement in Inconel 718 is severe at 650°C, [5] and thus it could be susceptible to off normal operating conditions where the temperature in the blanket is allowed to increase. A uniform elongation of 1% is considered adequate to maintain structural integrity during reactor operation. For this criteria, annealed Type 316 stainless steel has a lifetime of ~ 40 DPA while Inconel 718 has a lifetime of ~ 20 DPA.

Creep in the blanket will result in geometric changes as well as stress relaxation. Sufficiently high time-independent stresses in the blanket will result in creep rupture failure. The stresses discussed earlier are the driving

Fig. 3. Swelling as a function of irradiation.

Fig. 4. Ductility loss with irradiation.

force for creep. The effect of irradiation is to increase the creep rate at low temperatures and to reduce the total strain to failure. In the case of post-irradiation creep tests of Type 316 stainless steel, the strain at failure can be reduced to as low as 1% [8]. A comparison of the post-irradiation 10,000 hour creep lifetimes of the blanket materials at the maximum operating temperatures is shown in Fig. 5 [8,9]. At low irradiation levels, the rupture stress of annealed 316 stainless steel reaches a minimum of 147 MPa compared with 450 MPa for Inconel 718. At high irradiation levels the rupture stresses become comparable. A comparison of in reactor creep of the two materials is shown in Fig. 6 [4,9]. The stresses used in the comparison represent the maximum allowed design stresses of ASME Code Case 1592, based upon unirradiated mechanical properties at the maximum operating temperatures. At the temperatures of interest, thermal creep is

Fig. 5. Post-irradiation creep-rupture lifetimes (10,000 hr) as a function of irradiation.

Fig. 6. In-reactor creep as a function of irradiation.

insignificant. The curves in Fig. 6, which represent peak creep rates as a function of temperature, clearly shows the superior creep resistance of Inconel 718. The stresses shown in Fig. 6 are above the calculated stresses in the blanket during operation with the exception of the stresses due to differential swelling in annealed Type 316 stainless steel. Modifications in design or swelling properties may be required to reduce these stresses. A limit of 1% total creep strain has been set as a lifetime criteria due to the low strains to failure observed in irradiated materials. The lifetimes

predicted for this value are 25 DPA and 37 DPA for Type 316 stainless steel and Inconel 718, respectively.

Fatigue of the blanket structure will occur because of the cyclic nature of the burn cycle and the shutdown cycle of the reactor. There is little available fatigue data of irradiated materials, however. In order to make a fatigue evaluation, design curves from ASME Code Case 1592-12 for unirradiated 316 stainless steel were used. The data indicate that to achieve long fatigue lifetimes, the total strain range should remain below 0.1%. As shown previously, the cyclic strains due to temperature variations during normal operation are significantly below 0.1%, and thus the fatigue lifetimes will be high. The maximum strains that could occur during shutdown are $\sim 0.3\%$ calculated from differential thermal expansion. The number of allowable cycles for such strains is $\sim 10^3$. However, cracks will form prior to failure, and thus the actual lifetime of the blanket segments could be significantly less. In addition, irradiation hardening is expected to reduce fatigue lifetimes in the high strain range [10]. The predicted rates of crack growth in unirradiated material as a function of stress intensity are compared in Fig. 7 [11,12]. Inconel 718 exhibits somewhat lower crack propagation rates than Type 316 stainless steel. The range of stress intensity, ΔK , should remain below $\sim 8 \text{ MPa}\cdot\text{m}^{1/2}$, and for Inconel 718, ΔK should remain below $\sim 10 \text{ MPa}\cdot\text{m}^{1/2}$, to insure an extended lifetime.

Fig. 7. Crack growth rates as a function of stress intensity factor.

6. CONCLUSIONS

Inconel 718 and annealed Type 316 stainless steel each have predicted lifetimes of

approximately two years (20-25 DPA) for the conditions expected in EPR. Inconel 718 is limited in lifetime by the loss of ductility, while radiation swelling limits the lifetime of annealed Type 316 stainless steel.

Stresses due to swelling gradients could be large. Modifications in design or in the swelling properties of Type 316 stainless steel may be required.

Fatigue and crack growth do not appear to have an impact on the lifetime of the blanket segments during normal operation, due to the judicious design of the coolant channels as well as the fact that only neutron heating takes place in the blanket. Shutdown cycles of the reactor could have an impact on fatigue lifetimes.

The use of Inconel 718 and annealed 316 stainless steel appear acceptable for an EPR reactor, but the limited predicted lifetimes raise doubts as to their usefulness in commercial reactors.

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