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MATERIALS PROBLEMS IN MAGNETICALLY CONFINED PULSED FUSION REACTORS*

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Unique operating conditions in fusion power reactors will challenge materials severely. Materials are needed for structural support members, electrical insulators and conductors, heat conductors, neutron breeding materials, neutron moderating materials, and barriers between the corrosive coolant and corrosion prone materials. These materials must function in a satisfactory way without too frequent power generation interruption for part change out. And the materials must do so in spite of the intense high energy neutron flux, heat loads, stresses at temperatures ranging all the way from electrical superconducting temperatures to about 1300 K. Major materials problems have been discussed in a general way(1), and more specifically to a particular power plant(2,3). The specific problems were determined from a comprehensive engineering-design study of a Reference Theta Pinch Reactor (RTPR) completed by staff at Argonne National Laboratory and Los Alamos Scientific Laboratory. The purpose of the present report is to describe the materials challenge from an engineering viewpoint and to indicate how the mechanical response (a major unknown) of structural metals might be resolved for RTPR systems.

Fuel Cycle:

Fusion of a 50/50 mixture of deuterium and tritium yields 14 MeV neutrons and alpha particle ash, eqn. 1.

$$D + T \rightarrow {}^{4}He(3\ 1/2\ MeV) + n(14.06\ MeV) \quad (1)$$

There is sufficient deuterium to fuel many power producing fusion plants, but tritium must be bred as any naturally occurring tritium vanishes by radioactive decay with a 12 year half life. Tritium will be bred by reaction of Li with neutrons, eqn. 2.

$$n + {}^{6}Li \rightarrow {}^{4}He + T \quad (2a)$$

and

$$n + {}^{7}Li \rightarrow n' + {}^{4}He + T \quad (2b)$$

Every neutron produced by fusion isn't involved in a tritium breeding reaction because the Li blanket isn't infinitely thick and because structural materials, insulators, piping, etc. capture neutrons. Additional neutrons must be bred to replace those lost, as shown in eqn. 3.

$$n + {}^{9}Be \rightarrow 2n + {}^{8}Be \quad (3)$$

The breeding ratio is defined in eqn. 4

$$\text{Breeding ratio} = T(\text{breeding})/T(\text{fusion}) \quad (4)$$

where T (breeding) is the breeding rate of eqns. 2 and T (fusion) is the burning rate of eqn. 1. The breeding ratio must be greater than one if refueling is required or if additional reactors must be fueled. Graphite or carbon is used to moderate the neutron energy to adjust for the energy dependence of the cross sections of the various reactions.

The ion density x confinement time must exceed a certain minimum value at sufficiently high temperature if a reactor is to produce more energy than is consumed. This is known as the Lawson criterion, eqn. 5.

$$\text{Ion Density x Confinement Time} > 10^{14}\ \frac{\text{Ions Sec}}{cm^3} \quad (5a)$$

and

$$\text{Temperature} > 10\ kev \quad (5b)$$

The condition wherein the confinement time times the plasma density is equal to 10^{14} ions s/cm^3 corresponds to 1 percent fuel burnup and one percent alpha particle ash in the plasma. The RTPR reactor is a pulsed reactor with a confinement time slightly less than 0.1 s so its plasma density is large compared to steady state reactors. The burning will be stopped after 5 to 10 percent burn and restarted about 10 s later. The spent fuel containing 5 to 10 percent helium is removed and fresh fuel added to the reaction chamber between each burn cycle. Fuel ash (helium) is removed from the unburned fuel before it is returned to the discharge tube. Cryogenic distillation, mechanically pumped permeable metal membranes, gas chromatography and mass spectrometry are plausible separation methods(2). This method of refueling and fuel ash removal is feasible with all pulsed reactors and is considered an advantage over the techniques that must be developed for steady state reactors. The large amount of thermal energy present as kinetic energy in the plasma ions must be extracted, however, before the plasma is pumped out of the discharge tube. A neutral gas blanket separates the plasma from the first wall in theta pinch reactors. Heat conduction through this neutral gas blanket is not important during the burn, but will carry the heat energy away from the plasma

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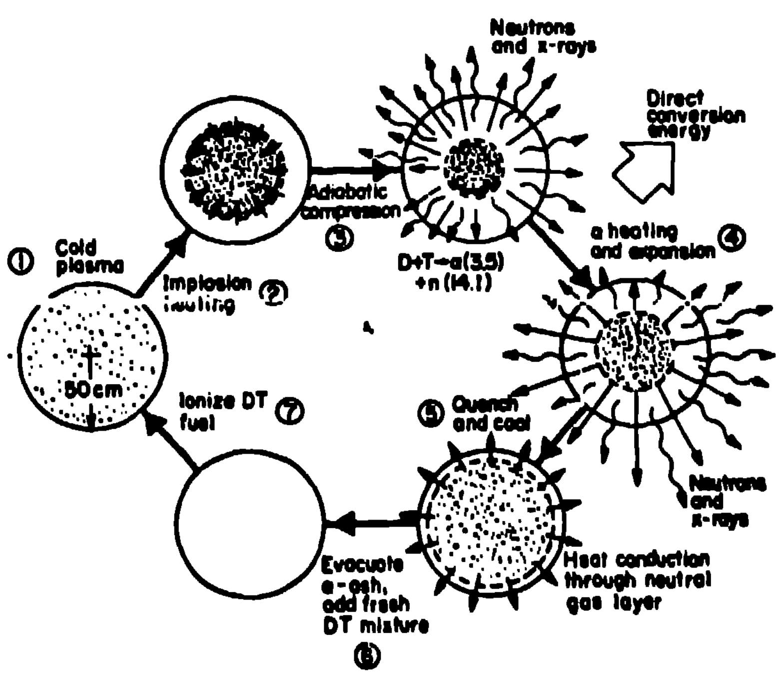
if the magnetic field is let down slowly so that the thickness of the gas blanket decreases. Tailoring of the field "let down" then controls the plasma cooling without excessive heating of the first wall. The energy deposited on the inner face of the first wall will generate temperature gradients in the wall which must be dissipated by conduction to the molten Li coolant before the next pulse. Thermal stresses, which vary in time, result from the mechanical restraint inherent in the design of the first wall. Additional temperature gradients, with attendant thermal stresses, are generated by variations in amount and rate of energy deposited in the first wall and other structures by neutrons, gammas, and Bremsstrahlung. The thermal fatigue stresses are discussed at greater length in a later section of this discussion.

The neutral gas blanket prevents any high energy ions from striking the first wall and so protects it from damage in the form of blistering, ion sputtering, chemical reactions and so forth by high energy ions.

A blanket structure surrounds the plasma and contains molten Li not only for tritium breeding but also to absorb heat deposited throughout the blanket structure by neutrons, by the plasma once the confining magnetic field acting on the plasma is released, by Bremsstrahlung radiation produced in the plasma, etc. The blanket is about 0.5 m thick and contains Be and C to achieve the desired breeding ratio, 1.1, for RTPR. Materials which corrode in molten Li, such as carbon, are clad with a protective layer of niobium. The molten Li is pumped to a heat exchanger electric power plant. The pulsed magnetic fields are off about 99 percent of the time so that there is no problem with pumping a molten conductor across magnetic field lines. This feature means that the pumping power is low for RTPR, relative to steady state machines using molten Li with the same electric power output as RTPR.

Tritium must be extracted from the molten Li for refueling. The lowest possible inventory of tritium is allowed to remain in the Li and the reasons for this are considered elsewhere(2). Many possible means for this have been considered including gas sparging, distillation, tritium permeation through a membrane, and chemical gettering, but extraction with a molten salt seems most promising at present.

The plasma density, time and temperature conditions required for success, eqn. 5, will be produced by a staged or sequenced magnetic field. The discharge tube is first filled with fuel, and it is then ionized. Next an implosion field acts on the plasma and accelerates the ions inward. This field is produced by discharging a capacitor bank around the discharge tube. The required electric field is established if the inner surface of the first wall is coated with an electrical insulator. A compression field is then established by a multi-turn copper coil operating at room temperature. The compression coil field energy is supplied by a cryogenic magnetic energy store located away from the discharge tube and the blanket to protect it from radiation damage. The energy in the compression coil is transferred back to the store reversibly at the end of the burn. The compression coil is further protected from excessive radiation damage by the blanket structure and the heat shield. There is some heating of the plasma by the alpha ash, as the alpha particles are created with an energy of 3-1/2 MeV and the deuterium and tritium ions have an energy of 10 keV, or so, at the start of the burn. The magnetic field does not penetrate the plasma in the theta pinch machine so the plasma heating by alpha particles pushes the compression field back with direct energy conversion. The sequence just outlined is illustrated in Figure 1.



RTPR Power Cycle

Figure 1. Staging of RTPR.

The arrangement of the plasma, blanket, cryogenic magnetic energy store and shock heating capacitors are shown schematically in Figure 2.

RTPR Design

The RTPR design study recommends that the blanket structure be fabricated in modular units with 100 sectors of blanket structure forming the circular cross-section of the torus, as depicted in Figure 3.

One sector of the blanket structure is shown in Figure 4. It is important to note that the first wall is a composite of Al_2O_3 insulator lining the inner surface facing

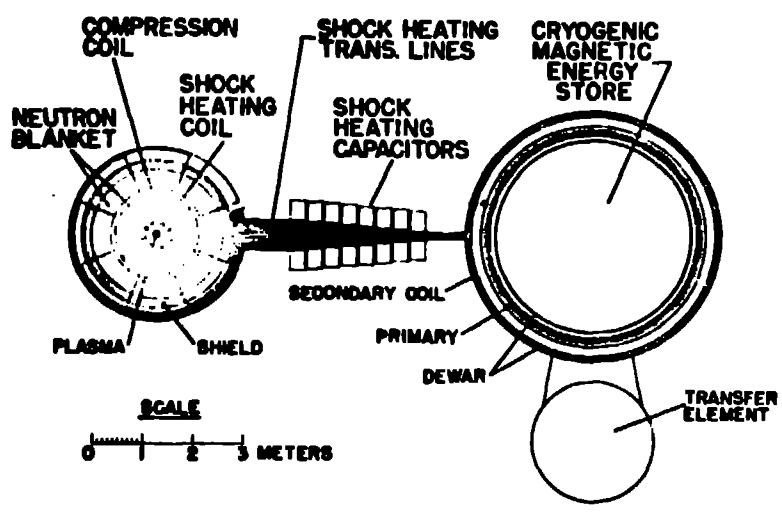


Figure 2. The arrangement of the plasma, blanket, and magnetic field stores (from Ref. 3).

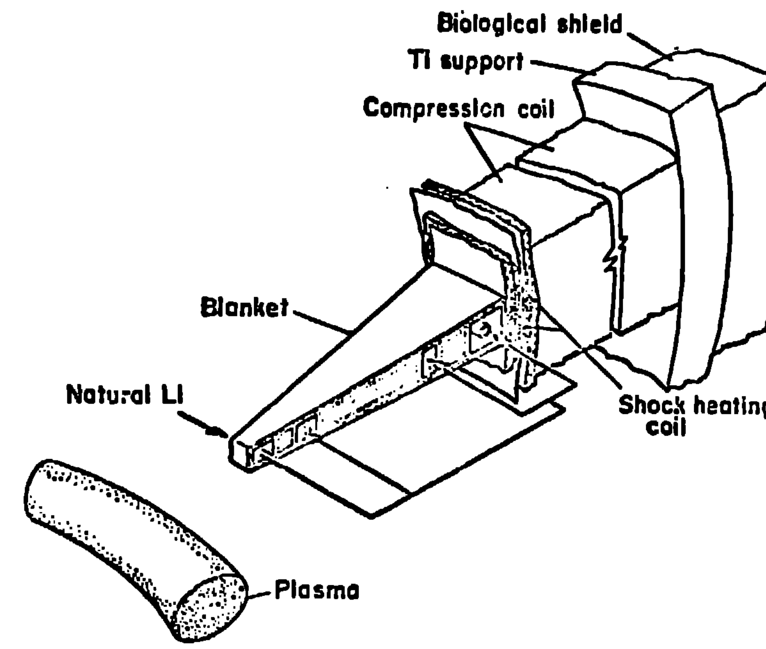


Figure 4. One sector of the blanket structure in detail (from Ref.3).

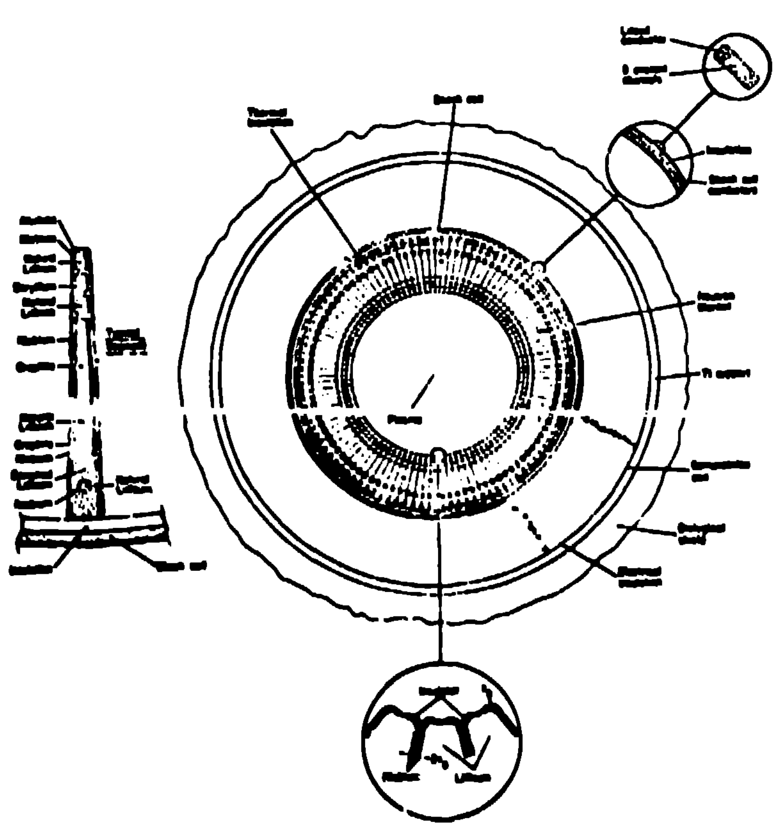


Figure 3. A view of the blanket structure in cross-section.

TABLE I

RTPR

Minor Diam - 1 m	
Major Diam - 112 m	
Plant Building Area 12 acres	
Blanket Thickness 0.4 m	
First Wall Al_2O_3/Nb	
Cycle 0.08 sec Burn - 10 sec Total Cycle	
T Breeding Ratio 1.1	
Burn Up/Pulse 10%	
Thermal Power/Recirculating: 16/1	
Recirculating Power Ratio 0.14	

TABLE II

NEUTRON LOADING OF THE RTPR FIRST WALL

Total n Flux Averaged over Power Cycle	9×10^{14} n/cm^2-sec
Ratio of Total n to 14 MeV n	9.1
Ave. Total n Flux during Burn	3.4×10^{16} n/cm^2-sec
Annual Fluence of all Neutrons	2.55×10^{22} n/cm^2

the plasma and of Nb backing which mechanically supports the insulator and transmits heat from the insulator to the coolant. The coolant would corrode the insulator if in direct contact.

Table I presents a few of the size features of RTPR which have already been discussed elsewhere in detail(2,3). The neutron loading of the first wall composite is summarized in Table II.

The unique feature of pulsed fusion reactors relative to other fusion reactors is the cyclic demands on materials resulting from short but intense radiation and heat loads, dielectric stresses, and so forth

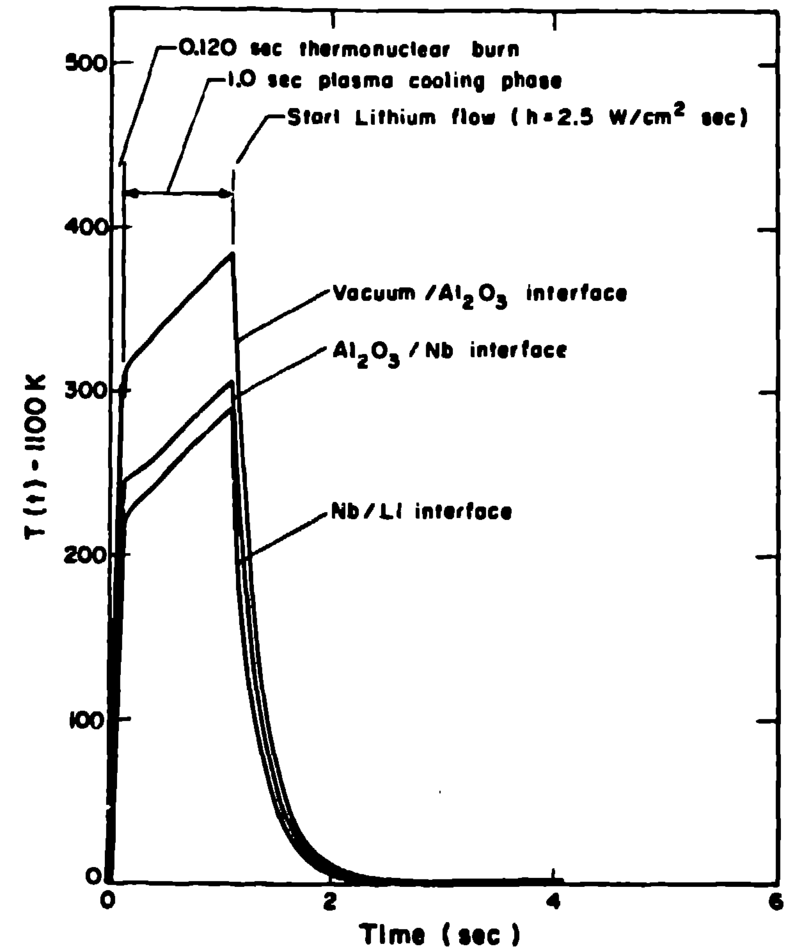


Figure 5. Temperature transients in the first wall structure of RTPR (from Ref. 3).

when loaded in the short but intense bursts shown in Table II. (The dielectric strength properties required of the insulator will not be discussed herein as this has already been done (3).) Energy will be deposited throughout the first wall and blanket structure during the burn and plasma quench stages and must be dissipated

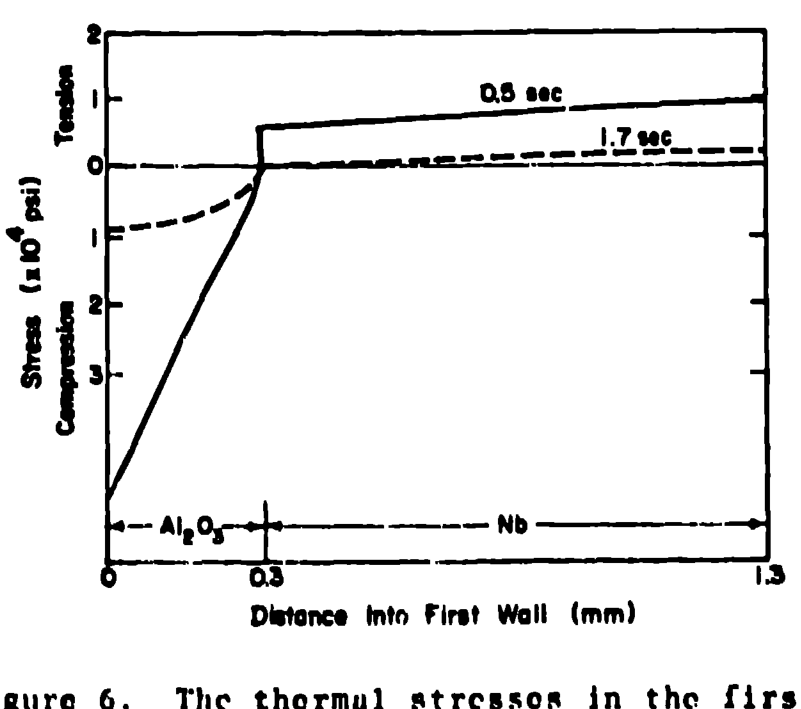


Figure 6. The thermal stresses in the first wall composite structure calculated for two different times for the temperature transients shown in Figure 5.

entirely by the molten Li coolant before the next burning pulse starts. Otherwise, the temperature of the structure could rise a little more with each pulse until the system would fail. The heat must flow down temperature gradients and these are cyclic in time. Figure 5 shows the temperature transients at various locations within the first wall, and Figure 6 shows the thermal stresses in the first wall composite structure at two different times (the stresses are at their largest values 0.5 sec after the start of the cycle).

A fundamental question may be posed relative to Figures 5 and 6 "How will such cyclic thermal stressing limit the useful life of structural components?" There are many possible limitations of materials which would limit the life of pulsed fusion reactors, such as buckling and distortion due to differential neutron induced swelling, failure of the insulator that establishes the shock heat magnetic field, radiation damage to the compression coil, or neutron moderating and breeding materials, but these possibilities have been considered elsewhere(2,3) and need no further consideration herein. The mechanical response to cyclic thermal stresses will be considered in the remainder of the space available.

Mechanical Response:

Thermal creep, radiation creep and fatigue are three different responses to cyclic stressing at elevated temperatures, any one of which could control the life of the first wall and other structural materials. Thermal creep is time dependent deformation of a solid under continuous stressing with thermal activation. Both crystallographic slip and grain boundary sliding occur during thermal creep and this process terminates usually by grain boundary cracking. Figure 7 summarizes over 2/3's of a century of scientific research on thermal creep. Any constant stress σ imposed at a constant absolute temperature T leads to a so-called steady state creep rate $\dot{\epsilon}_{ss}$ and a characteristic internal structure K as given in eqn. 6.

$$\dot{\epsilon}_{ss} = K \sigma^n \exp(-Q/RT) \qquad (6)$$

The stress exponent n is about 4 to 8 for pure metals, slightly lower for solid solution alloys and larger for dispersion strengthened alloys. The so-called activation energy for thermal creep is equal to the self diffusion activation energy, or about 39 T_m where T_m is the melting temperature of the metal under consideration, when the temperature is above 1/2 T_m; and Q is slightly less at temperatures below 1/2 T_m. The time to failure, t, and the steady state creep rate are related in eqn. 7.

$$t \, \dot{\epsilon}_{ss} = \text{constant} \qquad (7)$$

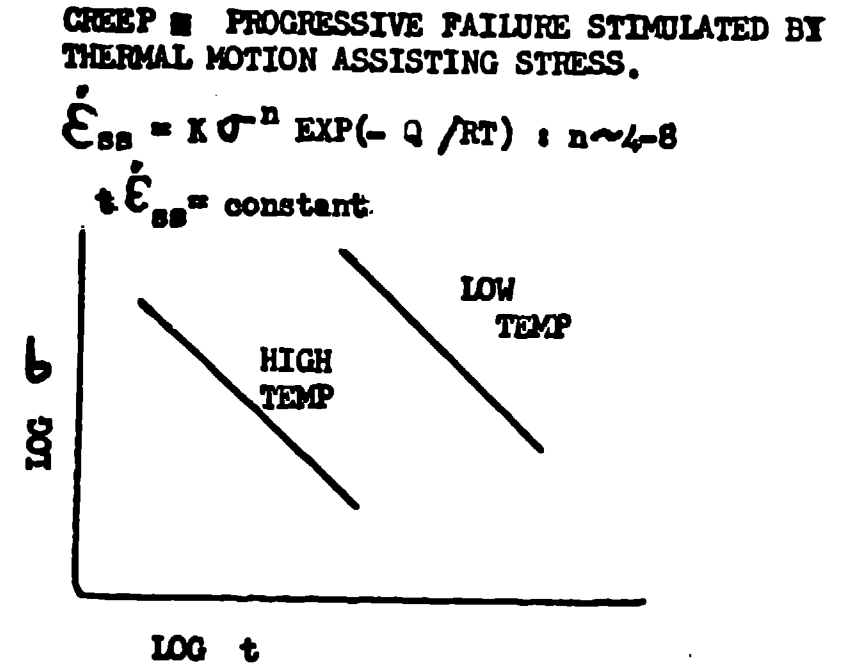


Figure 7. A summary of thermal creep.

Figure 8. Grain boundary cracks normal to the stress axis for creep deformed molybdenum.

Grain boundary cracks typical of creep failure are shown in Figure 8. Radiation creep doesn't depend on thermal activation and occurs under conditions of stress and temperature under which thermal creep isn't important. The rate of creep depends on neutron flux intensity and on stress raised to the first power. Radiation creep will not be considered at length herein. Fatigue is progressive deformation and failure

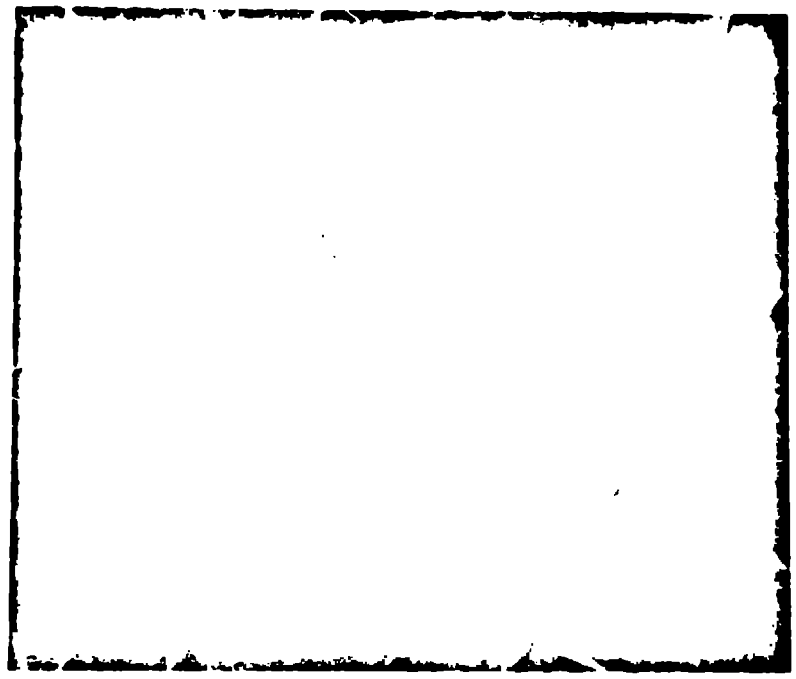


Figure 9. Extrusions related to crystallographic slip on the surface of a copper crystal after fatigue.

stimulated by many cycles of repeated stressing. Failure occurs by transgranular fracture. The transgranular deformation produced by fatigue is shown in Figure 9 where extrusions protrude from a copper single crystal after fatigue. Intrusions also occur and crack propagation is associated with the crystallographic slip which causes extrusions and intrusions.

All the knowledge on fatigue is summarized in Figure 10. The effect of temperature on fatigue crack growth is small and the number of cycles of stress to failure N is related to the peak stress in eqn. 8.

$$N \sigma^{a} = \text{constant} \qquad (8)$$

The stress exponent is usually between 8 and 15. Materials do not fail by fatigue crack propagation if the stress intensity is below a stress limit known as the fatigue limit.

At fusion reactor temperatures for the first wall, 900 to 1300 K, each cycle of stress will produce some creep deformation and some fatigue deformation.

Figure 11 depicts how the time to failure will depend on stress for low, medium, and high temperatures, for situations wherein many cycles of stress occur. Fatigue failure would dominate at low temperatures, creep at high, and either creep or fatigue, depending on stress level, at intermediate temperatures. Great care will be required to insure that accelerating techniques normally used in creep studies do not cause a transition between the competing mechanisms.

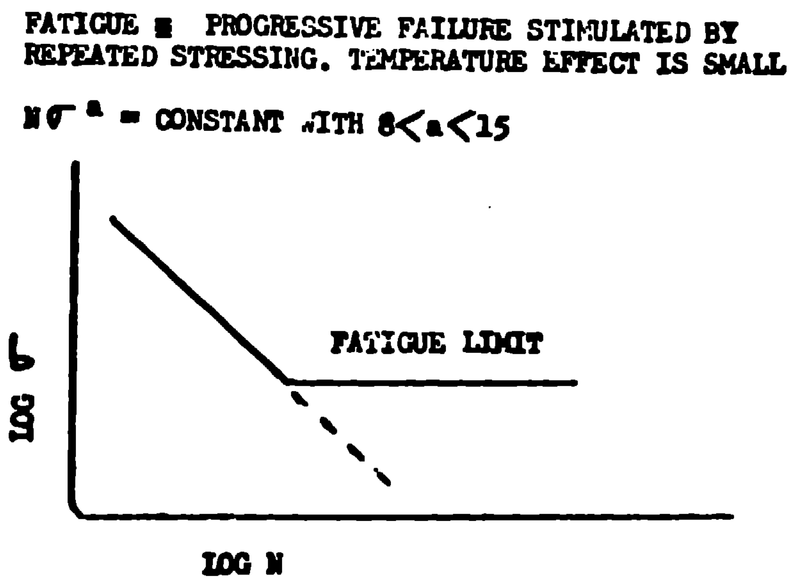


Figure 10. A summary of fatigue deformation.

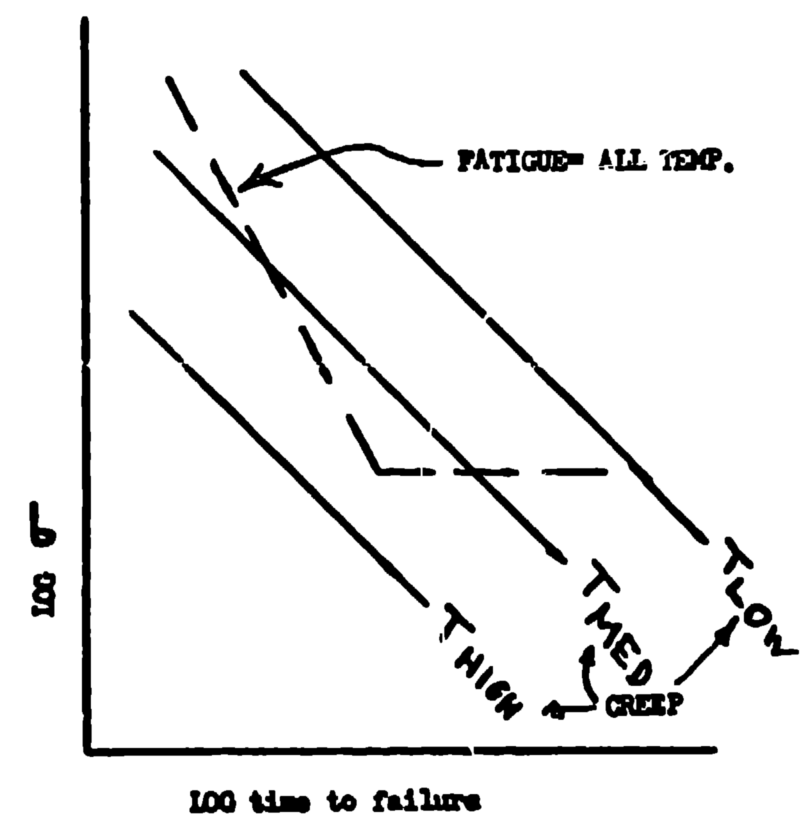


Figure 11. A summary of the response of materials to many cycles of repeated stressing at various temperatures.

(Creep of materials over long times are often evaluated by testing at higher temperatures and stresses.)

The competition between fatigue and thermal creep will occur in all pulsed fusion reactors, but with the additional possibility of radiation creep being the dominant deformation mode. Figure 11 then is transformed into a three coordinate system figure, but the method of considering the problem isn't changed by this addition. The response of structural support members to the effects of neutron irradiation, in pulses, of cyclic temperature transients, and therefore cyclic thermal stresses, and of elevated temperature must be evaluated for each different type of pulsed fusion reactor having different combinations of cyclic stress, steady stress, temperature, flux level, and metal choice. This evaluation represents a very challenging problem for the materials scientist.

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