Startup Scenarios of an Advanced Fuel Tokamak: First Wall and Shield Thermal Response

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DISCLAIMER

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STARTUP SCENARIOS OF AN ADVANCED FUEL TOKAMAK: FIRST WALL AND SHIELD THERMAL RESPONSE

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ABSTRACT

Three different startup scenarios, one using pure D-^{3}He, one using pure D-T to assist reaching the D-^{3}He operating point, and one using a mixture of D-T-^{3}He, have been analyzed, for the startup of ARIES-III. ARIES-III is a conceptual D-^{3}He tokamak fusion power reactor operating in a second stability configuration. The process of starting the plasma up and bringing it to the desired operating point has been optimized to minimize the need for auxiliary ICRF heating during startup. In the second and third startup scenarios, seeding the plasma with tritium during startup reduces the amount of ICRF power required, but leads to a 14 MeV neutron pulse. Neutronics calculations have been performed to generate the nuclear heating profiles in the first wall and shield. The neutronics results were scaled with the neutron power to determine the nuclear heating profiles at different times during the startup phase. In this work, a two-dimensional transient thermal analysis is performed for the startup phases and the temperature distribution in the first wall and shield as a function of time is presented. The analysis is performed for the worst conditions at the midplane of the outboard region.

I. INTRODUCTION

In the ARIES-III D-T-^{3}He conceptual tokamak fusion power reactor study, a mixture of D-T-^{3}He fuel has been adopted for the startup reference case.[1] A large amount of energetic 14.1 MeV neutrons are produced during the startup phase compared to the normal D-^{3}He operating phase. This necessitates careful examination of the impact on magnet heating and the thermal-hydraulics performance of the first wall and shield. Neutronics calculations have been performed for the ARIES-III first wall and shield to determine the nuclear heating profiles in the startup phase.

For a DT neutron power of 3000 MW during startup, the average neutron wall loading is 2.24 MW/m^2 and the peak outboard neutron wall loading is 3.13 MW/m^2. The total time-integrated DT neutron energy generated in the reference startup scenario is only 90 GJ. That results in a 0.45 J/cm^3 peak magnet heating due to 14 MeV neutrons; this is much lower than the maximum tolerable value.[2] Therefore, the increased magnet heating during the reference startup phase is not a concern.

Another concern related to the startup phase is the generation of large amounts of volumetric heating in the first wall and shield resulting from the large DT neutron generation rate in the plasma. The neutronics calculations performed for a 3000 MW DT neutron power produced the nuclear heating profiles in the first wall and shield. At this power level, the peak power density in the outboard first wall is 47 W/cm^3. The neutronics results were scaled with the neutron power to determine the nuclear heating profiles at different times during the startup phase. In addition to the volumetric nuclear heating, the first wall is exposed to significant surface heat flux, particularly in the latter part of the startup phase approaching the normal D-^{3}He operating point. A two-dimensional transient thermal analysis is performed and the temperature distribution in the first wall and shield as a function of time is presented. The analysis is performed for the worst conditions at the midplane of the outboard region.

II. STARTUP SCENARIOS

Startup of an advanced fuel second stability tokamak power reactor presents a number of challenging issues. The need to minimize the auxiliary heating during startup, the MHD stability during the transition from first stability to second stability, and the neutral beam current drive requirements are some of these issues.[1] Also, the various engineering systems must remain within their design limits during the startup process.

In the startup process, the working gas is injected into the discharge chamber and ionized to create a plasma. An initial plasma current is established to magnetically confine this plasma. The plasma is then heated and fuelled to bring it to the desired operating density, fuel mixture and temperature. Simultanously, the plasma current is increased to the final value so that the confinement and plasma stability is maintained. The criteria for optimization is to minimize the need for external startup power. The process of bringing the plasma to the desired operating point has been modeled using a time-dependent particle and power balance code. The code uses specified spatial profiles for the plasma density and temperature and averages over these profiles to obtain rate equations for the density and temperature of the various species in the plasma.

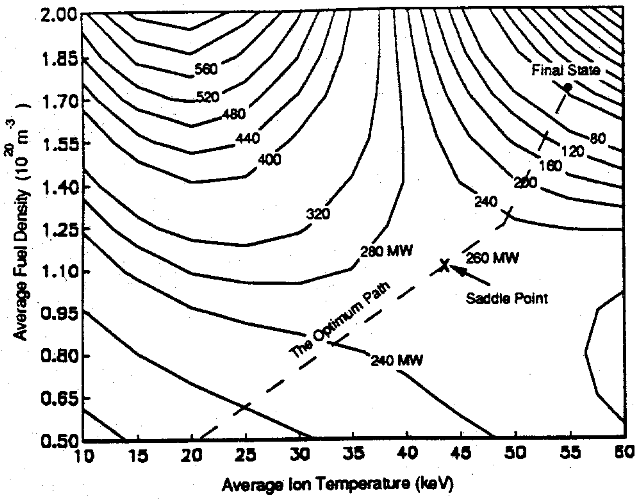

Fig. 1. Contours of injection power for pure D-^{3}He startup.

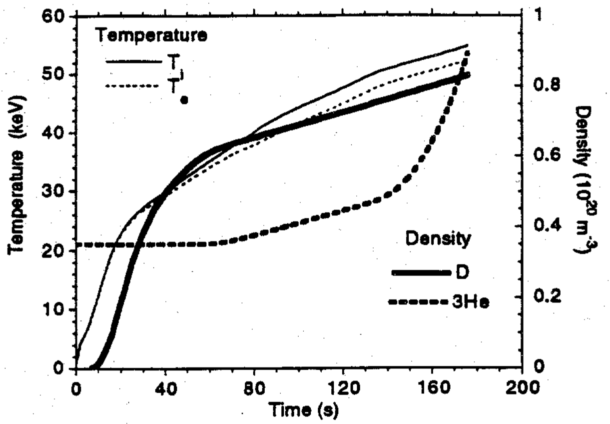

Fig. 2. Programming of fuel density and rise of the density-weighted average ion and electron temperature for pure D-^{3}He startup.

A. Critical Path Analysis

The influence of various paths on startup power can be studied using POPCON plots in a two-dimensional subspace of the multidimensional startup space. A POPCON plot is essentially a contour plot of the heating power required to sustain the plasma at a given density and temperature. The topography of the POPCON plot normally shows a "mountain range" in terms of heating power lying between the initial plasma state of low temperature and density and the desired operating point. The trajectory which minimizes the required auxiliary startup power is one which passes through the saddle point in this "mountain range" and avoids regions of higher required heating power. The rate equations determine the time at which various points along this trajectory are reached.

The POPCON plot for the temperature range of 10 keV to 60 keV for pure D-^{3}He startup is shown in Fig. 1. This plot assumes that the plasma entered second stability at less than 10 keV and the fuel mixture is 62% D and 38% ^{3}He: this fuel mixture minimizes bremsstrahlung and synchrotron losses for a given fusion power and therefore leads to a lower amount of auxiliary startup power.

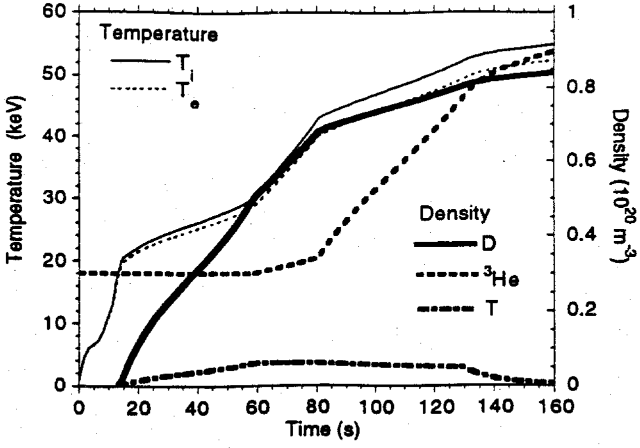

Fig. 3. Programming of fuel density and rise of the density-weighted average ion and electron temperature for pure D-T assisted startup.

1. Pure D-^{3}He startup. The deuterium and ^{3}He fuel densities are programmed as a function of the ion temperature, Fig. 2. The plasma is initially pure ^{3}He and the D density is increased once the plasma is in second stability. The D fraction increases to 62% and the total density to 1.1×10^{20} m^{-3} as the saddle point is neared. Once the saddle point is crossed, the ^{3}He/D ratio is increased to the desired value of 1.07 as the operating point is reached. The peak in the minimum power at early time occurs when the plasma starts to enter second stability and the H-mode confinement multiplier begins to increase. MHD stability calculations show that, with proper control of the current density profile, the plasma is MHD stable.[1]

2. D-T assisted startup. Adding tritium to the plasma is a way to increase the fusion power during startup and reduce the need for auxiliary startup power. The plasma composition is initially pure ^{3}He at a density of 3.1×10^{19} m^{-3} and it follows the same program as used with pure D-^{3}He startup. Deuterium and tritium are injected when the plasma gets to about 20 keV. The maximum tritium concentration in the plasma is 7%. The tritium fueling is shut off when the plasma reaches about 52 keV and the tritium density decays by burnup and diffusion out of the plasma. D-T reactions cause the required external heating power to decrease when the plasma reaches about 25 keV and the tritium concentration is sufficient to produce enough D-T fusion power. Figure 3 shows the deuterium, tritium, and ^{3}He fuel densities as programmed as a function of the ion temperature.

3. Pure D-T startup. The plasma composition is initially equal amounts of deuterium and tritium. When the plasma reaches about 20 keV, the density of ^{3}He starts to increase while the rate of the tritium fueling starts to decline. Figure 4 shows the programming of the fuel densities and ion temperature variation with time. This study shows that the pure D-T startup has the lowest need for required external heating power. Also, it shows an unfavorable characteristic: a large spike in the 14 MeV neutron power at early stages of startup which is one of the

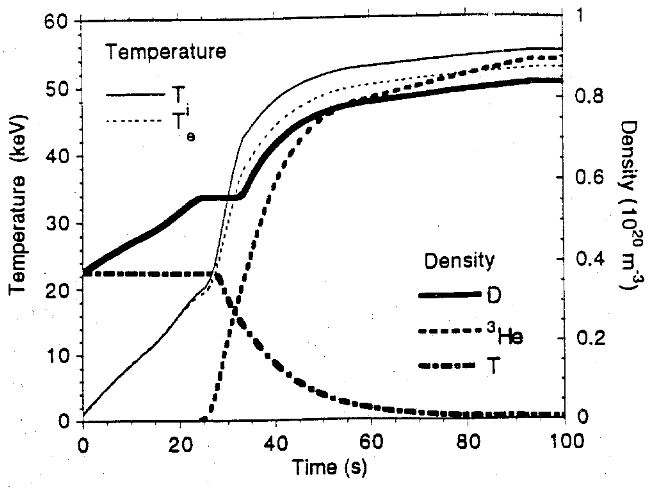

Fig. 4. Programming of fuel density and rise of the density-weighted average ion and electron temperature for pure D-T startup.

main reasons to adopt the D-T assisted scenario for the startup process.

III. THERMAL ANALYSIS

The thermal-hydraulics analysis is carried out using the following guidelines:

1. The first wall coolant (organic coolant (HB-40)) flow is single pass and is in the toroidal direction.
2. The coolant inlet temperature is initially 50°C. The coolant is allowed to heat up and is fed back to the coolant loop until its temperature reaches the steady state operating temperature.
3. The structure has the same initial temperature of 50°C.
4. The total coolant flow rate, as well as the flow rate through the shield coolant channels, is the same as under normal operating conditions.[2]

Two different startup scenarios, one using pure D-T to assist reaching the D-^{3}He operating point, and one using a mixture of D-T-^{3}He, have been analyzed. Figure 5 shows the time variation of the neutron power and the surface heat flux at the outboard reactor midplane in the case of D-T-^{3}He startup. Figure 6 shows the general distribution of nuclear heating in the outboard first wall and shield at the reactor midplane as obtained from the neutronics calculations for a total DT neutron power of 3000 MW.[2] The results of the neutronics analysis were scaled linearly with the neutron power variation to yield the volumetric nuclear heating variation with time.

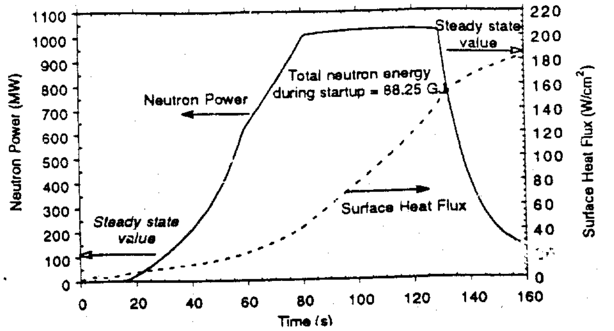

Fig. 5. Neutron power and surface heat flux variation during pure D-T assisted startup.

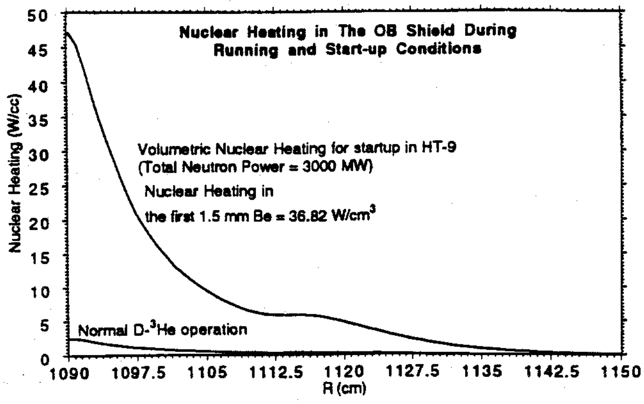

Fig. 6. Nuclear heating distribution during startup.

A. Lumped Adiabatic Heatup Analysis

First we considered a global thermal analysis, where the shield and the organic coolant are considered as one lumped heat-capacity system. The system is allowed to heat up adiabatically. Such a system is obviously idealized since a temperature gradient must exist in the material if heat is to be conducted into or out of the material. The purpose of this calculation is merely to estimate the temporal variation of the average temperature of the system for use with the transient thermal analysis. In the transient thermal analysis, the coolant temperature will be assumed to vary with time as the average temperature of the system.

In the case of D-T-^{3}He startup the total neutron energy generated in the plasma during the 160 s startup phase is 88 GJ. This leads to a total nuclear heating of 1.73×10^{11} J in the first wall and shield. During this period, the total surface heat deposited in the first wall is 9.7×10^{10} J. The ferritic steel (HT-9) in the first wall and shield amounts to 5930 tonnes and the total mass of organic coolant HB-40 in the system is 303 tonnes. Using the specific heats for HT-9 and HB-40, 650 J/kg K and 2570 J/kg K, respectively, the total heat capacity is determined to be 4.63 GJ/K. Since the total heating (surface and volumetric) in the 160 s startup phase is 2.7×10^{11} J, the average temperature rise at the end of the 160 s startup phase is 58°C. The system will continue to heat up after the normal D-^{3}He operation phase starts.

B. Two-Dimensional Transient Thermal Analysis

ANSYS, a commercial computer code for thermal and stress analysis application using the finite-element method,[3] is

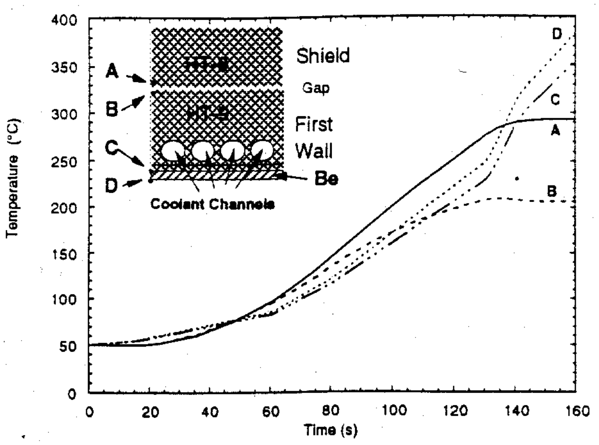

Fig. 7. Temperature variation of some important points during pure D-T assisted startup.

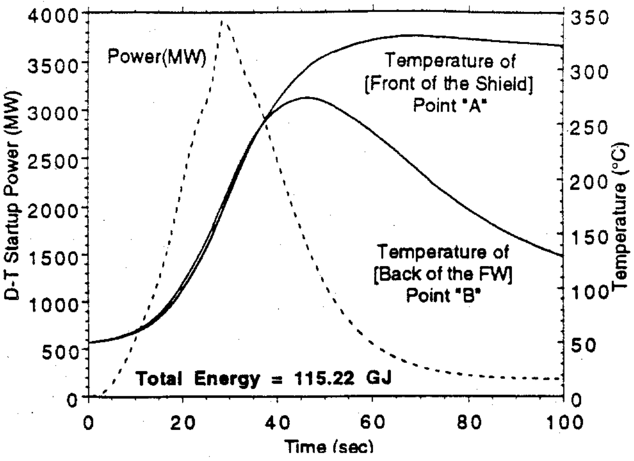

Fig. 8. Neutron power and temperature variation of some important points during pure D-T startup.

used to calculate the temperature distribution in the outboard first wall and shield. A two-dimensional finite element model is used with ANSYS. Temperature dependent properties of the first wall and shield materials (Be and HT-9) are furnished to the code. Here, we considered a model for an eighth of the outboard first wall and shield that covers regions of interest.

1. D-T-^{3}He startup. Figure 7 shows the temperature variation with time for four different important points in the first wall and shield. Point D is the midpoint of the front surface of the Be coating on the first wall where the maximum rise in temperature is expected. Point C is the midpoint at the interface between the Be layer and the HT-9 in the first wall. Point B is the midpoint of the back of the first wall. Point A is the midpoint at the front of the shield. It is of interest to note that the temperatures at points D and C are controlled by the surface heat flux and the first wall coolant bulk temperature, while the temperature at point B is controlled by the nuclear volumetric heating and the first wall coolant bulk temperature. In the meantime, the temperature at point A is controlled by the nuclear volumetric heating, the time constant of the first 9 cm of HT-9 of the shield, and the shield coolant bulk temperature.

2. Pure D-T startup. Although pure D-T startup is not the reference case, the thermal-hydraulics analysis given here proved its use is possible. Figure 8 shows the time variation of D-T neutron power and the temperature variation with time for two different important points in the shield for this startup scenario. In this model, the Be and HT-9 layers adjacent to the first wall coolant are not modeled, because of the moderate surface heat flux in the case of pure D-T startup. Point "A" is the midpoint of the front surface of the shield, where the maximum rise in temperature is expected because the nearest coolant channel is far enough to affect the temperature at point "A". Point "B" is the midpoint of the back of the shield where the first wall coolant channel is very close to have a direct effect on the temperature of Point "B".

IV. CONCLUSIONS

Unlike the normal D-^{3}He operating phase, D-T startup has a moderate thermal effect on the first wall because of the moderate surface heat flux, but has a greater thermal effect in the shield region because of the higher neutron generation in the D-T startup phase. If the initial temperature is 50°C, the first wall and shield thermal response to the reference D-T-^{3}He startup scenario and the alternative pure D-T startup scenario are as follows:

a) D-T-^{3}He startup: The maximum temperature for HT-9 in the first wall at midplane is less than 385°C at the end of the 160 s startup period.

b) D-T startup: The maximum temperature for HT-9 in the shield at midplane is less than 325°C at the end of the 100 s startup period.

The results indicate that during the startup phase, first wall and shield material temperatures will be lower than those during the normal D-^{3}He operation phase.

ACKNOWLEDGEMENT

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