Plasma Startup of the ARIES-III Second Stability Advanced Fuel Tokamak

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Abstract

The ARIES-III conceptual reactor design utilizes D-^{3}He fuel in a second stability tokamak configuration. The process of starting up the plasma and bringing it to the desired operating point has been analyzed using a time-dependent particle and power balance code in conjunction with MHD equilibrium and stability, and neutral beam current drive calculations. Two different startup scenarios, one using D-T to assist reaching the D-^{3}He operating point and one using only pure D-^{3}He, have been analyzed. In order to minimize the amount of ICRF auxiliary heating required, it is necessary to program the plasma current so that the plasma enters second stability as soon as practical; it has been assumed that confinement improves greatly when the plasma is in second stability. Seeding the plasma with tritium during startup reduces the amount of ICRF power required, but leads to a 14 MeV neutron pulse. The blanket and magnet heating due to this neutron pulse are within acceptable limits. The DT assisted startup has been chosen as the reference procedure.

Introduction

Startup of an advanced fuel second stability tokamak power reactor presents a number of significant problems: the programming of the density and temperature have to be chosen to minimize the need for auxiliary heating during startup, the plasma current and current density profile have to be programmed so that the plasma remains MHD stable as the plasma goes from first stability to second stability, and the neutral beam current drive system has to be programmed to provide the required plasma current versus time as well as avoid excessive neutral beam shine-through when the plasma density is low. It is also necessary that the various engineering systems remain within their design limits during the startup process. These problems have been analyzed within the context of the ARIES-III reactor study [1]. The emphasis in this study has been on the plasma physics questions of startup. The engineering aspects of first wall and shield heating have been looked at briefly and little consideration has been given to the question of bringing the entire power plant on line.

Computational Model

The process of bringing the plasma to the desired operating point has been simulated 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 calculate the various power and particle source and loss terms. This results in rate equations for the ion and electron temperatures, and the densities of the various ion species in the plasma. For the startup process, the deuterium and ^{3}He densities are programmed by appropriate choice of the fueling rates and the accumulation of the ash (protons, ^{4}He, and tritium) is calculated. The fusion reactions considered are ^{3}He(d,p)^{4}He, D(d,p)T, D(d,n)^{3}He, and T(d,n)^{4}He. Consequently, we have five coupled rate equations for the five variables: ion temperature, T_i; electron temperature, T_e; proton density, n_p; alpha density, $n_{\rm alpha}$; and tritium density, n_T. The deuterium density, n_D, and ^{3}He density, $n_{\rm He}$, are specified as functions of T_i for this study.

The rate equations for the temperatures include the power generated by the four fusion reactions given above, and power input from the current drive system and from an auxiliary heating system. The power losses included are bremsstrahlung, synchrotron radiation, and plasma transport across the magnetic field. Synchroton radiation is calculated using the Trubnikov [2] formula and averaging it over the specified profiles. Transport is calculated using the ITER-89P [3] scaling expression with a multiplier, f_H, to represent confinement enhancement due to H-mode operation, or some other means of improving confinement. For startup it is necessary to specify the variation of f_H as the plasma goes from first to second stability. For this study it is assumed that $f_H = 2$ (corresponding to the present experimental data base) in the first stability regime ($\varepsilon\beta_p < 0.5$), $f_H = 7.2$ in second stability ($\varepsilon\beta_p > 1$), and varies continuously and linearly in the transition region ($0.5 < \varepsilon\beta_p < 1$).

The rate equations for particle balance include the source of protons, tritium, and alpha particles due to fusion reactions and loss due to plasma transport. Tritium is also lost by burnup in the T(d,n)^{4}He reaction. A separate rate equation for the impurity density is not included; the impurity concentration is assumed to be instantaneously proportional to the fuel density. The contribution of fast fusion-produced ions to the plasma pressure is included using an analysis based on the slowing down approximation to the Fokker-Planck equation.

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. At the same time the plasma current is increased to the final value so that confinement and plasma stability is maintained. One can think of the startup process as following a trajectory in a multi-dimensional space. The optimum path is the one for which the need for additional startup power is a minimum because of the capital investment associated with the equipment.

POPCON Analysis

The influence of various paths on the startup power can be studied using POPCON plots in a two-dimensional subspace of the multi-dimensional startup space mentioned above. 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.

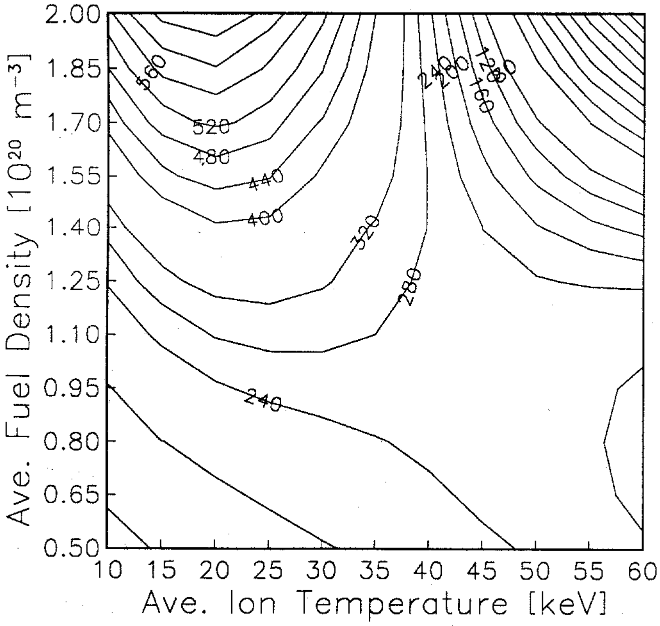

Fig. 1. Contours of injection power for pure D-^{3}He startup.

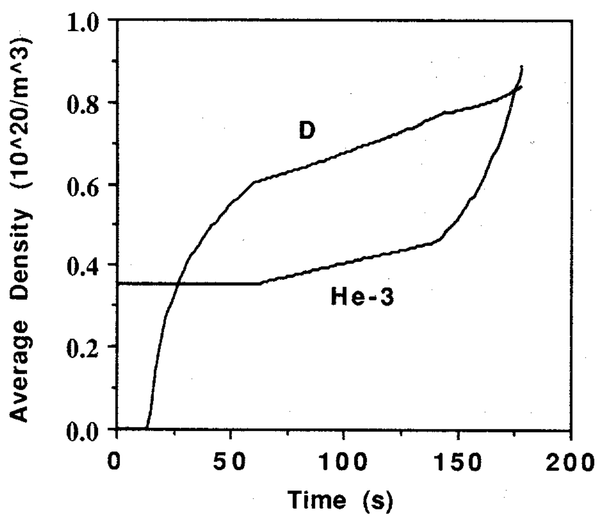

Fig. 2. Programming of the fuel density.

The POPCON plot for the temperature range of 10 to 60 keV is shown in Fig 1. This plot assumes that the plasma has entered second stability at less than 10 keV so that the confinement multiplier is 7.2 over the entire range shown. It also assumes that 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 lower requirements for the amount of auxiliary power needed to reach the desired operating point. The saddle point is located at a density of about 1.1×10^{20} m^{-3} and a temperature of about 43 keV; the required power at the saddle point is about 260 MW. The difference between the actual heating power and the required power given by the POPCON plot determines the rate of rise of the temperature. From this POPCON plot we see that about 275 MW of heating power are required; this includes the power input from the current drive system as well as the auxiliary heating power itself. The current drive system has a capability of 175 MW, but only about 75 MW can be utilized at the saddle point due to the lower beam energies used at that point in order to maintain the required current profile. This means that about 200 MW of additional power is required in order to get through the saddle point and reach the operating point.

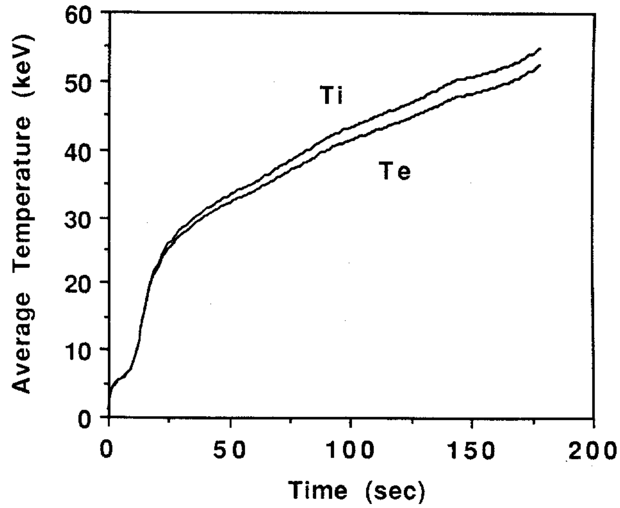

Fig. 3. Rise of the density-weighted average ion and electron temperatures.

Plasma Kinetics

Pure D-^{3}He Startup

To study the time dependence of the startup process the time dependent particle and power balance code described above has been utilized. The deuterium and ^{3}He fuel densities are shown in Fig. 2. The plasma is initially pure ^{3}He; this is to take advantage of the mass dependence in the energy confinement scaling. The deuterium density is increased once the plasma is in second stability and has improved energy confinement. The deuterium fraction is increased to 62% and the total density to about 1.1×10^{20} m^{-3} as the saddle point is neared. Once safely through the saddle point, the ^{3}He/D ratio is increased to the desired value of 1.07 as the operating point is reached. Fig. 3 shows the time dependence of the ion and electron temperatures starting from an initial condition of 1 keV for each. The total heating power is 100 MW initially; this is increased to 275 MW when $\varepsilon\beta_p = 1$ and the current drive system in turned on. The initial plasma current is 6.5 MA; this is held constant until $\varepsilon\beta_p = 1$. Once $\varepsilon\beta_p = 1$ is achieved, the current rises maintaining constant $\varepsilon\beta_p$ until the plasma is safely through the saddle point. Then $\varepsilon\beta_p$ is allowed to rise to the design value as the operating point is neared; this path of current versus $\varepsilon\beta_p$ in conjunction with appropriate control of the current density profile, maintains the MHD stability of the plasma during the startup process. Figure 4 shows the programming of the total heating power and the minimum power required to have $dT_i/dt > 0$. This minimum power is just the difference between the power losses from the plasma and the power input from fusion reactions; it does not include the power input from the current drive system. It should be noted that the minimum power depends on the amount of ash accumulation in the plasma, which in turn depends on how fast the plasma is heated. In the simulation shown, the ash accumulation has not reached steady-state so the minimum power is less than that shown on the POPCON plot. The peak in the minimum power at early time occurs when the plasma starts to enter second stability and the confinement multiplier begins to increase.

MHD stability calculations at various points along the path of plasma current versus beta show that, with proper control of the current density profile, the plasma is MHD stable. Maintaining this current profile requires control of the deposition profile of the neutral beams used to drive the current. This control is provided by adjusting the energies of the three beam lines during the startup process. Table 1 shows the various beam energies and powers, current drive efficiency, and beam shine-through at various times in the startup process. Figure 5 shows the current profile required and achieved at a beta of 8%, which is near the saddle point in the POPCON plot; the match is rather good. A similar match of profiles is achieved at other points during startup. The current drive efficiency is higher during startup than at the operating point since the startup path emphasizes lower density and high temperature. The shine-through during

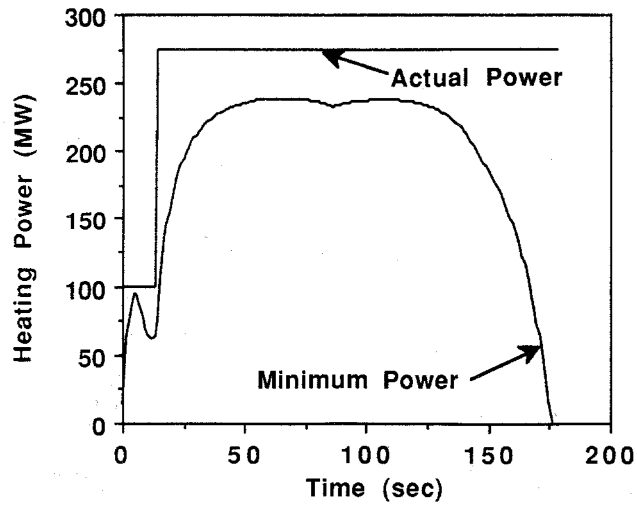

Fig. 4. Total external heating power (current drive and auxiliary) and the minimum power required to sustain the plasma at a given point for pure D-^{3}He startup.

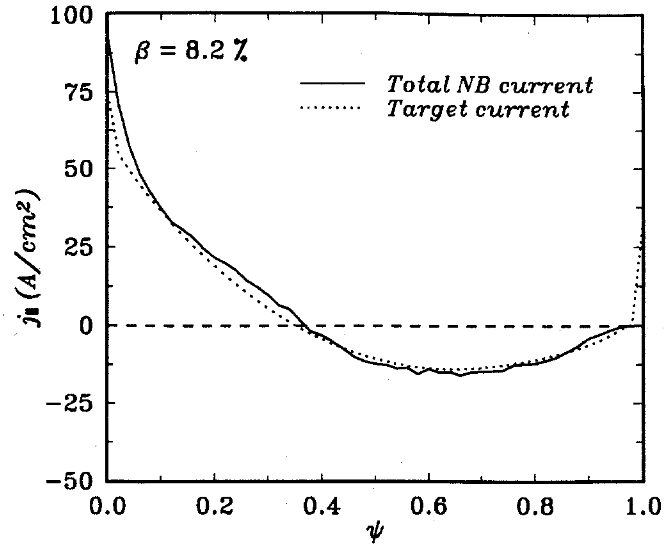

Fig. 5. Comparison of the NB-driven current density with the required current density at a beta of 8.2%

startup is acceptable even though the density is lower since the beam energies are reduced.

Table 1. Parameters of the NBCD During Startup Operations

time(s)	β	E_1	E_2	E_3	P_1	P_2	P_3	P_{tot}	f_s
14.0	0.010	3.0	3.0	1.0	10.0	12.0	35.0	57.0	0.065
29.0	0.038	4.0	3.0	1.0	10.0	18.0	40.0	68.0	0.061
84.0	0.080	5.0	4.0	1.5	10.0	25.0	40.0	75.0	0.0062
142.0	0.131	6.0	4.0	1.5	15.0	10.0	70.0	95.0	0.0021
179.0	0.225	6.0	6.0	3.0	25.0	25.0	120.0	170.0	≈ 0

D-T Assisted Startup

Adding tritium to the plasma is a way to increase the fusion power during startup and reduce the need for additional ICRF startup power. Shown in Fig. 6 is the density programming for a tritium assisted simulation. The plasma composition is initially pure ^{3}He at a density of 3.0×10^{19} m^{-3}. Deuterium and tritium are injected when the plasma gets to about 20 keV. The maximum tritium concentration in the plasma is about 7%. After the plasma reaches about 52 keV, the tritium fueling is shut off and the tritium density decays by burnup and diffusion out of the plasma. Shown in Fig. 7 is the total heating power applied to the plasma and the minimum heating power required to keep the plasma from cooling. The initial heating power is 100 MW, which is assumed to be ICRF heating; the total heating power increases to 175 MW when $\varepsilon\beta_p = 1$ is reached and 75 MW of current drive power is turned on. D-T reactions cause the required external heating power to decrease when the plasma gets to about 25 keV and the tritium concentration is sufficient to produce enough D-T fusion power. As the plasma current increases the current drive power is increased and the ICRF power is decreased, maintaining 175 MW of heating power. The minimum required heating power increases to 135 MW after the tritium fuelling is turned off. Figure 8 shows the evolution of the plasma temperature and Fig. 9 shows the 14 MeV neutron power versus time. The peak power in 14 MeV neutrons is 1000 MW and the total 14 MeV neutron energy released during startup is 87 GJ. This occurs over a time interval of about 80 seconds. At the end of the simulation presented in Fig. 6–9 the plasma is at the final fuel mixture and density and the final operating temperature. The tritium concentration is about 50% higher than the steady-state value and decaying towards it.

The pulse in neutron power during the startup process raises a concern about first wall, shield, and magnet heating. The total neutron energy deposited in the magnets is 0.45 J/cm^3 in a time of about 80 seconds, which is considerably less than the design guideline of 3 J/cm^3 for pulses of this duration. Hence the increased magnet heating during the startup phase can be handled. To evaluate the thermal response of the first wall and shield, a two-dimensional transient thermal analysis was performed. Neutronics calculations determined the volumetric heating rate in the first wall and shield. This, coupled with the surface heating of the first wall by radiation from the plasma, determines the evolution of the temperature profile in the first wall and shield. Shown in Fig. 10 is the temperature evolution at selected points in the first wall and shield. This calculation assumes the coolant is circulated without external cooling until the fluid temperature reaches the average coolant temperature for steady-state operation. Then external cooling is turned on maintaining the coolant temperature as the shield continues to heat. The shield temperature does not rise above the steady-state value in the startup transient. The time scale for the shield to reach the steady-state temperature is about an hour. Because of the thermal mass of the secondary side of the steam generator and the turbine, the time scale for the turbine to be brought online is at least three hours for adiabatic heatup and can be extended by dumping heat to the cooling towers.

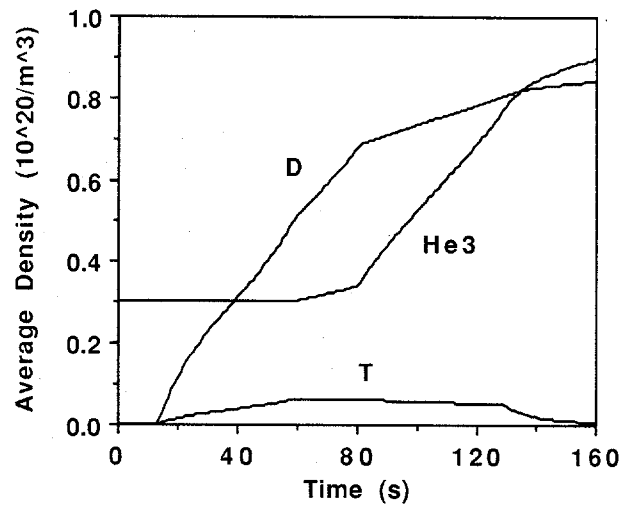

Fig. 6. Density programming for D-T assisted startup.

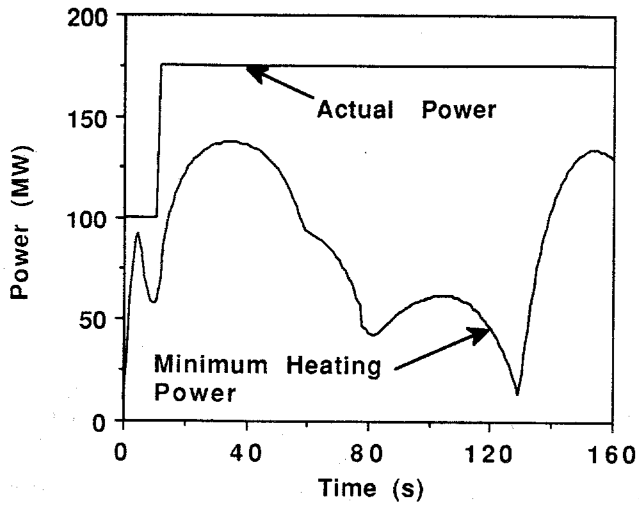

Fig. 7. Total external heating power (current drive and auxiliary) and the minimum power required to sustain the plasma at a given point for D-T assisted startup.

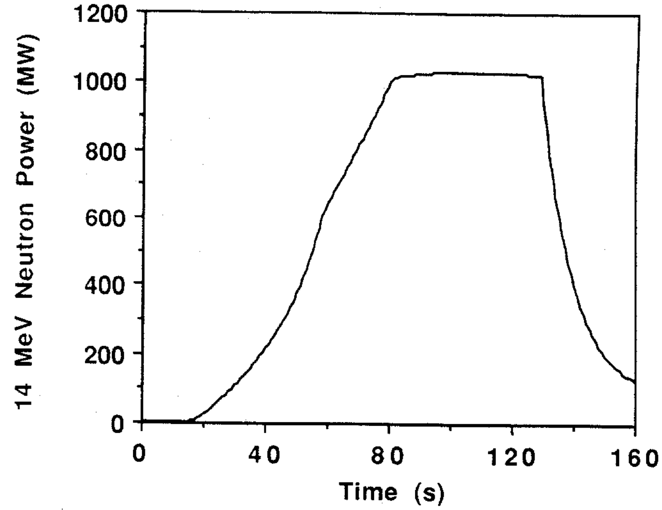

Fig. 9. The power produced in 14 MeV neutrons during D-T assisted startup.

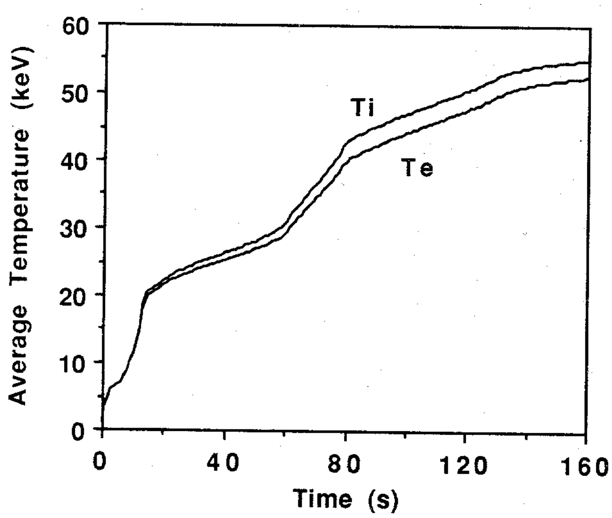

Fig. 8. Evolution of the ion and electron temperatures during D-T assisted startup.

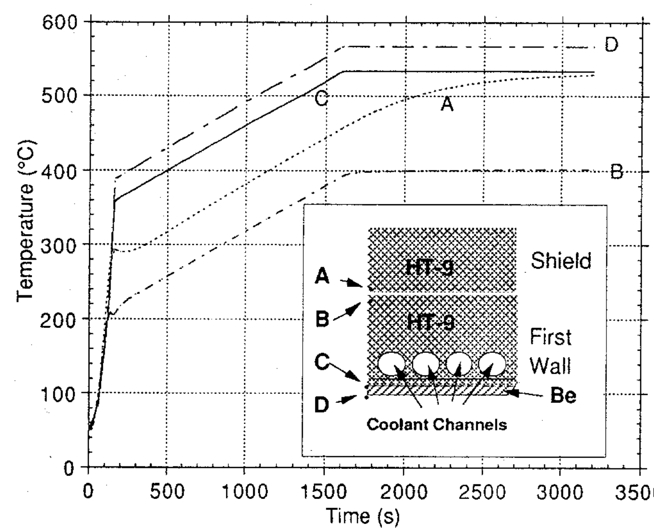

Fig. 10. Temperature variation at various points in the shield during D-T assissted startup.

Conclusion

We have shown that pure D-^{3}He startup of ARIES-III can be achieved with 200 MW of heating power in addition to that available from the current drive system. In the simulation shown, the time to get to the operating point is 180 seconds; this can be slowed down as much as desired and the plasma can sit at lower temperature and fusion power for long periods of time, since the installed heating power is capable of maintaining the plasma in a steady-state condition at these conditions.

An alternative startup scenario is to seed the plasma with a small amount of tritium and use the alpha heating from D-T reactions to reduce the need for additional ICRF power. In the simulation shown for this scenario, the required ICRF power is reduced to 100 MW. The drawback to this approach is the large 14 MeV neutron pulse and the rapid approach to full power. Preliminary analyses indicate that the neutron pulse is acceptable, but further study is needed of the startup of the balance of plant to more fully assess the feasibility of tritium-assisted startup.

Tritium assisted startup was chosen as the reference startup for the ARIES-III reactor study since it requires a smaller investment in auxiliary heating power.

Acknowledgments

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