

Conceptual Design of a Natural Circulation Cooled Nuclear Battery for Process Heat Applications

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Abstract: A feasibility study has been performed on a natural circulation cooled small nuclear reactor with a molten salt or tin as a coolant. This reactor is called the U-Battery. The study included neutronics calculations to obtain the minimum dimensions required for a critical system during burnup, the calculation of coolant temperature and core temperature reactivity coefficients, and an investigation of the thermal hydraulics to assess the possibilities for natural circulation cooling. For every coolant, core designs are feasible within the dimensions imposed and with natural circulation of the coolant.

1 Introduction

To be economically competitive, industrial energy consumers are in need of affordable power generation with a stable price setting. Since a significant part of the energy price is caused by the usage of the electricity grid, on-site power generation is an economically attractive option. Because of the stable price of nuclear energy, there is a large potential for small nuclear reactors placed on-site.

The U-Battery is a very small inherently safe, self regulating nuclear reactor (20MWth) for electricity generation or process heat applications. It can be operated for fuel cycles of 5-10 years without refuelling and is proliferation resistant. Natural circulation is the preferred cooling mechanism. Auxiliary safety or decay heat removal systems should be minimised. To be competitive with conventional on-site power generators, it should also be operated without intensive monitoring and with no on-site maintenance.

To minimise the impact on the surroundings, the U-Battery must be removable after shutdown. The primary circuit is incorporated into a transportable 'sealed' container. The size of the core is constrained by the fact that the core and primary heat exchanger must be incorporated into this container. The maximum height, width and length of the primary system should remain within 3.5 m, 3.5 m and 20 m, respectively, to make road transport possible.

This article presents the results of a parameter study that was performed to assess the feasibility of the U-Battery. Its dimension restrictions and fuel requirements were analysed for different fuel cycle lengths and coolant candidates, with natural circulation of the coolant as primary choice.

2 Neutronic Feasibility

The U-Battery is graphite moderated and uses TRISO coated UO₂ fuel particles with enrichment up to 20%. TRISO particles retain the fission products up to a fuel temperature of 1600°C for limited periods of time. To reduce neutron leakage, the dimensions of the reactor core without reflector where

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chosen to minimise the buckling [1]. A prismatic core design was selected because of the freedom in volume fractions of fuel, moderator and coolant.

For the core design of the U-Battery the following boundary conditions were set: 1) a fuel cycle of 5-10 years, 2) the use of maximally 20% enriched fuel, 3) a burnup of at least 10% FIMA, and 4) a combined core and reflector diameter less than 3.5 m. Besides these conditions other important parameters are the core volume, reflector thickness, and the coolant. The effects of these parameters on the feasibility have been assessed by burnup calculations during a desired fuel cycle length and a k_{eff} calculation at the end of the fuel cycle (EOC). When the k_{eff} at EOC is smaller than one, the design is considered not feasible.

2.1 Candidate Coolants

As a primary coolant liquid salt is used to allow operation at ambient pressure. The primary coolant candidates for this design are the fluoride salts ${}^7\text{Li-Na-Zr}$, ${}^7\text{Li-Na-K}$, Na-Be, Na-Zr and ${}^7\text{Li-Be}$. Also liquid tin is investigated based on the proposition in [2].

Due to the density and the composition of the liquid coolants they moderate and absorb neutrons. In case of voiding or loss of coolant, the reactivity increases due to less neutron absorption, and decreases due to less moderation. For a safe operation of the reactor it is required that the coolant does not lead to positive temperature reactivity effects. If coolant voiding introduces a positive reactivity this should be compensated by the Doppler effect. Of the candidate salts ${}^7\text{Li-Be}$ has the best neutronic properties [3].

2.2 Neutronic Calculation Model

To perform the burnup calculations and to calculate the k_{eff} at EOC, the SCALE code system has been used [4]. First the resonance shielding calculations are done using BONAMI and NITAWL after which a zone-weighted cross-section library is produced using XSDRNPM. This library is used to calculate the one-group cross-sections for every nuclide present. The average cross-sections and the normalized neutron flux (which is set to be uniform over the reactor core) are used in ORIGEN for a burnup calculation. The nuclide densities finally obtained are used in a 3D eigenvalue calculation with KENOva.. The Dancoff factor used in the resonance shielding calculations was obtained by an analytical procedure, which takes into account the double heterogeneity of the fuel design [5].

Some of the calculations performed were validated using a more elaborated burnup calculation method, which uses a space- and time-dependent power profile in the core [6]. For these calculations the reactor core of the U-Battery was divided into 9 cylindrical zones (r,z geometry) of equal volume, and the cycle length was cut into 11 time intervals. The input parameters used for all calculations are shown in Table 1.

Table 1. Input parameters for the burn up and eigenvalue calculations.

Input parameter	value
Thermal Power	20MWth
Fuel cycle length	5 & 10 years
FIMA	10, 12.5, 15 & 17.5 %
Fuel enrichment	12, 14 & 20 %
TRISO packing fraction (in fuel compacts)	35 %
Core volume (Height =0.924 Diameter)	1- 14 m ³
Reflector thickness	0 – 1.60 m
Uniform core temperature	1073 K
Coolant volume fractions	10 % (liquid salts), 3.5 & 5% (tin)

2.3 Results neutronic burnup and k_{eff} calculations

To investigate the effects of the coolants on the core volume and fuel enrichment, burnup calculations were performed with different initial enrichments and core volumes for the coolant candidates $^7\text{Li-Be}$ fluoride salt and tin for a 5-year cycle length. The result is shown in FIG.1. The tin coolant volume fraction (cvf) is 5% because no feasible solutions (k_{eff} at EOC >1) were found for larger coolant volume fractions. On the lower left side of the curves, the k_{eff} at EOC is less than one (not feasible) while on the upper right side of the curves the k_{eff} is larger than one (feasible). It can be seen that there is a significant trade off between the initial enrichment and core volume necessary for a feasible design. For both coolants the required fuel enrichment first decreases with increasing volume, reaches a minimum and then increases towards larger enrichments. At the minimum fuel enrichment, the moderating optimum is reached and a further increase of the C/U ratio will result in lower k_{eff} values, due to parasitic absorption in the graphite and coolant. Further it can be seen that the minimum fuel enrichment is much lower for $^7\text{Li-Be}$ than for tin, due to the large parasitic neutron absorption of tin.

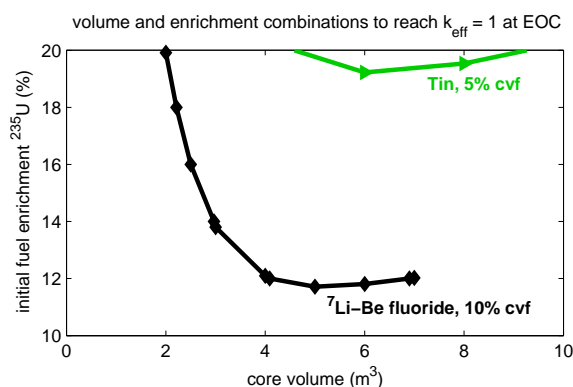


FIG. 1. Core volume and initial fuel enrichment combinations that reach a k_{eff} equal to one at EOC for $^7\text{Li-Be}$ fluoride and tin. The calculation was performed for a fuel cycle length of 5 yrs and a burn up of 10 % in both cases. The coolant volume fraction (cvf) was 10% for $^7\text{Li-Be}$ and 5% for tin. A 1.2 m thick reflector was used.

The reflector thickness in the calculations above was 1.2 m. When using slimmer reflectors, the core volume can be larger (up to 14 m³ when using a reflector thickness of 40 cm). Although the reflector effect is reduced for slimmer reflectors, the k_{eff} can increase due to the larger core volume (larger C/U ratio). In FIG. 2 the reflector thickness and core volume combinations are shown that yield a k_{eff} equal to one for an initial fuel enrichment of 20%, 14% and 12% using the $^7\text{Li-Be}$ fluoride coolant (black). In red the results are shown for the more elaborate calculation scheme using a space- and time-dependent power profile. Also shown in the figure is the total core diameter (i.e. core plus outer reflector diameter) in a contour plot.

It can be seen that larger core volumes in combination with smaller reflectors give the same k_{eff} values as small core volumes with thick reflectors using less total volume. It appears that the increase in moderation due to an increase in the C/U ratio has a stronger effect on the reactivity than the increase of neutron leakage in case of a slimmer reflector. The results for calculations with fuel enrichments of 14% and 12% also show a moderating optimum. To compensate the neutron balance for larger core volumes (larger C/U), more neutrons should be reflected and therefore the reflector thickness needs to increase to reach a k_{eff} equal to one. For the 20 and 14% cases, core volumes and reflector thicknesses can be found within the 3.5 m diameter constraint. This is not the case for the 12% case. The reference calculations performed with heterogeneous burnup confirm these results.

In FIG. 3 the results are shown for different coolant volume fractions (CVF) of tin with a cycle length of 5 yrs. No combination of reflector thickness and core volume can be found for a CVF of 5% tin. Therefore also a calculation was performed for a CVF of 3.5%. Both the uniform and heterogeneous results show that there are feasible combinations within the 3.5 diameter constraint.

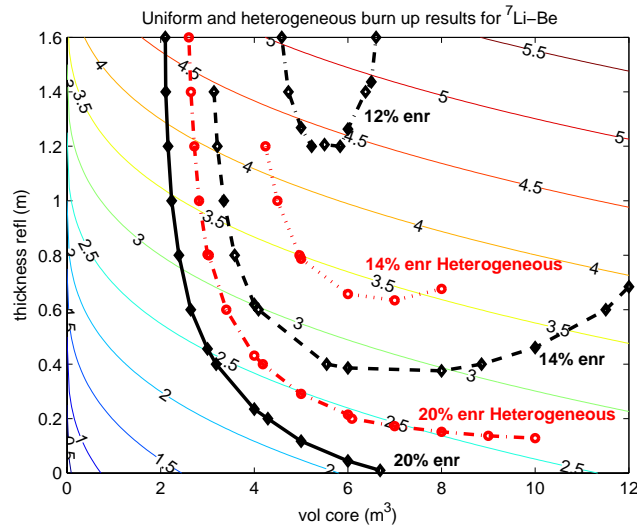


FIG. 2. The reflector thickness and core volume combinations that yield a k_{eff} equal to one for different enrichments using the ${}^7\text{Li-Be}$ fluoride coolant (5yr fuel cycle). In black the results of the uniform burn up calculations are shown; in red the results are shown for the reference calculations using the time dependent power profile and heterogeneous burnup.

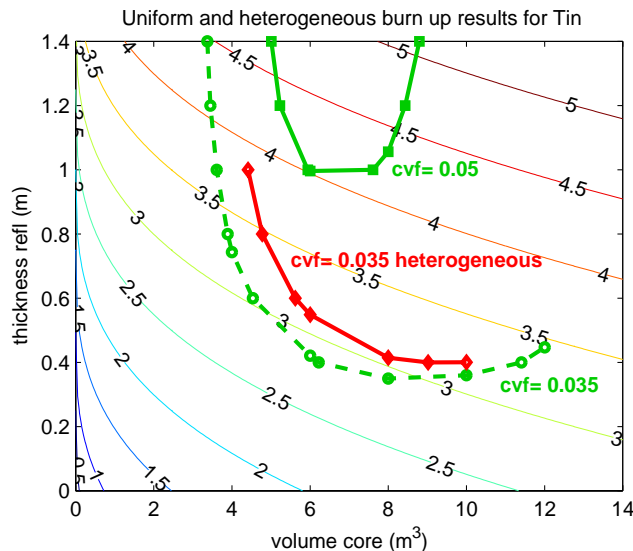


FIG. 3. The reflector thickness and core volume combinations that yield a k_{eff} equal to one for different coolant volume fractions (cvf) using the tin coolant (5yr fuel cycle). In green the results of the uniform burn up calculations are shown; in red the results are shown for the reference calculations using the time dependent power profile and heterogeneous burnup. The x-scale differs from FIG. 2.

If possible a fuel cycle length of 10 years or longer is desirable for the U-Battery. Therefore calculations have been performed for all liquid salts and tin for a fuel cycle length of 10 years. The results are shown in FIG. 4.

Here the reflector thickness and core volume combinations that give $k_{eff} = 1$ at EOC are shown for all coolants. The CVF is 10% for the salt and 3.5% for tin. Again also the total core diameter (i.e. core plus outer reflector diameter) is shown in a contour plot. It can be seen that for each case a wide range of core volumes and reflector thicknesses can be found for a 10 year fuel cycle within the 3.5m diameter constraint. The ${}^7\text{Li-Be}$ fluoride salt provides the largest range of feasible combinations (between the 3.5 diameter constraint and the $k_{eff} = 1$ curve). Although design freedom is less for Na-Zr fluoride and tin, both are promising candidates due to the absence of the toxic Beryllium and isotopic separation of ${}^7\text{Li}$.

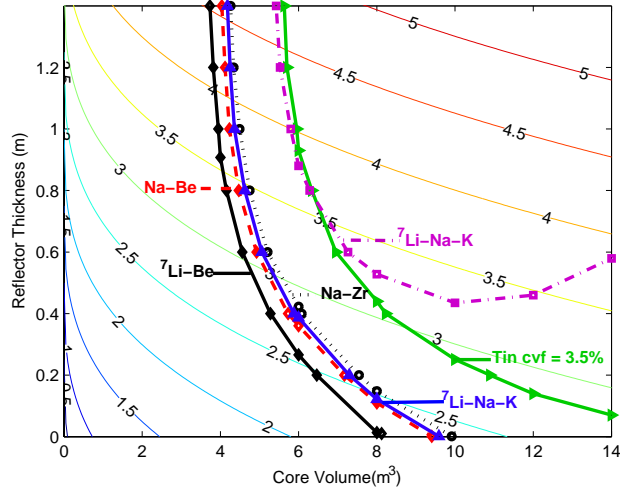


FIG. 4. The reflector thickness and core volume combinations that give $k_{eff} = 1$ at EOC for the salt coolants. In all cases the cycle length was 10 y with a nominal power of 20 MWth. The coolant volume fraction (cvf) is 10% for the salts and 3.5 % for tin.

2.4 Result coolant voiding reactivity and temperature reactivity effects

For safe operation of the reactor it is necessary that the coolant does not lead to positive voiding or positive temperature reactivity effects. The results of the uniform temperature and voiding coefficients at BOC are shown in Table 2. The temperature coefficients were calculated at 1073K by comparing the k_{eff} at the uniform temperature from 973K to 1173K. The complete voiding coefficient was calculated at a uniform temperature of 1073K.

Table 2. Results of uniform temperature and complete temperature reactivity coefficient for ${}^7\text{Li-Be}$, Na-Zr and Tin at 1073 K. The top, bottom and side reflector is 60cm in all cases.

Coolant	Core volume (m^3)	CVF	k_{eff}	Uniform temperature coefficient (10^{-5}K^{-1})	Complete voiding reactivity ($\$$)
${}^7\text{Li-Be}$ fluoride	4	0.1	1.38	-7.86	-1.66
Na-Zr Fluoride	6	0.1	1.39	-5.15	3.55
Tin	6	0.035	1.29	-4.16	12.0

As can be seen, the void coefficients are positive for Na-Zr fluoride and for tin. For Na-Zr the Doppler temperature effect of the fuel can compensate the reactivity increase due to complete voiding by a relatively small core temperature increase of 400K. For tin the temperature increase to compensate complete voiding reactivity is too large for safe operation (1300K). Therefore in this case measures must be taken to prevent complete voiding at all times.

3 Natural Convection and Heat Transfer

To minimise failure risks and operational costs circulation of the primary coolant by natural convection has preference. In this section the possibilities for natural convection are investigated for the coolants ${}^7\text{Li-Be}$ fluoride, Na-Zr fluoride and tin.

3.1 One Dimensional Natural Convection Model and Heat Transfer

To acquire insight into the dimensioning of the core, calculations were performed using a simple one-dimensional model for natural circulation in steady state conditions. The model is representative for incompressible fluids that satisfy the Boussinesq approximation, under the condition that the coolant present in the system is well mixed (turbulent), and that the riser and down comer are adiabatic.

The problem is described by the impulse and energy equations and can be solved by iteration between both. The impulse equation for this problem was found by multiplying the Navier Stokes equation by an elementary displacement dz over the loop and consequently integrating over the whole loop. If the Boussinesq approximation is applied the moment equation is then described by:

$$\oint \rho_0 g \beta (T - T_0) dz + F' = 0 \quad (1)$$

where

- ρ_0 is the density of the coolant at reference temperature (kg m^{-3}),
- β is the coolant expansion coefficient (K^{-1}),
- T is the temperature (K),
- T_0 is the reference temperature (K),
- dz is the elementary displacement over the loop (m),
- F' is the sum of all pressure losses by friction in the system ($\text{kg m}^{-1} \text{s}^{-2}$).

The left term in this equation is the sum of all buoyancy forces, while F' is the sum of all pressure losses by friction in the system. The pressure losses in the system have been modelled using relations for pressure loss due to a change in velocity, flow geometry or friction and pressure loss caused by dissipation and friction given in [7]. Pressure loss due to friction is not described in the transition zone between laminar and turbulent flow. To prevent discontinuities in the model, the friction factor in this zone is estimated with a glue function. It is assumed that during steady state, the heat produced in the core is completely transferred to the secondary coolant loop in the heat exchanger.

3.2 Conduction and Convective Heat Transfer

To estimate the fuel temperatures during steady state, heat transfer was modelled by defining a unit cell consisting of a coolant channel with radius R_1 surrounded by a cylinder of graphite with radius R_2 . It is assumed that the fuel is distributed homogeneously in the core. The temperature profile in the graphite/fuel region at a certain height of the core can be calculated with the Fourier relation for heat conduction using the boundary conditions $T(R_1) = T_{wall}$ and $dT(R_2)/dr = 0$. The temperature at the coolant/graphite interface (T_{wall}) is found by calculating the temperature gradient between the coolant and the graphite with Newton's law of heat transfer [7]. For the Nusselt number, no relation is given between Reynolds numbers $2300-10^4$ [8]. In this region the Nusselt is linearly interpolated. Nusselt numbers for tin are probably underestimated since the Prandtl number of tin is less than 0.7.

3.3 Natural Circulation Calculations

The fuel temperatures and Reynolds numbers for each coolant have been calculated as a function of the height of the primary system using input parameters shown in Table 3.

Table 3. Natural convection calculation input parameters.

Parameter	Value
Core volume (m^3)	6 (height = 1.87 m, diameter = 2.02 m)
Height heat exchanger (m)	core height
Length heat exchanger (m)	core height
Length riser (m)	Height riser + 3
Top and bottom reflector height (m)	0.6
Diameter coolant channel in core (m)	0.02
Diameter riser and down comer (m)	0.2
Relative roughness	0.01 (core and heat exchanger) 0.001 (riser, down comer)
Coolant inlet temperature(K)	973
System pressure (bar)	1
Coolant volume fraction	0.1 (Li-Be & Na-Zr) 0.035 Tin

3.4 Results Natural Circulation Calculations

The results are shown in FIG 5. From the maximum fuel temperatures shown on the left it can be seen that tin and ${}^7\text{Li-Be}$ fluoride will provide fuel temperatures lower than 1200°C for all heights of the primary system. Na-Zr fluoride provides solutions for heights of 7.4m and higher.

The Reynolds numbers in the core are shown in the right plot of FIG. 5. Tin has large Reynolds numbers for all primary system heights and will therefore provide a well mixed turbulent flow. For ${}^7\text{Li-Be}$ fluoride the Reynolds numbers are so low that a laminar flow is more likely, which means that the model assumption of a well mixed flow cannot be granted. For primary system heights larger than 7.5m, the Reynolds numbers of Na-Zr fluoride are well above 4000. Therefore, the flow will be in the transition zone between laminar and turbulent flow.

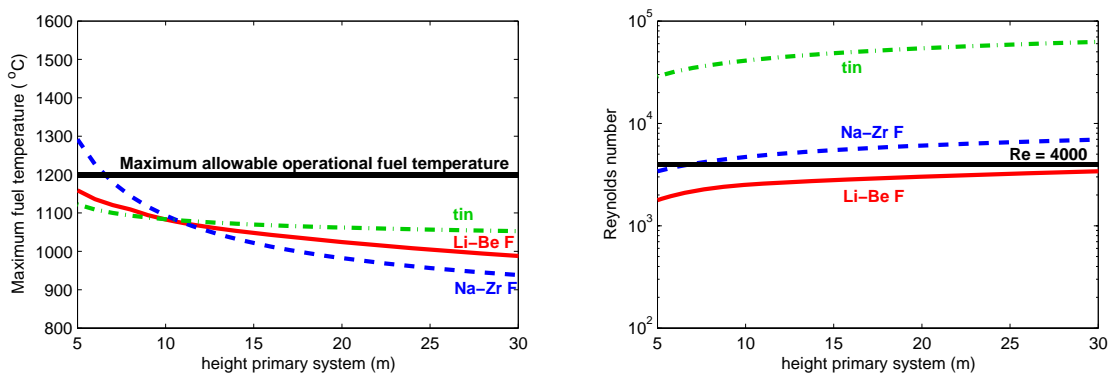


FIG. 5. Results natural circulation calculations: Left the maximum fuel temperatures as a function of the total primary system height. Right the Reynolds numbers as a function of the total primary system height.

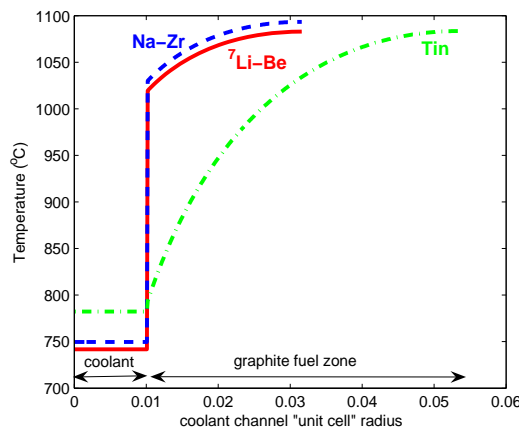


FIG. 6. Temperature profile of coolant and graphite fuel as a function of 'unit cell' radius in the core for a primary system height of 10 m.

In FIG 6, the temperature profile in the coolant and graphite/fuel zone of the core is shown as a function of the coolant channel 'unit cell' radius. The height of the primary system is 10m for all coolants, and the radius of the coolant channel is 0.01m. The coolant temperature in this graph is the coolant outlet temperature. The graphite/fuel zone for Na-Zr and ${}^7\text{Li-Be}$ is smaller than that of tin because their CVF is larger (see Table 3). For a primary system height of 10m, the maximum fuel temperatures are approximately equal for all coolants (see also FIG. 5). Further it can be seen that 1) the temperature difference between the coolant and the channel wall is smallest for tin (due to larger Reynolds numbers and larger heat conductivity), and that 2) the temperature profile in the

graphite/fuel zone is equal for the two liquid salts, because of their equal CVF of 10%. For tin the CVF is 3.5%, which means that fewer coolant channels with a diameter of 0.02 m are present in the core. The 'unit cell' diameter is therefore larger and a stronger temperature gradient is visible in the graphite matrix. This might be undesirable because it might increase the thermal stresses in the graphite. The effects of temperature gradients on the thermal stresses in the graphite of the U-Battery core should be subject of future study.

The input parameters of each coolant can be modified to improve the thermal hydraulic natural circulation possibilities. Preferably large Reynolds numbers for good heat transfer between coolant and coolant channel walls are needed and low maximum fuel temperatures. Besides the primary system height, changing the coolant channel diameter, reflector thickness, coolant inlet temperatures or others can give better conditions for natural circulation cooling.

4 Conclusions and recommendations

Feasible neutronic core designs can be made for a liquid cooled U-Battery with natural circulation. The ${}^7\text{Li}$ -Be fluoride salt provides the largest design freedom from the neutronics point of view. It also has a negative coolant voiding coefficient. Of the other salts Na-Zr fluoride is the most promising due to the absence of the expensive ${}^7\text{Li}$ and the toxic Beryllium. Parasitic neutron absorption is largest for tin, which decreases design freedom and which leads to a large and positive voiding reactivity coefficient.

Thermal hydraulics calculations show that cooling by natural circulation is possible. Tin is well suited for natural circulation cooling. For the liquid salt, however, it is difficult to obtain a turbulent flow. As a consequence, the heat transfer coefficient along the walls of the coolant channels will decrease leading to higher fuel temperatures. Future work will focus on the thermal hydraulics, burnup and shielding calculations, and further analyses of the reactor physics including passive reactivity control and several accident scenarios such as loss of coolant in combination with a passive decay heat removal assessment.

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