INVESTIGATION OF APPROXIMATIONS IN THERMAL-HYDRAULIC MODELING OF CORE CONVERSIONS

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ABSTRACT

Neutronics analyses for core conversions are usually fairly detailed, for example representing all 4 flats and all 4 corners of all 6 tubes of all 20 IRT-3M or -4M fuel assemblies in the core of the VVR-SM reactor in Uzbekistan. The coupled neutronics and thermal-hydraulic analysis for safety analysis transients is usually less detailed, for example modeling only a hot and an average fuel plate and the associated coolant. Several of the approximations have been studied using the RELAP5 and PARET computer codes in order to provide assurance that the lack of full detail is not important to the safety analysis. Two specific cases studied are (1) representation of a core of same-type fuel assemblies by a hot and an average assembly each having multiple channels as well as by merely a hot and average channel and (2) modeling a core containing multiple fuel types as the sum of fractional core models for each fuel type.

1. Introduction

All engineering analyses involve approximation. Decisions on the level of approximation involve several factors. In many cases the decision is driven by what tools are available. In other cases, complex tools may be available but their use requires more investment than can be justified by the importance of the result. In nuclear reactor analyses, the analyst invokes approximations in such a way that the resulting analysis is conservative from a safety perspective.

There are many analysis steps in the conversion of a reactor from high-enriched uranium (HEU) to low-enriched uranium (LEU) fuel: steady-state neutronics for criticality, steady-state thermal hydraulics for operational safety margins, transient burnup over fuel lifetime, and transient neutronics and thermal-hydraulics analysis during postulated accidents. Frequently the steady-state neutronics calculations are performed with rather fine spatial detail, which allows a fairly accurate determination of the peak power density. Coupling this analysis with a steady-state thermal hydraulics calculation allows identification of a hot channel which then becomes a focal point in checking steady-state margins and transient challenges. Transient calculations are often performed with less spatial detail in order to allow the analysis to proceed with a reasonable use of computer resources.

The purpose of this paper is to examine two approximations invoked when reducing the level of spatial detail in coupled neutronics/thermal-hydraulics calculations for transients: (1) use of merely a hot channel and an average channel for cores having only one fuel type and (2) modeling a core containing multiple fuel types as the sum of fractional core models for each fuel type.

2. Assumptions in PARET Affecting Its Usage

The PARET code [1] was initially developed in the 1960s for transient analysis of research reactors. The fuel geometry in use at that time was what is now referred to as "MTR", consisting of uniform flat plates containing fuel surrounded by cladding and plates separated from each other by uniform water gaps. A fuel assembly of this type is shown in Figure 1. The regularity of this geometry allowed PARET to represent an entire reactor core using only a few channels. Each channel consists of a half thickness of fuel plate and the half thickness of the adjacent water gap, as shown in the boxed portion of Figure 3. In many cases, the PARET model would use only two channels: one for the hot channel and one for the average channel (representing the majority of the core). Within a core model, all channels in PARET (up through code versions 6.x) must have the same fuel plate material and geometry. Over the years Argonne staff have made a number of improvements [2] to the original PARET model. In particular, newer versions of PARET/ANL [3] are allowing for more geometric variations.

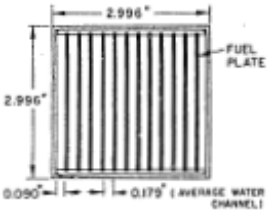

Figure 1 MTR Fuel Assembly

Some core conversion studies now involve fuel assembly geometries which are more complicated than MTR. For example the IRT-xM fuel has concentric square fuel elements within each fuel assembly; an IRT-3M fuel assembly is shown in Figure 2. Although the thickness of the elements is uniform and the spacing between elements is uniform along the flats, the power is not uniform along the circumference of the element and the hydraulics of each between-element water gap is somewhat different due to the bends at the corners.

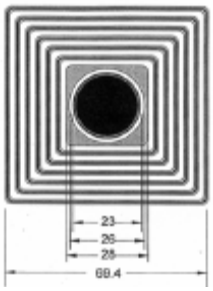

Figure 2 IRT-3M 6-Tube Fuel Assembly

Some core conversions are taking place on a gradual basis – a few HEU fuel assemblies are replaced with LEU fuel assemblies at each refueling time which requires several cycles of operation in order to complete the conversion from HEU to LEU. During the entire conversion period, there are two fuel types in the core.

There are other analysis tools which allow for geometries more varied than allowed in the original PARET. Some newer versions of PARET allow for concentric circular fuel elements, varied fuel element thickness, and varied water gap thickness. A more general code such as RELAP5 [4] has essentially unlimited geometric variation capability plus allows for multiple fuel and cladding

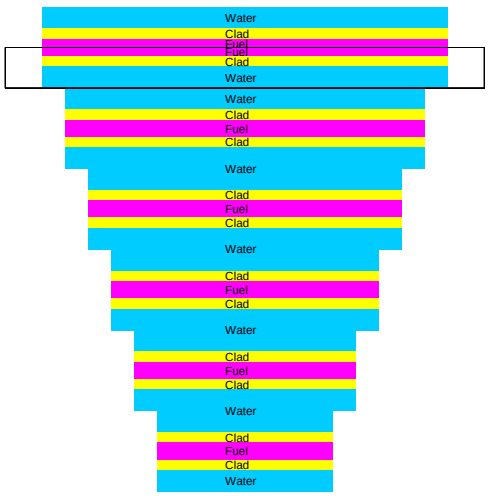

Figure 3 IRT-3M Model Geometry

materials. Either of these codes would allow for a repeated layering of water, cladding, fuel, cladding, water, etc. as shown in the main body of Figure 3, which can be viewed as a representation of the 6-plate IRT-3M fuel assembly. These codes might allow for modeling multiple fuel assemblies. The analyst must make a choice: is there a way to use an older PARET version in an approximate way or is a more flexible code needed? In many cases the answer is dictated by code availability; therefore, this paper explores two approximations to invoke when using older PARET versions. The codes PARET and RELAP5 should be considered examples; the same approximations could be tested for other pairs of computer codes.

The next two sections will evaluate two approximations: (1) representing an entire core of similar fuel assemblies using only two channels (i.e., hot and average) in PARET and (2) representing a core having two fuel types using two separate PARET runs, one for each fuel type.

The approximations will be examined using the VVR-SM reactor at the Institute of Nuclear Physics of the Academy of Sciences near Tashkent, Uzbekistan as an example. The reactor is currently operating at 10 MW using 18 IRT-3M HEU (36% enriched in ^{235}U) fuel assemblies. The plan is to convert the reactor to operate at a power of 11 MW using 20 IRT-4M LEU (20% enriched in ^{235}U) fuel assemblies. The conversion will take place over 9 refueling intervals. During the first refueling interval 2 IRT-3M fuel assemblies will be removed and replaced with 4 IRT-4M fuel assemblies, which expands the core from 18 to 20 fuel assemblies. The other 8 refueling intervals will replace 2 IRT-3M fuel assemblies with 2 IRT-4M fuel assemblies. There will be shuffling of fuel assemblies at each refueling. The neutronics analysis of this conversion plan was presented previously [5]. The IRT-3M and IRT-4M fuel assemblies are similar: both have 6 concentric square fuel element tubes, 0.6 m fuel length, and UO_2-Al dispersion fuel. Key differences are uranium enrichment (36 vs. 20%), fuel meat thickness (0.5 vs. 0.7 mm), fuel element thickness (1.4 vs. 1.6 mm), and water gap thickness (2.05 vs. 1.85 mm). Additional information about the conversion of VVR-SM is presented in other papers [6-7] at this meeting.

3. Approximation of Hot plus Average Channel

A typical PARET model of a reactor containing a single fuel type has 2 channels: (1) hot channel and (2) average channel. Each channel consists of one-half fuel plate thickness and the adjacent one-half thickness of water gap. The intent is for the hot channel to depict the maximum temperatures in the reactor core during the transients and for the average channel to provide appropriate temperature-dependent reactivity feedbacks.

The question to be examined is whether this approach overlooks anything significant that might be seen in a model having more than 2 channels? The question will be examined for a full HEU core in VVR-SM having 18 IRT-3M fuel assemblies, i.e., only one fuel type.

Three model geometries are compared. (1) The PARET model has the normal 2-channel assumptions: hot and average. (2) The “detailed” RELAP5 model has 2 fuel assemblies: hot and average; each of these fuel assemblies has 6 fuel plates and 7 water gaps; each fuel plate interacts with two water gaps rather than the half-plate plus half-gap approach in PARET. (3) The “plate” RELAP5 model has the same geometry assumptions as the PARET model: 2 channels, hot and average.

Two reactivity-induced transients are considered for each model. (1) A fast transient initiated by the assumed ejection of a shim rod, inserting 2.8 $ in 0.5 s. (2) A slow(er) transient initiated by the assumed continuous withdrawal of the automatic power control rod, inserting 0.4 $ in 35 s. All cases start at full power of 10 MW. All cases are terminated due to high power trip at 12 MW, with a scram delay time of 0.1 s and a safety rod insertion time of 0.5 s. Pumps continue to run after scram, providing flow of cooling water through the core.

The results for the fast transient are shown in Figure 4. The power increases above the 12 MW trip setting in 0.04 s; the safety rods start into the core 0.1 s later, limiting the peak power to 28 MW; this power behavior is essentially the same in all 3 core models. The initial peak clad surface temperature in the hot channel (red lines in figure) is the same in the 2-channel PARET and 2-channel RELAP5 models; it is a few degrees cooler in the detailed RELAP5 run due the fact that each fuel plate feels the effect of the other fuel plates and water gaps in the multi-plate model. During the transient, the peak temperature in the hot channel in the PARET model peaks a few degrees cooler than in either RELAP5 model; this is likely due to somewhat different treatments of the heat transfer coefficient in the two codes. The peak temperature in the average channel is in good agreement among all three models at steady state and during the transient.

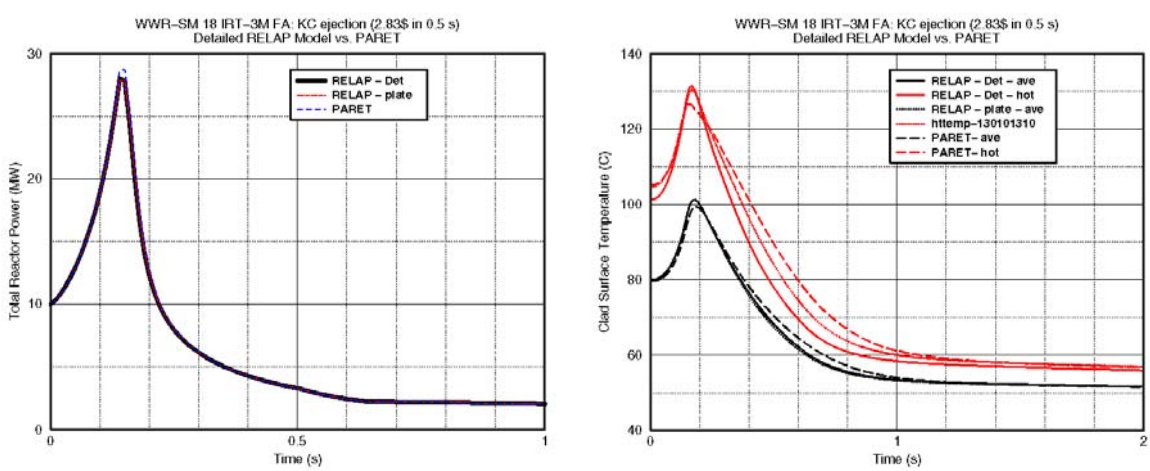

Figure 4 Two-Channel (RELAP Plate and PARET) versus Multi-Channel (RELAP Detailed) Approximation for Fast Transient

The results for the slow transient are shown in Figure 5. The power increases above the 12 MW trip setting in 7.5 s in the PARET model and in 8 s in the two RELAP5 models; the difference in timing is explained in the paragraph at the end of this section.

The power is reduced to decay level 0.6 s later due to insertion of the safety rods. There is the same initial temperature offset as explained for the fast transient; the difference persists during the transient due to the slow power increase. The peak clad temperature in the hot channel is a few degrees higher in the PARET model than in the two RELAP5 models, which is the reverse of the behavior seen for the fast transient. The peak temperature in the average channel is essentially the same for all three models. The difference in timing of temperature decrease is due to the difference in scram time.

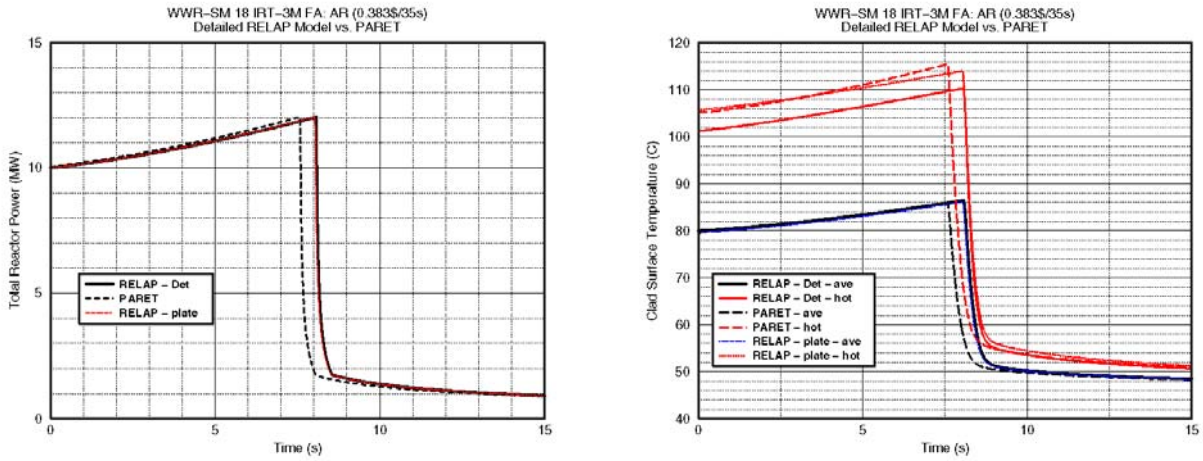

Figure 5 Two- versus Multi-Channel Approximation for Slow Transient

The agreement between detailed RELAP5 and 2-channel RELAP5 results supports the approach of representing a single-fuel core using a 2-channel (hot and average) model for IRT-3M (and hopefully, other similar fuel assembly types). This expands the approach beyond what had been demonstrated previously [8-9] for MTR type fuel. The difference between the 2-channel PARET and 2-channel RELAP5 results requires a further explanation.

Additional cases were run on the three models in order to understand the differences in timings noted above. Shown in Figure 6 are the results for the slow transient (i.e., 0.4 $ in 35 s) with no neutronics feedbacks; there is now no timing shift between PARET and RELAP5 results. Further investigation has found that the timing shift seen in Figure 5 is due to the steady-state portion of the PARET calculation not being fully converged. Therefore, the early part of the transient had a false positive reactivity feedback due to temperature decrease toward steady state, whereas in fact temperature should have been increasing due to the power increase due to the positive reactivity insertion from the assumed control rod withdrawal. The timing shift is not present in cases which start at uniform temperature (e.g., low power) and is not noticeable in fast transients. This inaccuracy has no significant impact on any reactor safety calculation performed previously; however, we are working with the developer of PARET/ANL to fix the inaccuracy.

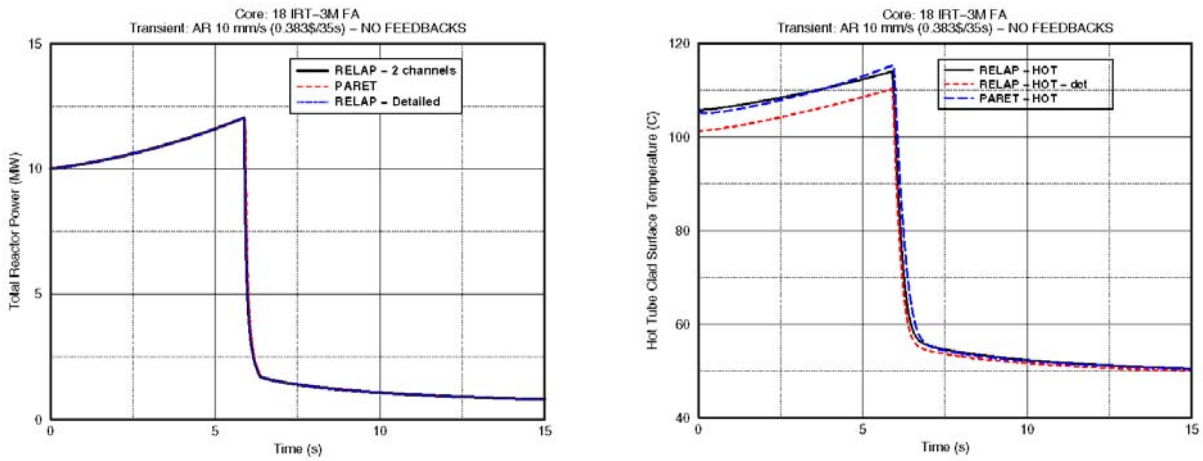

Figure 6 Two- versus Multi-Channel Approximation for Slow Transient with No Reactivity Feedbacks

4. Approximation for Multiple Fuel Types in Core

Many past core conversions have been accomplished in a single step – during a single refueling outage all HEU fuel is removed and replaced with LEU fuel. PARET is able to model both the HEU and the LEU cores in its normal mode of application since each core has only a single fuel type. The upcoming conversion of VVR-SM will perform the conversion gradually, replacing 2 (or 4) HEU fuel assemblies with LEU fuel assemblies during each refueling outage.

The question to be examined here is how can PARET be used model the transition cores each of which has 2 fuel types? The question will be examined for the first mixed fuel core in VVR-SM having 16 IRT-3M HEU fuel assemblies and 4 IRT-4M LEU fuel assemblies.

The suggested approach is to setup 2 PARET runs covering (1) IRT-3M part of core and (2) IRT-4M part of core, so each run only has one fuel type. Each run has initial power based on IRT-3M and IRT-4M power distributions from the neutronics analysis, which is 8.3 and 2.7 MW, respectively, for a total of 11 MW. Overpower trip in each run is steady-stated-based fractional part of 12 MW setpoint, or 9.1 and 2.9 MW, respectively. Each run has geometry, materials, and hot vs. average channel definitions consistent with that run's fuel type. The reactivity initiator and feedback coefficients are the same in both runs. The total reactor power for a transient is found by adding the power for the two runs at every time in the transient. Each run provides peak and average temperatures for that run's fuel type.

A comparison of this approach is made to a single RELAP5 run having 4 channels: (1) hot HEU, (2) average HEU, (3) hot LEU, and (4) average LEU. Each channel can have different geometry, materials, and power. Only a single set of reactivity initiator and

feedback coefficients are specified. A single run provides peak and average temperatures for both fuel types.

The same two reactivity-induced transients used in the prior section are considered for each model. (1) A fast transient initiated by the assumed ejection of a shim rod, inserting 2.8 $ in 0.5 s. (2) A slow transient initiated by the assumed continuous withdrawal of the automatic power control rod, inserting 0.4 $ in 35 s. (The reactivity initiator values are slightly different from the prior section due to rod worth differences between the HEU core and the first mixed HEU-LEU core.) All cases start at full power of 11 MW (which is by design higher than the 10 MW power in the HEU core). All cases are terminated due to high power trip at 12 MW, with a scram delay time of 0.1 s and a safety rod insertion time of 0.5 s. Pumps continue to run after scram.

The results for the fast transient are shown in Figure 7. The power increases above the 12 MW trip setting in 0.03 s; the safety rods start into the core 0.1 s later, limiting the peak power to 26 MW; this power behavior is essentially the same in both core models. The initial peak clad surface temperature in the hot and average channels is the same in both models. During the transient, the peak temperatures in all channels in the PARET model peak a few degrees cooler than in the RELAP model; this is likely due to somewhat different treatments of the heat transfer coefficient in the two codes. There is a small difference in the cooling rate after scram; however, the temperatures from both models are in agreement about 1 s after scram.

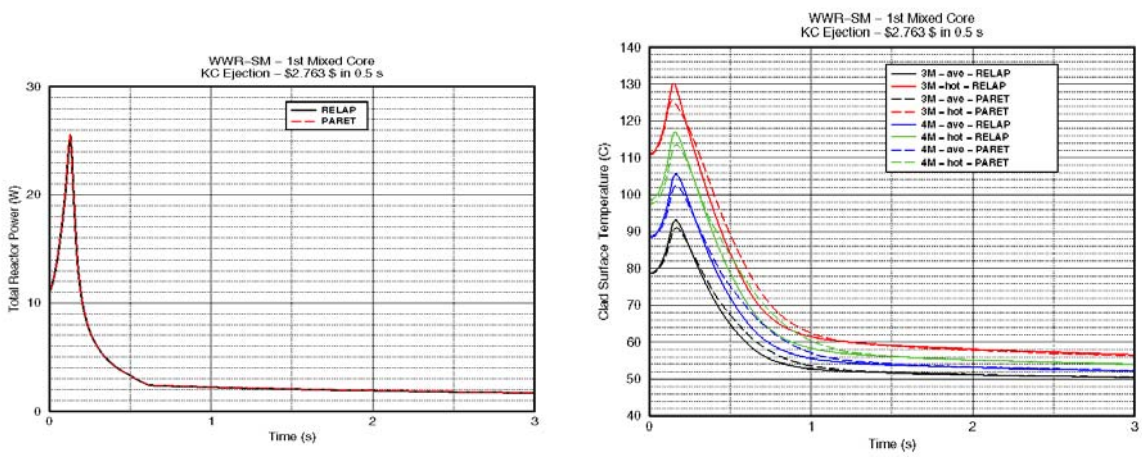

Figure 7 PARET HEU plus LEU Approximation versus RELAP5 Whole Core for Fast Transient

The results for the slow transient are shown in Figure 8. The power increases above the 12 MW trip setting in 3.5 s in the PARET model and in 4 s in the RELAP5 model; the difference in timing is the same as in the prior section. The power is reduced to decay level 0.6 s later due to insertion of the safety rods. The peak clad temperature in the hot channel differs by less than 2°C between the PARET model the RELAP5 model. The peak temperature in the average channel is essentially the same for both models. The

difference in timing of temperature decrease is due to the difference in scram time. The temperatures from both models are in agreement about 2 s after scram.

These results support the approach of representing a multiple-fuel core using a 2-channel (hot and average) model for each fuel type and adding the resulting powers.

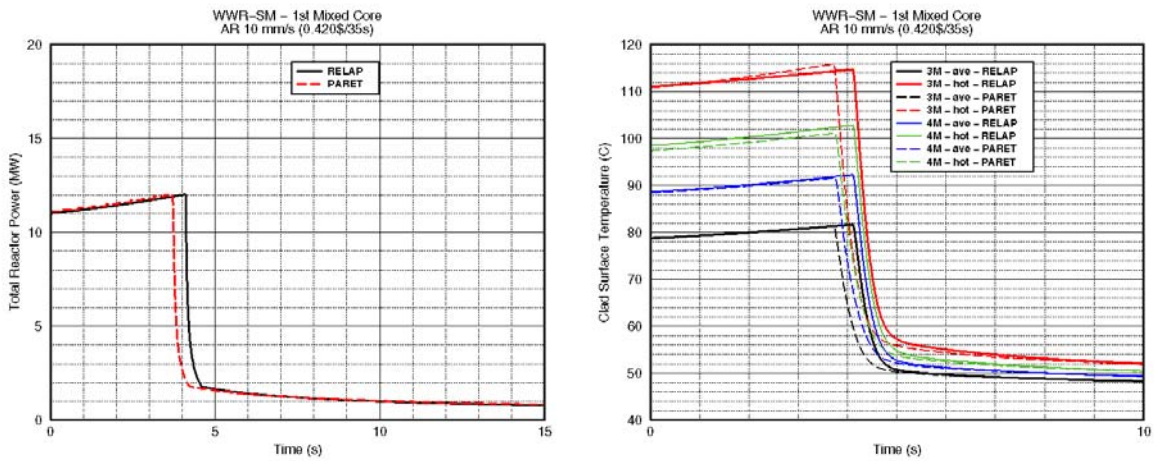

Figure 8 PARET HEU plus LEU Approximation versus RELAP5 Whole Core for Slow Transient

5. Conclusions

This paper has examined two approximations invoked when reducing the level of spatial detail in coupled neutronics/thermal-hydraulics calculations for transients: (1) use of merely a hot channel and an average channel for cores having only one fuel type and (2) modeling a core containing multiple fuel types as the sum of fractional core models for each fuel type. The approximations were found to be reasonable for cores containing IRT-3M HEU and IRT-4M LEU fuel assemblies.

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