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Estimation of Fuel Burnup Rate for Core Conversion for the Nigeria Research Reactor-1 (NIRR-1) Fueled With 19.75% Enriched UO_2 USING VENTURE PC Code

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Authors' contributions

This work was carried out in collaboration among all authors. Author JAR designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors JAR, MYO and DOS managed the analyses of the study. Authors JAR and DOS managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

A standardized burnup analysis using VENTURE-PC computer codes system has been performed for the core conversion study of Nigeria Research Reactor-1. The result obtained from this analysis showed that the mass of Uranium decreases with increase in the number of days of reactor operation while the quantity of Plutonium continues to build up linearly. The buildup of the fissile isotope in the Low Enriched Uranium (LEU) core is very much greater than in the Highly Enriched Uranium (HEU) core. The quantity of Uranium-235 consumed and the amount of Plutonium-239 produce in the core of the reactor were 13.95 g and 0.766745 g respectively for the period of 11 years of reactor operation which is in good agreement with other literatures. This results obtained showed that uranium dioxide (UO_2) fuel is a potential material for future Low Enriched Uranium (LEU) core conversion of Nigeria Research Reactor.

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1. INTRODUCTION

The excess reactivity of the Miniature neutron source Reactor (MNSR) (which is similar to Nigeria research Reactor-1 (NIRR-1)) decreases with the reactor in operation time because of the fuel burnup and accumulation of fission product within the reactor core at NIRR-1 [1].

Nuclear reactors have evolved from an embryonic research tool into the mammoth electrical generating units that drive many central-station power plants round the world nowadays [2].

The recent insufficiency of fissile fuels has showed it to be quite apparent that nuclear fission reactor will play a dominant role in meeting man's energy necessities for many years to come. The dominant role played by nuclear fission reactors within the generation of electric power are often expected to continue well into the subsequent century. Nuclear energy can represent the sole viable alternative to fissile fueled plants for many nations [3].

For years in the field of nuclear science, the study of the burnup analysis of research reactor has posed a major challenge in research activities. Burnup analysis have been performed on several research reactors in the world while in some, such have not been done. One of the highly qualified LEU fuels that will be used in this work to perform burnup analysis for NIRR-1 is UO_2 fuel enriched to 19.75%. The basis for the import to carry out this study on reactor burnup is considered necessary because performing this burnup analysis gives information on:

- Changes in the concentration of isotope in the fuel.
- Changes in the fission product buildup in the system.
- How to determine the burnup rate of the system for a given period of time.
- How much fuel is been consumed or how much fuel is left for a couple of years.
- What happens to the fuel in the system on daily, weekly, monthly or even yearly basis.

It has been quite some decades since the primary nuclear reactor achieved an essential fission chain reaction. Since then, an in depth worldwide effort has been directed towards nuclear reactor analysis and development in an effort to harness the large energy contained inside the atomic nucleus for peaceful application [3].

During reactor operation, the fuel composition will change as fissile isotopes are consumed and fission products are produced, hence, during the design of a nuclear reactor, this process must be monitored over core life in an effort to ascertain fuel composition and reactivity as a function of energy removal. This requires the studying of the burnup and production chains for the principal isotopes (eg, Uranium 235-Uranium 238 or Uranium 233-Thorium 232) coupled with the equations determining the neutron flux in the core. The calculation of the core multiplication and power distribution must be made many times over the operating lifetime of the core as the core composition changes [2].

Fuel burnup analysis deals with predicting the long-run changes in reactor fuel composition caused by exposure to neutron flux throughout reactor operation. Such changes have a very important bearing on the operating lifetime of a reactor, likewise as on its stability and management [3].

Nuclear processes must be monitored during burnup study, this include the consumption of fissile nuclides (fuel burnup) and the conversion of fertile isotopes into fissile isotopes and the production of numerous fission product.

Also, reactivity balance to ensure core criticality must be monitored by determining the changes in reactivity over a period of core operation and then adjusting control to compensate for this reactivity change.

During the operation of a reactor the amount of fuel contained in the core of the system constantly burnup or decreases. If the reactor is to operate for a long period of time, fuel in excess of that needed for exact criticality must be added when the reactor is built. The positive reactivity due to the excess fuel must be balanced with negative reactivity from neutron absorbing material. Moveable control rods containing neutron-absorbing material are one method used to offset the excess fuel [4].

Due to the burnup of the poison material, the negative reactivity of the burnable poison (Materials that have high neutron absorption cross section that are converted into materials of relatively low absorption cross section as the result of neutron absorption) decreases over core life. Ideally, it is expected that these poisons should decrease their negative reactivity at the same rate that the fuel's excess positive reactivity is burnup.

Reactor fuel burnup has been established to be linearly dependent on the thermal reactor power which also shows that the reactor thermal power calibration is very important for precise fuel burnup calculation. The reactor power can then be determined by measuring the absolute thermal neutron flux distribution across the core in horizontal and vertical plane [5]. The geometry representation of the LEU fuel cell used in this burnup analysis is illustrated in Fig. 1.

Fuel sustainability of the reactor which directly relate to fuel conversion capability has been generally attributed to the fuel conversion process of fissile production from fertile isotopes. Feasible area of conversion and negative void reactivity has been estimated which confirms that fissile of U-233 contributes to better fuel conversion and effective for obtaining negative void reactivity coefficient as the main fissile material.

2. MATERIALS AND METHODOLOGY

The present NIRR-1system is fueled with about 1kg of highly enriched uranium pins, containing 90.2% of this enriched uranium material like every other commercial MNSR [5]. The active fuel material in this pin is uranium aluminide-aluminum alloy with a chemical symbol UAl_4-Al [1]. The active material in the reactor fuel pin has a diameter of about 4.3 mm and 230 mm long. It is surrounded with aluminum alloy of about 0.6 mm thick called the guide tube. The total length of the fuel pin including the non-fuel regions is about 248 mm and it contains 2.88 g of U-235 [7]. Equivalent diameter of a unit fuel cell for NIRR-1 is as shown in Fig. 1.

The reactor proper consists of a core containing the fuel, coolant channels, structural components, control elements and instrumentation systems. The core of a typical reactor has a cylindrically shaped lattice roughly 350 cm in diameter by 370 cm in height consisting of long fuel assemblies or bundles. These assemblies consists of a large number of long narrow fuel rods or fuel elements, which are metallic tubes containing the nuclear fuel in the form of ceramic pellets [2].

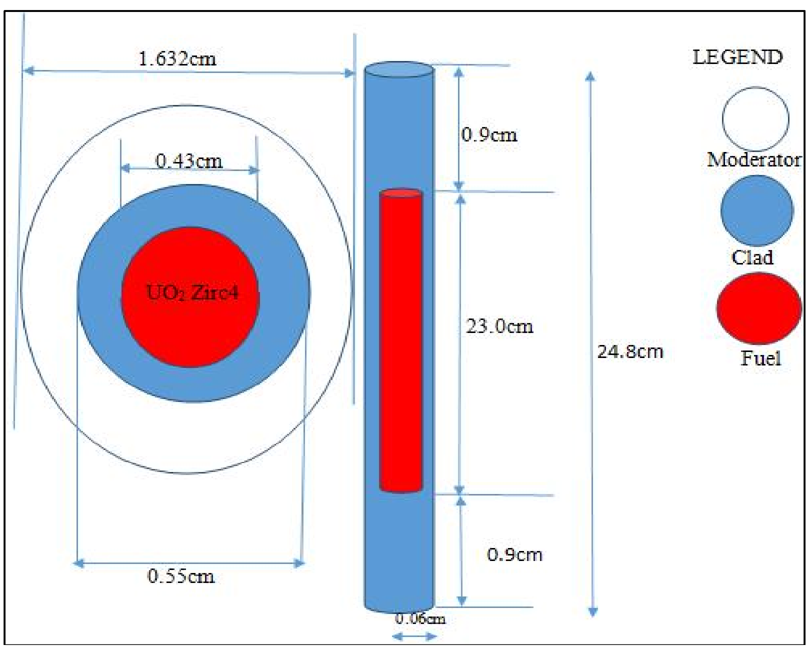

Fig. 1. Equivalent diameter of a unit fuel cell for NIRR-1 [6]

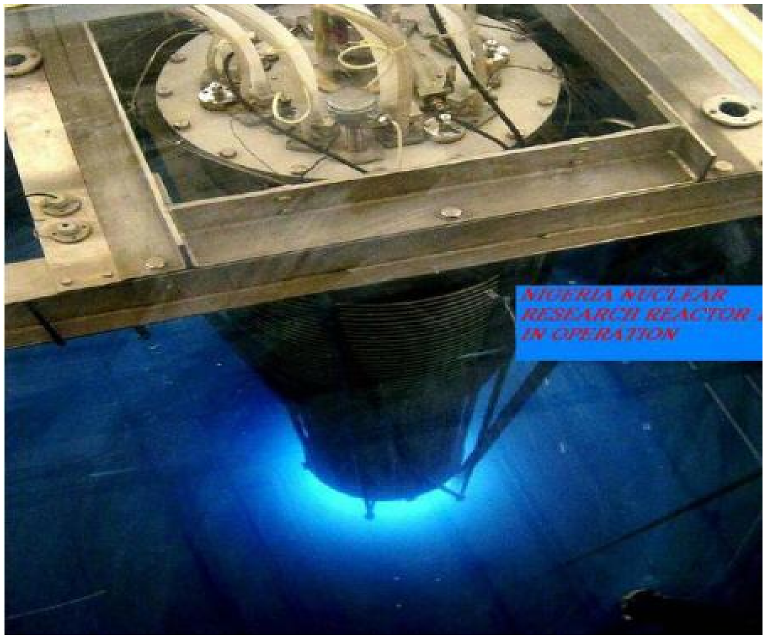

Fig. 2. Sectional view of NIRR-1

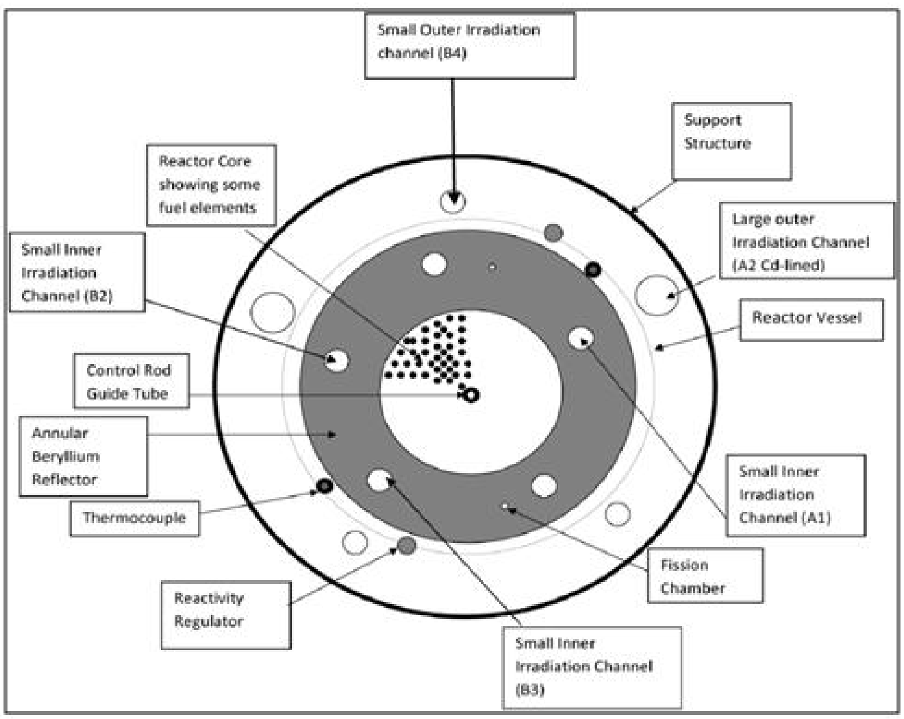

Fig. 3. A layout of NIRR-1 core configuration showing the irradiation

The uranium enrichment percentage was increased to about 19.75% in the proposed LEU fuel for NIRR-1 core conversion studies. This LEU fuel is made of UO_2 surrounded with zirc4 alloy of about 5.5 mm thick as the cladding material. The top and bottom plate of the fuel cage of Aluminum material in the HEU core were replaced with Zirconium material in the LEU core.

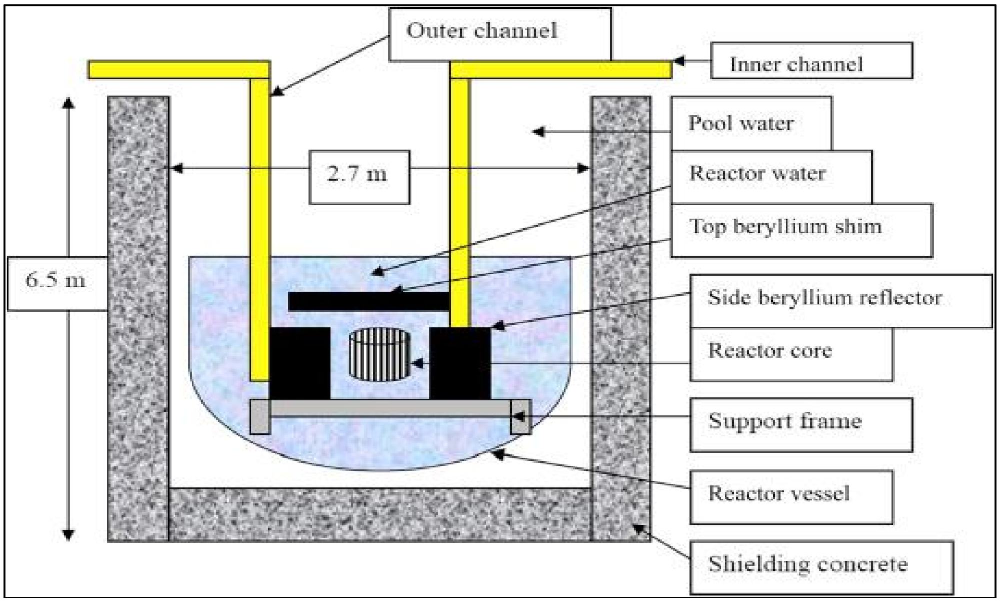

Fig. 4. Side view of the NIRR-1 showing various components

Most of the physical data used in the development of core models for NIRR-1 have been provided in Table 1.

Table 1. The geometry representation of the dimension of NIRR-1 fuel element

Fuel pin Dimension	
Active fuel diameter	0.43 cm
Active fuel length	23.0 cm
Total pin length	24.8 cm
Clad thickness	0.06 cm
Fuel cell diameter	1.2384 cm

The quantities of uranium consumed and plutonium generated in the reactor core, the concentrations of radionuclides of the most significant fission products and actinide radionuclides accumulated in the reactor core, and the total radioactivity of the reactor core can be estimated using the GETERA code as well as VENTURE PC code [8]. These Reactor physics codes are typically used to support the performance of the core as well as to provide results to be used in the system thermal hydraulic codes for accident analysis [9]. The VENTURE PC code was used in this work.

3. RESULTS AND DISCUSSION

The estimation of fuel burnup rate in the core of NIRR-1 using the VENTURE PC code for the proposed LEU is presented in Table 2.

As the number of days of reactor operation increases, the mass of U-235 in the core decreases proportionately, hence there is a perfect correlation ($R^2 = 1$) between exposure time steps and the mass of fuel material (U-235) in the core of the reactor.

The approximate estimation of U-235 burnup within 360 days which is equivalent to 1 year of NIRR-1 operation is approximately 13.95 g in the proposed LEU core. This shows that the burnup in NIRR-1 system and the LEU core is equivalent to 1% of the initial fuel within 360 days of reactor operation. This lifetime core is equivalent of 11 years from the time when NIRR-1 was commissioned in 2004 to 2015 before next cycle operations if it is operated at its maximum flux for 3 hours a day, 3 days a week.

The amount of U-238 burnup in the core within this same period of reactor operation, with a perfect correlation value ($R^2 = 0.9999$) is estimated to be approximately 0.88 g which is a negligible value when been compared to the change in mass of U-235 atoms in the system.

However, the amounts of plutonium-239, plutonium-240 and plutonium-241 produced in the core of the reactor for the period of reactor operation (360 days) were 0.766745 g, 0.00337342 g and 0.0000324559 g respectively which will continue to increase with increase in number of days of reactor operation.

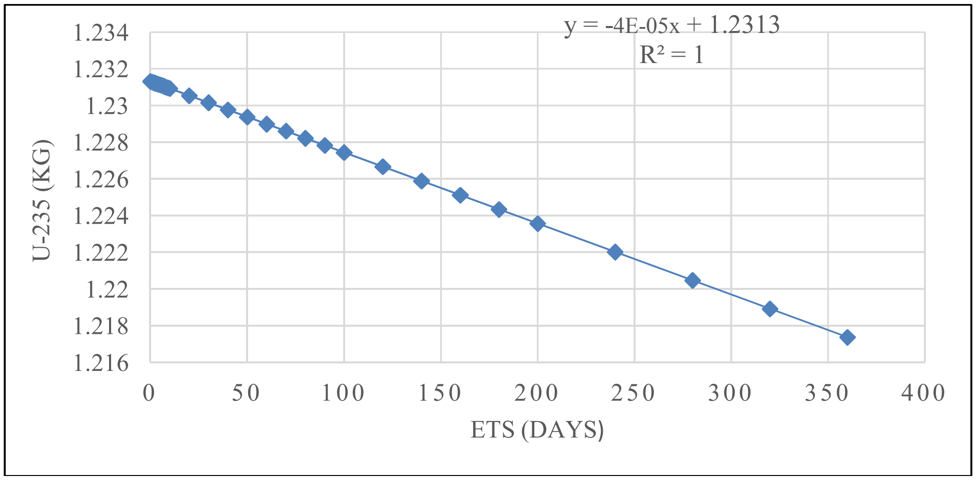

Fig. 5. Daily burnup rate of U-235 in the core of NIRR-1

Table 2. Table for changes in fissile isotope in the core of NIRR-1

	Inventory of Isotopes in the core				
Exposure Time Steps (ETS) (days)	**U-235 (kg)**	**U-238(kg)**	**Pu-239 (kg)**	**Pu-240 (kg)**	**Pu-241 (kg)**
0.0000	1.23132	5.00431	0.0000	0.0000	0.0000
1.0000	1.23128	5.00431	2.89344×10^{-7}	2.43872×10^{-12}	5.03909×10^{-17}
2.0000	1.23124	5.00431	1.05699×10^{-6}	1.82133×10^{-11}	7.63845×10^{-16}
3.0000	1.23120	5.00430	2.18153×10^{-6}	5.75607×10^{-11}	3.66853×10^{-15}
4.0000	1.23116	5.00430	3.57215×10^{-6}	1.28117×10^{-10}	1.10167×10^{-14}
5.0000	1.23113	5.00430	5.16104×10^{-6}	2.35574×10^{-10}	2.56006×10^{-14}
6.0000	1.23109	5.00430	6.89765×10^{-6}	3.84171×10^{-10}	5.06149×10^{-14}
7.0000	1.23105	5.00429	8.74430×10^{-6}	5.77066×10^{-10}	8.95538×10^{-14}
8.0000	1.23101	5.00429	1.06729×10^{-5}	8.16614×10^{-10}	1.46135×10^{-13}
9.0000	1.23097	5.00429	1.26626×10^{-5}	1.10456×10^{-9}	2.24242×10^{-13}
10.000	1.23093	5.00429	1.46724×10^{-5}	1.44015×10^{-9}	3.26670×10^{-13}
20.000	1.23054	5.00426	3.59669×10^{-5}	7.67018×10^{-9}	3.68685×10^{-12}
30.000	1.23016	5.00424	5.76142×10^{-5}	1.92183×10^{-8}	1.42951×10^{-11}
40.000	1.22977	5.00421	7.92717×10^{-5}	3.61098×10^{-8}	3.65004×10^{-11}
50.000	1.22938	5.00419	1.00921×10^{-4}	5.83423×10^{-8}	7.46513×10^{-11}
60.000	1.22899	5.00416	1.22561×10^{-4}	8.59125×10^{-8}	1.33089×10^{-10}
70.000	1.22861	5.00414	1.44192×10^{-4}	1.18816×10^{-7}	2.16146×10^{-10}
80.000	1.22822	5.00411	1.65813×10^{-4}	1.57051×10^{-7}	3.28143×10^{-10}
90.000	1.22783	5.00409	1.87425×10^{-4}	2.00611×10^{-7}	4.73409×10^{-10}
100.000	1.22744	5.00407	2.08965×10^{-4}	2.49366×10^{-7}	6.55773×10^{-10}
120.000	1.22667	5.00402	2.52136×10^{-4}	3.63046×10^{-7}	1.15104×10^{-9}
140.000	1.22589	5.00397	2.95268×10^{-4}	4.97967×10^{-7}	1.84797×10^{-9}
160.000	1.22512	5.00392	3.38360×10^{-4}	6.54100×10^{-7}	2.78069×10^{-9}
180.000	1.22434	5.00387	3.81411×10^{-4}	8.31413×10^{-7}	3.98319×10^{-9}
200.000	1.22357	5.00382	4.24264×10^{-4}	1.02920×10^{-6}	5.48431×10^{-9}
240.000	1.22202	5.00372	5.10146×10^{-4}	1.48922×10^{-6}	9.53899×10^{-9}
280.000	1.22047	5.00362	5.95855×10^{-4}	2.03343×10^{-6}	1.52095×10^{-8}
320.000	1.21892	5.00352	6.81389×10^{-4}	2.66159×10^{-6}	2.27609×10^{-8}
360.000	1.21737	5.00343	7.66745×10^{-4}	3.37342×10^{-6}	3.24559×10^{-8}

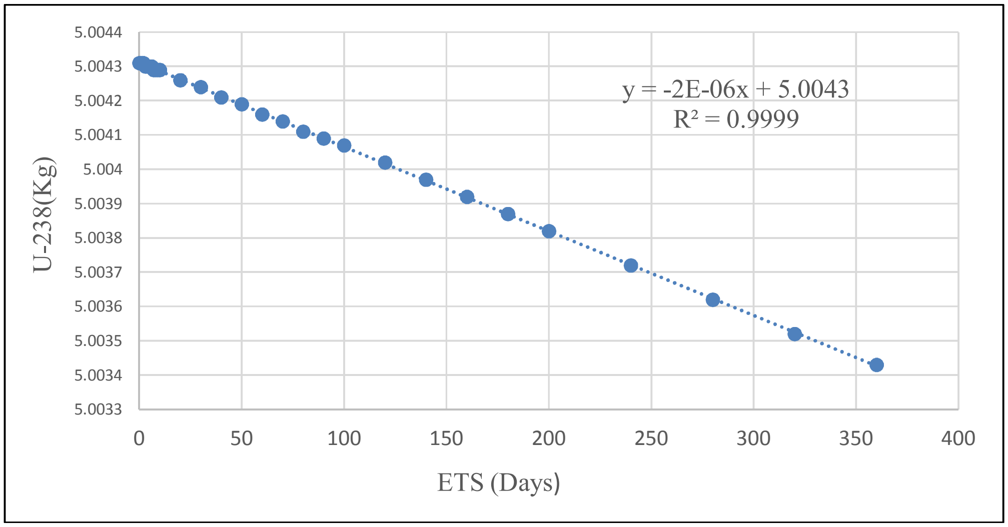

Fig. 6. Daily burnup rate of U-238 in the core of NIRR-1

4. CONCLUSION

The Nigeria Research Reactor -1(NIRR-1) is one of the reactor around the world that require conversion from HEU to LEU fuel. It is a compact low power nuclear research reactor designed by China Institute of Atomic Energy. Several analyses have been going on around the world on core conversion studies of this type of research reactor. The VENTURE computer code was used in this work to estimate the fuel burnup rate in the core life time expectancy of the reactor for the proposed LEU system for NIRR-1, with 19.75% enriched UO_2 as the fuel material. The quantity of U-235 consumed and the amount of Pu-239 produce in the core of the reactor were 13.95 g and 0.766745 g respectively.

The results of the fuel burnup estimation performed in this study proved to be in consistency with the other literatures for similar calculation using different approach. The result of the core lifetime expectancy shows that the reactor can be operated for over 10 years.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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