

Uranium diboride, the potential candidates of ATF, feature and application

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Abstract

It is universally acknowledged that power generation is most fundamental facility required by every industry, as almost all things require electricity to work. Among all the methods of electricity generation, nuclear power always faces considerable scrutiny. Undoubtedly, nuclear power brings about feelings of fear and unknown horror, especially after the accidents at Fukushima and Chernobyl. Such concerns are not unreasonable, as people's fear of nuclear power is a good measure to prevent accidents from happening. However, Taiwan people are too afraid of using this technology, turns out the result is miss out the opportunity to improve our ecosystem and make it more environmentally friendly. In this research, I would put the focus on the potentially fuel, Uranium diboride UB_2 , an interesting fuel that nowadays are research to be an ATF candidate fuel. Its physical properties also make it suitable for use in GEN-IV reactors, which require high standards to reaction. All of these factors make UB_2 show on my eyes, and this research aims to explore its potential.

Keywords: ATF, Uranium diboride, GEN-IV

1. Introduction

Uranium diboride is potentially material which on closely debating to be the next generation reactors fuel, especially known as ATFs (Advanced Technology Fuels or Accident Tolerance Fuels). UB_2 have unique talent that play a important role in. And ATFs is aim to increase the reactors power up-rates, longer cycle lengths, improved performance, and reduced stored energy in the core etc. And allow have more time to coping during accident scenarios.[1]

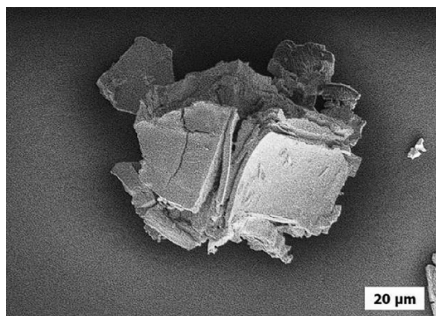


Figure 1: UB_2 Micrographs Picture[1]

2. History

The accident of Fukushima is the most impactable nuclear accident in 2011th, after Fukushima daiichi power

plant accident, many country and organization going to figure out why the accident happened and find out solutions, although there's a big part of research is about the Zircaloy Cladding technology, but it also gave rise to the development of a new field, ATF.

ATF has a lot of candidates, like U_2Si_3 , UC, UN, UB_2 and some kind of material is on debating. Such that, the next-generation reactors (GEN-IV Reactor) has benefited on these development, with ATFs, the reactor can function more safety and efficiency.

UB_2 has great talent to be the LWR (Light Water Reactors), PBR (Pebble Bed Reactors) and some kind of FBR reactors fertile fuel material.

3. Properties

In many candidate of ATFs material, the Uranium diboride has higher Uranium density than the others. Also, it has better thermal conductive that make itself have lower fuel centre-line temperatures on working, result in many positive effect such like; reduce the rate of temperature-dependent release of fission products, reduce the energy stored inside the fuel (This properties also is the most important that the UB_2 need.)

3.1. Neutron Poison

In last century, physicist found that there have a special material will absorb the thermal neutron in reactors, that is "Boron".

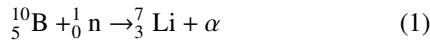
Table 1: The abundance and thermal neutron cross-section reaction type

Boron isotope (Mass Number)	Abundance(a/o)	The Cross-section of Thermal Neutron (Barn)	Reaction Type
B – 9	trace	-	-
B – 10	19.8[2]	3837[2]	Alpha Absorption
-	-	0.5	Gamma Absorption
B – 11	80.2[2]	0.01	Gamma Absorption
B – 12	trace	-	-

Boron has two main isotope in the natural, Boron-10(B-10, natural abundance is 19.8%) and Boron-11 (B-11, natural abundance is 80.2%), like Table 1. Boron-10's high cross-section make it will capture more thermal neutron then obstruct fissile fuel capture thermal neutron and finally stop the reaction after decay heat was cool down.

This properties make boron have a long time ago to be the material of neutron absorber in control rods, and nerver consider about to explored as fuel materials. But, after the accident of Fukushima daiichi, the Boron-10 begin to re-search on ATF.

Boron-10's high neutron cross-section makes it particularly effective at capturing thermal neutrons. This properties enable boron-10 to serve as a "Control Poison" within the broader category of "Neutron Poisons."



If boron-10 capture a thermal neutron like (1), it will release Lithum-7 and a alpha particle, this reaction is also been applied on BNCT(Boron Neutron Capture Treatment).

Althought alpha particle(Helium-4 nuclei) is ionization radiation and have very high ionization abillity, it can't release neutron and will slow down the reaction in reactor.

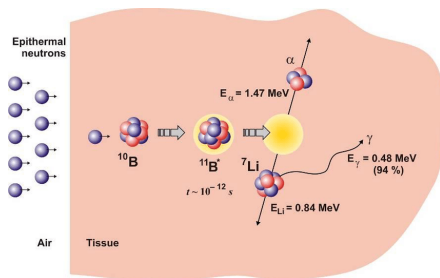
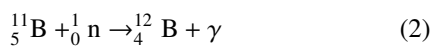


Figure 2: The Boron-10 in BNCT radiation reaction[3]



Boron-11 is not a good neutron absorption, if Boron capture thermal neutron, its mostly reaction chain is like (2) and still can not release neutron to keep chain-reaction.

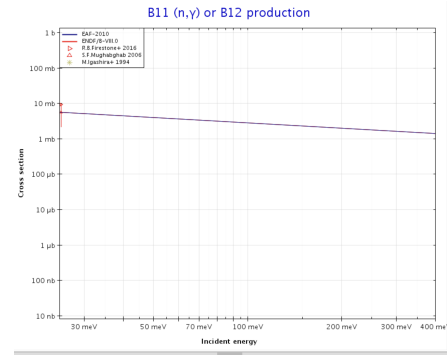


Figure 3: Boron-11 [3]

Neutron poison in fuel like UB_2 can make the Number of neutron in reactor decreaseing and avoid the accident chance, improve the safety margin, and with higher melting temperature, boron can . But in the other hands, neutron poison makes simulation need to think about more circumstance and finally interface the critical operation's problem. But UB_2 more benefits make up for its disadvantage. Please look the next section.

3.2. Uranium density

In physics, density is about a material mass per unit of volume, and larger uranium density which means that the material can contain more uranium atom like U-235, U-233 fissile fuel, it would make longer cycle lengths, and more Uranium atom also means theres have more capture can happened simultaneously.

Table 2: The Uranium density compare with UO_2 , recent generation fuel

The type of ATFs	UO_2	UB_2	UN}	UC	U_3Si_2
U-Density (U-g/cm ³)	9.6	11.7	13.5	12.7	11.3

$$\rho = \frac{\Delta k}{k} = \frac{k_{eff} - 1}{k_{eff}} \quad (3)$$

Higher Uranium-density will interface the effective neutron multiplication factor like(3), if $k_{eff} = 1$ the system will critical, this result will become a factor in monte-carlo simulation and GEN-IV reactor operation.

Table 3: Thermal conductivity compare with ATFs

Type of ATFs	UO ₂	UB ₂	UN	UC	U ₃ Si ₂
Thermal conductivity (W/m · K at 300 °C)	6.5(95% TD)	25(100% TD)	16.6(95% TD)	20.4(99%TD)	14.7(98% TD)

3.3. Thermal conductivity

The thermodynamics is a huge topic of physics, but in general, higher thermal conductivity can improved the fuel performance, UB₂ have the best thermal conductivity ability compare with ATF candidates, such that, the heat can quickly transfer from pellets and coolant according to the heat transfer equation like (4), and UB₂'s thermal gradient of fuel pellets is smaller than UO₂, smaller thermal gradient has less thermal stress difference inside, and there is less cracking (cracking affects heat transfer)

$$\frac{\partial u}{\partial t} = k \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) = k(u_{xx} + u_{yy} + u_{zz}) \quad (4)$$

This properties is more discuss about fuel economic and safety, occationally, some kind of natural accident like earthquake, tsunami etc. happen, control rods insert into the reactor, the reaction immediately stop and can make fuel's decay heat more efficiency exchange with coolant, this properties also have benefited on fuel economic, significantly reducing downtime, resulting in increased annual reactor operating time.

4. Application

UB₂ talents that make it to be a special role in LWR and next generation reactor, but there have a exception, SMR.

The SMR is brand-new nuclear technology that many country and company are trying to replace the traditional reactor.

4.1. Light Water Reactor

Light Water Reactor have two type, Boling and Pressure(BWR and PWR), using water(H₂O) to be the coolant and moderator, UB₂ is design for this originally, with that, the LWR can improve its performance, longer cycle lenghts and reduced stored energy in core, and prevent to occurry the accident like Fukushima daiichi nuclear power plant.

4.2. Pebble Bed Reactor

The PBR is a newly reactor design that is suitable for thermal neutron reactor, but if we to change the reflector material and fuel purity of uranium, that will suit for FBR(or other fertile material, the fast neutron breeder reactor is on debating, there's more thing need to developed that finally become a candidate of fast neutron reactor fuel of GEN-IV reactor)

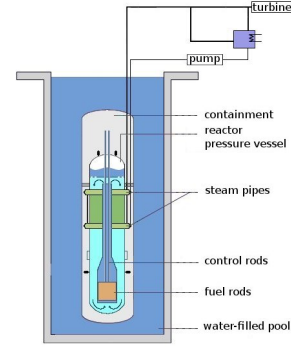


Figure 4: The Simple Version of LWR. [4]

According to UB₂ is ceramic materia, in LWR, we will using metal creamic fuel like UO₂ to make the pellets, but in PBR, the pebble fuel is like TRISO fuel, coated with four layers of three isotropic materials deposited through fluidized chemical vapor deposition [5].

UB₂ be the contain in TRISO, the coolant like helium can cross the gaps between TRISO, UB₂ high melting temperature can make the counterpart of reator core run at higher temperatures, such the heat transfer equation like (4),and boron can be the safety margin when the PBR function.

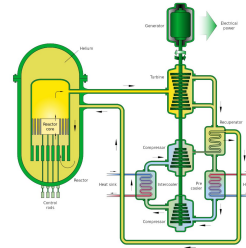


Figure 5: The Gas-cooled Fast Reactors [5]

4.3. Small Modular Reactor

SMR is nowadays debating, but almost research is for business running test, the biggest chanllenge of UB₂ is synthesis and enrich the correct purity present of Boron-10 and Boron-11 because burnable neutron poison properties, in a smaller system, the neutron will interface the function as well as D₂O and H₂O difference.

But UB₂ is potential candidate fuel with SMR, I hope the day which the UB₂ can supply to factory production line.

4.4. Nuclear Thermal Reactor

This is a special counterpart with UB_2 , recently, the NASA back to moon project called "Artemis" is planning to develop the nuclear technology paving the way for future out of solar exploration plans, the nuclear engine and MMR (Micro Modular Reactor, the relative with SMR) to be the out-space energy supply.

Based on the nuclear is a very stable supply source that can afford the mission that is far away of solar system, compared to the traditional energy supply system in spacecraft, the nuclear can use decay heat via thermoelectric effect to generate the power, this generator's early application is on the Apollo Project known as "SNAP-27" or the recent version of discovery program "ASRG" these reactor is using decay heat to generate the power and heat, but the application in Nuclear Thermal engine need to use the chain-reaction to heat up the fuel like liquid hydrogen.

In traditional chemical rocket engine, the combustion chamber is required combustion accelerant to work, this will decrease the containment of fuel, and result in lower specific impulse.

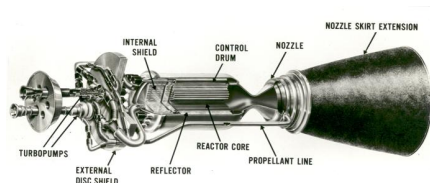


Figure 6: The early version of NASA VERA engine design[6]

But with nuclear thermal reactor, the burning chamber is replaced with nuclear reactor, the reactor can keep in a stable temperature to heat up the fuel, and don't need the combustion accelerant, this engine will breakthrough the challenge in how to design the fuel configuration.

Thermal nuclear rocket is based on phase state to decide the working temperature with the fissile material, gaseous, liquid and solid, in general, the solid has the highest working temperature that can make the fuel have maximum performance, but the solid material is very hard to make and its performance is not a big gap with gaseous version, and gaseous is what we can make to nuclear thermal rocket.

The UB_2 potential is being developed to be the nuclear thermal rocket fuel material, with that, the exploration can (1) more safety due to the safety margin of burnable neutron poison can reduce the chance of accident when the spacecraft on mission (2) Longer specific impulse to significantly increase the distance of solar exploration (3) UB_2 very easy to administer, cause its stable physical properties and ceramic hard to crack.

5. Conclusion

UB_2 and all of candidate with ATFs, is the most fundamental nuclear technology advanced, with ATFs, the reactor can effect more efficiency and more safety.

In spacecraft, the nuclear generator will become the energy and heat provider when the mission is far from solar system and can explore farther planet with NTR.

Taiwan's government need to find a way to solve the energy problem; and the SMR is good methods to using less plant and money to build up a power provide system, Taiwan IC industry is on flourish, and finally the energy problem will grown into a monster.

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