IBC Advanced Alloys

# Nuclear Fuels Initiative

Increasing Efficiency and Safety

January 26, 2011


## Abstract

The current level of public, and political attention being paid to fossil fuel based power sources is higher than ever before. This provides a prime opportunity for the nuclear power industry to grow. To facilitate this growth, the continued increase in the efficiency with which nuclear power plants operate, as well as the continued improvement of the safety of employees, the public and the plants themselves is paramount. Research, funded by IBC Advanced Alloys and conducted at Purdue and Texas A&M Universities has indicated that the inclusion of Beryllium Oxide ($BeO$) can increase both the efficiency with which fuel is used, as well as increase the safety with which the reactor operates. These improvements are largely realized through increasing the thermal conductivity of the fuel, thus decreasing its average temperature.


## 1 Introduction

Reliance on nuclear power sources is increasing (Figure 1). Nuclear power plants can provide power on the scale required to meet ever increasing demand, and can do so without emitting greenhouse gases. While renewable sources of power continue to see increased adoption, they lack the proven track record of nuclear sources and are generally still more expensive than traditional power sources. The biggest issues facing the nuclear industry today are perceived safety and environmental issues as well as the need to continue to decrease operating costs. IBC Advanced Alloys (IBC) has been working to aid and fund research being conducted at Purdue University as well as Texas A&M University in order to both increase safety margins as well as decrease operating costs and environmental impact through the improvement of nuclear fuel.

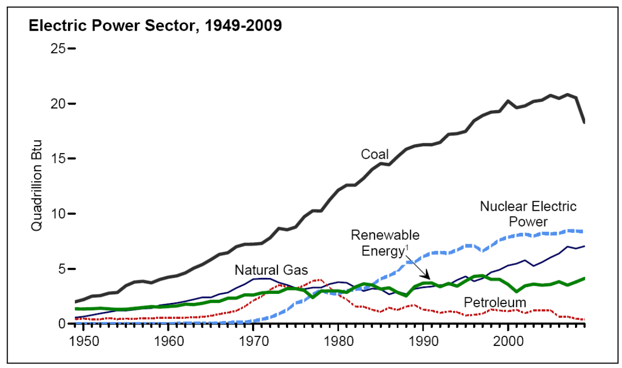


Figure 1: U.S. dependence on nuclear power sources is growing. Increased focus on the carbon emissions of power sources places carbon free nuclear power in an ideal position for growth. [1]

## 2 Nuclear Fuels

There are three isotopes of uranium, of which uranium-238 makes up 99.3%; uranium-235 (the power generating isotope) and uranium-234 comprise the remainder, with natural abundances of approximately 0.7% and 0.005% respectively [2]. Uranium to be used in pressurized water reactors (PWR), which constitute the majority of Western reactors, must have it's U-235 content increased to between 3 and 5% [3].

The standard process for producing nuclear fuel rods involves first forming uranium dioxide $UO_2$




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which is then pressed and sintered into fuel pellets. These pellets are then stacked and surrounded by a protective cladding which separates the fuel from the cooling system. A simplified assembly is shown in Figure 2.

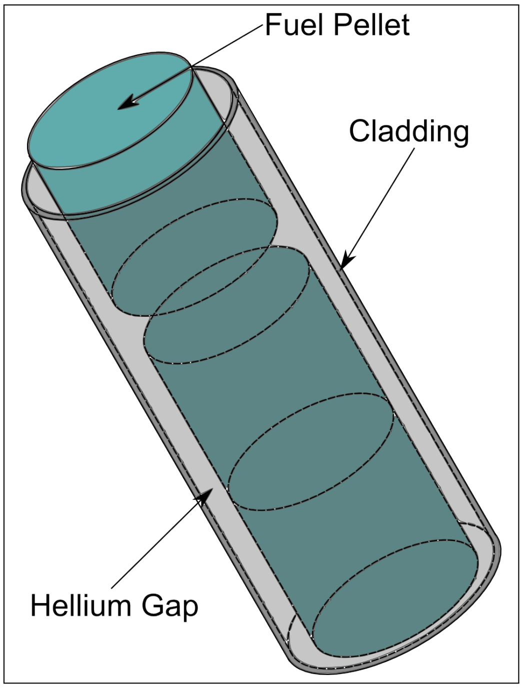


Figure 2: A fuel rod is comprised of stacked fuel pellets enclosed within a protective cladding. There is a small gap between the cladding and the fuel pellets which is filled with helium gas.

The issue at present is the poor thermal conductivity of $UO_2$. Low thermal conductivity results in a large temperature gradient through the pellets (Figure 4), with the centre of the pellets getting much hotter than their surfaces. These high temperatures limit reactor performance in a number of manners. High temperatures can cause the $UO_2$ pellets to expand, leading to their coming into contact with the protective cladding which surrounds them [4]. Likewise, higher temperatures can increase the rate at which reaction gases build up. This buildup increases the pressure inside the cladding, and can eventually result in it's failure [5, 6].

# 3 Thermal Conductivity Improvements

Improving the thermal conductivity is the most direct method of addressing the heat issues facing current nuclear dioxide fuels. Modifying the thermal conductivity requires introducing a new material. Whatever material being introduced needs to be unreactive, even at high temperatures, with the $UO_2$ in order to protect the fuel's integrity.

Beryllium oxide was chosen as an ideal material as $BeO$ remains unreactive with $UO_2$ all the way up to $2100^oC$ and has the best thermal conductivity of any oxide. The issue has been finding a manufacturing process for combining $BeO$ with $UO_2$ which is viable on an industrial scale. IBC funded research, conducted at Purdue and Texas A&M Universities is yielding not only proof of that improvements can be had, but also an industry viable manufacturing solution for $UO_2 - BeO$ fuel pellets.

# 4 Manufacturing Pellets

The $BeO$ added to the $UO_2$ needs to be continuous; separate clumps of $BeO$ wouldn't be able to channel heat away from the center of the fuel pellets. To address this, researchers have developed a 'co-sintering' technique. Standard practice for producing fuel pellets is to form $UO_2$ into small granules and then sinter them together. It is turning out to be a relatively simple matter to introduce $BeO$ powder to the granulated $UO_2$ prior to sintering. The result is that granules are surrounded by high thermal conductivity $BeO$ which channels heat away from the center, towards the surface of the pellet (Figure 3). One of the principal advantages of this manufacturing route is that it is actually very similar to current manufacturing techniques. Minimal capital investment is required to modify existing fuel pellet manufacturing facilities to produce the proposed fuel pellets.

# 5 Modelling Results

## 5.1 Performance and Environmental Improvements

The effect of the inclusion of $BeO$ to the fuel pellets has been modelled. The system modelled kept the mass of uranium-235, the energy generating isotope, constant as compared to a normal pellet , but

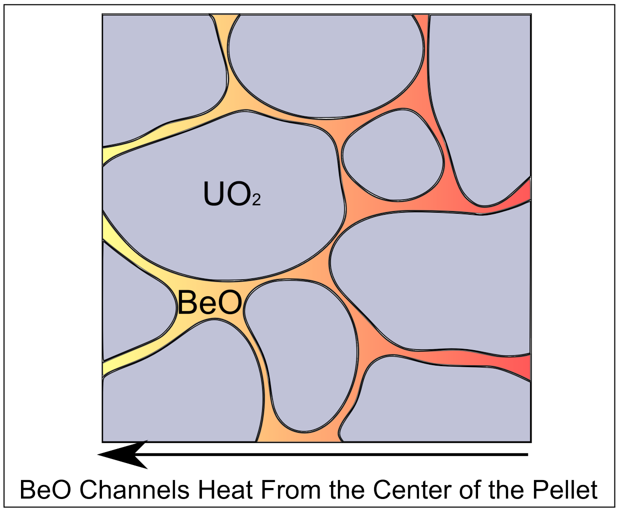


Figure 3: $UO_2$ granules are surrounded by $BeO$, allowing heat to be channeled from the center of the fuel pellets to their surface.

included 10% $BeO$ by volume. The modelled results of this composition pellet are dramatic. At the simulated average power density, the temperature at the centerline of the pellet, the hottest point, was decreased by $200^oC$ from $800^oC$ to $600^oC$ while keeping the surface temperature constant (illustrated in Figure 4). This is crucial as it is the surface temperature of the pellets which determine their power output. Therefore, the same power is generated, but with a far lower centerline temperature than in a tradition $UO_2$ fuel pellet. This reduces the likelyhood of cladding interaction as well as cracking of the pellets due to uneven thermal expansion. It also means that the average temperature of the pellet is reduced by approximately $100^oC$.

A further effect of the decreased centerline temperature in the pellets is that current models predict that they will have a longer life span. The initial reactivity of the fuel pellets is actually higher, as is the initial burnup rate, though the difference decreases over the lifespan of the pellet. The improved characteristics imbued by the $BeO$ actually increases the lifespan of the pellets though, despite the increased reactivity. The simultaneous increased reactivity, burnup and lifespan are possible because the $BeO$ has a positive effect on the neutronics of the fuel. What this means is that either the fuel pellets, at a given amount of U-235, can last longer, requiring less frequent refueling, or the amount of U-235 could actually be decreased, allowing the same refueling schedule to be used. It is currently estimated that these improvements could directly lead to a 4% reduction in fuel consumption. A 4% increase in fuel efficiency would allow current reserves of Uranium to last long enough to power 9 nuclear reactors for 18 months. This not only results in decreased fuel costs, but also decreases the environmental impact of operating reactors, as less uranium needs to be mined.

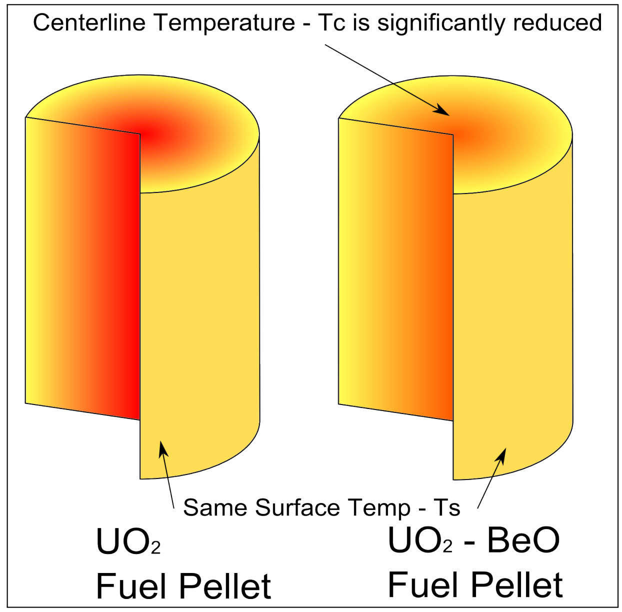


Figure 4: The inclusion of $BeO$ increases the thermal conductivity of the fuel pellet. This decreases the thermal gradient through the pellet, decreasing average temperature and increasing efficiency.

### 5.2 Safety Improvements

These results suggest significant benefits are possible by employing $UO_2 - BeO$ fuels. While nuclear power sources have been repeatedly proven to be both safe and reliable, any potential improvements to the margin of safety within which the reactor operates can only be beneficial in helping further assuage public concern. This is crucial as the continued growth of the nuclear power industry in contingent on public confidence in nuclear power.

These improved safety margins are derived from the same sources as the improved operational performance. Conventional power sources can be stopped very quickly, fossil fuel based generators can effectively be simply turned off; nuclear fuel pellets on the other hand take longer to 'turn off'. The reactive material in the fuel pellets continues to produce heat for some time. Thus, the cooler the fuel can be kept, the quicker the reactor can be shut down. The decreased temperature of the fuel pellets also means that in the event of an instability during operation, there is more time for corrective action to be taken, directly increasing the safety of the reactor.

The improved thermal conductivity decreases the temperature difference between the centerline and surface of the pellet (Figure 4). This results in a decreased likelihood that the pellets will crack or break due to thermal stresses as well as a decrease in the fission gases produced. Broken or cracked pellets can result in radioactive material escaping the fuel rod assembly and entering the coolant system in the event of cladding failure. The likelihood of cladding failure is also reduced though as the decreased average temperature of the fuel pellets, the $BeO$ inclusion means that the amount of thermal expansion the pellet undergoes is also decreased, resulting in a decrease in pellet-cladding interaction. Decreasing temperature also decreases the buildup of gases produced by the fission process. Once again, this increases safety as the buildup of fission gases with fuel rods can likewise endanger the integrity of the cladding.

## 6 Conclusion

Nuclear power has proven itself an economic, safe and environmentally friendly power source and is ideally situated for increased adoption in the light of increased environmental concerns. This does not, however, mean the industry can rest on its laurels, particularly in the face of the ever increasing efficiency of renewable power sources. The industry must continue to strive to decrease costs while increasing safety.

Current, IBC funded, modelling work has made the potential benefits of the incorporation of $BeO$ into $UO_2$ fuel pellets clear and is resulting in significant industry interest. The prospect of fuel pellets that operate more efficiently, with significant safety margin improvements is obviously highly attractive. Moving forward, the research is continuing into refining the manufacturing process with the goal of testing samples at the US Department of Energy's Advanced Test Reactor (ATR). This work at ATR will provide experimental corroboration of the benefits indicated by current modelling efforts.

## References


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