Journal of Nuclear Materials 392 (2009) 301–306

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Economic benefits of advanced materials in nuclear power systems

J.T. Busby [*]

Oak Ridge National Laboratory, 1 Bethel Valley Rd., P.O. Box 2008, Oak Ridge, TN 37831-6138, USA

ABSTRACT

A key obstacle to the commercial deployment of advanced fast reactors is the capital cost. There is a perception of higher capital cost for fast reactor systems than advanced light water reactors. However, cost estimates come with a large uncertainty since far fewer fast reactors have been built than light water reactor facilities. Furthermore, the large variability of industrial cost estimates complicates accurate comparisons. Reductions in capital cost can result from design simplifications, new technologies that allow reduced capital costs, and simulation techniques that help optimize system design. It is plausible that improved materials will provide opportunities for both simplified design and reduced capital cost. Advanced materials may also allow improved safety and longer component lifetimes. This work examines the potential impact of advanced materials on the capital investment cost of fast nuclear reactors.

Published by Elsevier B.V.

1. Introduction

As future advanced fast reactors are designed, there will be several key requirements which drive commercial development and deployment of advanced fast reactor systems. Overall, cost is a major factor in commercial nuclear applications and evaluation of that cost is complex. The costs of virgin or reprocessed fuel and waste disposal must be considered as well as safety and non-proliferation factors, in addition to reactor costs. Fast reactor technology must be economically competitive with existing light water reactor systems. If a fast reactor system represents a significant increase in capital investment over more traditional technology, it will not be adopted nor commercially deployed. In addition, fast reactor technology must be flexible and allow for a number of different missions. These may include power generation; testing of materials, fuels, or coolants; production of isotopes or transmutation of isotopes (so called ‘burning’). Finally, the fast reactor technology must have improved safety. Inherent safety features and defense-in-depth will be required for any new system to receive regulatory approval.

The use of advanced materials can positively impact all three requirements. In terms of economy, improved materials may allow for increased revenues by enabling higher temperature performance, longer lifetimes, and more efficient power generation. Improved materials may also allow for a reduction in capital costs via reduced material volumes (or raw material commodities) and design simplifications. Better material performance may also permit improved flexibility and allow designers greater options in mission, component, and system design. Finally, improved material performance also enables greater safety margins and more stable performance over a longer lifetime, promoting greater reliability and power generation.

Economics are arguably the most important factor in promoting commercial deployment of any reactor technology. One of the key obstacles to the commercial deployment of advanced fast reactors (for either burning or power generation) has traditionally been the capital cost. As noted by Hill [1] there is a perception of higher capital cost for fast reactor systems than advanced light water reactors (ALWR). However, the cost estimates for a fast reactor come with a large uncertainty due to far fewer fast reactors having been built than light water reactor (LWR) facilities. Further, the large variability of industrial cost estimates complicates accurate comparisons. For example, under the Gen IV program, the Japanese Sodium Fast Reactor (JSFR) has a stated capital cost estimate that is comparable to current LWR estimates [2].

Further reductions in capital cost must be made for US fast reactor systems to be considered economically viable. Three key approaches to cost reduction can be pursued. These include design simplifications, new technologies that allow reduced capital cost, and simulation techniques that help optimize system design. Improved materials will provide opportunities for both simplified design and reduced capital cost by allowing the same performance with less material. For example, if 316 stainless steel can be replaced with a steel that is twice as strong, only about one-half the raw material is required for the same component, assuming all other properties are still adequate (e.g., fracture toughness, etc.). While allowances must be made for differences in fabrication, joining, and quality assurance, it is apparent that advanced materials may reduce capital costs, relative to 316 stainless steel. While this assumption is plausible, the economic benefit of advanced materials has not been quantitatively analyzed.

---

[*] Tel.: +1 865 241 4622; fax: +1 865 241 3650.
E-mail address: busbyjt@ornl.gov

0022-3115/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.jnucmat.2009.03.018

The objective of this paper is to examine the potential impact of advanced materials use on the capital investment costs of nuclear power systems. The impact of cost fluctuations in traditional reactor materials will first be examined. Then, the impact of better materials performance on fast reactor capital costs will be discussed. Finally, the reduction of capital costs via design simplifications will be addressed.

2. Impact of price fluctuations

Reactor economics and the capital costs of the reactor have always been important considerations during the design, construction, and operation of nuclear power systems. Design changes and structural material choices are available means of making reactors more economical. It is also important to note that recent market fluctuations (more specifically, increases) in the cost of raw materials will also have a large impact on the cost of components and commodities. For example, stainless steel is composed primarily of chromium (12–18%), nickel (8–15%) and iron. The majority of components in any advanced fast reactor design are made of 316 grade stainless steel. Recent increases in the price of nickel have had a significant impact on the cost of stainless steel.

Historically, there has been considerable fluctuation in nickel prices, as shown in Fig. 1. These are driven by increasing demand for stainless steel and superalloys as well as interruptions in limited supplies [3–5]. Recently, the price of Ni reached historic highs as costs have increased significantly over the last five years and have recently been more than five times the 2003 price [3–5].

This fluctuation is reflected in the cost of stainless steel. As of March 2008, the cost for drawn bar stock of 304 SS was $4900/ton. For 316 SS, the cost of the same product forms was $7900/ton. This is almost an order of magnitude increase from 10 years ago when prices were only $600/ton and $820/ton for 304 and 316 SS, respectively. Clearly, commodities costs have a direct impact on the cost of components and may add millions of dollars to the price of a reactor. While these costs are not insignificant, the potential impact of advanced materials on capital costs and revenue generated are much larger.

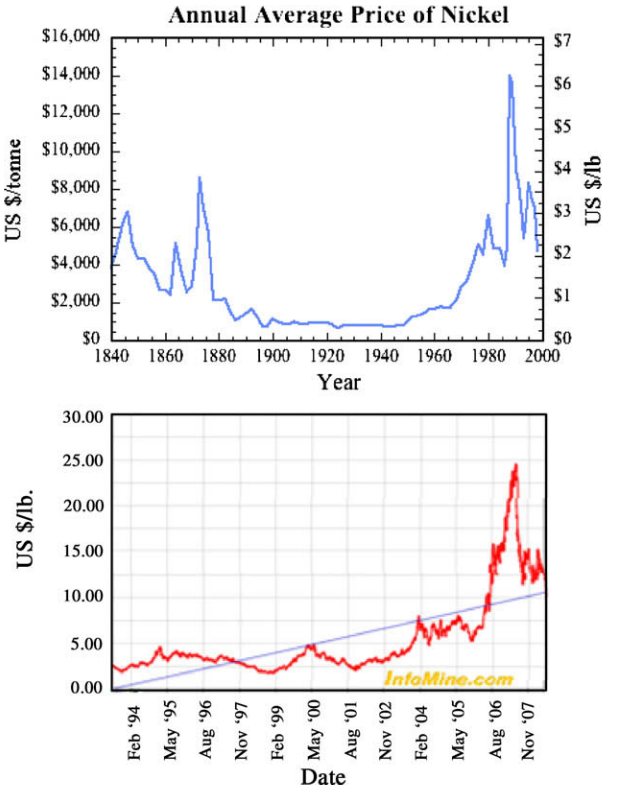

Fig. 1. The historical cost of nickel from (a) 1840 to 2000 and (b) 1993 to present [3–5].

3. Impact of advanced materials on capital costs

As noted above, improved materials provide several viable means of improving fast reactor economics. Improved materials may promote an increase in power generation and revenues by enabling higher performance (higher temperatures, longer lifetimes, or reduced downtime). Another method is to reduce the volume or mass of material required by providing improved structural material performance. Any improvement in strength, creep resistance, or other limiting properties may allow proportional reductions in component thickness or size, assuming sufficient ductility is maintained. Finally, improved performance of a component may permit design simplifications such as reducing redundant systems. Each of these possibilities will be examined in the following sections.

4. Increased revenues

The generation and sale of electricity is the primary mission for most reactor designs, thermal or fast. As a result, any means of improving the total power generated is favorable and will help offset the capital investment in the reactor. In the simplest terms and as a first-order approximation, revenue from power generation can be given as

$$\begin{aligned}\text{Electric Power Revenue} = {} & \text{Thermal Power} \times \text{Thermal Efficiency} \\ & \times \text{Capacity Factor} \times \text{Reactor Lifetime} \\ & \times \text{Price per unit energy}\end{aligned}$$

Improved materials may improve at least three of these factors. First, improved performance of structural materials results in components with higher reliability which leads to reduced downtime and a higher capacity factor. Similarly, improved performance and tolerance to irradiation-induced degradation allows for longer operating lifetimes and reduces the need for component repair or replacement.

In addition, improved materials may influence thermal efficiency by allowing higher operating temperatures. This factor alone may greatly increase revenues. The potential for improved thermal efficiency is shown in Fig. 2 where plant efficiency is plotted as a function of reactor operating temperature. The ideal, Carnot efficiency ($1 - T_{\text{cold}}/T_{\text{hot}}$) is plotted, although other losses and operating factors will reduce the total efficiency by 10–15%. This is illustrated by the actual thermal efficiency data for all sodium fast reactors constructed to date. The anticipated thermal efficiency for the S-PRISM (Super-Power Reactor, Innovative, Small Module) design is 0.38 and is plotted in Fig. 2 as well. The S-PRISM is chosen as an example as it represents one of the most mature sodium fast reactor designs available today. Improvements in existing materials to increase the upper temperature limit by $\sim$100 °C will lead to increases in thermal efficiency of 3–8% over the current S-PRISM value. More revolutionary materials offer even higher gains. However, increased operating temperatures may be limited for sodium fast reactors, due to safety considerations and the boiling point of sodium.

One can estimate the potential impact of improved material performance on revenue generated by using the simple equation above. Assuming conservative values such as an 80% capacity factor (although the current LWR fleet operates at over 90% today)

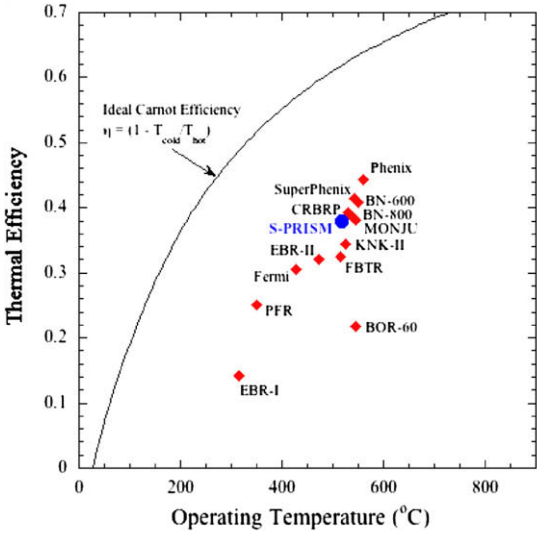

Fig. 2. The ideal thermal efficiency and actual thermal efficiencies of sodium fast reactors.

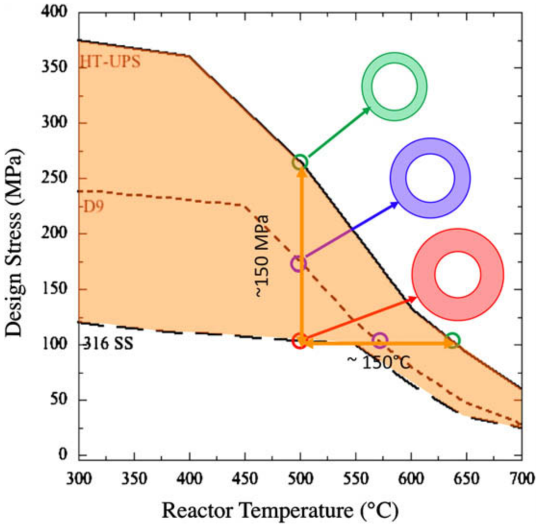

Fig. 3. Temperature-design stress curves for 316 SS, D9, and HT-UPS steels. Higher strength can reduce commodities for components [concept after [17]].

and electricity price of \$0.06/kW h, the total power revenue can be calculated for 60 years of operation of a 1000 MW th reactor, although higher power levels may be achieved with commercial deployment. If the thermal efficiency of an S-PRISM can be increased from 0.38 to 0.43, then increased revenues of US \$1.25 billion could be realized.

5. Reduced commodities

Improved materials will also provide key opportunities for reduced reactor cost through reduced commodities. That is, stronger materials allow the same components to be thinner and require less material, again assuming all other property requirements are satisfied. Smaller component sections can also provide advantages in component fabrication (welding, heat treatment, etc.), transportation, and field erection.

Any new material must meet many different criteria to be accepted for service in a reactor environment. For an advanced fast reactor, the exact operating conditions will vary with the final reactor design. Furthermore, operating conditions will vary with location and lifetime. In general, however, structural materials in a sodium fast reactor may expect operating temperatures ranging from 450 to 550 °C in a sodium environment, and the structural components will be required to survive a 60 year lifetime and irradiation doses up to 5–10 dpa, with much higher fluences possible within the reactor core.

Typically, stainless steels are used for components such as the reactor vessel, reactor vessel enclosure, guard vessel, plenum, core barrel, and internal supports. Ferritic/martensitic steels are usually chosen for cladding, piping and heat exchanger components as well as selected internal components due to their better thermal properties and radiation tolerance [6]. However, composites (e.g., SiC/SiC, AlN), refractory metals (e.g., Mo, TZM, Ta-alloys, Nb-alloys), oxide-dispersion strengthened steels (e.g., 14YWT, MA-957, PM-2000), and superalloys (e.g., Inconels, Hasteloys) may also be considered for some applications.

The impact of material performance and component design can be summarized in a single plot showing the allowable operating regime in stress–temperature space. Fig. 3 summarizes the stress–temperature design window for 316 stainless steel [7]. This analysis is based on the extensive experimental database of tensile properties and thermal creep [8–10] for stainless steel. The maximum stress limit at 50–550 °C (323–823 K) is defined as 1/3 of the ultimate tensile strength, which is a more conservative design limit than 2/3 of the yield stress for stainless steel. The stress limit at higher temperatures is defined as 2/3 of the creep rupture strength at 10^5 h. Also shown in Fig. 3 are the stress–temperature design curves for alloys D9 and high temperature, ultrafine precipitation strengthened (HT-UPS) steels. It is also important to note that other factors must ultimately be considered in component design in a nuclear system (such as fatigue, earthquake conditions, etc.), although such treatments are beyond the scope of this initial analysis.

Alloy D9 is an advanced austenitic steel that was developed during the United States National Cladding and Duct Development program in the 1970s and 1980s [10–13]. D9 has a greatly improved tensile strength over 316L stainless steel. This is also illustrated in Fig. 3 in temperature–stress space along with the 316 stainless steel. The HT-UPS alloys are 14Cr–16Ni austenitic stainless steels that were developed in the late 1980s by the US Fusion Reactor Materials program for improved radiation-resistance [14–16]. The HT-UPS steels offer even higher performance than the D9 alloys in terms of strength and creep resistance, although there is considerably less experience with irradiation effects in these alloys.

As shown in Fig. 3, both the D9 and HT-UPS offer considerably increased performance. The impact of improved strength on commodities is also illustrated schematically using piping as an example [17]. For increased strength, a thinner pipe wall will withstand the same pressures and volumes, which will clearly impact cost. D9 has a higher tensile strength than 316 stainless steel, providing an additional 75 MPa of design stress at temperatures up to 500 °C, although the creep performance is similar to 316L stainless steel at the highest temperatures. The HT-UPS steel offers an additional 165 MPa over 316 SS at 500 °C. This increased strength at a constant temperature will allow reduced section sizes, and allow for longer lifetimes under stress, greater safety margins, or any combination of these. In addition, improved performance may also enable increased operating temperatures at a fixed stress. In the case of HT-UPS, an increase of ~150 °C is possible with no reduction in allowable stress, unless other reactor design limitations intervene.

The higher performance of these alloys will come with a cost premium, however. Higher alloying content, use of expensive elements in the steel, and special processing may all impact alloy cost.

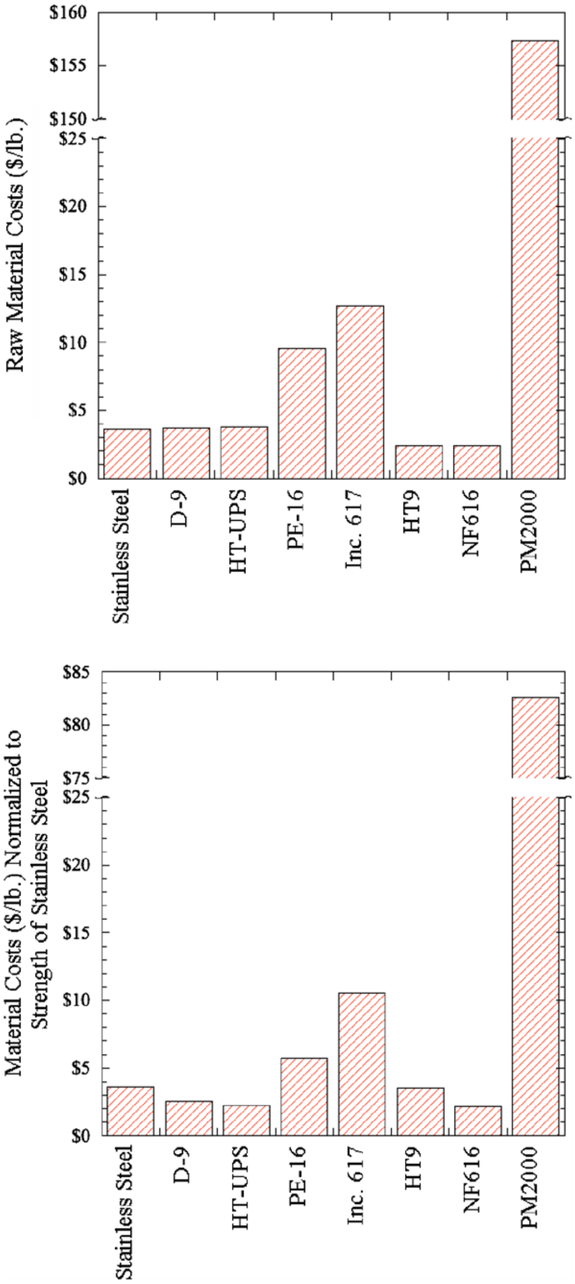

Fig. 4. Comparison of costs 316 SS and other advanced alloys in terms of (a) raw materials and (b) normalized for maximum design stress at 500 °C, relative to 316 SS. Material costs were estimated from recent purchase of stock of all the alternative materials.

This is illustrated in Fig. 4 where the raw material cost for 316 stainless steel is compared to a number of advanced alloys on a $/lb. basis. In addition to the traditional 316 SS, D9 and HT-UPS described above, the plot also shows the cost of PE-16 and Alloy 617 (Ni-base superalloys), HT9 (a ferritic/martensitic steel used in past sodium reactors), NF616 (a 9Cr advanced ferritic/martensitic steel originally developed for super-critical boiler applications), and PM-2000 (the only commercially available oxygen-dispersion strengthened alloy). The cost for all the alternate alloys in Fig. 4 was estimated from recent purchases at Oak Ridge National Laboratory for various research programs. Clearly, the more advanced alloys are more expensive in raw material cost.

The improved strength of the advanced alloys must also be considered. The cost/lb. of each alloy has been normalized to the strength of 316 SS in Fig. 4(b) and shows the effective cost for a fixed strength. When normalized in this way, the advantage of the advanced materials becomes more apparent. For example, while the HT-UPS steel costs approximately $0.15 more per pound, the considerably higher strength makes it effectively $1.40 per pound cheaper. As a result, NF616 and HT-UPS are the most cost effective materials when compared to traditional materials like 316 SS and HT9.

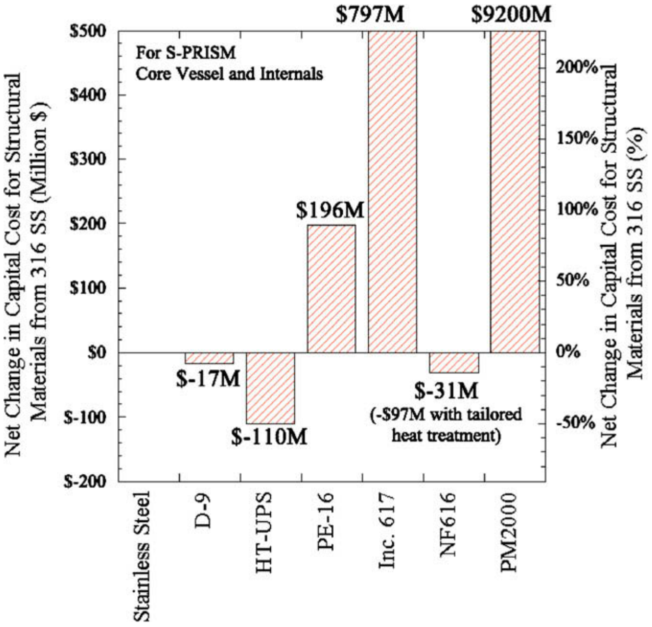

Fig. 5. Comparison of material costs for a PRISM reactor constructed using 316 SS or advanced alloys.

While this is a better measure, other factors must be considered for materials to be used in a nuclear reactor application, including fabrication, joining, quality assurance, availability and compatibility. If a material is harder to machine and fabricate raw stock into components, costs will go up proportionally. Similarly, for materials such as PM-2000 (an oxide-dispersion strengthened steel) more advanced joining methods must be used to maintain properties and as a result, costs will be increased. Conversely, stronger materials with similar welding properties may lead to reduced cross-sections and easier joining at a lower cost. Quality assurance must also be considered. If fewer lots of material or reduced joining can be achieved, the associated cost of inspections will be reduced. Finally, compatibility must be considered. Increased or decreased corrosion rates in the reactor coolant may impact required component thicknesses and commodities.

The effect of improved performance and reduced commodities on cost warrants more detail and evaluation. This can be illustrated with relatively simple calculations when the 316 stainless steel volume required for a PRISM reactor is replaced with several advanced materials. Hoffman [2] has estimated that the PRISM reactor design contains 81.0 m^3 of type 316 stainless steel in the reactor vessel and core internals. This includes 29.0 m^3 for the vessels and 52.0 m^3 for core internals (structural supports, ducting, and vessel shielding). At a density of 8000 kg/m^3, this corresponds to 640 metric tons of steel required for the PRISM structural materials. Hoffman has estimated the capital cost for these components at $211 million. This value also includes costs associated with fabrication, joining, installation, inspection, and quality assurance.

A similar analysis has been performed here with several different advanced alloys, including the same advanced alloys listed above and in Fig. 4. The amount of material needed to replace the 640 metric tons of steel was determined by comparing the strength and density to 316 stainless steel and accounting for differences in fabrication, joining, quality assurance, and installation costs as well as corrosion rate. The impact on capital cost of using an improved material is shown in Fig. 5, both in terms of actual costs and percent change in capital cost. As above, the current cost of 316 stainless steel stock was taken as $7900/ton.

By substituting D-9 or HT-UPS for 316 stainless steel, a net reduction of $17 million or $110 million dollars in capital investment is feasible. Further improvements may lead to even more economic grades of steel. The NF616 alloy can reduce capital cost by $31 million in its current state. However, recent developments in the heat treatment of this alloy [18] can greatly increase strength and could triple this reduction in capital cost to a savings of $97 million. On the other hand, while high Ni-alloys may offer superior high temperature performance, the recent increases in the cost of Ni makes this option less attractive. Similarly, the PM-2000 is very expensive for such a large volume of material and is not suitable for an entire reactor structure. But, both the PM-2000 ODS and Ni-base alloys may have uses in specific reactor components.

One should note that the costs listed in the discussion above do not account for the effort and costs associated with qualifying a new material for reactor service. Developmental costs are difficult to estimate and will depend on the maturity of the candidate alloy, use in other applications, and most importantly, data needs to satisfy licensing requirements. The United States National Cladding and Duct Development Program, which qualified HT-9 for fast reactor clad applications, is commonly estimated at $212 million over 14 years [11,19]. Alloys such as HT-UPS and NF616 steels already have a considerable database from other applications such as fossil energy power plants, which will reduce development needs considerably. Using the experience from the United States National Cladding and Duct Development as a guide and accounting for existing experience, the cost to qualify HT-UPS or NF616 can be estimated at $35–45 million. As this cost is less than the potential savings in capital cost presented in Fig. 5, an investment in advanced materials development may be recovered in the first reactor, even if the development costs are significantly higher.

6. Design simplifications

One of the most effective means of reducing reactor capital cost is through design simplification. If improved designs can eliminate unneeded components, costs will also be reduced. Advanced reactor materials may also allow design simplifications, although the effect on cost is more difficult to quantify. For example, one of the innovative features of the Japanese Sodium Fast Reactor is a reduced number of coolant loops. This can be achieved only if high strength materials with low coefficients of thermal expansion can be utilized. Alloys such as NF616 may have suitable properties to permit this design change and result in much lower capital cost. If advanced materials with increased radiation tolerance can be utilized a reduction in the shielding placed at the top of the reactor core is possible, thereby reducing commodities and reactor height. Similarly, high strength, stable alloys may allow for thinner reactor vessels, thereby reducing total reactor footprint and size of the surrounding containment structures.

Design simplifications may also allow for secondary improvements in reactor costs. Each system and subsystem will require installation and inspection during construction of the reactor. Further, during operation, each system and subsystem requires monitoring, inspection, and maintenance. A simplified design may permit reduced costs throughout the reactor lifetime.

7. Conclusions

Advanced materials have the potential to improve the performance of advanced fast reactors by improving safety margins for components and systems, allowing greater design flexibility, and improving fast reactor economics. Indeed, reductions in the capital costs of any advanced fast reactor must be realized for these advanced designs to be more competitive with existing light water reactor systems. Advanced materials can positively impact the economics of fast reactor technology in a number of different manners, including increased revenue and reduced capital cost through both reduced commodities and design simplifications.

Improved materials may improve the total revenue generated over a reactor lifetime. Improved performance of structural materials results in components with higher reliability which leads to reduced downtime or a higher capacity factor. Similarly, improved performance and tolerance of irradiation allows for longer operating lifetimes and reduces the need for component replacement. Finally, improved materials may influence thermal efficiency by allowing higher operating temperatures. This factor alone may greatly increase revenues.

While advanced alloys may be more expensive per pound than traditional materials such as 316 SS and HT9, they also offer considerably higher performance. This improved performance can more than overcome the higher raw material cost, which becomes even more important as the costs of traditional materials undergo large increases in price. When normalized for strength, advanced alloys like HT-UPS and NF616 are the most cost effective. Indeed, a simple analysis shows that replacing 316 SS with advanced alloys in a reactor such as the PRISM design can reduce the capital cost of the materials by nearly $100 million (or 5–8%). Costs can also be reduced significantly via design simplifications although these are more difficult to quantify.

The analysis shown above, while relatively simplified, clearly illustrates the positive impact of advanced reactor materials on the economics of nuclear power plants.

Acknowledgements

Support for this analysis was provided by the US Department of Energy AFCI program under the Fast Reactors Campaign. The comments and suggestions offered by Drs Corwin and Wiffen are also greatly appreciated.

References

[1] B. Hill, Argonne National Laboratory, Private Communication, 2007.
[2] E. Hoffman, Argonne National Laboratory, Private Communication, 2007.
[3] MEPS, World Stainless Steel Product Prices, June 2007, <https://www.meps.co.uk>.
[4] London Metals Exchange, June 2007, <http://www.lme.co.uk/nickel.asp>.
[5] U.S. Geological Surveys, Metal Prices in the United States through 1998, <http://minerals.usgs.gov/minerals/pubs/metal_prices/>.
[6] M. Morishita, T. Asayama, M. Inoue, S. Kotake, T. Mizuno, ANS Trans. 98 (2008) 947.
[7] S.J. Zinkle, L.J. Ott, D.T. Ingersoll, R.J. Ellis, M.L. Grossbeck, in: Space Technology and Applications International Forum-STAIF 2002, vol. 608, Melville, NY, USA, 2002, p. 1063.
[8] M.L. Grossbeck, K. Ehrlich, C. Wassilew, J. Nucl. Mater. 174 (1990) 264.
[9] F. Tavassoli, in: EU Fusion Materials Assessment Meeting, FZK-Karlsruhe, 2001.
[10] M.F. Marchbanks, in: Nuclear Systems Materials Handbook, vol. 1, TID 26666, Oak Ridge National Laboratory, Oak Ridge, TN, 1978.
[11] J.J. Laidler, J.W. Bennett, Nucl. Eng. Int. 25 (1980) 31.
[12] P. Sivaprasad, S. Venugopal, V. Maduraimuthu, M. Vasudevan, S. Mannan, Y. Prasad, R.C. Chaturvedi, J. Mater. Process. Technol. 132 (2003) 262.
[13] S. Venkadesan, S. Venugopal, M. Vasudevan, P. Sivaprasad, Mater. Sci. Technol. 9 (1993) 1.
[14] P.J. Maziasz, in: B.L. Bramfitt, R.C. Benn, C.R. Brinkman, G.F. Vander Voort (Eds.), Proceedings of the Symposium MiCon 86, ASTM-STP 979, ASTM, Philadelphia, 1988, p. 116.

[15] P.J. Maziasz, R.L. Klueh, A.F. Rowcliffe, MRS Bull. XIV (1989) 36.
[16] P.J. Maziasz, J. Nucl. Mater. 205 (1993) 118.
[17] R. Viswanathan, W. Bakker, in: ASME Proceedings of the 2000 International Joint Power Generation Conference, Miami Beach, FL, July 23–26, 2000.
[18] R.L. Klueh, M. Sokolov, N. Hashimoto, J. Nucl. Mater. 374 (2008) 220.
[19] A.R. Rowcliffe, Oak Ridge National Laboratory, Private Communication, 2007.