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APPLICATION OF THE THORIUM FUEL CYCLE*[1]

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Because of the increasing cost of natural uranium, there appears to be increasing interest in the application of the thorium fuel cycle in various reactors. The use of thorium rather than ^{238}U as the basic fertile material does not decrease the mined uranium requirement associated with meeting initial reactor inventory needs; however, since the ^{233}U bred in the thorium cycle has a relatively high eta in thermal reactors, the fuel burnup requirements over the lifetime of a reactor can be decreased by using the thorium fuel cycle. Both reactor inventory and fuel burnup requirements influence mined fuel requirements as well as economic performance. Also, it is not necessarily true that improved fuel conversion ratio will automatically lead to improved economic performance. However, the impact of improved conversion ratio is one of the factors to be included in the economic evaluation of reactor systems. Since use of thorium requires mining of uranium for initial fissile inventory and makeup needs, there is still a large need for mined uranium even though the thorium cycle is applied. Overall, the basic role that thorium fuel cycles will play in power reactors will be determined by their ability to generate lower cost power than that generated by use of the uranium cycle.

In thermal reactors, the primary advantages of the thorium cycle are associated with relativelty high eta values for ^{233}U, and some physical property advantages associated with thorium - relative to uranium-based fuels. In fast reactors, the primary advantages are associated with more negative reactivity coefficients than those of the uranium cycle, and some physical property advantages if metallic fuels are utilized. However,

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the nuclear performance of the thorium fuel cycle in fast reactors is relatively poor compared to that of the uranium cycle, and so there is little emphasis on the use of that cycle in fast reactors at this time. If metallic fuels were employed, however, the better irradiation performance of thorium metal relative to uranium metal would lead to use of mixed thorium-uranium fuel cycles. However, it is not anticipated that metallic fuels will be utilized in commercial fast reactors for some time.

For the case where excess bred fuel from fast reactors is used to fuel thermal reactors, there appears to be an advantage for utilizing a thorium blanket for producing that excess fissile fuel. However, it is anticipated that fast reactors will first utilize all of their bred fuel for expanding an economic, fast reactor economy as the means of solving the fissile resource problem, and under such circumstances the blanket would be uranium. Only after the fissile resource problem has been resolved favorably may it be economically desirable to utilize thorium as a fertile material in the blanket of a fast breeder and to use the excess fissile material generated in the blanket as a source of fissile material for thermal reactors. Thus, it is not anticipated that thorium will be used in a fast reactor as a means of decreasing overall mined fuel requirements. Thus, no further consideration of thorium use in fast reactors will be given here, and emphasis will be placed on use of thorium in thermal reactors.

Interest in the thorium fuel cycle in thermal reactors stems primarily because that cycle can in the long term provide improved fuel utilization over that of the uranium cycle. At the same time, use of the thorium cycle places importance on developing an economic fuel recycle technology. Further, the presence of fissile material in uranium gives that cycle an inherent advantage; the ability of utilizing low-enriched uranium as the initial fuel rather than the highly-enriched fissile material required in the thorium cycle leads to lower fuel inventory costs, and to a reduced need for recovering fissile fuel from irradiated elements.

Over the next several decades, Light Water Reactors will be applied to a much larger extent than any other reactor type; thus, if fuel utilization is to be improved significantly by use of the thorium cycle, that cycle should be applied in Light Water Reactors. At the same time, most of the emphasis on use of the thorium fuel cycle has been in reactors such as the High-Temperature Gas-Cooled Reactor and the Molten-Salt Reactor. Further, Canada has been performing studies relative to the use of thorium in Heavy Water Reactors for a number of years.

Relative to the above thermal reactor types (namely, LWRs, HWRs, HTGRs, and MSRs) and their use of the thorium fuel cycle, the following summary can be stated. The reactor systems which inherently tend to favor the thorium cycle over the uranium cycle are the HTGR and the MSR. This is due to the basic designs of these reactors, leading to a fuel which is relatively homogeneously dispersed (in a nuclear sense) throughout the core region. The relatively homogeneous dispersion of fuel along with the relatively high energy component of the neutron spectrum leads to higher uranium enrichments in the uranium cycle than is the case for more hetergeneous systems. Thus, the thorium fuel cycle in the HTGR and MSR systems starts out on more even terms with the uranium cycle than is the case for water reactor systems. Further, in the MSR, there is a basic physical property advantage inasmuch as uranium can be readily separated from thorium by the fluoride volatility process in the thorium cycle, whereas plutonium is not so readily separated from uranium in the uranium cycle. As a result, in molten-salt reactor systems the thorium fuel cycle shows both economic and fuel utilization performance advantages over the uranium cycle, with a cycle cost advantage of about 1/2 mill/kWhr (based on a uranium ore price of \$25/lb U_3O_8 and a separative work cost of \$75/kg) and a conversion ratio advantage of about 0.25.

For the HTGR, the relatively high costs of fuel reprocessing and refabrication make it important that a high fuel exposure be obtained. This requirement assists the thorium cycle relative to the uranium cycle because it increases inventory and burnup costs relative to the thorium cycle. Nonetheless, if irradiated fuel elements from HTGRs could indeed be disposed of inexpensively in the form they leave the reactor, use of the uranium cycle in HTGRs could be economically attractive for some time. However, an economic, acceptable long-term disposal method has not been established to date. If separation of plutonium from fission products is necessary, many of the same problems associated with fuel recycle would have to be faced in the uranium cycle. For either cycle, fuel recycle improves fuel utilization, with the thorium cycle obtaining more benefits. Assuming establishment of a large-scale recycle industry, and considering mined uranium and separative work costs of $25/lb U_3O_8 and $75/kg separative work, respectively, use of the thorium fuel cycle is more economic than the uranium cycle by about 0.4 mill/kWhr. Further, the conversion ratio in the thorium cycle is about .05 higher than that in the uranium cycle; total mined U_3O_8 requirements in the uranium cycle are about 10% more than that in the thorium cycle, considering a reasonable power growth condition.

In the heavy water reactor concept, the ability to use natural uranium fuel gives it an inherent fuel cycle advantage which makes it difficult for the thorium fuel cycle per se to compete. Use of the thorium cycle does, however, lead to savings in D_2O inventory which is an important advantage (this advantage is limited by the minimum spacing between pressure tubes which is practical). Overall, the thorium fuel cycle is estimated to have power costs which are about 1/2 mill/kWhr higher than that of the uranium fuel cycle, using previous uranium ore and separative work costs. However, the use of a mixed thorium-uranium fuel cycle appears to show promise, particularly if plutonium from a natural uranium cycle is utilized to inventory the thorium fuel cycle. Mixed cycles involving slightly enriched uranium and thorium are possible, but such use complicates the situation significantly, and does not appear as attractive as use of plutonium-thorium. A key factor is the price of plutonium; if the effective price of plutonium is 70% that of highly enriched uranium (which appears to be reasonable for plutonium recycle in LWRs), use of thorium-plutonium oxides in HWRs can have power costs slightly less than that for the uranium cycle.

Light water reactors can also operate on either the thorium or the uranium fuel cycle. However, those presently being built make use of the uranium cycle because of the economic preference for that cycle. The relative performance of the thorium and uranium fuel cycles in LWRs is very dependent upon the economic factors employed, such as the effective fuel inventory charge rate, the cost of reprocessing, and the cost of refabrication for the two cycles. At the present time, an effective inventory charge rate of about 15% per year appears appropriate (and is used here), and reprocessing and refabrication costs are relatively high. At the same time, the cost of uranium ($25/lb U_3O_8) and separative work ($75/kg SWU) is relatively high compared with previous times. Because of the higher core specific power in the PWR vs the BWR, and because of the higher fissile inventory in the thorium cycle, the PWR should be the LWR of choice for the application of the thorium cycle.

Comparison of the uranium and thorium fuel cycles per se in PWRs using the above ground rules indicates that the uranium cycle has about 1/2 mill/kWhr(e) advantage because of lower fuel inventory costs and lower fuel recycle costs. The advantages of the thorium cycle are associated with a higher conversion ratio (of about 0.1), and a longer reactivity lifetime. A key factor influencing the economic application of the thorium cycle is use of recycle plutonium in thorium (basically a mixed cycle). Based on a price of plutonium which is about 70% of that of highly enriched uranium, use of PuO_2 in ThO_2 in present PWR core designs gives fuel cycle costs slightly less than that of the uranium cycle, assuming establishment of a large fuel recycle industry.

Mention should also be made of the Light Water Breeder Reactor, which is based on application of the thorium fuel cycle to obtain a breeding ratio of about unity. The core design is quite different than for a conventional PWR in order to attain breeding, and the fissile fuel inventory is relatively high. The fuel cycle cost for this type reactor is higher than that for a conventional PWR fuel cycle because of high inventory and fuel recycle costs. Nonetheless, use of the thorium cycle in PWRs can be economic under the circumstances indicated previously.

In summary, all of the thermal reactors discussed here have lower fuel cycle costs when plutonium is used with thorium on the bases given above, in which plutonium is considered to be recycled in thermal reactors. For the latter condition, plutonium acts as a "buffer" fissile fuel, and has to compete with slightly-enriched uranium on a per-unit-value basis. The resulting value of plutonium permits its use with thorium in a mixed cycle. Such use appears economic, and maintains a relatively low inventory of plutonium in the power reactor economy. Because this study was general and not detailed enough to look at many matters which need investigation (such as reactivity control, reactivity coefficients, and power peaking factors), considerable more work still needs to be performed. However, the results do indicate that recycle of plutonium in thorium in thermal reactors, including LWRs, should be studied in detail.

One final point should be noted. Recycle of plutonium with thorium of course implies the need for ^{233}U recycle in subsequent cycles. Since the economics of ^{233}U recycle in one reactor may be different than the economics of ^{233}U recycle in another reactor, there exists the possibility that ^{233}U recycle in a particular reactor type is preferred. For example, ^{233}U can be recycled in either LWRs and HTGRs if both start with plutonium/thorium; the cost of ^{233}U recycle in one of these reactor types may be economically preferable, and limiting recycle to the preferable type could decrease the R&D effort needed for developing ^{233}U recycle technology.

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