RESOURCE IMPLICATIONS OF ALTERNATE FUEL CYCLES IN CONVERTERS AND BREEDERS

by

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DOCTOR TILL: The conference has concentrated to the present time on the seriousness of the problem faced by the industry to the year 2000. I have been asked to bring a somewhat different perspective to this afternoon's discussion, that is, to bring out the possibilities beyond the year 2000.

In the absence of the policy changes of the last two years there would be little to debate in the basic course of the nuclear option. LWR's to be followed by FBRs, when required, with discussion and concern about timing and so on, but very little debate about the basic course of reactor development.

All of this, of course, changed dramatically with the President's April 7th message and the policy that has evolved since then. The breeder was deferred, and attention was focused on what were called alternative cycles. I want first to cover briefly what the alternative cycles are and what they are not, and what they are capable of in terms of resource savings. Then leading into the timing of the breeder, I will cover the possible place for the alternative cycles in deferring the need for the breeder under various conditions. Finally, to examine the strength of the need for the breeder, internationally and domestically, I will compare it against the other possibilities.

The Presidential Nuclear Power Policy Statement, referred to previously, has as its third point, "We will redirect funding of the U.S. research and development programs to accelerate our research into alternative nuclear fuel cycles which do not involve direct access to materials usable in nuclear weapons."

In the months since then the precise definition of such alternative nuclear fuel cycle has not been absolutely clear. Later policy statements defined alternative nuclear fuel cycles as alternative to an economy based on the separation of pure plutonium or enriched uranium,
and in the studies that were set underway by the policy announcement, alternative cycles have basically been defined as being of two types, one type the variants based on $^{233}\text{U}/\text{Thorium}$ cycles, and the second, the variants of the current once-through cycle.

The reason for the small number of alternatives is not hard to understand. If you rule out plutonium recycling, the only two isotopes remaining are $^{235}\text{U}$ and $^{233}\text{U}$. $^{235}\text{U}$ is the basis for the once-through cycle, and $^{233}\text{U}$ is the fissile isotope in the thorium cycle. The basic alternatives therefore are very limited indeed.

The types of reactors implied by these alternative cycles follow directly from the basic nuclear properties of uranium and thorium. Basically, thermal reactors are implied.

Fast reactors, of course, could operate on the $^{233}\text{U}$ thorium cycle, and there was some interest, at least in the early days of the alternative cycle studies, in that cycle for FBR's. I believe there is considerably less interest today, at least for the cycle in its pure form in fast breeders. The point is, of course, that the breeding properties on that cycle are sharply limited, and the incentive to undertake the effort to develop and deploy breeders would, under those circumstances, be correspondingly limited.

Further, the whole system would require reprocessing of a similar kind to that required for the $^{238}\text{Pu}$ cycle, and because of the $^{233}\text{U}$ enrichments required in fast reactors, any gain from the viewpoint point of fissile material inseparability would certainly be small.

Once-through cycles, as you all recognize, are even less suited to the fast breeder. Basically the high enrichments and correspondingly high inventories in a fast reactor require you to discard too much fissile material in the spent fuel.

The next thing that can be said is that, in water-moderated reactors at least, once through cycles pretty much rule out thorium. The once-through cycle implies $^{235}\text{U}$ fissile fueling, and with thorium replacing $^{238}\text{U}$, and the higher neutron absorption of thorium, a fundamental property, requires a higher $^{235}\text{U}$ enrichment to balance it. The result is that in any calculation that I am aware of, the fuel utilizations are invariably worse than for the corresponding $^{235}\text{U}/^{238}\text{U}$ cycle.
So the basic point is that improvements in the fuel utilization from the first alternative, the $^{233}$Th cycle, require reprocessing. With such reprocessing, the gains in fuel utilization can, of course, be substantial, with net $^{235}$U consumptions of the order of half of those of the current once-through cycle probably easily achievable, and on paper at least net consumptions as low as a quarter are achievable. Thermal reactors in which this cycle is used form the class of reactors called Advanced Converter Reactors. The reactors themselves are just variants of the current types. If the moderator is heavy water, the reactors are CANDUs, if it is graphite, HTGRs, and if water it is an LWR or an LWBR. The design aim in any of these reactors, of course, is to decrease the neutron losses to allow additional conversion in the thorium. The LWBR is probably the best example of the lengths designs can go to in order to do that.

The problems with the Advanced Converter Reactors are really twofold as far as the neutronics of these systems are concerned.

First of all, to minimize the neutron losses so as to get conversion ratios up near one, relatively short burnups are required. Correspondingly high fuel discharge rates are implied, and this in turn increases the amount of reprocessing required, the cost, and the amount of fissile material always in process.

Second, measures that push the conversion ratio up inevitably increase the fissile inventory that the reactor requires. Thus in all these cycles, there is a real trade-off between the fuel utilization on one hand the inventory and burnup on the other, and therefore in the amount of reprocessing required annually. The basic point is that in all of them reprocessing is fundamental, and in this they have requirements similar to the fast breeder reactor.

Figure 1 gives a rough gauge of the amount of fuel utilization improvement possible with various of these cycles. In the figure, the shaded bars correspond to the once-through versions of each of the four reactor types.
Fig. 1. SUMMARY OF CONVERTER REACTORS FUEL UTILIZATION CHARACTERISTICS
(70% Capacity Factor, 0.2% Tails Assay)
The fuel utilizations for full recycle in either the HTGR or the CANDU cases show very substantial improvements over the 5600 short tons of \( U_3O_8 \) required for the LWR once-through cycle (all calculations for 70% capacity factor.)

Now, in asking the question of the place of these systems in an overall deployment strategy, the so-called "window concept" is often introduced. This concept suggests that by introduction of the ACR with the better fuel utilization the uranium resources may be effectively stretched so that the breeder is not needed as soon as it otherwise would be. The question is how wide is the window, that is, how long the deferment, and is the length of it worth the effort to try to bring the new system in.

Clearly the answer depends on one's perception of the resource/demand picture. Figures 3 and 4 attempt to show the possibilities for two different resource base assumptions.

The first, a 2.4 million short ton case, the ERDA "prudent planning estimate," of a year or so ago, and the second, the 4.3 million short ton case, is taken as a reasonable upper limit on the domestic \( U_3O_8 \) high grade resources. In Figs. 3 and 4 are plotted a series of calculations of the kind shown in Fig. 2. Figure 2 defines a quantity called the converter phase out year as being the last year that the reactor of the type shown could be built before its 30 year commitment requirement exhausts the resource base. This is shown as the circled point. From then on the reactors on-line would be retired according to their retirement rate. The converter phase out year, so defined, is the year phase-out would have to begin because of resource base exhaustion.

Figures 3 and 4 require considerable digestion. First, let me direct your attention to the X axis. The upper scale gives the converter phase out year, as just defined a moment ago. On the Y axis, I have plotted a quantity called the system average lifetime \( U_3O_8 \) requirement. The need to define that particular quantity arises because of my wish to plot the capabilities of a whole range of reactor types on a single figure. In any system of LWRs followed by ACRs, the whole system over its lifetime will have an average \( U_3O_8 \) requirement per reactor
Fig. 2. EFFECTS OF CONVERTER REACTOR IMPROVEMENTS ON REACTOR PROGRAM TIMING (ASSUMED RESOURCE BASE 2.4 MILLION ST U₃O₈)

RANGE OF ONCE-THRU CYCLES
TAILS RED. TO 0.1%
RANGE OF RECYCLE REACTOR TYPES
TAILS RED. TO 0.1%

SYSTEM AVERAGE LIFETIME U₃O₈ REQUIREMENT
10³ ST U₃O₈

GWe/yr
10
20
30

CONVERTER PHASE OUT YEAR
FULL SCALE FBR DEPLOYMENT
INITIATION FBR DEMO CONSTRUCTION

2000 2010 2020 2030 2040 2050
1995 2005 2015 2025 2035 2045
that is a weighted average of the ACRs and the LWR's brought on-line up to the year that all new acquisitions are ACR's. (In the figures it is assumed that LWR's are installed to 1995, ACR's beyond then.) The calculation assumes a capacity of 380 GWe in the year 2000, and then follow-on growth rates of 10, 20, or 30 GWe/year, as shown.

Now the upper horizontal line gives the case of continuation of the present once-through cycle. For this system, therefore, the system average \( U_3O_8 \) requirement is just the 5,600 short ton requirement of the LWR.

For the lower resource base (Fig. 3) the full range of the once-through cycles is shown on the Y axis as extending from 5,600 down to about 4,600 ST \( U_3O_8 \) system average lifetime requirement. Then translating this to X axis, it can be seen that bringing on improved once-through cycles for that resource base would extend the duration of the nuclear enterprise just a very few years.

Tails reduction of 0.1% is being considered, and the effect of this is also shown on the figure. The effect for any of the growth rates considered is again an extension of a few years only.

Below the once-through cases on the figure are the range of thermal reactor recycle types. The lowest bound is given by the CANDU reactor on full self-generated \( ^{233}U \)/thorium recycle. If, for example, the 10 GWe year growth rate after the year 2000 is assumed, and we note that the LWR case phases out two or three years after the year 2000, and it can be seen that the window provided by that particular ACR is of the order of 30 years (for that combination of growth rate and resource base.) The upper bound of the range of recycle types is given by the LWR on \( ^{233}Th \) recycle, and the window provided by it is of the order of a decade or so.

Figure 4 gives the same set of calculations done for the larger resource base, that is, 4.3 million short tons, and in this case the situation is relaxed very considerably. Given that the capacity in the year 2000 is 380 GWe, for a growth rate of 10 GW/year, the LWR phase out year comes about 2020. For 30 GW/year growth rate the phase out comes around 2010. Again the width in years of the window provided by the ACR can be read from the figure.
Fig. 4. ILLUSTRATION OF CONVERTER REACTOR PHASE-OUT YEAR

ASSUMED RESOURCE BASE = 4.3 MILLION ST

NUCLEAR CAPACITY ON-LINE, GWe

YEAR

1975  2000  2025  2050  2075

20 GWe/yr
Now, I want next to draw your attention again to the X axis where I have tried to indicate the corresponding times for initiation of FBR Demo construction. For the large resource base case you can see that for the highest growth rate (30 GWe/year) and continuation of the LWR once-through cycle, that initiation of breeder Demo construction should have started a year or two ago. For the lowest demand case, (10 GWe/year) Demo initiation can be pushed back to the mid-1980's.

However, for the much more constrained resource base of Fig. 3, even for the low GW/year growth rate after the year 2000, the timing just does not work. The time for initiation of FBR Demo construction basically has passed, and the window provided by the introduction of any advanced converter reactor is not large enough to help very much.

The final thing that I want to illustrate is the effect on the uranium consumption of the choice of basic reactor type. I want to do this for the international estimates of demand and resources, because the breeder question is really an international one. I will use the OECD/NEA estimates\(^1\) as the basis for my comparisons as at the moment they represent the best such information available.

The OECD/NEA estimates of nuclear electric demand to the year 2000 are summarized in Fig. 5.

The lower case gives a projection of the present trend for the year 2025 of 2,000 GWe. This is the case I have used. Those of you who have read the NEA report will recognize the accelerated case as one that was based on a return to a post-oil embargo sense of urgency. I think it is fair to say that this estimate is being heavily discounted at the present time.

Figure 6 provides the estimates of uranium resources. The NEA resources are classified in two categories, reasonably assured and estimated additional. A sizable fraction of these resources are in the U.S. The reasonably assured plus estimated additional resources are roughly equivalent to what the U.S. usually refers to as reserves and probable potential resources. Two additional categories are used by the U.S. agencies charged with making such estimates, called possible and speculative, and they would increase the total U.S. resource base to about 3.2 million tons — approximately double what is shown for the U.S. in the NEA numbers.
### Fig. 5 WORLD URANIUM RESOURCE POSITION (Thousand Tonnes U)\(^a\)

<table>
<thead>
<tr>
<th></th>
<th>Reasonably Assured Resources</th>
<th>Estimated Additional Resources</th>
<th>Total</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>&lt;$ 80/kg U(^b)</td>
<td>$ 80-130/kg U</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(&lt;$ 30/lb U(_3)O(_8))</td>
<td>($ 30-50/lb U(_3)O(_8))</td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>289</td>
<td>7</td>
<td>345</td>
</tr>
<tr>
<td>Canada</td>
<td>167</td>
<td>15</td>
<td>838</td>
</tr>
<tr>
<td>South Africa</td>
<td>306</td>
<td>42</td>
<td>420</td>
</tr>
<tr>
<td>United States</td>
<td>523</td>
<td>120</td>
<td>1696</td>
</tr>
<tr>
<td>Other African countries</td>
<td>218</td>
<td>6</td>
<td>352</td>
</tr>
<tr>
<td>Western Europe</td>
<td>57</td>
<td>325</td>
<td>460</td>
</tr>
<tr>
<td>Countries not included above</td>
<td>87</td>
<td>29</td>
<td>176</td>
</tr>
<tr>
<td><strong>Total (rounded) 10^3 tonnes U</strong></td>
<td><strong>1650</strong></td>
<td><strong>540</strong></td>
<td><strong>4290</strong></td>
</tr>
<tr>
<td></td>
<td><strong>10^3 ST U(_3)O(_8)</strong></td>
<td></td>
<td><strong>5580</strong></td>
</tr>
</tbody>
</table>

\(^a\)Reproduced from Ref. 1

\(^b\)Defined as "reserves"
Fig. 6. International-aggregate Nuclear Energy Demand Projections (Data Source: OECD Nuclear Energy Agency, Ref. 1).
In effect applying a similar ratio to non-U.S. resources, I will also indicate the effects of doubling the international resource base. Figure 7 shows, in terms of cumulative uranium consumption, the effect of the choice of reactor type in meeting the postulated present trend demand. Four simplified reactor deployment scenarios are shown. The top one is the LWR once-through cycle only. The second is the LWR, utilizing full uranium and plutonium recycle. The third, LWR once-through followed by an advanced converter reactor, takes for the ACR the CANDU on the thorium/233U cycle. The final case assumes the LWR on uranium recycle followed by fast breeder reactors introduced full-scale in the year 2000. The range shown is an indication of the choice of fuel for the breeder, whether oxide or advanced fuel.

The introduction date for both the advanced converter reactors and the FBR was assumed to be the year 2000. The introduction rates are very high indeed, unrealistically so I am sure. They were aimed at giving the upper limit on what is possible for each deployment scenario. The introduction constraint was 150 GW total to be installed internationally over the first five years. At the very least these rates imply that well before the year 2000 there must have been much successful reactor deployment of the new type assumed.

The figure displays the cumulative uranium consumption against the background of the resource estimates. It is apparent that the continuous resource usage of converters, greater or lesser, depending on the type, exhausts the reasonably assured plus estimated additional resources very soon after the year 2010 for any of the converter scenarios. Further, if 30 year forward requirements were required before commitment to construction, this point would be reached by the year 2000.

An additional point that should be noted is that these dates correspond very closely to the low U.S. domestic case shown in Fig. 3, as might be expected from the fact that the ratios of demand to resource bases for the two cases are quite similar. Just as in Fig. 3 for the domestic case, if these resources were all that were to be available, phase out of nuclear power internationally should therefore begin about the year 2000. As in the domestic case advanced converter reactor introduction in significant numbers only on that time scale does not help.
Fig. 7. Cumulative Uranium Consumption as a Function of Time for Various Deployment Options.
The date, probably the minimum realistic, of the year 2000 for any sizable advanced converter reactor introduction means that the LWR's constructed to that date have already consumed the majority of the reference resources. Even allowing for further resources so that the LWR does not have that effect, it is still worth noting that the ACR cumulative uranium consumption follows the LWR once-through curve for quite awhile before it finally starts to drop below it. (The reason is its higher initial inventory requirements.) It is only after the consumption of resources about double the reference value that the ACR shows any improvement over the LWR on recycle.

On the other hand, for all the breeder cases, the uranium consumption for this demand schedule begins to show significantly around 2025, and for the advanced breeder cycles, no additional uranium is consumed after 2030. For the lower gain oxide breeder, uranium consumption does continue, but levels off when the breeder doubling capability catches up with the energy growth.

Summarizing this: For the small resource base, incentives for advanced converter reactor introduction do not exist because the resource base is consumed mostly in the LWR once-through cycle before the advanced converter reactors could be deployed. For the large resource base, LWR recycle is as resource effective as the ACR for quite awhile. For the fast breeder reactor the energy supply potential is high for either resource base: For the smaller resource base case, advanced breeders using advanced fuels would actually meet the assumed demand, essentially forever, and in the large (doubled) resource situation, essentially any breeder would.

Figures 8 and 9 show these same considerations from a different viewpoint. They compare the ultimate energy generation potential for the same two international resource bases -- the 5.6 million ST U_3O_8 reference case, and the 11.2 million ST U_3O_8 doubled case. The integrated areas under each curve gives the total energy generation potential of each of the different reactor type.
Fig 8. Energy Supply and Growth Potential of Various Deployment Options for a Fixed Resource Base of 5.6 Million ST U₃O₈.
Fig. 9. Energy Supply and Growth Potential of Various Deployment Options for a Fixed Resource Base of 11.2 Million St U$_3$O$_8$. 
In the 11.2 millions short ton case it can be seen that an incentive for bringing on the ACR on recycle does exist. With this amount of resource available, ACR introduction approximately doubles the possible energy generation from the nuclear enterprise.

In summary, international need for the breeder is apparent. In the domestic case, the amount of relief given by the advanced converter reactor depends very much on the resource base assumption. It varies from a window of no width at all for the low resource base, whether for high or low demand; in the higher resource/low demand case, it can be as much as several decades.

REFERENCES