RESULTS OF HEAVY WATER REACTOR
CALCULATIONS MADE WITH SWEDISH CODES,
BOP AND BIOP

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RESULTS OF HEAVY WATER REACTOR CALCULATIONS
MADE WITH SWEDISH CODES, BOP AND BIOP

INTRODUCTION

The Heavy Water Reactor Program Office (HWRPO) has several reasons for desiring comprehensive calculations of the performance of the pressure vessel heavy water reactor (HWR) concept. Foremost of these is the desire to compare the capital, fuel cycle, and operating costs of this reactor with those of the pressure tube designs more common in the United States, Canada, and the United Kingdom. The second is the desire to evaluate potential design or fuel cycle improvements that might result from the appropriate research and development effort. Third, it is important to make an assessment of the sensitivity of this concept to changes in economic conditions.

A B Atomenergi has developed two comprehensive computer programs, BOP and BIOP, to optimize the design respectively of direct cycle and indirect cycle pressure vessel HWR's. In order to evaluate the effectiveness of these codes it was decided to make a large number of calculations investigating some of the economic parameters of interest in the U.S. By inspection of the results of these calculations and by comparison with known data, it would be possible to evaluate their usefulness. With these goals in mind, three weeks during November and December 1967 were spent in the Stockholm offices of the A B Atomenergi. With the aid of Atomenergi personnel a number of cases were run on their IBM 7044 computer. The results of these calculations and conclusions as to the methods used in the code are presented in this report.

SUMMARY AND CONCLUSIONS

A 1000 MW_e, indirect cycle, pressure vessel HWR was calculated, by the Swedish BIOP code, to generate power at 3.38 mills/kW-hr. The sensitivity of this concept to capital

costs was demonstrated when the power costs rose to 4.6 mills/kW-hr with an increase in the interest rate from the original 7% to 12%. The reference pressure vessel design has a lower total capital investment than a comparable pressure tube HWR. A decrease in the plant capacity had a marked effect on power costs; a sharp increase in power costs was noted below 500 MW.

Increases in the price of heavy water caused an increase in power costs; the code optimized the design to minimize these effects. The reference reactor showed a flat response in power costs around the optimum enrichment of 1.14%. As the enrichment approached that of natural uranium, the costs rose rather sharply to 3.55 mills/kW-hr. Uranium feed price increases caused power costs to increase at a rate about half that of a comparable light water reactor (LWR). This confirmed the conclusion that the power costs of this concept were more sensitive to capital than fuel cycle costs.

Variations in reactor pressure had surprisingly small effects on power costs. Increased reactor expenses were largely balanced by decreased turbine costs as the pressure was raised above the calculated optimum value of 1020 psi.

The cost of making the void reactivity coefficient a more negative value was found to be negligible for the particular cases studied.

Comparison of the indirect cycle costs with the direct cycle version of the pressure vessel reactor showed the latter to yield slightly higher cost power (3.42 as compared to 3.38 mills/kW-hr). Since the direct cycle design showed lower capital costs, it was concluded that it would probably show more favorable power costs than the indirect cycle if higher interest rates were assumed.

It was further concluded that with lower interest rates the pressure vessel HWR concept would be competitive with the

light water reactors. The concept would suffer from higher interest rates but would benefit, on a relative basis, from an increase in uranium prices.

DESCRIPTION OF PROGRAMS

A B Atomenergi started writing this optimization program in 1963, and have been improving and adding to the routine since then. In checking the results of this code against some of their more elaborate codes they have found good agreement.

There are several versions of the optimization program. The version that uses a direct cycle concept is called BOP. It optimizes on 14 independent variables (15, if the option of substituting plutonium for uranium enrichment is considered). The version for the indirect cycle is called BIOP, and utilizes 17 independent variables. These variables are listed in Table I. Natural or forced circulation through the core may be used with either program. Likewise, the programs can calculate optimum uranium enrichment. Therefore, either a natural or enriched uranium fuel cycle may be used.

Any one or all of the independent variables may be fixed. Alternately, the programs can optimize for all of the independent variables.

There are also restraints that can be put on the calculations. These include such items as burnout heat flux, center-line melting, void reactivity, steam velocity in the dome, water velocity in the downcomer zone, and other restrictions that may be desired. For example, the program can be instructed to consider only those designs in which the maximum heat flux does not exceed 50% of the burnout flux (calculated in a subroutine). Any design that does not satisfy this restraint will not be accepted.

TABLE I. *Independent Variables of BIOP and BOP Codes*

	<u>Indirect Steam Cycle (BIOP)</u>	<u>Direct Steam Cycle (BOP)</u>
1. Volume of reactor including reflector and riser	x	x
2. Ratio of core height to diameter	x	x
3. Ratio radial reflector thickness to core radius	x	x
4. Ratio axial reflector thickness to core height	x	x
5. Number of fuel channels	x	x
6. Reactor pressure	x	x
7. Temperature feed water, reactor inlet	x	x
8. Inlet throttling coefficient	x	x
9. Atom fraction ^{235}U in U	x	x
10. Macroscopic radial form factor	x	x
11. Fuel rod diameter	x	x
12. Ratio coolant area to fuel area	x	x
13. Specific mass flow	x	x
14. Difference between the saturation temperature of primary and secondary cycles	x	
15. Moderator mass flow rate	x	
16. H_2O temperature at the economizer inlet	x	
17. Number of rods of a fuel element	x	x

The programs have been described in considerable detail elsewhere, so only a brief description will be given here.^(1,2) The chained codes consist of a large number of subroutines, which calculate such diverse design characteristics as core geometry, thermal hydraulics,^(3,4) neutron flux spectra, and burnup. Reactor and turbine plants are designed and costed.⁽⁵⁾ The output from these routines is individually tested against the imposed boundary conditions. If any solution violates one of the specified boundary restrictions, this point calculation is rejected by the program. A predetermined number of point calculations are made in the first phase of the calculations. The number of these valid point solutions is usually set at twice the number of independent variables that are being used for the particular optimization routine (15 independent variables result in 30 valid point calculations). After the required number of valid point calculations have been accumulated, the main program automatically switches over to an optimization routine. A simplexing operation on the point calculations derives an optimized solution. The variance of the last group of points calculated by the program is used as a test of convergence of the system. Once this variance criterion (usually 10^{-5}) is met, the program shuts down. It may also be set to terminate after making a predetermined number of calculations. If greater accuracy is desired, the last output cards from the program may be resubmitted for further optimization.

RESULTS

A 1000 MW_e (net) plant with the basic assumptions shown in Table II was used as a reference.

Since the reference reactor concept was indirect cycle, the BIOP code was used for this set of calculations.

TABLE II. *Assumptions for Reference Case*

Amortization period, Capital	30 years
Amortization period, D ₂ O	40 years
Construction period	4 years
Interest rate during construction	7%
Interest rate for amortization	7%
Natural Uranium price	\$8.00/lb U ₃ O ₈
D ₂ O price at reactor	\$20.00/lb
Load factor	80%
Pressure vessel	Concrete
Cooling water temperature	18 °C
Coolant cycle	Indirect, forced convection

REFERENCE REACTOR

The results of the calculations for the reference case are presented in Table III. The code utilizes Swedish units (the MKS system and Swedish crowns). The units, wherever they are unfamiliar, are converted in this report to English ones; the crowns are converted at the present rate of 5.16 Swedish crowns per dollar.*

VARIATIONS OF INTEREST RATE

As can be seen from the table, the specific investment in the reference heavy water reactor is about \$150/kW installed. This is exclusive of the specific heavy water cost, which is approximately \$24/kW. As will be discussed in a later paragraph, it is often misleading to compare one reactor calculation with another unless the basic assumptions have been normalized.

* Copies of the computer output for the 24 cases calculated are available from the author upon request.

TABLE III. *Summary of Reference Case Calculations*Capital Costs, \$M^(a)

Building and structures	13.809
Reactor and auxiliaries	39.536
Turbine and auxiliaries	47.094
Instrumentation and control	2.225
Common processes	<u>5.242</u>
Subtotal	107.907
Contingency	11.953
Interest during construction	18.408
Design and administration	<u>11.623</u>
Total	149.891

Specific capital cost, \$/kW	149.9
Heavy water cost, \$M	24.236
Specific heavy water cost, \$/kW	24.2

Unit Energy Cost, mills/kW-hr

Manufacture	0.260
Uranium	0.408
Interest, uranium and manufacture	0.099
Reprocessing	0.213
Credit uranium	0.000
Credit plutonium	<u>0.239</u>
Fuel costs, Total	0.743
Capital costs	1.724
Heavy water costs (including losses)	0.293
Operation, maintenance, and insurance	<u>0.623</u>
Total	3.383

(a) \$M = millions of dollars

FIGURE 1. Power Costs as a Function of Interest Rate

The combined reactor and D_2O investments make this concept more capital cost oriented than a corresponding LWR which would cost 140 to \$150/kW under similar assumptions. The sensitivity of HWR power costs to financing costs is illustrated in Figure 1. When the interest rate is varied from 4 to 12%, the total power cost varies from about 2.6 mills/kW-hr to over 4.6 mills/kW-hr. By inspection of the various components of Figure 1 it can be seen that most of this rise in power cost comes from the capital costs contribution. While fuel cycle costs and D_2O costs both rise slightly, these are relatively unimportant compared to the very large rise in the capital component. In Figure 1 and all subsequent figures, only the three major components of power are plotted along with the total. The operation, maintenance, and insurance components are not plotted. These are almost constant for all cases studied, and total a little more than 0.6 mill/kW-hr.

PLANT CAPACITY

When power costs are studied as a function of plant capacity, the dependence of this design on capital cost is again illustrated. Figure 2 shows the rapid rise in total power costs as plant capacity goes below 500 MW. Most of this rise is accounted for by the rather sharp increase in the capital component. As can be seen in the figure, the capital cost curve is almost identical in shape to that of total cost. While the fuel cycle component and the D_2O component increase slightly as plant capacity is decreased, they are both quite flat. The trend in these two components illustrates the increased neutron leakage that is to be expected in the smaller plants. This leakage is compensated for, however, by increasing the reflector thickness, which results in an increased D_2O expense.

The method by which the code calculates an optimum reactor, whose fuel cycle cost stays almost constant with size,

FIGURE 2. Power Costs as a Function of Plant Capacity

can be seen from Table IV. In this table is listed the heavy water inventory as a function of size. When the investment is expressed in terms of costs per unit of capacity (as it is here), it becomes evident that the optimization routine calls for considerably more D_2O in the smaller reactors. For example, the specific inventory in the 400 MW design is almost 20% higher than that for the 1000 MW case.

TABLE IV. Specific Heavy Water Investment as a Function of Plant Capacity

<u>Capacity, MWe</u>	<u>Specific Heavy Water Investment, \$/kW</u>
400	29.17
600	26.94
800	25.68
1000	24.44

A common mistake made in analyzing reactor calculations is the comparison of results with those of another reactor concept made with other codes and, as often as not, with grossly different assumptions. While fuel cycle costs involve a multitude of basic assumptions that are difficult to normalize unless the calculations are done in the same manner, capital investments can be compared for two different reactors if reasonable care is exercised in normalizing such factors as site costs, interest during construction, architect-engineering fees, and other overhead factors.

The costs of the Canadian General Electric vertical pressure tube HWR have been described by Holt.⁽⁶⁾ Recent design changes have modified these costs to some extent.⁽⁷⁾ The direct costs were changed to reflect these newest designs;

indirect costs were derived by using the same multiplier as derived for the corresponding size pressure vessel in the BIOP calculations. While there still exists the inherent discrepancies between the Canadian and Swedish estimates of labor, material, equipment, etc. the major differences assumed for contingencies, interest during construction, nuclear engineering, and other indirect costs have been eliminated

Likewise the estimates of heavy water and fuel inventories may be compared by using the same prices of uranium and D_2O for each design. The data presented in Holt's paper⁽⁶⁾ have been corrected for a 12% increase in D_2O inventory arising from a change to the 4 in. Pickering fuel element from the 3 1/4 in. CANDU size. The \$5/lb U_3O_8 prices used by Holt have been adjusted to the \$8/lb value used in the Swedish calculations, and 1973 fuel fabrication costs have been assumed. These comparisons are shown in Table V.

While the natural uranium fuel used in the pressure tube design results in a fuel inventory lower by 9 to \$10 million, the plant cost for this concept is about \$30 million higher than that of the pressure vessel design. The heavy water inventories are comparable in each case with the pressure tube inventory slightly higher. This difference probably arises from the difference in enrichment between the two designs.

Heavy Water Costs

Power costs are only moderately sensitive to D_2O price, which can be seen in Figure 3. The power cost rises about 0.2 mill/kW-hr as the D_2O price is increased from 14 to \$24/lb. As can be seen from the curve, almost all of this increase comes from the D_2O component. The code minimizes the impact of increasing D_2O prices by increasing the height to diameter ratio and decreasing the thickness of the radial reflector.

TABLE V. *Comparison of Investment Required for Pressure Vessel and Pressure Tube HWR Designs*

<u>Unit Size, MW</u>	<u>400</u>	<u>600</u>	<u>800</u>	<u>1000</u>
<u>Capital Cost, \$/kW</u>				
Pressure Vessel Design	202.2	170.4	159.9	149.9
Pressure Tube Design	241.1	208.9	190.8	180.2
<u>Heavy Water Inventory, \$/kW</u>				
Pressure Vessel Design	29.2	26.9	25.7	24.4
Pressure Tube Design	29.4	28.0	26.8	25.9
<u>Fuel, \$/kW</u>				
Pressure Vessel Design	19.0	18.2	20.4	18.8
Pressure Tube Design	9.7	9.5	9.5	9.4
<u>Total Investment, \$/kW</u>				
Pressure Vessel Design	250.4	215.5	206.0	193.1
Pressure Tube Design	280.2	246.4	227.1	215.5

The program tends to maintain the capital costs at a minimum value. This can be seen from Figure 3 where the capital costs are almost a straight line.

Effect of Enrichment Variations

The heavy water reactor has the particularly effective degree of freedom of a variable moderator-to-fuel ratio and reflector thickness. These adjustments make the reactor design adaptable to large changes in the cost of uranium and D₂O. The ability of this concept to adjust itself can be easily seen in Figure 4, where power costs are plotted as a function of fuel enrichment. Whereas light water reactor costs are usually very sensitive to enrichment level, the heavy water reactor is able to adjust its design to accept a

FIGURE 3. Power Costs as a Function of D₂O Price

FIGURE 4. Power Costs as a Function of Enrichment

rather large range of enrichment with only minor effects on the cost of generated power. While the program calculates an optimum enrichment of 1.14% for the particular reactor design being considered (indirect cycle, forced convection cooling), power costs show a flat response on either side of this optimum enrichment value.

As can be seen in Figure 4, the fuel cycle costs show a flat minimum value around the optimum enrichment. On the other hand, the D₂O costs show a continued decrease with increasing enrichment, and the capital costs show a very slight decrease as the design departs from optimum enrichment. These trends are reflected in the decrease of reactor volume with increasing level of enrichment (Table VI).

TABLE VI. Reactor Volume for Various Enrichments

<u>Enrichment, % ²³⁵U</u>	<u>Reactor Volume, m³</u>
0.711	690.36
0.800	640.53
1.140	494.97
1.250	494.88
1.40	457.50

As is to be expected, the use of natural or very low enrichment requires a much larger reactor volume. Near the optimum enrichment, the reactor design changes very little. The primary effect of the increased enrichment is an increase in fuel burnup. Optimum fuel burnup as a function of enrichment is shown in Table VII.

It is interesting to note from Figure 4 that the power costs do go up noticeably as the enrichment approaches natural uranium (0.711% ²³⁵U). The minimum power cost of 3.38 mills/kW-hr, calculated for an enrichment of 1.14%, has increased to

TABLE VII. *Optimum Fuel Burnup for Various Enrichments*

<u>Enrichment, % ^{235}U</u>	<u>Optimum Burnup, MWd/MT</u>
0.711	10,315
0.800	13,069
1.140	18,610
1.250	20,911
1.400	23,262

3.47 mills/kW-hr when the enrichment is decreased to 0.8%. A sharp increase is noted as the enrichment is further decreased to natural uranium. At this point power costs have risen to 3.55 mills/kW-hr. This means that the use of natural uranium fuel in a 1000 MW plant of this type (operating at 80% plant factor) would result in power generation costs about \$1,200,000/yr higher than those of a design utilizing the optimum enrichment of 1.14%.

URANIUM FEED COSTS

The insensitivity of this concept to fuel cycle costs is further illustrated when power costs are calculated as a function of uranium feed costs. The results of these calculations are shown in Figure 5. As can be seen from this figure, fuel cycle costs and total power costs rise somewhat as uranium feed costs are raised from 6 to \$12/lb U_3O_8 . Power generation costs rise from 3.30 mills/kW-hr to 3.53 mills/kW-hr as the feed costs are increased over this range.

If the reactor design is optimized for each uranium feed price, the power generation costs vary from 3.28 to 3.51 mills/kW-hr over the same 6 to \$12/lb U_3O_8 range of feed costs. The design code tends to reoptimize the design slightly as the feed costs change. This is done primarily by investing in slightly more heavy water as the price of feed increases. This trend

FIGURE 5. Power Costs as a Function of Uranium Cost

may be seen in Figure 5 (a plot of the cases in which the program was allowed to reoptimize design for changing feed costs). The heavy water component of cost can be seen to increase slightly from 0.30 to 0.31 mill/kW-hr as the feed costs increase from 6 to \$12/lb. The calculated increase of about 0.23 mill/kW-hr that results from the doubling of uranium feed prices should be contrasted with the 0.39 mill/kW-hr that has been calculated for an increase in light water reactor costs with the same increase in feed costs.⁽⁸⁾ This indicates that the power costs of light water reactors are about twice as sensitive to increasing uranium feed costs as are those of the heavy water reactors.

REACTOR PRESSURE

The optimum design pressure for this reactor concept was calculated to be 1020 psi. The effects on power generation costs of going below and above this optimum design pressure were calculated in the next series. These results are shown in Figure 6. Interestingly enough, total generation costs vary only slightly with reactor operating pressure. While fuel cycle costs decrease slightly, capital costs tend to increase, making the total power generation costs almost flat when plotted against pressure. This result may be somewhat surprising to those familiar with the costs of steel pressure vessels of this size, where the vessel costs go up very rapidly with pressure. This is also an interesting contrast to the HWR pressure tube concept in which the optimum design is very sensitive to pressure. In the prestressed concrete design assumed in these calculations, the pressure vessel costs do not go up very rapidly as the pressure is increased above optimum. These costs are very nearly balanced by a decrease in turbine costs. Table VIII lists the reactor and turbine costs as a function of pressure.

FIGURE 6. Power Costs as a Function of Reactor Pressure

TABLE VIII. *Reactor and Turbine Costs for Various Reactor Pressures*

<u>Reactor Steam Pressure, psi</u>	<u>Reactor and Auxiliaries, \$M</u>	<u>Turbine and Auxiliaries, \$M</u>	<u>Total Plant Cost, \$M</u>
727	40.170	48.514	152.198
1020	39.536	47.094	149.890
1520	40.976	46.403	150.920

As can be seen from this table, the reactor and auxiliaries increase some \$1.4 million as the design pressure is increased from the optimum of 1020 to 1520 psi. This increase is balanced somewhat by a \$0.6 million decrease in the turbine and auxiliaries cost.

As may be expected, fuel cycle cost decreases slightly with increasing pressures. This may be noted in Figure 6, where the fuel cycle component decreases from 0.74 to 0.70 mill/kW-hr as the pressure increases from 727 to 1520 psi. The increase in net thermal efficiency with increasing pressure is shown in Table IX.

TABLE IX. *Net Thermal Efficiency for Various Reactor Pressures*

<u>Reactor Steam Pressure, psi</u>	<u>Net Thermal Efficiency</u>
727	32.3
1020	33.6
1520	35.2

As can be seen the calculated net thermal efficiency increases from 32.3 to 35.2% as the reactor steam pressure is increased from 727 to 1520 psi. The latter value seems high compared to

U.S. practice; it is due primarily to an extrapolation of Swedish turbine development. The questions of turbine design and concrete pressure vessel costs are ones that should be carefully reviewed before any definitive comparisons are made between Swedish, Canadian, and U.S. technologies.

PLANT FACTOR

When the assumed plant factor was increased from 80 to 85%, the total generation cost decreased from 3.40 to 3.24 mills/kW-hr. As is to be expected, most of the decrease is realized from the capital cost component, which was reduced by 0.10 mill/kW-hr. Fuel cycle costs decreased slightly (0.04 mill/kW-hr), which is a reflection of the fixed component of fuel cycle charges (inventory charges) that is reduced as the plant factor is increased.

VOID REACTIVITY COEFFICIENT

Heavy water reactors fueled with natural uranium tend to have a positive void coefficient of reactivity. For example, the case calculated for natural uranium was found to have a positive 18.07 pcm/% void (10^{-5} $\Delta k/k$ per one percent void) coolant reactivity coefficient. Inasmuch as there is some question as to the acceptability of a reactor concept with a positive coefficient of coolant reactivity, it was decided to investigate the cost of making this coefficient negative. While the reference calculation showed a coefficient which was almost zero (0.70 pcm/% void), two other cases were run which had -5.34 and -10.30 pcm/% void coefficients. This particular design, which uses enriched uranium, is not cost-sensitive to the forced increase in negative void reactivity coefficient. The code achieved this decrease in void coefficient by increasing the coolant channel diameter from 162.61 to 173.83 mm for the -10.30 reactivity coefficient design. The attendant effect on power generation cost was negligible.

DIRECT CYCLE CONCEPT

In the last series of calculations, two other design concepts--the direct cycle, forced and natural convection cooling--were compared with the reference concept. These results are summarized in Table X.

TABLE X. *Power Generation Costs for Three HWR Design Concepts*

<u>Design</u>	<u>Capital</u>	<u>Fuel Cycle</u>	<u>D₂O</u>	<u>Total</u>
1000 MW _e , indirect forced convection	1.72	0.74	0.29	3.38
1000 MW _e , direct forced convection	1.66	0.82	0.32	3.43
1000 MW _e , direct natural convection	1.66	0.81	0.33	3.42

As can be seen, there is little change in power generation costs when the direct cycle is used under these assumptions. While there is improvement in the capital cost component, the fuel cycle and D₂O costs go up. As has been discussed earlier (see Figure 1), the power costs of HWR's of this design are sensitive to interest rates. It is probable that the use of a higher rate than the 7% of this series would make the direct cycle concept look more favorable than the indirect, for it has significantly lower capital costs. Most of these capital cost savings come from the reactor costs. These savings in the direct cycle nuclear steam generator are partially offset by the increase in D₂O inventory, which goes from 527 to 589 tonnes in the direct cycle design.

The power generation costs calculated in this section all use a 7% interest rate. It is to be expected that power costs will go up sharply with interest rates. Whereas the costs

range from 3.38 to 3.43 mills/kW-hr with 7% interest rate, they might be expected to be around 4.5 mills/kW-hr with 12% interest rates. Light water reactors of this size have been calculated to have power costs of about 3.5 mills/kW-hr at 7% interest.⁽⁸⁾ With the assumptions used for these calculations, it would appear, then, that the heavy water reactor concept, using a pressure vessel design, could be competitive with light water reactors. They would lose much of their competitive edge as interest rates rise. An increase in uranium costs would, however, favor the heavy water design; to a lesser extent the lowering of D₂O costs would also make the heavy water design more competitive.

RECOMMENDATIONS

It is recommended that efforts be made to obtain the BOP and BIOP codes for use by the HWRPO. From the parametric studies that have been run it would seem to be a most useful tool for studying the heavy water pressure vessel design. If this concept is to be compared with other heavy water reactor designs, or with light water reactors, it is essential that such a code be available. While it is possible to approximate the economics of any plant design using one of several survey codes, this is a poor substitute for a program such as this in which the plant is optimized for any given conditions. This approach allows a realistic analysis of costs under any set of economic assumptions. Since this code is the only one of its kind, it is impossible to compare it to any other one. From the results and the available literature describing the sub-routines, it appears to be a well designed, accurate program. If this code is obtained there are several minor changes that should be made. The first of these is the conversion of the code for use on our machines. Since it is written in FORTRAN for the IBM system, this should be a simple matter. A sub-routine should be written to convert English to Swedish units

for input and another subroutine to convert the output back to English. This is a relatively foolproof method for changing units at a minimum cost.

The various subroutines that calculate costs should be modified, where necessary, to make sure that U.S. labor and materials costs, where different, are substituted for Swedish values. Likewise, the economics subroutine should be reviewed to ensure that it uses the same calculational techniques as used in our present codes. The above comments apply equally well to any foreign-written codes that are being considered for use in the U.S. If calculations of different reactor concepts are not made under the same ground rules, the comparison of the results is of dubious value. More specific recommendations for the use of BIOP follow.

Several subroutines should be examined in detail when they are available. The physics code, which uses the Westcott notation, should be evaluated by comparing results with a more sophisticated code.⁽⁹⁾ The effect of neutron temperature on cross sections and burnup may cause serious errors with the approach used if enrichment increases and particularly if plutonium is substituted for uranium as the major fissile element. The assumption that the neutron temperature is equal to that of the moderator is not valid and should be modified.

The fuel fabrication cost equations could be revised on a different basic assumption: a plant with a given fuel weight capacity rather than rod capacity. This will mean that the overhead charges will not change as rapidly with rod diameter as is presently the case.

Likewise the plant capital costs should be modified by normalizing to U.S. equipment and labor prices. While the expressions are undoubtedly accurate for Swedish conditions, there is an excellent possibility that they would give a distorted cost picture of a plant built on an American site.

The boiling burnout calculations are done by a subroutine based on a rod bundle correlation developed by Becker.⁽¹⁰⁾ A relatively simple correlation such as this is entirely acceptable for a survey calculation such as is done in the optimization codes. It would be advisable, though, to check the results of this subroutine against a more sophisticated one that considers such effects as differences between channel configurations, cross channel mixing, cold wall effects, and upstream thermal history of the coolant.⁽¹¹⁾ If there were any significant difference in the results, the Becker correlation could be adjusted to make it more realistic.

Lastly, the calculations of thermal efficiency should be examined in greater detail. The calculated values are based on an extrapolation of turbine technology; the validity of this extrapolation should be reviewed.

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