NOTES ON FISSION ENERGY

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PREFACE

Dr. Karl Cohen, Palo Alto, worked at IIASA on the Energy Systems Program from April 8, 1978 to June 10, 1978. During that period, he was associated with the nuclear energy activity of the Program, and did some drafting of the nuclear chapter for the IIASA book "Energy in a Finite World". Parts of his drafts have persisted through the many revisions and reorganizations of that chapter, and are attributed to him. This working paper records the material that he drafted, and from which his contributions are cited.

The only editorial changes that have been made have been deletions of references that are not easily checked at IIASA, of cross references to the other parts of the book as it was conceived during Cohen's time at IIASA, and of material introducing topics which were not yet ready for presentation. The editor (B.I. Spinrad) hopes that, with this editing, the paper published here can be read in the spirit of observations by a senior nuclear scientist (Cohen) on a set of related nuclear topics.

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I. GENERAL REMARKS ON FISSION ENERGY

Nuclear fission power is unique among man's potential future sources of energy in the following combination of qualities:

a) It is deployed on a substantial scale and an industry and technical manpower exist ready to expand its use;
b) The environmental impact of large-scale deployment is less than that of other already deployed energy sources;
c) It offers a potential inexhaustible supply of energy by well-understood technology;
d) Its fuel is highly concentrated and thus transportation is not a hindrance to its use any place on the globe, including underwater;
e) Nuclear electric power is generally economical compared to conventional fossil power stations.

It also has unique drawbacks:

a) The generation of fission power is accompanied by the production of radiation six orders of magnitude larger than any other human activity;
b) Fission reactions use as fuel, and have as products, the materials of man's deadliest weapons;
c) Because of these two circumstances fission power is subject to unprecedented governmental regulation, based on considerations of national security, foreign policy, and health and safety;
d) Further, because of a) and b) it arouses considerable public apprehension which can easily be turned into hostility.

The drawbacks make many people reluctant to commit unreservedly to the nuclear option, so long as the urgency of committing to any major energy option is not clear to them, and so long as the hope exists that one could have all the benefits of nuclear power without any of the drawbacks--for instance fusion by the D-D reaction or some technical/economic breakthrough in solar power.

Global energy requirements by the year 2030 may be so high and the institutional, capital and production-organizational requirements to meet this demand so severe, that the time for choices and commitments cannot be postponed much longer. Thus, we must indicate what possibilities exist to meet a substantial part of this future demand with nuclear fission power. We do not here argue the risk/benefit ratio of the nuclear option compared to other options. What we do here is present what we believe are feasible nuclear options, granted a decision to exercise them is made by 1985-1990.

What is feasible depends on the frame of reference. In a war-time mobilization many things are possible which cannot be accomplished by business-as-usual. The purpose of planning, however, is to avoid, as much as possible, the necessity for crash programs to make up for a lack of foresight. We may not be able to attain our goals by business-as-usual, but it should be our ambition to depart from it as little as possible: to make plans which work with and not against normal economic forces and normal economic rhythms.

In determining what is feasible, we assume political and social constraints--such as prohibitions on recovery and reuse of plutonium--to be removed. But we take account of the practical constraints of men, materials, economies, information (technology) and organization. It will turn out that the more ambitious the energy program, the more constrained the nuclear options are. (Obviously, in the other extreme, where little nuclear power is needed, any option is feasible.)

II. NUCLEAR TARGETS AND TRAJECTORIES

Targets

We consider two alternative requirements for nuclear power, taking for definiteness the year 2030 as our target year. Corresponding to a 35 TW high and 24 TW low scenario for world primary energy demand (oil equivalent basis) in 2030, we choose 8 TWe and 4 TWe of nuclear power for that year. Somewhat arbitrarily, we assume further growth past 2030 to be at 100 GWe/yr, and 50 GWe/yr, respectively.

Aside from the use of solar energy for space and hot-water heating, which are real but minor constituents of final energy, the principal secondary energy sources are liquid fuels and electricity. Any global energy option--nuclear fission, nuclear fusion , coal, or solar energy--must be converted into electricity or liquid fuels to meet the bulk of mankind's needs. So far--aside from trivial district heating application--nuclear fission power has been applied only to generate electricity in central power plants. It has been postulated that this is the likely future path for nuclear fission. Others have postulated large application as high temperature process heat suppliers. Experimentation on gas reforming has been underway. We are proposing in this paper a synthesis of these ideas. Some nuclear energy will be marketed as secondary energy in the form of electricity: some as liquid or gaseous fuels. There are a number of ways in which nuclear energy may produce liquid or gaseous fuels in addition to high temperature process heat.

The efficiency of transformation of nuclear energy into fluid fuels varies somewhat between these various applications. To fix our ideas, we select 3 TWeyr/yr of electricity for the grid, and 5 TWeyr/yr for fluid fuel production via electrolysis.

Power systems traditionally have run at 55% of peak capability or 66% of capability excluding reserve. Base-loaded fossil and nuclear plants approximate this latter figure. Part of the difference between 66 and 100% is attributable to lack of system demand, and part to unavailability because of plant outages for maintenance and (for the nuclear plants) refueling. We assume that nuclear plants used to generate electricity for distribution on grids will improve to 75% load factor, and that plants which generate electricity for production of liquid fuels run 10 points higher or 85% load factor. Then if 3 TWe are used for electricity and 5 TWe for liquid fuels, the total installed capability needed would be ~10,000 GWe in 2030.

Similarly, for the 4 TWe scenario, a total of 5000 GWe installed capability is required.

Definition of Present Nuclear Energy Trajectory

The nuclear report to the Conservation Committee of the World Energy Conference [1] presents the following projections:

Table I. Projected world nuclear power installations (GWe)

Regional Grouping	1975	1985	2000	2020
1. OECD	68	247	955	2423
2. Centrally Planned Economies	7	33	402	1610
3. Remainder	1	23	186	1000
Total	76	303	1543	5033

The figures are based on an extrapolation of present programs and plans of nuclear power plant construction. Of interest to us is only the trajectory estimated to 2000 (we do not make use of the estimate shown for 2030). For the period 1975-2000 the figures are less than previous OECD forecasts [2] and represent in large measure a response to conservationist pressure on energy growth in general and on nuclear energy in particular.

The acceleration in nuclear installations shown between 1985 and 2000 in the Centrally Planned Economies, and in the Remainder of the World, seems excessive. It does not correspond with presently published plans [3] which show a target of ~40 GWe in the CMEA countries for 1993; or to any established program in the U.S.S.R., which, because of its enormous fossil reserves, has never adopted as ambitious a construction program as the OECD. We therefore adjust downward the projection for 2000 by ~200 GWe to 1350 GWe. Extrapolating between 1985 and 2000 with a smooth curve we obtain 900 GWe in 1995 and 540 GWe in 1990 to give the following appraisal of the present tranjectory.

Table II. Estimated world nuclear power installations (GWe) (present trajectory)

	1975		1980		1985		1990		1995		2000
Cumulative	76		150		300		540		900		1350
Annual average		15		35		50		70		90	

Possible Accelerated Trajectories

The maximum number of nuclear plants which can be completed in 1985 is nearly impossible to change. Indeed it is likely that all plants which will actually be operating in 1990 are already in some stage of planning. Even assuming (as we do) a resolution of the present social, political and economic uncertainties surrounding nuclear power in the OECD countries by 1985, it would still be some time before the number of nuclear plants installed could be increased above those presently planned.

A study "Resource Needs for Nuclear Power Growth" undertaken in 1972/73 by the Atomic Industrial Forum [4] calculated that an acceleration program begun in 1973 could increase the number of additions (in the U.S.) between 1980 and 1985 from 154 GWe to 220 GWe, thus increasing the average rate of additions approximately 10 years later by about 50%. There are many differences between the case examined by the AIF and the present U.S. situation. The reference case called for a vigorous nuclear growth to 500 GWe in 1990, while the present trajectory is directed towards 200 GWe for the same year. It is generally agreed that the nuclear industry in the OECD nations is operating below its theoretical capacity. It is probably easier to increase capacity additions from the present low rate, than from the high rate assumed in the AIF study. Nevertheless it would be unrealistic to expect one could change the present U.S. trajectory (which is 17±3 GWe/year additions over the period 1990-2000) to more than 40 GWe/yr in the same period, even after removal of all public constraints by 1985.

In the world outside of OECD there are a few evidences of artificial constraint on nuclear power growth. Thus it is unlikely that an acceleration program could double the rate of nuclear additions in the period 1995-2000 for the world as a whole. It is our judgment that an acceleration program decided on in 1985 could increase the growth of nuclear power stations for the period 1995-2000 from the forecast ~90 GWe/year to at most ~150 GWe/year.

Preliminary General Comments on the 10,000 GWe and 5,000 GWe Targets

For the upper target of 10,000 GWe in 2030, counting replacements for the 900 GWe expected to be in operation by 1995, we are faced with building 10,000 GWe in 35 years, or 300 GWe/yr average. This might be achieved by starting at the rate of 150 GWe/yr in 1995, and ending at perhaps 450 GWe/yr in 2030. A priori, an acceleration of construction rates by a factor of 3 over 30 years, given that our present trajectory is scheduled to multiply additions by almost this factor in 15 years, appears to be an achievable objective. The number of plants and power station sites will grow more slowly than the number of GWe, as we deploy large power stations with multiple units (say 4), and increase unit outputs by modest factors (~2).

It is when we come to the mix of reactor types that the difficulties arise. The following quotation from the WEC report [1] is worth noting:

> In 1975 the world's installed capacity was 76 GWe, of which 80% was provided by light water reactors, 12% by gas-graphite reactors, and 4% by heavy water reactors, all of which operate on the once-through uranium cycle, where U-235 is the principal fissioning isotope. The remaining 4% of the capacity was provided by prototypes of the liquid metal-cooled fast breeder reactor (LMFBR) and by high-temperature gas-cooled reactors (HTGR).
>
> Obviously nuclear power will grow in different ways in different countries but most of the growth indicated in Table I will come from technologies which are already known.

The task of building large numbers of power stations is of course the easier the more the later power plants resemble those with which we have already acquired significant operating experience, and have established an infra-structure of developed technology, existing manufacturing and processing facilities, trained manpower, and a licensing and regulatory framework. Thus there is a significantly different problem to building 150 GWe/yr of light water reactors in 1995, given that our present peak capacity is over 40 GWe/yr, and building substantial numbers of reactors which may not be fully developed and deployed commercially before 2000. This applies equally to LMFBRs, HTGRs, and other advanced concepts, and to a lesser extent to major modifications of developed reactors, such as changes in fuel or fuel cycles.

From these considerations it is evident that from the standpoints of committing hardware of known performance and on some predictable cost basis (even if it is only an extrapolation from past experience) the most practical way to build up to 10,000 GWe of nuclear power would be to build LWRs with a once-through fuel cycle. However this runs into another obstacle: it requires an indefinitely increasing supply of enriched uranium fuel.

Enriching the uranium is not a major obstacle. Several technologies already exist which are adequate; capital investments in enriching plants are a minor perturbation on capital investments in the power plants they serve; and there is prospect for continued technical and economic improvement in both established and new enrichment methods.

Opinions differ widely about the ultimate quantity of uranium which can be extracted economically. Many cost-benefit analyses by FBR proponents have assumed a finite uranium resource, occasionally as low as 1.7 million tons of U in the U.S. and ~3.7 million tons in the world [5]. Opponents of the FBR and those opposed to chemical reprocessing on the grounds of the danger of nuclear weapons proliferation are more optimistic about uranium resources. Even within the nuclear industry there is little unanimity. Some maintain the periodic DOE reports on world resources (which show world resources up to nominal cost of $50/lb yellowcake to be quite limited (~5 million tons)), represent the only prudent planning base, while others, using mathematical and statistical models, are confident that undiscovered recoverable resources in the tens and hundreds of million tons exist.

The WEC paper, and more recently the CONAES study [5] stress a different problem: can the rate of uranium extraction be increased to match a demand growing from ~25,000 tonnes U/year in 1975 to over 200,000 tonnes/yr in 2000? Note that at an average ore grade of 0.1% U_3O_8, which is expected to prevail in 1990, 200,000 tonnes/yr U requires extracting 250,000,000 tonnes of ore per year. If one considers more dilute resources such as the Chattanooga shales (50-60 ppm) the mining effort per unit of primary energy produced in light water reactors is about the same as that for coal.

In a situation where many experts differ it is not appropriate to be dogmatic. We therefore must face the implications of both a limited and unlimited resource base.

Definition of Scenarios to be Studied

Reliance on natural uranium mining to the extent required by a scenario of all light water reactors with approximately present resource requirements cannot be excluded as a logical possibility, but it depends on unprovable assumptions about resource availability, is clearly wasteful of natural resources, requires a massive mining effort and for this reason is not readily adaptable to changed requirements. Therefore it is not a prudent planning base for a global nuclear option, even if uranium is available in indefinitely large amounts.

Possible alternative scenarios to remedy the excessive dependence on uranium mining of present LWR operations range from

I. Ultimately replacing LWRs with another reactor type or types which are more economical of uranium;
II. modifying LWRs to reduce their resource consumption significantly (factor of at least two);
III. supplementing LWRs with FBRs which can replenish their fuel supply (LWRs are modified as little as possible).

A combination of these three scenarios is likely to occur, but they will be considered separately to clarify the advantages and disadvantages of each.

Let us examine more closely Scenario I, to illustrate the method of analysis which will be used on all scenarios. Changing to a new reactor type (e.g. HTGR) requires proving out the design of a large plant through the demonstration stage, building up an an industry to supply it, constructing fabrication and reprocessing plants for its fuel, and so forth. It will not be possible to change overnight from an industry which is producing substantial numbers of LWRs to one which is deploying the same number of HTGRs. Thus unless we continue to build LWRs, we shall fall hopelessly behind in our attempt to meet the target amounts of nuclear power. We end up with a mixed reactor economy which can be evaluated in terms of its economics and resource requirements. A key question is how fast can one technology replace another in a given market. This will be investigated at some length from a number of different points of view.

In Scenario I we envisage ultimately replacing LWRs. In Scenarios II and III we do not replace LWRs, but try to remedy their deficiencies. The boundary between the modifications to LWRs envisaged in Scenarios II and III is not clear cut. The LWBR would clearly belong in Scenario II. Using a Pu-U oxide core, with Pu produced by an FBR, is clearly Scenario III. An LWR modified to use U-233/Th fuel could be in either scenario, depending on how easily the modification could be backfitted in existing reactors. The major distinction between Scenario II and Scenario III is the introduction of FBRs in Scenario III.

III. INTRODUCTION OF NEW NUCLEAR TECHNOLOGIES: HISTORICAL INFERENCES

In evaluating scenarios, we will have to make projections of the rates at which conventional LWRs can be built, at which modified LWRs can be built, and at which reactors not based on LWR technology can be built. We shall approach this problem in three ways: by looking at the history of reactor commercialization, by estimating a priori the time required for new developments to be completed and for a supply industry to be created, and by using economic models to account for observed regularities in replacement of new products and technologies for old ones.

History of Introduction of LWRs

General Observations

The development of water-cooled reactor for commercial use had its roots in technologies and large-scale installations previously established for military purposes. Mines and mills for the production and purification of uranium, and gaseous diffusion plants for the enrichment of U-235, were available on a scale which would not be reached by the requirements of the civilian power industry for two decades.

The Introduction of LWRs in the U.S.

Table 1 shows the annual installations and cumulative installations of LWRs in the U.S. from 1957 to 1977 [6].

Table 2 shows the <u>scheduled</u> installed capacity from 1978-1987 as they were reported in early 1977. This represents an <u>upper bound</u> of future installed capacities.

As of mid-year 1978 it appeared likely that this schedule would be substantially underrun. Table 3 is a reported DOE projection [7].

It now appears highly unlikely that the national Energy Policy goal can be exceeded.

One can identify from Table 1 four distinct periods. From 1960-1962 a number of demonstration plants whose average size was ~200 MWe were installed in the U.S. The plants were pre-economic and partly subsidized by the utilities, the manufacturers, and the government. During 1963-1967 operating experience with the demonstration plants was accumulated and fed back into the design of a number of commercial plants of the size range 500-800 MWe committed and under construction in this period. From 1968-1972 these first fully commercial plants were brought into operation. During the same period many commitments for even larger plants (800-1100 MWe) were made. After 1973 a complex of circumstances caused utility projections of load growth to drop from 7-8%/year to 4.5-6%/year. Some of these circumstances

Table 1. Installation of LWRs in the U.S. (historical)

Year	Installed/year		Average size	Cumulative		%	
	No.	GWe	MWe	No.	GWe		
1957	1	0.09	90	1	0.09		
1960	1	0.20	200	2	0.29		
1961	1	0.18	175	3	0.47		
1962	2	0.34	170	5	0.81		
1963	1	0.06	60	6	0.87	7	
1968	2	1.01	560	8	1.88	116	
1969	3	1.28	430	11	3.16	68	
1970	4	2.44	610	15	5.60	77	
1971	4	2.70	680	19	8.30	48	
1972	8	5.51	690	27	13.81	75	or 27
1973	7	5.49	780	34	19.30	46	
1974	12	9.82	820	46	29.12	53	
1975	8	7.11	890	54	36.23	24	
1976	4	3.99	1000	58	40.22	11	
1977	7	6.15	880	65	46.37	15	

Table 2. Installation of LWRs in the U.S. (owner's schedules)

Year	Installed/year (GWe)	Cumulation (GWe)
1977		46.37
1978	7.1	53.5
1979	9.0	62.5
1980	11.1	73.6
1981	11.2	84.8
1982	15.6	100.4
1983	17.8	118.2
1984	21.5	139.7
1985	13.6	153.3
1986	11.8	165.1
1987	7.7	172.8

Table 3. Preliminary DOE projection of cumulative LWR installations in the U.S.

Year	Low	Reference	High	National Energy Policy Goal
1985	100	111	122	127
1990	157	172	182	195
2000				380

were: an economic downturn, increased environmental concerns, electricity price rises from suddenly increased prices of fossil fuels, construction cost inflation, consumer resistance to further electricity price increases, and consequent utility financial difficulties. As a result the utilities stretched out their construction schedules in the period 1974-1978, and nuclear (and fossil as well) power plant installation rates stopped growing.

Applying this pattern mechanically to project the future introduction of a new reactor technology may not be productive, since there were so many special circumstances which will not be repeated. It is more rewarding to consider the conclusions drawn from this experience by the participants.

It will be noted that some operating experience from the 200 MWe reactor generation was obtained before the ~650 MWe generation was committed. Subsequent plant commitments gradually escalated in size. The assumption was made that operating experience from somewhat smaller reactors would be available in a timely manner to influence the design of the larger plants. This expectation was only partly fulfilled. The unanticipated extension of construction schedules beginning in ~1970 was a principal factor in this delay in operating experience. Further, there was a rapid evolution of standards, accelerated by continually escalating public concern over reactor safety. The slow construction schedules and the rapid changes of standards resulted in much redesign and backfitting. It is unlikely that vendors or owners will expose themselves again to this kind of technical and economic risk. We anticipate that future changes in plant sizes and design parameters will be more deliberate, and commitment of numbers of plants at a given performance level will wait for actual (rather than scheduled) operation experience. In short the concept of standardized plants, which has been merely an oratorical cliché for a decade, will be seriously applied.

The Introduction of LWRs in the World as a Whole

Table 4 exhibits the history of the installations of LWRs (PWRs, BWRs, and LWGRs) in the world as a whole. Comparing it

Table 4. Installation of water-cooled reactors in world (historical, includes PWRs, BWRs, LWGRs)

Year	Installed/year No.	Installed/year GWe	Average size MWe	Cumulative No.	Cumulative GWe
1957	1	0.09	90	1	0.09
1960	1	0.20	200	2	0.29
1961	1	0.18	175	3	0.47
1962	2	0.34	170	5	0.81
1963	1	0.06	60	6	0.87
1964	3	0.46	155	9	1.33
1965	1	0.25	250	10	1.58
1966	3	0.98	325	13	2.56
1967	3	0.75	250	16	3.31
1968	3	1.27	420	19	4.58
1969	10	2.93	295	29	7.51
1970	6	3.10	515	35	10.61
1971	6	3.60	600	41	14.21
1972	15	8.79	585	56	23.00
1973	11	7.26	660	67	30.26
1974	20	15.42	770	87	45.68
1975	18	13.33	740	105	59.01
1976	12	9.72	810	117	68.73
1977	13	10.34	795	140	79.07

with Table 1, it will be observed that in the years 1964 through 1968 a number of demonstration plants of approximately 250 MWe capacity similar to those installed in the U.S. between 1960 and 1962, were installed outside the U.S. In Western Europe and Japan larger plants, similar to those which began operating in the U.S. in 1968 and 1969, were brought on line in 1971 and 1972.

The Soviet Union carried out an independent line of development. A period of experimentation with various plant types of small sizes led eventually to the serial production of 440 MW PWRs, the first (Novo-Voronezh-3) becoming operational in 1972; and to serial production of 1000-MW LWGRs (light water-cooled graphite-moderated reactor), the first (Leningrad-1) becoming operational in 1974. The 440 MW PWRs are being built in the European CMEA countries as well as in the U.S.S.R.

The Soviet PWR development showed a five-year hiatus between the operation of Voronezh-1 (210 MWe) and Voronezh-2 (365 MWe), and three years between Voronezh-2 and Voronezh-3. Multiple units of 440 MWe were however committed without provision for extended operating experience on the first one. The first 1000 MWe PWR (Voronezh-5) is scheduled for 1978, six years after Voronezh-3. Standardization is already in practice in the USSR.

A significant development by the USSR is construction near Volgodonsk of the Atommash heavy nuclear component factory, which is nearing completion. It is planned to produce components for 8000 MWe in its first year of operation. Another development in the same sense is an agreement whereby the C.S.S.R. will construct steel furnaces of 24,000 tons/yr to produce heavy forgings for nuclear plants.

Future Rates of Growth of Nuclear Power Plants

In preliminary general comments on the 10,000 GWe and 5,000 GWe targets, we ventured the opinion that constructing an average of 300 GWe/yr of conventional LWRs in the 35 years from 1995-2030 appeared achievable. this was based on the assumption that the present trajectory, which requires a construction rate of 90 GWe/yr in 1995-2000, can and will be achieved. Table 4, however, shows that the maximum rate of addition so far achieved has been 15 GWe.

One cannot assert that the present trajectory will be achieved. The following argument supports the assertion that it can be.

Most of the plants which are scheduled to come into operation between 1980 and 1985 are already under construction and at least the beginning of fabrication of equipment has been made for the rest. 30 GWe/yr for 1980-1985 seems on capacity to produce pressure-vessels, fabricate fuel elements, etc. The U.S. nuclear industry present capacity is estimated as 25-30 GWe/yr. Adding the capacities in Western Europe, Japan, and the CMEA countries, the LWR hardware capacity (excluding uranium production) of the world appears to be no less than 40 GWe/yr.

The annual increment of power plant capability for the world is about 100 GWe/yr. At a growth rate of total electric power of only 4%/year, the annual increment will become in 2000, ~235 GWe/yr. It should not be difficult for the nuclear industry, to keep up with it and to reach 90 GWe/yr.

Incidentally, the ratio 40:100 serves to remind us of the importance of the nuclear industry to the world's power economy, and the disaster which would be inflicted if it were allowed to decay.

Inferences from History

To sum up, attainment of a nuclear hardware capacity of the order of 1500 GWe by the year 2000, based on LWR plants whose technology was demonstrated in the early 60s and became commercial in the late 60s, appears an attainable goal. Reservations must be expressed about the ability of the uranium industry to fuel these reactors at the rate called for (~200,000 tons/year of yellow-cake, for a once-through fuel cycle in LWRs, even assuming a 30% improvement in fuel economy).

It would also seem reasonable to infer that a new technology, commercial by 1995, which would offer the same advantage over LWRs that LWRs offered over fossil plants, would be able to be built to at least this level (1500 GWe) by 2030. This should be all the easier because of the far larger world economy post 2000. (An influence in the other direction is that in the 60s it was possible to commit and complete a nuclear plant in 5 or 6 years, and it now takes about twice that.)

One limitation on the introduction of new technologies is the time it takes to bridge the gap between succuessful development and the first commercial installation. We are concerned here, not with the long period of basic technology development, which begins with loops and in-pile experiments in test reactors, basic materials and physics experiments, construction of pilot plants, and finally the operation of one or more small (<300 MWe) demonstration reactors, but with the transition period to large, commercially licensed standard plants. This is the stage that the HTGR, the LMFBR, or a re-design of CANDU to use enriched uranium, would still have ahead. Other reactors--such as the GCFBR, or the molten salt reactor--have not yet reached the transition stage.

We envisage the following scenario: a large plant (~1000-1500 MWe) is designed and built. Real cost experience is obtained. The plant is operated long enough for a standard burn-up of at least part of the first load. Post-irradiation examination of the fuel confirms the expected neutron economy of the reactor and the integrity of the fuel. This process will take from 8-10 years, at the conclusion of which one could in principle deploy with confidence any number of the same reactor design. If one wanted to deploy a larger reactor (say 2000-3000 GWe) the same procedure would be followed, less the post-irradiation examination of the fuel which might be dispensed with. This cycle would be of 7-9 years.

The next limitation on deployment would then be the rate at which an industry, including ancillary facilities, could be mobilized. (The second limitation, which will be discussed at length below, would be the economic incentive to do so.) Based on history, the time it takes to increase production rates from one or two plants/year to 40 or 50 per year is on the order of 20 years.

Changing reactor fuel cycles--provided they are backfittable into existing reactors--can be accomplished more expeditiously. Thus Indian Point 1 changed from a U-235/thorium fuel charge to a U-235/U-238 fuel charge early in its career with no difficulty. A change from present fuel cycles based on clean enriched uranium to one using radioactive U-233 will depend on the rate at which reprocessing plants and remote fuel fabrication facilities can be built and shaken down. This should not take more than five years (although under present conditions in OECD countries it is likely to take ten).

IV. ECONOMIC FACTORS IN INTRODUCING NEW TECHNOLOGIES

It has been observed by J.C. Fisher and R.H. Pry [8] that the substitution of one technology for another follows a particularly simple law. If f_1 is the market fraction of an old technology, and f_2 the fraction of a new technology

$$\ln f_2/f_1 = At \quad ,$$

where A is a constant, t is time. This generalization was shown to hold for 17 technical substitutions ranging from synthetic/natural rubber to BOF/open hearth steels.

Marchetti [9] applied the Fisher-Pry concept to the substitution of different primary energy sources (wood, coal, oil, gas) and showed that the same regularities exist.

V. Peterka [10], using an observation made in 1961 by Mansfield [11] that the rate of technical change is positively correlated with the profitability of the new technology, and negatively influenced by the relative capital investment needed to introduce the new technology, developed a theory which accounted for the Fisher-Pry observations, and related the substitution constant A to the production costs and capital investments of the competing technologies.

The basic equation of the Peterka theory is, if $P_i(t)$ is the rate of production of the i^{th} competing technology (Peterka, Equ. 4.2)

$$\alpha_i \dot{P}_i(t) = P_i(t)\{p(t)-c_i\} \qquad i = 1,2...n \qquad (1)$$

where α_i is the specific investment for commodity i (capital needed to increase the production rate by one unit), c_i is the specific production costs (costs, including capital charges, of producing one unit), p(t) is the market price of a unit of production.

For power plants P_i is in kilowatts, α_i is in \$/kW and it is convenient to express p and c_i in \$/kWyear.

This equation asserts that a producer's investment in technology i on the average will equal his return from production using technology i.

It is plain that in the long run a producer cannot invest in a technology <u>more</u> than his return--he cannot subsidize it indefinitely. Further, if he wishes to retain his market share in a growing economy, he must continue to invest.

Equations (1) are intuitively of the right form--the increment of production being proportional to the present production, and the observations of Mansfield are nicely incorporated.

Conceptual difficulties* on how utilities make decisions on which technology to adopt (for example if $\alpha_i = \alpha_j$, $c_i < c_j$ why is any of technology j purchased?) could probably be eliminated by a more elaborate theory incorporating:

a) Variations in costs for different utilities for each technology,
b) uncertainties in all the cost parameters, and/or
c) a non-deterministic decision-making model.

We therefore adopt the Peterka equations as a working hypothesis, and see what light they shed on the LWR-fossil substitution which we are currently observing in the U.S.

First, we rewrite (1) as follows:

$$\dot{P}_i(t) = P_i(t)\,\frac{f_i(t)}{\alpha_i(t)}\,\{p(t) - c_i(t)\} \qquad i=1,\ldots n \quad . \tag{2}$$

Summing over i

$$\frac{d \ln P(t)}{dt} = p \sum \frac{f_i}{\alpha_i} - \sum \frac{c_i f_i}{\alpha_i} \tag{3}$$

at any time t all the quantities with subscripts are known, d ln P(t)/dt may be estimated from long-term trends, and p is then determined. We can then go back to (2) and find d ln P_i(t)/dt. By iternation one can advance through time.

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*Pointed out by Dr. A.M. Perry

Usually our knowledge of the coefficients as a function of time is not precise enough to warrant such a procedure.

It is worth taking a moment to compare this procedure with a standard linear programming approach. For example, the HEDL linear program, in describing the economic competition between different reactor types, introduces new reactor types as soon as their electricity costs are lower than those of an existing type. The initial rate of introduction is limited (e.g. to 1,2,4,8,16 every biennium) but this limitation is not related to the degree of economic advantage; a small advantage has the same effect as a large advantage. Further, there is no distinction between high and low capital cost systems.

Under the Peterka formulation a rapid growth of a new technology requires a large economic advantage--large compared to the unit capital cost required. To a first approximation (Peterka Equ. 5.12) this is expressed by ($\alpha_2 \neq \alpha_1$)

$$\frac{d}{dt} \ln \frac{f_2}{f_1} = \frac{c_1 - c_2}{\alpha_1} - \left(\frac{\alpha_2}{\alpha_1} - 1\right) \frac{d \ln P}{dt} \quad .$$

Let us first take the case $\alpha_2 = \alpha_1 = \alpha$. Then the second term disappears on the right and the solution is exact

$$\frac{d}{dt} \ln \frac{f_2}{f_1} = \frac{c_1 - c_2}{\alpha} \quad .$$

If $c_1 - c_2$ is small compared to α, the rate of substitution will be small. To get a feel for this expression refer to the last formula in A-3 which gives the BWR burn-up costs. The terms in X and Y for X = 100, Y = 60 (which might describe the situation late in this century) contribute $35 to the annual operating cost (5.3 mills/kWh). If we were to introduce a new system, costing $700/kW which completely eliminates the burn-up costs, and none of the other costs were increased as a result, the new system would grow at the rate

$$\frac{d}{dt} \ln \frac{f_2}{f_1} = 0.05 \quad .$$

The ratio f_2/f_1 would increase by a factor e in 20 years. If the initial penetration were 2%, it would only be 5% in 20 years. Only when Y is large will the penetration be rapid.

If the new system has a larger capital cost than the BWR, the term

$$-\left(\frac{\alpha_2}{\alpha_1}-1\right)\frac{d \ln P}{dt}$$

is negative and the market penetration rate is slowed down further.

Now let us analyze the competitive situation between base-load fossil and LWR plants in the U.S. now and in the year 2000 with the aid of the Peterka model, and see whether we can obtain a consistent picture.

Economic Balance Between LWR and Fossil Plants in 1978

In the Appendix an equation is derived for the annual operating cost of a BWR on a once-through fuel cycle (subscript one refers to LWRs)

$$c_1 = \alpha_1(0.125) + 7.01 + 5.0$$

$$+ (0.748 + 0.142X + 0.486Y)$$

The terms represent, respectively

c_1 = capital charges + fuel processing + operation and maintenance + (heavy metal costs).

X = unit price of separative work, \$-kgU.

Y = unit price of yellow-cake, \$/lbU_3O_8.

In the fuel processing and heavy metal costs, inventory charges are included at 10%. The expression may be expressed more conveniently as

$$c_1 = 0.125\alpha_1 + 12.76 + 0.142X + 0.486Y \text{ (BWR-OT)}.$$

Similarly for fossil plants (subscript zero)

$$c_o = \alpha_o(0.125) + 5.0 + 59.2Z ,$$

where

Z = fossil fuel cost, \$/million btu.
(9000 btu/kWh, 75% capacity factor).

Capital costs for 26 operating U.S. LWR plants of over 500 MWe rating, completed between 1972 and 1977, can be correlated with an expression

$$\$/\mathrm{kW} = A(1.22)^{C.M.}\, R^{-0.35} \quad , \tag{4}$$

C.M. = mean year of construction, R = rating (MW).

The 26 plants have net costs between 150 and 690\$/kW, with a median of \$350/kW. We choose this as representing the cost of our existing nuclear park, and \$200/kW as the cost of our existing fossil park. Nuclear fuel costs for fuel now in reactors are X = 60, Y = 20. Average fossil fuel costs are about Z = \$1.20/mill.btu. Substituting in the previous equations for c_1 and c_o

$$\alpha_1 = \$350/\mathrm{kW} \qquad c_1 = \$75/\mathrm{kWy}$$

$$\alpha_o = 200 \qquad c_o = \$101/\mathrm{kWy} \quad .$$

In 1977 approximately 12% of all electricity generated in the U.S. was nuclear. The nuclear fraction of the base-loaded plants was higher, approximately 15%. Thus $f_1 = 0.15$, $f_o = 0.85$. The current growth rate of electric capability is $\frac{d \ln P}{dt} = 0.055$.

Putting these values into Equation (3) and solving for p we find

$$p = \frac{\frac{d \ln P}{dt} + \sum \frac{c_1 f_i}{\alpha_i}}{\sum \frac{f_i}{\alpha_i}} = 100 \quad .$$

Then

$$\frac{d \ln P_1}{dt} = \frac{110-75}{350} = 0.100 \qquad (1978) \quad .$$

Projecting P_1 and P forward, noting that

P_1 (end 1977) = 46 GWe

P_1 (end 2000) = 459

P (end 2000) = 1063 .

Our trial value for f_1 in 2000 is then 0.43.

Economic Balance in 2000 Between LWR and Fossil Plants

Equation (4) shows that nuclear power plant costs have been escalating at a rate of 22%/year, which is much faster than general inflation. A similar phenomenon has been observed with fossil power plants. We expect that this super-inflation of construction costs, which has complex causes, will slow down--perhaps eventually stop--but it is not yet finished.

The Economic Ground Rules used in U.S. NASAP evaluations quotes (deflated) capital costs of LWRs as $625/kWe, including interest during construction, and capital charges (also deflated) of 10%. If in fact the super-inflation were to continue through 2000 at as little as 2%/year, as opposed to the past experience of 15%/year, this procedure will underestimate capital charges by a factor of 1.6 by 2000. To avoid this we make the following explicit (and optimistic) assumption: LWR power plant costs will continue to inflate in constant 1978$ to a level of $1000/kW but not increase beyond this value. This might be thought of as a continuation of the super-inflation for 3.5 years, or as a continuous creeping super-inflation of 2%/year. We assume that fossil power plant costs will behave the same way. (Note that we use the slightly higher value of 12.5% for the deflated cost of capital for depreciating assets, 10% for non-depreciating assets).

On this basis we take $\alpha_1(2000)$ = $1000/kW (in 1978$), $\alpha_o(2000)$ = $800/kW. Fuel costs are taken as X = $100/kg sep. work, Y = $60/lb yellow-cake, Z = $2.50/million btu. $f_1 = 0.43$, $f_2 = 0.57$. We assume $\frac{d \ln P}{dt}$ has slowed to 5%.

We then find $c_1 = 181$, $c_o = 253$, $p = 270$

$$\frac{d \ln P_1}{dt} = \frac{270-181}{1000} = 0.089 \qquad (2000) \quad .$$

There is no fundamental reason the values of $\frac{d \ln P_1}{dt}$ in 1978 and 2000 should agree: each depends on a monetary competitive situation. Further, the cost assumptions are far too uncertain for us to take the exact values of the growth coefficients for P_1 literally. Nevertheless the average of these values predicts the LWR capcity in the year 2000 to be 400 GWe. This is unlikely to be far wrong, and gives the insight that the present low projected growth of LWRs reflects primarily economic, and only secondarily sociological or political forces.

This exercise shows that the Peterka model can account for observed economic trends, and suggests that it has some value as a predictive device. We shall now use it to investigate the substitution of LMFBRs (subscript two) for LWRs.

Since we are interested in the penetration of a new reactor into an established market, f_2 is usually small and we further simplify Equation (3) by setting $f_2 = 0$. Then

$$p = \alpha_1 \frac{d \ln P}{dt} + c_1 \quad \text{(approximate)} \tag{5}$$

Since $\alpha_2 \geq \alpha_1$ $c_2 < c_1$ this will overestimate p and hence market penetration rates. (If necessary the error can easily be rectified when f_2 becomes appreciable by returning to (3)). Then

$$\frac{d \ln P_2}{dt} \leq \frac{\alpha_1 \frac{d \ln P}{dt} + (c_1 - c_2)}{\alpha_2} \quad . \tag{6}$$

Economic Balance After 2000 Between LWR and LMFBR

We have from the appendix the following relations

$c_1 = 0.125\alpha_1 + 12.76 + 0.142X + 0.486Y$ BWR-Once-Through

$c_1 = 0.125\alpha_1 + 16.26 + 0.126X + 0.365Y$ BWR-Recycle

$c_2 = 0.125\alpha_2 + 28.12 + 0.023X + 0.081Y$ LMFBR

BWR-recycle will be more economic than BWR-once-through when

$$Y > 29 - 0.13X \quad ,$$

which is almost the case when Y = 20, X = 60. Thus for all future values of X and Y it will be more economical. Since obviously there will be no LMFBRs unless Pu is available, we shall compare LMFBRs with recycle BWRs.

Then we have

$$c_1-c_2 = 0.125(\alpha_1-\alpha_2) - 11.86 + 0.103X + 0.284Y$$

and for X = 100, which we will henceforth assume

$$c_1-c_2 = 0.125(\alpha_1-\alpha_2) - 1.56 + 0.284Y \quad .$$

We remark in the first place that if the capital cost of fast breeders exceeds that of LWRs by $200/kW fast breeders do not become economical until Y is approximately $100/lb (1978$).

Following our earlier discussion, let us take P(1995) = 900 GWe. We consider two scenarios: total nuclear power installation in 2030, 5000 GWe (low growth) and 10,000 GWe (high growth). Overall average growth rates are respectively 4.9% and 6.9%. We take $P_2(1995) = 10$ GWe.

Table 5 gives the approximate number of LMFBRs which would be installed in 2030 according to the Peterka formulation using the values of c_1 and c_2 previously calculated, and taking

$$700 \leq \alpha_1 \leq 1000$$

$$700 \leq \alpha_2 \leq 1500$$

Table 5. Economic penetration of LMFBRs by 2030
(Initial value = 10 GWe in 1995)

Nuclear growth:	10,000 GWe in 2030				5,000 GWe in 2030		
α_1/α_2	Y=100	200	300	400	100	200	300
700/700	410	1490	4210	7500	205	745	2100
700/850	100	330	1000	2500	55	180	600
1000/1000	280	710	1720	3600	135	350	850
1000/1200	75	180	400	940	40	100	230
1000/1500	-	-	80	160	-	-	50

all numbers in 1978$

α_1 = capital cost of BWRs $/kW

α_2 = capital cost of LMFBRSs $/kW

Y = cost of yellow-cake $/lb

X = separative work cost = $100/SWU

The approximate formula (6) was used unless penetrations were larger than 12%, where more exact formulations were used.

We observe from this table that market penetration is markedly slowed by high capital costs, and even more so by a capital cost disadvantage of as little as 20%. In the 1000/1200 case, which may be the most likely, even astronomical uranium prices are not sufficient to produce significant LMFBR penetration in 35 years. (Note that very favorable fuel processing cost assumptions have been made for the LMFBR.)

The driving force in the preceding cases is the reduction in uranium utilization, and hence uranium costs, less the increase in inventory costs. The LMFBR has a negative uranium utilization, but its inventory of 5g fissile Pu/kWe determines a net positive component to LMFBR fuel cost from natural uranium and separative work prices. Since advanced converters also tend to have increased fissile inventories, and have at best zero uranium utilization, the exercise we have just concluded applies also to advanced converters.

We conclude that the LMFBR will not achieve substantial market penetration by the year 2030 through purely economic forces unless

1. its capital cost is no higher than that of an LWR, and also
2. the costs of natural uranium, in 1978$ exceed $300 at an early date.

The same conclusions hold a fortiori for advanced converters.

Equation (4), p. 18, suggests that building LMFBRs in larger size than competing LWRs could be a way of improving their economics. Assume (4) applies as well for LMFBRs and for all ratings up to ~5 GWe. If LMFBRs cost 20% more than LWRs at equal ratings, building the former 1.7 times larger than the latter would reduce the cost disadvantage to zero. This may be well within the range of possibilities, since LMFBRs do not have to contend with size limitations on pressure vessels, and early LMFBR designs are probably not at the specific power limit. (A cost spread of 50% would require average LMFBR ratings to be 3.2 times larger than average LWR rating, which would probably take another 10 years to achieve.)

There are two ways that government decision makers could foster the growth of LMFBRs, and so reduce dependence on uranium mining. The first is to subsidize early creation of an LMFBR industry. If 20 GWe of LMFBRs were operating in 1995 instead of 10 GWe, the 1995 industrial base would be twice as large and successive annual increments would be doubled. Note that the later an acceleration program is started, the more expensive it will be.

Second, one could envisage a tax on natural uranium (applied after essentially all central station power plants are nuclear) to increase the economic incentive to convert from LWRs to LMFBRs.

Back-Fittable Improvements in Neutron-Economy

The Peterka model agrees with the history of change of energy technologies, that it takes time for a new technology to grow to a substantial capacity. It adds the information that rapid market penetration (10 to 50% in ten years) can be expected if the cost improvements are large compared to the capital needed to implement them (specifically if $\Delta c/\alpha \geq 0.22a^{-1}$).

In this light, let us look at the introduction of BRW recycle when X = 100 and Y = 60. The fuel cost advantage between BWR-OT and BWR recycle is $5.40 kWyr.

When Y = 100, it is $10.2/kWyr.

Assuming a 1500 ton/yr reprocessing plant costs $2 billion, and services 50 GWe, the added capital cost is $40/kWe. The relative rates of introduction are

$$Y = 60 \qquad \Delta c/\alpha = 0.135/\text{yr}$$

$$Y = 100 \qquad \Delta c/\alpha = 0.256/\text{yr} \quad .$$

At the present time, world reprocessing requirements for LWR fuels is 2400 tons/year. Perhaps 10% of this amount is operating. Then at Y = 60, in 16 years 50% of all LWR fuels would be reprocessed and reused in LWRs. At Y = 100, this would take only 8 1/2 years.

With Pu and U recycle, uranium utilization for a 1000 MWe LWR drops from 196 tons U_3O_8/yr to 123 tons/yr. Now suppose a further back-fittable fuel change, involving some ractor reconstruction, could reduce the fuel utilization another 60 tons/yr (to approximately 1/3 its present value). Assuming no increase in inventory, and no increase in separative work costs--this would result in saving of $0.12Y/kWyr. The capital costs might be $50/kW in direct costs and $100/kW for one year lost in production--$150/kW. Then

$$Y = 100 \qquad \Delta c/\alpha = 0.08$$

$$Y = 200 \qquad \Delta c/\alpha = 0.16 \quad .$$

It would take 27 and 14 years, respectively, to go from 10 to 50% substitution of this improvement.

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APPENDIX

Fuel Cycle Costs for BWR (Once-Through) BWR (Pu Recycle) and LMFBR (Producing U-223)

Assumptions (constant 1978$)

Capacity factors, all reactors		0.75
Capital charges on depreciating assets		12.5%
Capital charges on non-depreciating assets		10%
Fabrication costs of LWR fuel (U-235/28)		$100/kg H.M.*
Throwaway cost of spent fuel		$115/kg H.M.*
Reprocessing and waste disposal costs of spent fuel		$220/kg H.M.*
Separative work costs "X"	Now	$ 60/kg U
	Post-1980	$100/kg U
Yellow-cake sots "Y"	Now (avg. US)	$ 20
	1980-2000	$ 60
	Post-2000 >	$200
Tails fraction		0.2%
Transformation cost, U-UF_6		$ 4/kg U
Cost of U as UF_6 ($/kg U)		4 + 2.60 Y

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[*] These values are from NASAP

Value of Pu = 0.8 value of U-235 in 2.8% fuel minus $5/g fabrication cost penalty

Value of U-233 = 1.1 value of U-235 in 2.82% fuel

Operating and maintenance costs, all reactors $ 5/kW

Fabrication and reprocessing costs of LMFBR fuel:
set to make LMFBR fuel cycle cost = BWR recycle fuel cost when X = 60 Y = 20

Properties of BWR

Initial enrichment	2.82% 235
Final enrichment	0.8% 235 0.5% Pu (fissile)
Burnup	28,000 MWd/ton H.M.
Specific power	30 kWt/kg H.M.
Thermal efficiency	33%
Out-of-pile inventory	0.2 cores

Properties of LMFBR

Burnup	75,000 MWd/ton
Thermal efficiency	38%
Average inventory	5g Pu/kWe (fissile)
Excess fuel produced per year	0.210g U-233/kWe

Side-Calculation: Values of BWR Fuel Components

To produce 1 kg U @ 2.82% U-235, 0.2% tails

feed = 5.137 kg U separative work = 3.920 kg U

To produce 1 kg U @ 0.8% U-235, 0.2% tails

feed = 1.176 kg U separative work = 0.105 kg U

Cost of 1 kg 2.82% U = 3.920X + 5.137 (4 + 2.60Y)

Value of 1g contained U-235 = 0.139X + 0.182 (4 + 2.60Y)

Value of 1g Pu fissile = 0.111X + 0.146 (4 + 2.60Y) - 5

Value of 1 kg 0.8% U = 1.105X + 1.176 (4 + 2.60Y)

Value of 1g U-233 = 0.153X + 0.200 (4 + 2.60Y)

BWR Once-Through Cycle

Burnup costs associated with heavy metals

Each kg fuel produces 28 MWd = 28 x 8000 kWhe

One kWyear @ 75% C.F. = 8766 x 0.75 = 6574.5 hrs.

$\therefore$ 1 kWyear uses $\frac{6574.5}{28\text{x}8000}$ = .02935 kg fuel

(.02935) cost of 1 kg 2.82% U

= 0.115X + 0.1508 (4 + 2.60Y) \$/kWyear

Burnup costs associated with fuel processing

Fuel fabrication \$100/kg
Fuel throw-away \$115/kg
\$215/kg

$\frac{\$215}{\text{kg}}$ x .02935 $\frac{\text{kg}}{\text{kWyear}}$ = \$6.31/kWyear

Inventory costs associated with heavy metals

Average in-core inventory value = 0.5 initial value
Out-of-core inventory value = 0.2 initial value
0.7 " "

Inventory value = 0.7 {3.920X + 5.137(4 + 2.60Y)} \$/kg

Capital charge = 0.10/yr; kWe/kg fuel = 10

Annual inventory charge = 0.0274X + .0360(4 + 2.60Y) \$/kWa

Inventory costs associated with fuel processing

Average fabrication value = 0.7 x 100 = \$70/kg

Annual inventory charge 70 x 0.1 x $\frac{1}{10}$ = 0.70 \$/kWa

Annual once-through BWR costs: (α_1 = capital cost \$/kWe)

$0.125\alpha_1$ + 7.01 + 5.0 + {.142X + .187(4 + 2.60Y)}

Capital charges + fuel processing+ operating & maintenance + (heavy metal costs)

BWR, Pu and U recycle

Burnup costs associated with heavy metals

Initial value 3.920X + 5.137(4 + 2.60Y) \$/kg

Residual values

0.8% U 0.105X + 1.176(4 + 2.60Y) \$/kg
5 g Pu 0.555X + 0.73 (4 + 2.60Y) - 25 \$/kg

Net cost = 25 + 3.26X + 3.231 (4 + 2.60Y) \$/kg
= 0.734 + 0.0957X + 0.0948 (4 + 2.60Y) \$/kWyr

Burnup costs associated with fuel processing

Fuel fabrication	100 \$/kg
Fuel reprocessing + waste disposal	220 \$/kg
	320 \$/kg

$\frac{\$320}{\text{kg}}$ x $\frac{.02935\text{kg}}{\text{kWyear}}$ = \$9.39/kWyr

Inventory costs associated with heavy metals

Inventory = 0.7 (initial value) + 0.5 (residual values) =

$0.7\ \{3.920X + 5.137(4 + 2.60Y)\}$

$0.5\ \{0.105X + 1.176(4 + 2.60Y)\}$

$\underline{0.5\ \{0.555X + 0.73\ (4 + 2.60Y) - 25\}}$

$3.074X + 4.549(4 + 2.60Y) - 12.5$ \$/kg

$0.0307X + 0.0455(4 + 2.60Y) - 0.125$ \$/kg

Inventory costs associated with fuel processing

Average fabrication value = 0.7 x 100 = \$70/kg

Annual inventory charge 0.70 \$/kg

Annual recycle BWR costs

$0.125\alpha_1 + 10.09 + 5.0 + \{0.1264X + 0.1403(4 + 2.60Y) + .609\}$

LMFBR

Fuel production credit

In one year, produces at 75% C.F. 0.210g U-233/kW or a value of

$0.210\{0.153X + 0.200(4 + 2.60Y)\}$ \$/kWa

$= 0.0321X + 0.042(4 + 2.60Y)$ \$/kWa

Inventory charges for

5g Pu/kWe = $0.555X + 0.73(4 + 2.60Y) - 25 \times 10\%$

$= -0.0555X + 0.073(4 + 2.60Y) - 2.5$ \$/kWa

Total heavy metal associated costs (inventory charges minus credits)

$0.0234X + 0.031(4 + 2.60Y) - 2.5$ \$/kWa

Now to get the LMFBR costs associated with fuel processing, call them A. Assume per page 1 of this appendix

Annual recycle BWR fuel costs =

Annual LMFBR fuel costs when X = 60, Y = 20

$10.09 + \{0.1264X + 0.1403(4 + 2.60Y) + 0.609\} = 26.14$

$= A + \{0.0234X + 0.031(4 + 2.60Y) - 2.5\}$

$A = 26.14 - 0.64 = 25.50$

Annual LMFBR costs (general)

$\alpha_2(0.125) + 25.50 + 5 + \{0.0234X + 0.031(4 + 2.60Y) - 2.5\}$