EMERGY* Analysis of the Nuclear Power System

in the United States

by

Christopher W. Lapp

Department of Environmental Engineering Science

University of Florida

A Masters Paper with Prof. H.T. Odum

EES 6916

August 6, 1991

---

* Spelled with an "M"

ABSTRACT

The purpose of this article is to evaluate the contribution of nuclear power to the United States economic system while also considering environmental impacts. An EMERGY analysis was made of the power plants, the system of fuel supplies, regulations, and environmental interactions. The resources, environmental systems and economic inputs to nuclear power were expressed in solar EMERGY equivalents, the energy of one kind to produce other kinds. Net EMERGY contributions were compared with other sources of electricity such as fossil fuel plants typically contributing 2.5 times to the economy than is used from the economy in the process. The study here presents both a cumulative analysis (1960-1990) and a hypothetical quasi-steady state analysis for the time period beginning in 1990.

A 1975 study by Kylstra and Ki Han of the net contribution of a nuclear power plant using coal equivalents was revised using recent factors for estimating solar equivalents. The net contribution to the economy, the net EMERGY yield ratio (yield/economic inputs) of this previous study was 2.7, not very different than that of fossil fuel electrical production (2.5).

The annual contribution of all nuclear power plants in the United States was evaluated to also include environmental impacts and EMERGY losses due to the Three Mile Island accident. A rough EMERGY analysis of the Chernobyl accident was also done for comparative purposes. The cumulative (1960-1990) net EMERGY yield ratio of U.S. nuclear plants to the economy for the cumulative analysis was 4.64 more than the inputs used from the economy, a ratio higher than that found earlier when the industry was in its infancy and higher than fossil fuel plants operating with fuels at 1990 prices. A second evaluation of a hypothetical future steady state analysis for the net EMERGY Yield ratio in the 1990's was calculated to be 6.28 without the Chernobyl EMERGY loss and 5.9 when this accident was assessed to the U.S. nuclear system.

TABLE OF CONTENTS

INTRODUCTION

The purpose of this study is to evaluate the contribution of the nuclear power to the U.S. economic system including environmental impacts from nuclear accidents. This analysis uses EMERGY (spelled with an "M"), which puts environmental and economic inputs on a common basis using energy as one form of a common denominator.

This paper updates a similar study by Kylstra and Han (1975) which determined the Net EMERGY yield of a typical nuclear plant in its lifetime, except that now the entire U.S. nuclear system is analyzed from 1960 to 1990. The previous study included the EMERGY of regulation, construction, fuel cycle and services, but did not include the EMERGY of natural resources (concrete, steel, etc.) Since then a substantial number of nuclear plants have completed the construction phase and now are producing electricity. A second analysis uses the total inputs and yield of nuclear power evaluated for all the U.S. plants at the current quasi-steady state including completion of 5 power plants a year. In analyzing the quasi-steady state case scenario an added decommissioning charge for 5 power plants was also accounted for. Yearly decommissioning charges (assessed over 30 year lifetime) of the existing 113 power plants in the U.S. were included with the 5 decommissioned every year. Included in this report were evaluations of nuclear accidents with their associated economic and environmental impacts.

The previous analysis performed on the U.S. Nuclear System during the mid-seventies showed the enormous initial investment into nuclear power before many of these plants came into commercial operation. The Net EMERGY Yield Ratio for nuclear power was similar (2.7/1) to fossil fuel power plants (2.5/1). Results of the previous studies are located in Table A, Appendix A. The aim of the work here was to both update this type of analysis for the whole U.S. nuclear system and present a possible steady state future scenario. As previously mentioned this study also concerned itself with a steady state analysis evaluated in units of solar emjoules (sej) instead of fossil fuel equivalents as in the previous study. For the quasi-steady state analysis fuel enrichment with a 50/50 mix of diffusion/centrifuge uranium enrichment was considered. For the cumulative study presented here only the diffusion enrichment case was considered. Since the U.S. is not now engaging in a breeder reactor program the associated fuel reprocessing EMERGY analysis was not performed. Because some of the imported uranium was enriched using centrifuge techniques and the fact that such facilities are under construction in the U.S. an analysis for centrifuge enrichment is performed for the future steady state scenario.

For economic and environmental evaluations, EMERGY calculations of the Three Mile Island (TMI) accident and local on-site degradation due to operation were included along with a comparative EMERGY analysis of the Chernobyl accident.

In the case of fuel cycle reprocessing the current U.S. policy is not to reprocess spent nuclear fuel as is done in other countries such as France. Spent nuclear fuel in the United States is to be sequestered at an underground storage facility. The reprocessing of spent fuel allows a portion of the uranium and plutonium to be recycled as useable fuel. This process also reduces the amount of high level nuclear waste to be stored; however, reprocessing also requires additional facilities and energy to be required in the overall nuclear fuel cycle.

Enrichment of Uranium-235 with gaseous diffusion was and still is the primary method used in the U.S., however, this is changing as new centrifuge facilities are built domestically and foreign fuel (using centrifuge enrichment) purchases are made. Gaseous diffusion requires a great deal of energy to enrich Ur-235, which is why newer facilities will be of the centrifuge variety. Centrifuge enrichment requires only 4% (Benedict,1981) of the energy necessary for older gaseous diffusion effects.

The economic cost of the Three Mile Island (Pa.) accident were converted to an EMERGY value. These costs included both the loss of facility, cleanup and purchased power supplies. As mentioned a rough estimate of the Chernobyl accident and its environmental consequences were examined and shared with all power plants globally. The economic and environmental EMERGY loss of the Three Mile Island and Chernobyl accidents were added to the value of (F) which is the feedback of U.S. economy to the U.S. nuclear industry.

Concepts, Models and Definitions

The methods of this analysis have been described as the EMERGY concept which places values on natural resources and human services by the amount of embodied energy of one kind that was required to produce that resource over time. The amount of solar and geological energy input was defined in Solar Emjoules abbreviated sej and was determined for the resources of interest like uranium, concrete and steel. For direct or indirect human services valued by currency an EMERGY/money ratio for the economy (sej/$) was used to estimate EMERGY contributed on the system. This ratio was calculated from all the renewable resources and fossil fuels used in the U.S. in one year divided by the GNP for that year. EMERGY values were expressed in solar emjoules (sejs) instead of fossil fuel kilocalories sometimes used in energy analysis. The transformity is defined as the EMERGY/energy (sej/Joule) and is used to convert energy values to EMERGY. Transformities convert the heat value of a resource (sometimes it is expressed as sej/mass) into the amount of embodied energy in solar calories it took to originally create that resource.

Figure 1 shows an overview of the U.S. nuclear system in relation to the environmental inputs and the overall economy. This diagram shows how the U.S. nuclear industry interacts with the renewable environmental inputs as well as non-renewable stored resources of uranium and fossil fuels. On the right side of the diagram is the interaction of the U.S. economy with the market which is the sale of electricity to society and the purchasing of goods and services from society. Below Figure 1 is the definition for the Net EMERGY Yield Ratio. The net EMERGY yield of uranium ore is the quotient of the EMERGY in electrical yield divided by all the other inputs that have to be purchased and brought to the Nuclear installations from outside to process uranium. These include EMERGY in materials, fossil fuels and services involved. Figure 1 shows the inputs of uranium (N), fossil fuels (N_f), materials (M) and the goods and services required (S) from society. These inputs interact to produce the facilities and fuel to produce electricity. The quantities that were evaluated in this study included:

1) Net Electrical Yield
2) Regulation and Research
3) Construction (includes canceled facilities)
4) Operation and Maintenance
5) Fuel Cycle (including a waste processing charge)
6) Accidents
7) Decommissioning
8) Materials for Construction
9) Fossil Fuels to produce materials
10) Fossil Fuels to build the power plants

To correctly assess all aspects of nuclear energy production the environmental and economic impacts of normal operations and accidents were considered. During normal operations a large nuclear plant rejects waste heat which is a necessary thermodynamic consequences as heat energy is transformed to the higher quality form of electricity. This rejected heat when released to the environment has potential for benefit or stress depending on the environmental interfaces which were involved.

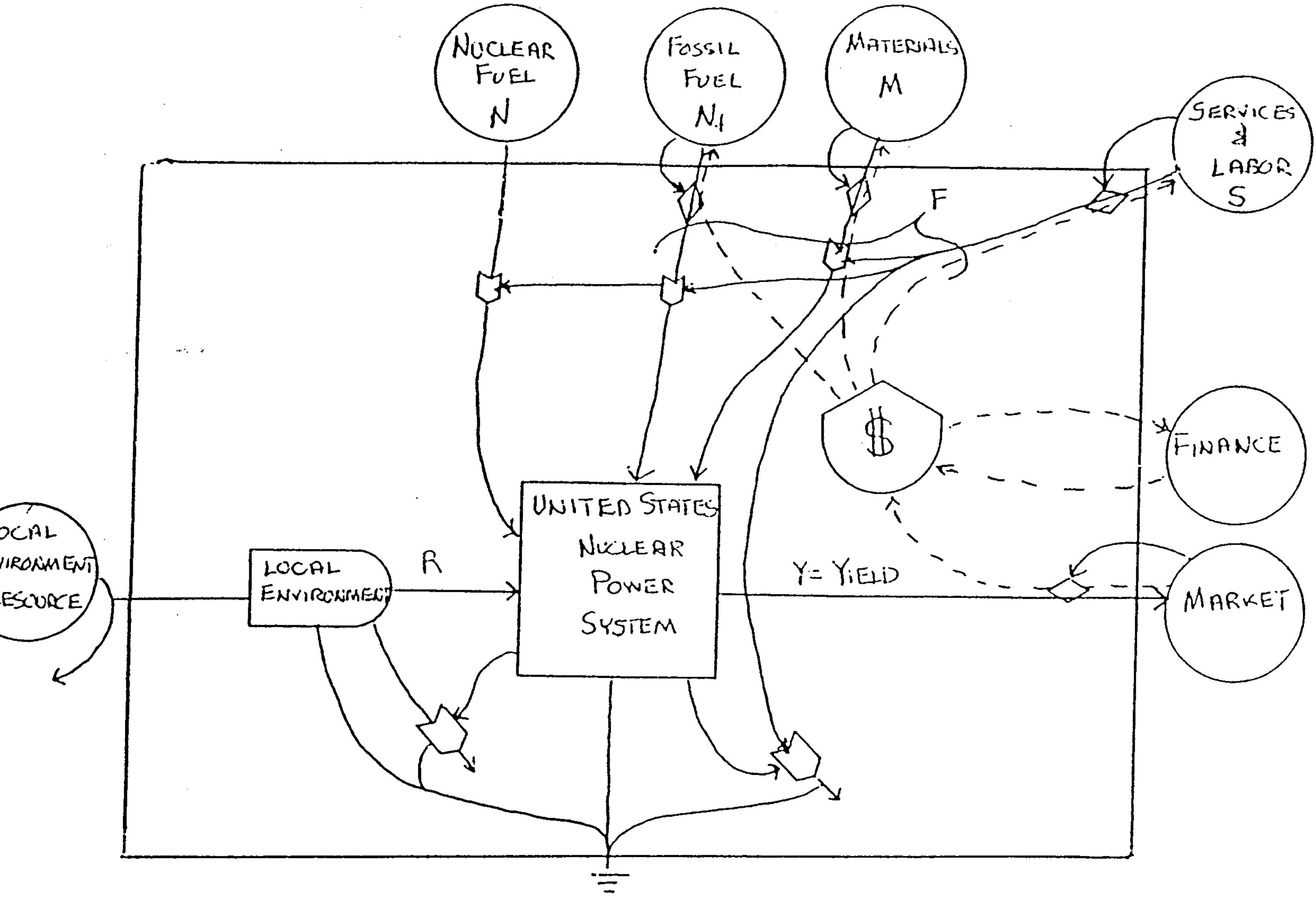

Figure 1

Overview of the U.S. Nuclear Industry with both the Environment and the Economy

Definition of the Net EMERGY Yield Ratio

$$\text{Net EMERGY Yield Ratio} = \frac{Y}{S + N_f + M} = \frac{Y}{F}$$

where $F = S + N_f + M$

Previous Studies on Nuclear Power

An evaluation by Lem and Bolch (1972) of the U.S. Nuclear industry showed that the energy input to build and operate a 1000MWe plant (30 years, 80% capacity) required 63E12 kcal versus 180E12 kcal (540E12 kcal fossil fuel equivalent thermal) of high quality output. The previous energy analysis cited here by C. Kylstra and Ki Han (1975, Dept. of Nuclear Engineering, University of Florida) considered the Net energy yield of a single Nuclear power plant during its lifetime. This ratio was defined by the following relationship:

$$\text{Yield Ratio} = \frac{\text{coal equivalents of electric yield}}{\text{coal equivalents of required input}}$$

This is now called the Net EMERGY yield ratio. A higher value of the Net EMERGY Yield Ratio is desirable for an energy source since society receives more units of energy out of the process than for each unit of society's and nature's input in deriving energy from that source. Their analysis was done for two cases, (1) steady state reference and (2) accumulated through the time of study (1975).

Previous studies analyzing the energy payback for nuclear power have used energy units in the classical sense, but have not considered the embodied energy (EMERGY) of natural inputs and did not always account for labor and services. In this study transformities were used for weighting energy flows of different qualities (position in hierarchy). Some previous studies, however, were very thorough in considering all the energy that went into producing the goods used to build and operate the nuclear power plant. These studies used various indicators to define the energy payback or net energy from the process of utilizing nuclear power. For instance one rigorous study (Perry, Rotty, Reister, 1977) showed that for a single 1000MWe power plant (operating 30 yrs at 75% capacity factor) required 10E6 MWhr(elec) and 37.1E6 BTUs while producing 197E6MWh(elec). This showed a substantial payback in energy terms when the work of nature was not considered. The authors of this article also described four ratios to define different aspects of energy analysis as shown below:

$$R_1 = \frac{\text{Electrical output}}{\text{Fossil Fuel Subsidy}} = \frac{\text{MWh Electrical}}{\text{(Elec Reqd.x3.34)+Thermal}} = 3.98$$

$$R_2 = \frac{\text{Electrical output}}{\text{Electrical Subsidy}} = \frac{\text{MWh Electrical}}{\text{Elec Reqd.+(Thermal/3.34)}} = 13.31$$

$$R_3 = \frac{\text{Electrical output}}{\text{Elec. + Ther. Reqd.}} = \frac{\text{MWh Electrical}}{\text{Elec. MWh + Thermal MWh}} = 8.92$$

$$R_4 = \frac{\text{Elec. (out-input)}}{\text{Thermal Required}} = \frac{\text{Elec. (Output-input) MWh}}{\text{Thermal MWh}} = 17.85$$

The values for the ratios showed favorable returns for the nuclear plant analyzed at that time. Though prices have changed, most of their analysis was based on energy requirements and for the most part are still valid. Others (Price, 1974) have attempted to show dynamically that nuclear power could not payoff in a growing nuclear economy because the energy produced by existing plants could not produce the energy to build the plants under construction.

Another study (Wright, 1975) argued that such an analysis was flawed on some of the growth rate assumptions made for the nuclear industry at that time. Of course the small number of nuclear plants operating initially could not pay the energy requirements of the many under construction with a significant growth rate. Those under construction were subsidized initially by fossil fuels which were readily available at lower costs.

Many previous evaluations of nuclear power did not include all of the necessary contributions from the economy embodied in goods and services. An effort is made in this study to include all requirements.

METHODS

Calculation of Yield and Economic Feedback

The method for determining the net EMERGY Yield ratio analyzed for the entire U.S. Nuclear industry for both the cumulative and steady state condition were based on EMERGY which represented all inputs and outputs as solar emjoules, abbreviated sej (Odum, 1987). For more detailed descriptions of this method and its applications see Odum, Energy Analysis of Environmental Value (1987). To determine net EMERGY Yield ratio the yield of electrical power, the economic feedback from society and the contributions from the environment were calculated. For the quasi-steady state case an assumption was made that 5 power plants per year are being completed. The EMERGY of 5 power plants under construction was added to the data for 1990. Each step of the process was detailed in the following sections.

Yield

1. Electrical Energy Production

To determine the amount of electrical production accumulated to 1990 an annual energy review (Dept. of Energy, 1988, Energy and Economic Data Base, 1990) was consulted. For the steady state case the last year of production was utilized. The data from 1960 to 1990 was for net electrical production. The electrical production was then converted to solar EMERGY units (sej).

2. Administrative Costs (Nuclear Regulatory Commission)

In the previous 1975 report the administrative governmental arm for nuclear power was the Atomic Energy Commission (AEC). This agency served two roles as both the regulator and promotor of nuclear power. To prevent the two roles from conflicting the AEC was split into the Nuclear Regulatory Commission (NRC) for regulation and the Department of Energy (DOE) for other services. Earlier analysis showed a rather large portion of the energy budget going into regulation and development. Today the amount of reactor development funding has dropped from the pioneer days of nuclear power.

Data from the 1975 report for the AEC were calculated up until 1972, the data cited here covered the period from 1960 to 1990. Formation of the NRC from the AEC happened before 1975 (1974) so a couple of years were split for AEC, NRC and DOE budgeting. To account for this split the intervening years were estimated by interpolating the 1972 to 1975 data. Since the DOE budget included many items related to national defense and not commercial nuclear power these were not included in the analysis.

An estimate was made that the amount spent by the DOE on nuclear plant development was equal to that spent by the NRC on regulation. To convert the dollar values to EMERGY an EMERGY/Dollar (sej/$) ratio was employed.

3. Construction Costs

The costs of constructing a nuclear plant since the previous report have sharply increased. Most nuclear plants were built at a slightly higher cost relative to most coal plants up until the past several years. To determine the cost of installed capacity the cost per kilowatt was multiplied by the number of kilowatts per power plant. For this analysis an average cost/kilowatt for a given time period is multiplied by the number of kilowatts installed during that time period. These were summed to give a cumulative cost for construction.

To obtain the steady state construction cost an assumption was made that 5 power plants a year are being completed and that their EMERGY was added for that year as opposed to depreciating it over the lifetime of the plant (30 years). The value of the 5 plants was added to that for all existing nuclear plants built up to 1990. These existing power plants have their EMERGY assessed over the lifetime (30 years) of the facility as was done in the 1975 study by Kylstra and Han. Many plants are seeking plant life extensions and new designs are planning for 40 to 60 year lifetimes. Extending plant life extracts more energy from existing resources which would increase the EMERGY Yield ratio.

These values were determined by using the appropriate sej/$ for the time period in which the nuclear plants were built. The construction value of partially built nuclear plants were included to cover all aspects of this analysis. This was done to include all the materials and services invested into the U.S. nuclear system. A rough estimate of the value of canceled nuclear power plants might run to 15 billion dollars (Greenwald, 1991).

4. Operation and Maintenance Costs

The report by Kylstra and Ki Han used a percentage of the capital cost as a guideline for the cost of operation and maintenance (O&M). This value was 1.5% of the capital for yearly operation and maintenance. However, plant costs since then have increased dramatically which in turn increases the O&M contribution as these plants become more complex. Because some power plants have had to replace major components like steam generators, a more conservative figure of 3% was used for O&M costs. This value of 3% was applied to power plants built up until 1978. Most post 1978 power plants became far more complex so a more conservative (higher) estimate for the O&M was used (EPRI,1989). Operation and maintenance costs were only applied to those plants that are operational, not canceled or mothballed.

A recent report (Electrical Power Research Institute/Technical Assessment Guide 1989) determined operating and maintenance expenses for both fixed and variable costs depending on the amount of installed capacity and the amount of electricity produced. A fixed cost for installed capacity of $61.1/kwe/yr (1990) and a variable cost for production of $.0011/kwhe (1990) was used for O&M determination. An assumption was made that this value was half that in 1979. Power plant fixed operation and maintenance costs from 1979 to 1990 were given a linearly increasing value up to that value cited for 1990. For variable cost the value of $.0011/kwhe was used for all time periods which gives a more conservative estimate of cost. For the quasi-steady state analysis the 1990 data was used for estimating operations and maintenance expenditures.

5.Energy Requirements for Nuclear Fuel Processing

To determine the EMERGY requirements for the nuclear fuel cycle both service costs and energy uses were considered as follows:

1. mining the uranium ore
2. milling the ore
3. conversion of the ore to form for enrichment
4. enrichment of the fuel
5. fabrication of the fuel
6. reprocessing of the fuel for recycling Pu and Ur (optional)
7. waste disposal costs

The Kylstra and Han report (1975) evaluated all of these, but some items on this list have now changed. For instance the reprocessing of spent fuel for plutonium and uranium may not happen and the spent fuel may instead by stored for future retrieval. At the time of the 1975 report the AEC had processed and delivered more fuel than was actually consumed by utilities. It should be noted that even though the production of uranium ore has fallen in the U.S. this does not mean that less is being used, but rather, that the fuel is being imported (Wargo, 1986).

The various aspects of the fuel cycle were evaluated with the following assumptions. It was assumed that the following processes have the same coal-equivalent kilocalorie (KC)/kg conversions as used by Kylsrta and Han (1975) and that no increase in process efficiency has occurred since then, except centrifuge enrichment.

If fuel reprocessing were considered EMERGY would have to added to the fuel cycle, but this would be offset by reduced high level waste and reuse of fuel supplies. This would save much of the up-front fuel cost since enormous amounts of Ur-238 have already been mined, milled and processed. For the quasi-steady state case the fuel use in 1990 was utilized along with a 50% mix of centrifuge enrichment.

For the high level nuclear waste there is an energy charge for processing the material. EMERGY is also required to build and maintain the facility for long term disposal. Maintenance EMERGY would be negligible when compared to the facilities construction since the facility would be sealed and closed when full. The major EMERGY debt for the facility would be in its construction. In the U.S. there are plans to build a long term facility for high level nuclear waste after the year 2000. Even if this facility costs tens of billions it would only lower the net EMERGY Yield ratio a few decimal points. Since this facility has not even been approved it was not analyzed here.

6. Decommissioning

After a nuclear plant has reached the end of its useful life the facility has to be decommissioned. During the life of the plant a surcharge has been added to the plant cost to account for the funds that will be needed to decommission the facility or the utility may issue bonds to cover decommissioning costs. An estimate by the Electric Power Research Institute (1990) puts the decommissioning cost at 200 million dollars for each plant.

7. Accidents

In order to fairly assess the net EMERGY yield ratio for nuclear power it was necessary to also include the cost of accidents. It has been estimated that the cost of the Three Mile Accident for loss of facility, cleanup and replacement power are approximately 2 billion dollars (Greenwald, 1991). The true cost is much higher because of increased regulation and higher construction costs which have already been accounted for in the previous sections. To convert the 2 billion dollars to EMERGY the sej/$ ratio was used for the time period of cleanup. The analysis of the Chernobyl accident was discussed in a seperate section.

8. Materials

The large quantities of building materials utilized in building nuclear plants contain within them the embodied energy that nature had invested to produce these resources. For some products the EMERGY also includes the processing energy supplied by man with fossil fuels. These resources include steel, concrete, aluminum and wood. All materials are listed in Table 2 with their EMERGY calculations.

9. Fossil Fuels for Material production

In order to create and process the large quantities of building materials needed also requires large amounts of energy. The energy of processing was converted to EMERGY using a transformity that was an average between coal, oil, and natural gas since these are all used in industrial applications. Its should be noted that some of the EMERGY required for processing has already been accounted for in item 8. This did create some double counting, but it was a conservative estimate since it lowers the net EMERGY Yield ratio.

10. Fossil Fuels used in Construction

During the many years that a power plant was under construction a large quantity of energy was used in moving and assembling materials. It was assumed that the majority of the fuel source was petroleum.

The results of the data calculated in sections 1 through 10 were used to determine the Net EMERGY Yield ratio for a steady state U.S. nuclear power system as outlined in Table 1 for the cumulative case and Table 1a for the quasi-steady state case.

Evaluation of Natural Resources

The measure of the economic contribution of resources is the ratio of feedback from society in goods, services, and other energy sources required to that of the natural resource inflow including nuclear fuel (Figure 1) and natural resources utilized at the plant site along with the materials of construction. To determine the EMERGY of resource inflow, the quantity of solar and geological energy it took to produce these resources was estimated. Resource transformities were given as sej/unit, where the units in this case were in mass (grams, tons). In analyzing the amount of EMERGY in a product double counting was avoided when possible.

For instance the transformity of concrete takes into account the natural energy to create the base products and the energy to extract and prepare the product. But the transformity does not take into account the fuel, labor and equipment used to transport and form the final product. To determine the transformity of these post-production processes the cost of these items was aggregated and converted to an EMERGY value by using the sej/$ ratio. The EMERGY of post-production processes was then consolidated into the feedback from society (F). For this analysis the following major products were considered in the EMERGY evaluation of resources inflows (R+N, Figure 1, Table 2,2a):

1) Concrete for construction
2) Structural steel
3) Piping steel
4) Large plant components
5) Copper
6) Aluminum
7) Wood
8) Uranium ore

1) Concrete

Nuclear plants require large amounts of concrete for structural and radiation shielding purposes. The EMERGY value of concrete for a typical nuclear installation was calculated to be: (Table 2, 2a)

Concrete EMERGY = 6.9E21 sej cumulative
= 5.4E20 sej/yr 1990 quasi-steady state

2) Structural Steel

Another item that was used in large quantity in concert with concrete to create the nuclear plant. EMERGY for a typical unit was calculated as:

Structural Steel EMERGY = 5.8E21 sej cumulative

= 4.4E20 sej/yr 1990 quasi-steady state

3) Piping Steel

Nuclear power plants utilize large quantities of piping in order to process thermal heat into electrical energy. The calculated value for most power plant piping was:

Piping Steel EMERGY = 9.1E20 sej cumulative

= 1.2E20 sej/yr quasi-steady state

4)Large Plant Components

This category consists of major plant components like the steam generators, reactor vessel and turbine generator. Since they are made mostly of steel the steel transformity is used to obtain an EMERGY of:

Large Components EMERGY = 7.5E20 sej cumulative

= 8.6E19 sej/yr quasi-steady state

5) Copper

Almost 5 million feet of cable was used in a nuclear plant which consists of copper and rubber/vinyl coatings. This and other items require almost 4,000 tons of copper which yields an EMERGY of:

Copper EMERGY = 3E20 sej cumulative

= 2.1E19 sej/yr quasi-steady state

6) Aluminum

In constructing a nuclear power plant almost 500 tons of aluminum were used. The amount of EMERGY contained in the aluminum for plant construction was:

Aluminum EMERGY = 8.4E20 sej cumulative
= 6.8E19 sej/yr quasi-steady state

7) Wood

In setting the concrete in place large quantities of wood were used to make forms and supports. The 33,000 tons of wood used at each plant correlates to an EMERGY of:

Wood EMERGY = 3.7E20 sej cumulative
= 3E19 sej/yr quasi-steady state

8) Uranium Ore

Every year 38E6 pounds of U3O8 are used by U.S. Utilities. Besides the energy required to make it usable fuel, there is natural energy required to make it concentrated enough to mine effectively. Knowing the gross heat generated by nuclear fuel a solar to nuclear fuel transformity (sej/J) gives the solar EMERGY of uranium. Calculation of this resource was done to give the EMERGY of uranium ore as 1.14E22 sej/yr.

Though there are many other items in nuclear plants besides the ones mentioned here they are minor compared to the major categories calculated above.

The environmental resource values (1 through 7, Table 2, 2a) were added together to obtain the natural EMERGY for the value of resources.

Evaluation of Major Accidents

The major accidents related to the commercial use of nuclear power are the Three Mile Island (TMI) accident in the U.S.A. and Chernobyl accident in the U.S.S.R. The TMI accident caused primarily economic damage which is composed of the following:

-Actual capital loss of facility

-Cleanup costs and replacement power

The cost for the loss of the facility and cleanup was approximately 1.35 billion dollars while replacement power purchases raised the cost to about 2 billion dollars (Greenwald, 1991). Of course the actual cost of the accident to the U.S. nuclear system was much higher due to increased regulation which is reflected in the increased cost of nuclear plant construction and maintenance. The capital cost was amortized over 30 years. Costs over the approximately 10 year cleanup period were spread over the 30 year life of the plant as with the capital cost. The annual EMERGY of TMI was 1.34E20 sej/yr, while the cumulative was 4.6E21 sej.

Though Chernobyl did not affect the United States directly it is of interest to see how such an accident would effect an EMERGY analysis for this power source. One way of considering the impact of the Chernobyl accident was to estimate the displaced productivity of land areas multiplied by the time of interruption. Then this EMERGY loss was prorated over the approximately 472 power plants operating and under completion globally. A cumulative

EMERGY loss of the Chernobyl accident was done for a time period of 300 years (10 half lives of Cs-137).

It might be unfair to add the Chernobyl accident to the U.S. Nuclear EMERGY analysis since EMERGY has already gone into the system to prevent such a disaster. EMERGY is added to the U.S. nuclear system as regulation (NRC) and added building materials (containment domes, safety systems). Regulation by the NRC insures that the design is safe, that inspections were made during construction and that personnel and the plant operate according to strict guidelines. The design of the Chernobyl reactor could not have been licensed in the U.S. since the core had a positive reactivity feedback coefficient. However, to do a conservative analysis the EMERGY loss of Chernobyl is divided by the total number of nuclear plants world wide. This EMERGY loss per plant per year is then added to the denominator in the net EMERGY Yield ratio for the U.S. analysis.

Design regulations for Light Water Reactors (LWR), which operate in the U.S., require many safety systems and a containment dome which can retain radioactivity in case of a severe accident (like Three Mile Island). Chernobyl type reactor designs have no containment domes, thus allowing radioactive contamination over a large area in the Ukraine and elsewhere in the U.S.S.R.

An evaluation was made of the impact if shared over the world nuclear power industry obtaining an impact per nuclear plant. The methodology in determining an EMERGY evaluation for Chernobyl was accomplished by an empower density analysis for land loss. By taking the areas of land impacted and their relative level of contamination an empower density (sej/km^2) for that type of land was used to obtain an EMERGY debt value per year. The U.S.S.R. has defined 3 contamination zones according to Cs-137 levels (Ginzburg, 1991). They are ;1) Closed Zone (>40 Ci/km^2), 2) Permanent Control (5<40 Ci/km^2), 3) Periodic Control Zone (>5 Ci/km^2) which were assessed the following degradation values:

1) 90% unusable-no human habitation or crops (2520 km^2)
2) 60% degradation of environment-may have animal habitation (10,000 km^2)
3) 30% degradation of environment-some human populations,crops (24,060 km^2)

A empower density (sej/km^2) value was multiplied by the area that applies to one of the categories above and by the percent degradation. The contaminated area is agricultural in nature so an empower density of 413E9 sej/m^2/yr (Brown, 1991) is used to convert land area to EMERGY. Land area contamination figures varied in the literature so the higher estimates were used here. For the foreseeable future the Closed and Permanent Zones will be for the most part unusable.

Another part of Chernobyl accident was the economic loss to the Soviet Union. The Soviet estimates of the monetary cost of the accident were transformed from currency to EMERGY with a sej/$ ratio for the U.S.S.R. realizing that the dollar/ruble exchange rate is variable if not questionable. The Soviet Union estimates that by the year 2000 as much as 300 billion rubles may be spent on cleanup and restoration. At the time of writing the commercial rate was 3 rubles to the dollar. Details of the analysis are located in Table G, Appendix A. An approximate EMERGY value for both land and economic loss from the Chernobyl accident is estimated below using the commercial exchange rate:

Chernobyl EMERGY Loss/yr = 1.91E22 sej/yr to year 2000
= 6.51E21 sej/yr after year 2000

For the 472 operating (and under completion) nuclear plants in the world the EMERGY per facility from the Chernobyl accident was 4E19 sej/yr before the year 2000. In the cumulative net EMERGY Yield analysis the Chernobyl EMERGY loss was not included since it occurred so recently. Though an estimate can be made for total EMERGY loss to a given future date it is difficult to estiamte the cumulative electrical yield to that date. For this reason the Chernobyl EMERGY debt was not included in the cumulative analysis. For the quasi-steady state analysis, however, a yearly EMERGY loss was included. An estimate as to the total future EMERGY loss was accomplished assuming that it would take 300 years to reduce contamination (10 half-lives of Cs-137) to negligible levels. Over this time period it was assumed that conditions improve as the radiation decays away. A linear approximation reduces the total by one half (see Table G).

TABLE 1

Cumulative EMERGY of U.S. Nuclear Power System

Note	Item	Raw Units	Solar EMERGY/unit sej/unit	Solar EMERGY E22 sej
Yield				
1.	Electrical Prod.	5885E6MWHe	7.2E14/MWHe	424
Feedback from the Economy				
2.	Administrative			15.07
3.	Construction			31.06
	Canceled Units	1.5E10$	2.5E12/$	3.75
4.	Operation & Maintenance			
	Fixed Cost			5.13
	Variable Cost			1.68
5.	Fuel Cycle			
	Gaseous Enrichment			24.1
	Waste: Energy for processing (.55% of 1kw produced)	(.0055) x 5885E6MWHe/y	7.2E14/MWHe	2.33
6.	Decommission	2.26E10$	1.6E12/$	3.62
7.	Three Mile Island	2.0E9$	2.3E12/$	0.46
8.	Steel, Concrete, Wood Copper, Aluminum			1.49
9.	Processing Energy* of Materials	4.2E17J	4.69E4/J	1.96
10.	Energy required for Construction	1.2E17J	5.3E4/J	0.63

*Possible double counting with EMERGY in item 8.

Footnotes to Table 1:

1. Electrical Production: Gross electrical production 1990 (1. Energy Economic Data Base, report to DOE, Phase 9 update July 1988, DOE-NE-0091; 2. Annual Energy Review, Energy Information Administration, Table 85, DOE/EIA-0384(88),1988)

   Values for Cumulative Electrical Production from Table B

   Elec. Production * Conversion Factors
   (86E4KC/MWHe)*(4186J/kcal)*(2E5sej/J) = 7.2E14sej/MWHe

   Net Electrical Production = 5885E6MWHe

   Note: 2E5sej/J ref. H.T. Odum, 1987

2. Administrative Costs: AEC/NRC/DOE costs (Annual Costs, DOE/EIA-0473(88), Office of EIA, Wash. D.C.) (see Table C, Appendix A)

3. Construction Costs: Average cost of nuclear units 1968-91 (Annual Energy Review,Nuclear Construction/EIA, Wash. D.C. DOE/EIA-0473(88)
   (see Table D,Appendix A)

   A weighted sej/$ ratio was used to reflect the time periods when these plants were built.

   An allowance is made here for canceled nuclear units and is added to the yearly cost of construction (15E9 dollars) (Greenwald, J. "Time to Choose",TIME Magazine pg. 54, April 29,1991).

   Note: 2.5E12sej/$ is the appropriate ratio for the time of cancellation

4. Operation and Maintenance:(Kylstra,C., Han, Energy Analysis of the US Nuclear Power System, Nuclear Engineering Sciences, University of Florida, Gainesville, 1975, pg 162.)

   (Analysis of the Cost of Electricity from Coal, Gas, Oil and Nuclear Power, USCEA, Washington D.C., 1991)

   (For details see Table E, Appendix A)

5. Fuel Cycle: Cost of different phases in fuel production (1.World Nuclear Fuel Cycle Requirements 1990, EIA, Wash. D.C. DOE/EIA-0436(90), 2. Kylstra c., Han K.,Emergy Analysis of the U.S. Nuclear Power System, Nuclear Engineering Sciences, University of Florida, Gainesville, 1975)

   Components of the fuel cycle are below:

Front End of Cycle, Mine+Mill+Convert+Enrich+Fabricate

Mine
1.64E5KC/Kg x 1.67E8sej/KC = 2.7E13 sej/kg
Mill
1.23E6KC/kg x 1.67E8sej/KC = 2.0E14 sej/kg
Conversion
1.34E5KC/kg x 1.67E8sej/KC = 2.2E13 sej/kg
Enrichment
3100(kwhe/kg of SWU) = 1.07E7(KC/kg SWU) at 100% capacity of facility
1.4E6 KC/kg SWU for depreciation and 80% capacity

4.306SWU and 6.4 kg U_3O_8 for 1 kg enriched 3% U235

4.306SWU/6.4kg x(1.07 + .14)E7 = 8E6KC/kg enriched

8E6KC/kg x 1.67E8 sej/KC = 1.33E15 sej/kg
Fabrication
$74/kg of Uranium, 80,000KC/$ for fabrication
increase $74/kg by factor of 3 for inflation from 1975

($74x3)(8E4KC/$)(1/6.4kg 3%) = 2.75E6 KC/kg
2.76E6 KC/kg x 1.67E8 sej/KC = 4.6E14 sej/kg

Total Front End of Fuel Cycle

(2.7E13 + 2.0E14 + 2.2E13 + 1.33E15 + 4.61E14)= 2.0E15sej/kg

This is used to estimate the EMERGY of the fuel cycle, for details see Table F, Appendix A.

Waste Processing

For disposal of nuclear waste an energy charge of 0.55% per 1KW of electricity produced was assessed.

Note: Tranformaties from Kylstra and Han

6. Decommissioning (USCEA, Advanced Design of Nuclear Energy Plants:EPRI/DOE ALWR program)

(200E6$/plant)*(113 nuclear plants) = $2.26E10

7. Three Mile Island (Greenwald,1991)

2.0E9$ for loss and cleanup
2.3E12sej/$ for an average ratio during the cleanup period

8. EMERGY of Building Materials (N.R.C., Final Environmental Impact Statement, Floating Nuclear Plants, Part II, Vol. 2, 1976)

(see Table 2, items 1 to 7)

The EMERGY of major building materials was calculated in Table 2 where 90% of the value found was used since the average installed capacity of nuclear units is below 1200MWe, which was the assumed size for the data (additive sum of items 1 to 7 in Table 2).

(1.65E22sej)*(0.9) = 1.49E22sej

9. EMERGY of Fossil Fuels used for Materials Processing (Final Environmental Statement, Floating Nuclear Plants, Part II, Volume 2, September 1976, pg 12-71 to 12-78)

The value here was found in Table 2 and multiplied by .9 because the estimate was for a 1100 MWe power plant.

Item	Quantity (T)	Process Energy (10^6Btu)	Energy(E19Btu)
Steel	55,000	26.5	1457
Cement	135,000	6.6	890
Wood	33,000	39	1287
Aluminum	500	155	77
Copper	4,000	47	188
Total			3899

Energy Required * Conversion * No. of Plants
(3899E12Btu/plant)*(1054J/Btu)*(113Plants)*(.9) = 4.2E17 J

10. EMERGY of Fossil Fuels used during Construction (Final Environmental Statement, Floating Nuclear Plants, Part II, Volume 2, September 1976, pg 12-71 to 12-78)
Estimated Fuel use was 1E12 Btus

Energy Required * Conversion * No. of Plants
(1E12Btu/plant)*(1054J/Btu)*(113plants) = 1.2E17 J

TABLE 1a

Annual EMERGY Flux of U.S. Nuclear Power System

Note	Item	Raw Units	Solar EMERGY/unit sej/unit	Solar EMERGY E22 sej/y
Yield				
1.	Electrical Prod.	606E6MWHe/y	7.2E14/MWHe	43.6
Feedback from the Economy (Services)				
2.	Administrative	1.0E9$/y	1.6E12/$	0.16
3.	Construction			
	a)completed	4.57E9$/y		1.14
	b)canceled units	4.95E8$/y	2.5E12/$	0.12
	c)5 power plants/yr	1.5E10$/y	1.6E12/$	1.92
4.	Operation & Maintenance			
	a)fixed cost	5.6E9$/y	1.6E12/$	0.89
	b)variable cost	6.6E8$/y	1.6E12/$	0.11
5.	Fuel Cycle			
	50% Centrifuge	1.77E7kg/y	1.39E15*(.7)	1.72
	Waste:			
	Energy to process (.55% of 1kw produced)	(.0055) x 606E6MWHe/y	7.2E14/MWHe	0.24
6.	Decommission	7.5E8$/y	1.6E12/$	0.12
	5 plants/yr	1E9$/y		0.16
7.	Three Mile Island	6.7E7$/y	2.3E12/$	0.015
8.	Steel,Concrete,Wood Copper, Aluminum			
	a) Existing plants			0.046
	b) 5 plants/yr			0.061
9.	Processing Energy* of Materials			
	a) Existing plants	1.4E16J	4.69E4/J	0.066
	b) 5 plants/yr	1.86E16J	4.69E4/J	0.087
10.	Energy required for Construction			
	a) Existing plants	4.2E15	5.3E4/J	0.022
	b) 5 plants/yr	5.6E15	5.3E4/J	0.030

*Possible Double counting of EMERGY with item 8.

Footnotes to Table 1a:

1. Electrical Production: Gross electrical production 1990 (1. Energy Economic Data Base, report to DOE, Phase 9 update July 1988, DOE-NE-0091; 2. Annual Energy Review, Energy Information Administration, Table 85, DOE/EIA-0384(88),1988)

   606E6MWHe electricity/y (1990 production)

   Conversion * Conversion * Transformity
   (86E4KC/MWHe)*(4186J/kcal)*(2E5sej/J)= 7.2E14sej/MWHe

2. Administrative Costs: AEC/NRC/DOE costs (Annual Costs, DOE/EIA-0473(88), Office of EIA, Wash. D.C.) (Table C, Appendix A)

   1990 appropriated 438.0E6 $, assume DOE contribution equal
   Total Administrative = $ 876E6/y

   Increase above figure to 1E9 $/y to cover increased NRC regulation for new plants being built.

3. Construction Costs: Average cost of nuclear units 1968-91 (Annual Energy Review,Nuclear Construction/EIA, Wash. D.C. DOE/EIA-0473(88)

   See Table C for details

   For the 5 plants per year completed it is assumed that each costs 3E9 dollars.

4. Operation and Maintenance:(Analysis of the Cost of Electricity from Coal, Gas, Oil and Nuclear Power, USCEA, Wash. D.C.,1991)

   Fixed Cost $61.1/KWe/yr installed capacity
   Installed Capacity = 91.88KWe (Table D)
   Yearly Power Production = 606E9KWhe (1990), (Table B)

   ($61.1KWe/yr)*(91.88E6KWe installed) = $5.6E9/yr

   Variable Cost 1.1 mill/KWHe generated

   ($.0011/KWHe)*(606E9KWHe/yr) = $6.6E8/yr

5. Fuel Cycle: Cost of different phases in fuel production (1.World Nuclear Fuel Cycle Requirements 1990, EIA, Wash. D.C. DOE/EIA-0436(90), 2. Kylstra c., Han K.,Emergy Analysis of the U.S. Nuclear Power System, Nuclear Engineering Sciences, University of Florida, Gainesville, 1975)

Components of the fuel cycle are below:

Front End of Cycle, Mine+Mill+Convert+Enrich+Fabricate

Mine
1.64E5KC/Kg x 1.67E8sej/KC = 2.7E13 sej/kg

Mill
1.23E6KC/kg x 1.67E8sej/KC = 2.0E14 sej/kg

Conversion
1.34E5KC/kg x 1.67E8sej/KC = 2.2E13 sej/kg

Enrichment
3100(kwhe/kg of SWU) = 1.07E7(KC/kg SWU) at 100% capacity of facility
1.4E6 KC/kg SWU for depreciation and 80% capacity

4.306SWU and 6.4 kg U_3O_8 for 1 kg enriched 3% U235

4.306SWU/6.4kg x(1.07 + .14)E7 = 8E6KC/kg enriched

8E6KC/kg x 1.67E8 sej/KC = 1.33E15 sej/kg

Fabrication
$74/kg of Uranium, 80,000KC/$ for fabrication
increase $74/kg by factor of 3 for inflation from 1975

($74x3)(8E4KC/$)(1/6.4kg 3%) = 2.75E6 KC/kg
2.76E6 KC/kg x 1.67E8 sej/KC = 4.6E14 sej/kg

Total Front End of Fuel Cycle

(2.7E13 + 2.0E14 + 2.2E13 + 1.33E15 + 4.61E14)= 2.0E15sej/kg

50/50 Enrichment by Centrifuge and Diffusion

This case uses 51% of the energy of 100% diffusion enrichment which gives:

.51*(1.33E15)=6.78E14sej/kg;

Front end EMERGY is 1.39E15sej/kg

Note: In Table 1 item 5 the values for fuel fabrication are multiplied by .7 to account for the Plutonium credit since 30% of the core energy comes from creation of Pu-239 from Ur-238.

Transformities from Kylstra and Han

6. Decommissioning (USCEA, Advanced Design of Nuclear Energy Plants:EPRI/DOE ALWR program)

Decommissioning = 200E6$/Power Plant

(200E6$/plant)*(113 nuclear plants)/30y = $7.5E8/yr

5 Plants/yr
(200E5$/plant)*(5 Plants) = 1E9$/yr

7. Three Mile Island (Greenwald, 1991)

2.0E9$/30 year depreciation = 6.7E7$/y
2.3E12sej/$ as an average ratio for the time of cleanup

8. EMERGY of Building Materials (see Table 2)

The EMERGY of major building materials was calculated in Table 2 where 90% of the value found was used since the average installed capacity of nuclear units is below 1200MWe, which was the assumed size for the data.

Values from Table 2 were divided by 30 years for existing power plants.

9. EMERGY of Fossil Fuels used for Materials Processing (Final Environmental Statement, Floating Nuclear Plants, Part II, Volume 2, September 1976, pg 12-71 to 12-78)

The value here was found in footnotes to Table 1 and multiplied by .9 because the estimate was for a 1100 MWe power plant.

Values were divided by 30 years for existing power plants.

a) 4.2E17J/(30y) = 1.4E16J/y

b) (3.72E15J/plant)*(5 plants/y) = 1.86E16J/y

10. EMERGY of Fossil Fuels used during Construction (Final Environmental Statement, Floating Nuclear Plants, Part II, Volume 2, September 1976, pg 12-71 to 12-78)
Estimated Fuel use was 1E12 Btus

Energy Required * Conversion * No. Plants

a) (1E12Btu/plant)*(1054J/Btu)*(113plants)/30y = 4.2E15 J/y

b) (1E12Btu/plant)*(1054J/Btu)*(5 plants/y) = 5.6E15J/y

TABLE 2

Cumulative Natural Resources to U.S. Nuclear Power System

Note	Item	Raw Units	Transformity sej/unit	Solar EMERGY E22 sej
1.	Concrete	2.88E13g	2.4E8sej/g	0.69
2.	Structural Stl	3.3E6T	1.78E15sej/T	0.58
3.	Piping Steel	5.1E5T	1.78E15sej/T	0.091
4.	Major Comp.	4.2E5T	1.78E15sej/T	0.075
5.	Copper	4.52E5T	2E15sej/T	0.09
6.	Aluminum	5.13E10g	1.63E10sej/g	0.084
7.	Wood	5.6E16J	6.7E3sej/J	0.037
8.	Uranium Ore	6.34E18J	1790sej/J	11.06

*all values of building materials were for a 1200MWe power plant

ref. Transformities from Odum, Environmental Analysis of Environmental Value, University of Florida, Center for Wetlands, 1987.

Footnotes to Table 2:

1. Concrete: (Economic Energy Data Base, EEDB, Phase 9 Update, DOE-NE-0091)

   Concrete/plant* Conversion * Density * No. Plants

(132,000yrd^3/plant)*(7.7E5cm^3/yrd^3)*(2.5g/cm^3)*(113plants)=2.88E13g

2. Structural Steel: (Ibid ref.1)

   Steel/plant * No. Plants
   (29,000T)*(113 plants) = 3.3E6 T

3. Piping Steel: (Ibid ref.1)

   (4500T)*(113 plants) = 5.1E5 T

4. Large Plant Components: (Systems Summary of Westinghouse Pressurized Water Reactor, Westinghouse Electric Corp. Aug 1973)

   Reactor Vessel & Head = 350 Tons
   Steam Generator (400T@4) =1600 Tons
   Turbine/Generator(2E6lbs) =1000 Tons
   Transformers (3@250T) = 750 Tons
   Total 3700 Tons
   Add 50% for all other smaller pumps, heat exchangers and tanks

   (3700 T x 1.5 x 113 plants) = 4.2E5 Tons

5. Copper (Final Environmental Statement, Floating Nuclear Power Plants, Part II, Volume 2, NRC)

   (4000T/plant)*(113 plants) = 4.52E5T

6. Aluminum (Final Environmental Statement, Floating Nuclear Power Plants, Part II, Volume 2, NRC)

   (500T/plant)*(113 plants)*(2000lbs/T)*(450g/lb) = 5.1E10g

7. Wood (Final Environmental Statement, Floating Nuclear Power Plants, Part II, Volume 2, NRC)

   (33,000T/plants)*(2000lbs/T)*(450g/lb)*(113plants)=3.4E12g
   (3.4E12g)*(4kcal/g)*(4186J/kcal) = 5.6E16J

8. Uranium Ore: (World Nuclear Fuel Cycle Requirements 1990, Energy Information Administration,DOE/EIA-0436(90) Wash.D.C.)

   (38.9E6lbs/y U3O8)*(238U/336U3O8)*(.007U235)*(450g/lb)
   *(7.95E10J/gU235) = 6.34E18 J/y

TABLE 2a

Annual Natural Resources to U.S. Nuclear Power System

Note	Item	Raw Units	Transformity sej/unit	Solar EMERGY E22 sej/y
1.	Concrete	9.63E11g/y	2.4E8sej/g	0.023
	5 plants/y	1.28E12g/y		0.031
2.	Structural Stl	1.1E5T/y	1.78E15sej/T	0.019
	5 plants/y	1.45E5T/y		0.025
3.	Piping Steel	1.7E4T/y	1.78E15sej/T	0.003
	5 plants/y	2.25E4T/y		0.004
4.	Major Comp.	2.1E4T/y	1.78E15sej/T	0.0037
	5 plants/y	2.78E4T/y		
5.	Copper	1.5E4T/y	2E15sej/T	0.003
	5 plants/y	4E4T/y		0.008
6.	Aluminum	1.7E9g/y	1.63E10sej/g	0.003
	5 plants/y	2.3E9g/y		0.0038
7.	Wood	1.9E15J	6.7E3sej/J	0.0013
	5 plants/y	2.5E15		0.0017
8.	Uranium Ore	6.34E18J/y	1790sej/J	1.14

*all values of building materials are 1200MWe power plant

ref. transformities from Odum, Energy Analysis of Environmental Value, University of Florida, Center for Wetlands, 1987

Footnotes to Table 2a

1. Concrete: (Economic Energy Data Base, EEDB, Phase 9 Update, DOE-NE-0091)

   Concrete/plant*Conversion*Density *No. Plants
   (132,000 yrd^3)*(7.7E5cm^3)*(2.5g/cm^3)*(113 plants)/30yr=9.6E11g/y

   5 plants
   (132,000 yrd^3)*(7.7E5cm^3)*(2.5g/cm^3)*(5plants/y) = 1.28E12g/y

2. Structural Steel: (Ibid ref.1)

   (29,000T/plant)*(113 plants)/30y =1.1E5 T/y

   5 plants
   (29,000T/plant)*(5plants/y) = 1.45E5T/y

3. Piping Steel: (Ibid ref.1)

   (4500T/plant)*(113 plants)/30y = 1.7E4 T/y

   5 Plants
   (4500T/plant)*(5plants/y) = 2.25E4T/y

4. Large Plant Components: (Systems Summary of Westinghouse Pressurized Water Reactor, Westinghouse Electric Corp. Aug 1973)

   Reactor Vessel & Head = 350 Tons
   Steam Generator (400T@4) =1600 Tons
   Turbine/Generator(2E6lbs) =1000 Tons
   Transformers (3@250T) = 750 Tons
   Total 3700 Tons
   Add 50% for all other smaller pumps, heat exchangers and tanks

   (3700 T x 1.5 x 113 plants)/30yrs = 20950 Tons/yr

   5 plants
   (3700T/plant x 1.5 x 5plants/y) = 2.78E4 T/y

5. Copper (Final Environmental Statement, Floating Nuclear Power Plants, Part II, Volume 2, NRC)

   (4000T/plant)*(113 plants)/30 years = 1.5E4T/y

   5 plants
   (4000T/plant)*(5 plants/y) = 4E4T/y

6. Aluminum (Final Environmental Statement, Floating Nuclear Power Plants, Part II, Volume 2)

(500T/plant)*(113 plants)*(2000lb/T)*(450g/lb)/30 years = 1.79E9g/y

5 plants
(500T/plant)*(5 plants)*(2000lb/T)*(450g/lb)/30 years = 2.3E9g/y

7. Wood (Final Environmental Statement, Floating Nuclear Power Plants, Part II, Volume 2)

(33,000T/plants)*(2000lbs/T)*(450g/lb)*(113plants)=3.4E12g
(3.4E12g)*(4kcal/g)*(4186J/kcal)/30 years = 1.87E15 J
(33,000T/plants)*(2000lbs/T)*(450g/lb)*(5plants)=1.5E11g
(1.5E11g)*(4kcal/g)*(4186J/kcal) = 2.5E15 J

8. Uranium Ore: (World Nuclear Fuel Cycle Requirements 1990, Energy Information Administration,DOE/EIA-0436(90) Wash.D.C.)

(38.9E6lbs/yU3O8)*(238U/336U3O8)*(.007U235)*(450g/lb)
*(7.95E10J/gU235) = 6.34E18 J/y

TABLE 3

Calculation of Net EMERGY Yield Ratio

1. Net EMERGY Yield Ratio = Y/(F)

a. Cumulative

Y = line 1 of Table 1 = 424.6E22sej
F = line 2,3,4,5,6,7,8,9,10 of Table 1

Adim.+ Const.+ Cancel+ O&M + Fuel Cycle + Waste + Decomm + TMI + Material EMERGY + Process EMERGY + Const. EMERGY = Total

15.07+31.06 + 3.75 + 6.81 + 24.1 + 2.33 + 3.67 +.46
+ 1.49 + 1.96 + 0.63 = 91.3

Net EMERGY Yield Ratio = 424E22sej/91.3E22sej = 4.64

b. Quasi-Steady State Case

Y = line 1 of Table 1a = 43.6E22sej/yr
F = line 2,3,4,5,6,7,8,9,10 of Table 1a

Adim.+ Const.+ Cancel + O&M + Fuel Cycle + Waste + Decomm + TMI + Material EMERGY + Process EMERGY + Const. EMERGY = Total

0.14 + 3.06 + 0.15 +1.0 + 1.72 + 0.24 + 0.28 + .015
+ 0.126 + 0.153 + 0.052 = 6.78 sej/y

Net EMERGY Yield Ratio = 43.6E22sej/6.78E22sej = 6.28

Including Chernobyl EMERGY loss
(Table G)

EMERGY loss =(4E19sej/yr/plant)x(113 plants)= 0.45E22 sej/y

Net EMERGY Yield Ratio = 43.6E22sej/7.23E22sej = 5.9

RESULTS

The contents of Table 1 are divided into the Yield (Y) of electrical production (item 1) and the Feedback (F) (items 2-10) from the economy (inputs to the nuclear system) which consists of administrative, construction, operations and maintenance, fuel cycle, decommissioning and materials EMERGY requirements. Items 2 through 10 represent the effort (EMERGY) society and nature expended in order to build, operate, regulate, fuel and cleanup the U.S. civilian nuclear power industry.

The administrative costs of both the Nuclear Regulatory Commission (NRC) and the Department of Energy (DOE) are converted to EMERGY using an average EMERGY(sej)/dollar ratio for the U.S. economy. For determining the construction EMERGY (item 3) the appropriate EMERGY(sej)/dollar ratio was used for the time period in which nuclear plants were built. The value of sej/$ varies with time which can be seen in Table I, Appendix A. For item 4, the operation and maintenance EMERGY was calculated for both fixed and variable costs. Fixed costs represent the effort required to maintain existing power plants while the variable cost represents what is required to support operations which depends energy production (there was a range of estimating O&M costs so the more expensive one was used).

The fuel cycle EMERGY was calculated for the year 1990 and then this usage was then applied to the previous years according to the amount of power produced for that year. Table F has the calculations for the fuel cycle by year according to the power production. For item 6 in Table 1 the decommission EMERGY was determined by the 200 million dollars required for each power plant to be decommissioned times the sej/$ ratio for the present day (1990). The Three Mile Island accident (item 7, Table 1) was converted to EMERGY using an average sej/$ ratio for the time period of the cleanup.

Table 1a contains the same data as Table 1 except that it was not cumulative, but rather, it was on an annual basis. Data for the items from Table 1 for (F) were assessed over the 30 year lifetime of the nuclear plant with the last years energy production used for the yield (Y). Another difference utilized for the quasi-steady state case in Table 1a was the addition of 5 plants per year being completed in a renewed nuclear program. The EMERGY of construction for these power plants was not assessed over the 30 year lifetime like those that have already been completed. Instead the EMERGY for all 5 was added in for 1 year since those resources would be required then to complete them while others are being built.

Table 2 represents the EMERGY of materials (purchased inputs) to construct the power plant (items 1-9), the change in resource flow of natural energies at power plant site. This list represents only the major items involved with nuclear plant construction and does not include the labor required to build the nuclear facilities which was included in services of Table 1 and Table 1a. These items can be considered as the materials (M), fossil fuels (N_f), nuclear fuel (N) and natural resources (R) that are in Figure 1.

For the quasi-steady state case in Table 2a for the annual natural resource flows the same type of analysis in Table 2 was applied here except that it is assessed over the 30 year life of the facilities. The 5 power plants that were being completed have their material needs assessed for that year.

Table 3 has the EMERGY indices calculated for the Net EMERGY Yield ratio for both the cumulative and quasi-steady state cases. As performed in the previous 1975 study the EMERGY Yield ratio was determined by dividing the electrical yield by items 2-10 in Table 1. The Net EMERGY Yield Ratio for the cumulative case was determined to be 4.6. For quasi-steady state case the net EMERGY Yield Ratio was determined to be 6.28 to 1, but when considering the Chernobyl EMERGY loss the same ratio was 5.9 to 1..

sources as fossil fuels diminish. With a cumulative net EMERGY Yield ratio of 4.6 nuclear power can accomplish the task of replacing some portion of present day fossil fuels. The environmental impact on local environments was minimal since nuclear plants displaced very little land area.

Orders for new nuclear plants have been almost nonexistent for over a decade in the United States. Of the many aspects listed in Table 1 the ones which could be improved with existing technology are the construction phase and fuel cycle. A positive scenario for nuclear power, which was not analyzed would be:

1) Most fuel being enriched with centrifuge processes
2) Reprocessing and recycling fuel with breeder reactors
3) Lower the construction cost with more efficient methods

Of the three items above the author has personally developed a new approach for the third component, construction, with modular design and fabrication processes. However, until new power plants are ordered and built with these techniques this case can not be analyzed realistically, but some speculations were made as in the quasi-steady state case by assuming 3 billion dollars per power plant (1000MWe) for capital costs. Using more efficient construction methods and standard designs could allow the capital cost of nuclear plants to be reduced which would increase the net EMERGY yield ratio. The second item, fuel reprocessing, cannot be analyzed yet since the U.S. has no on going breeder reactor program from which to gather data.

The first possibility can be addressed, though it might not

DISCUSSION

Compared to the previous study (Kylstra, Han, 1975) the higher net EMERGY yield ratio indicates that nuclear power was producing more energy per unit energy used than in the early to mid-seventies. This is somewhat expected since at that time nuclear power was in an infant stage with its high associated start-up costs. With nuclear power in a mature quasi-steady state mode a more realistic examination of its contribution to society was assessed.

Results of this study show that nuclear power is a beneficial source of energy production which helps maintain a healthy economic base. Even with the many plant cancellations, Three Mile Island and Chernobyl the Net EMERGY Yield ratio still compared favorably with other energy sources. Most fossil fuels today have ratios of 6/1 for heat conversion and 2.5/1 for heat to electrical conversion which is lower than that for nuclear power (4.6). The higher value for the quasi-steady state case as compared to the cumulative case indicates the previous investment in nuclear power used inexpensive fossil fuels and the associated lower construction costs. Since the investment has already been made further investment today would be beneficial tomorrow.

As nuclear power evolves from a construction phase to a quasi-steady state production phase, it displaces scarcer fossil fuels. The fossil fuels of today help build the nuclear power of tomorrow until nuclear power can subsidize itself and other new energy happen for some years to come. Using a situation with increased centrifuge enrichment of uranium-235 (which uses only 4% of the energy of gaseous diffusion) the fuel cycle EMERGY would decrease. The result would increase the Net EMERGY Yield ratio for the U.S. nuclear industry.

The net EMERGY Yield ratio varies somewhat with the average capacity factor (percentage of time reactor is operating) of U.S. reactors. In the past U.S. capacity factors have not been as high as in some of the other industrialized countries, but this trend is changing and should increase for the future. An increased capacity factor will increase the net EMERGY yield ratio as more energy is produced from existing resources.

Comparison with other Fuel Sources

The values represented here should be compared with other energy sources like oil, coal and solar energy. In analyzing other energy sources one must take into account the environmental impact of transporting and burning fossil fuels and the use of land/resources for solar power. A sound energy policy should maximize the energy source that has the highest Net EMERGY Yield ratio, while considering environmental and resource impact. To maximize energy utilization the quality of the energy used should match the quality of its use. For instance high quality electricity should be used for high quality use such as driving machinery while lower quality (diffuse) solar energy would be well suited for heating domestic water and heating enclosed buildings.

Compared to the net EMERGY yield ratios for some renewable energy sources like wind generated electricity which is 0.28 (Odum, et al, 1976) nuclear power is much higher. When the net EMERGY yield ratio is less than 1 more units of effort are put in the process than are received out of the process.

Amount of Electrical Generation

Another factor to consider in this study is the amount of electricity that could be used in the U.S. economy. A completely electric economy is not feasible and not necessarily efficient. The use of electricity for low quality uses does not maximize useful power, but using it to amplify lower quality resources is efficient. The ratio of electricity to fuel source depends on the position of the economy in world energy hierarchy. The percentage of electricity for the total energy use in the U.S. economy has been increasing over the past several decades as the U.S. becomes one of the centers of high quality energy.

At the time of this study the percentage of electric energy usage was 35% of the total energy mix. More highly developed industrialized countries tend to have a higher percentage of their energy usage from electricity. Whether the future energy mix will include a greater amount of electrical generation relative to other energy forms depends on the total world growth and the position of the U.S. in that growth.

The use of electricity as a feedback to lower quality energies in order to increase their resource flow would allow the whole system (the U.S. economy) to operate at higher maximum power.

Nuclear plants are also used in some countries as a heat source for district heating and some industrial processes may use high temperature gas cooled reactors as an energy source.

Resource Limitations

The reserves of uranium are also limited which gives a limit to the amount of time present day reactors could operate. Uranium ore concentrations will diminish over time as the top grade mines become depleted. Mining uranium from very low concentration ores requires more energy to be expended in the fuel cycle which in turn reduces the Net EMERGY Yield ratio for nuclear power. In order for nuclear power to last for any amount of time beyond the middle of the next century there would have to be a breeder reactor program utilizing the already mined uranium-238 for use as a fuel.

CONCLUSIONS

The analysis of the U.S. Nuclear Power System shows that according to the Net EMERGY yield ratio nuclear power over the last 30 years generated more electricity per unit contribution from the economy than fossil fuel plants. Nuclear plants are almost on par with fossil fuels (6/1 heat conversion) as a general energy source when analyzed in the quasi-steady state case (6.28), even when considering the Chernobyl EMERGY loss (5.9).

Since the most effective use of electrical energy is in interactive amplification of lower quality sources, the need for nuclear electricity will depend on the position of a country in the world economic hierarchy. The use of nuclear power to produce electricity could help the demand for electricity during the time when uranium resources are still available at reasonable cost.

APPENDIX A

TABLE A

Nuclear Energy System Flows (1970)

Item	Steady State 1970 (10E12 KC/yr)	Accumulated 1972 (10E12 KC)
1. Electrical Production	77.8 (3.71E22sej/y)	495(2.36E23sej/y)
Economic Feedback		
2. Atomic Energy Commission	15.2 (7.25E21sej/y)	709(3.38E23sej/y)
3. Completed or under construction	1.92 (9.1E20sej/y)	238(1.14E23sej/y)
4. Operation and Maintenance	.9 (4.2E20sej/y)	8.4 (4E21sej/yr)
5. Fuel Cycle	10.8 (5.13E21sej/y)	525 (2.5Esej/y)
Total	28.8 (1.37E22sej/y)	1480 (7E23sej/y)
Net(Yield-Feedback)	49.0 (2.34E22sej/y)	-985.4(4.7E23sej/y)

Net EMERGY Yield Ratio = Yield/Feedback = 77.8/28.8 = 2.7

ref. Kylsrta, C. and Han, K., Energy Analysis of the U.S. Nuclear Power System, University of Florida, Gainesville, FL, 1975

Footnotes to Table A: Taken verbatum from Kylstra and Han

1. Gross Production

a. 1970 Typical and Steady State Flows
1970 Central Power Station production was 23.6E6MWHe at a load factor of 38%. Using the average load factor of 46.6%, a more typical value should have been 28.6E6MWHe. Converting into fossil fuel equivalent units,

$$(28.9\text{E6 MWHe/yr})*(1\text{heat}/.32\text{elec})*(86\text{E4KC/MW}) = 77.8\text{E12KC/y}$$

b. 1972 Accumulated
Accumulated production through 1972 was 184..2E6 MWHe

$$(184.2\text{E6MWHe})*(86\text{E4KC}/.32\text{MWHe}) = 495\text{E12 KC}$$

2. AEC Related

The AEC affects all phases of the nuclear system, through regulation, control, research, development, and operation and ownership of facilities. Additional efforts in the areas of fusion, military, and other activities complicated determination of dollar and energy expenditures related to the U.S. Nuclear Power system (Light Water and Breeder reactors)

a. 1970 Typical Flow
For 1970 the total budget was 1.866E9$, a lower value than previous or later years. Using $2E9 as a more representative value, and estimating that approximately 50% of the AEC's activities are Nuclear System related, gives

$$(\$2\text{E9})*(24{,}300\text{ KC}/\$)*(.5) = 24.3\text{E12 KC/yr}$$

b. 1970 Steady State Flow
Research and development would be minimal at steady state, plus all aspects of regulation. The fuel cycle would be proportional to the steady state level of reactors. Assume that mining and enriching activities reduced by the ratio of U-235 consumption to production in 1970 (9.4%), reactor development cut to zero, and the rest of the AEC activities continued at 1970 rates, thus, the steady state costs would be,

$$[(181\text{E6})*(.094)+(210\text{E6})*(0)+(609\text{E6})]*24{,}300\text{KC}/\$ = 15.2\text{E12KC/y}$$

c. 1972 accumulated
Accumulated dollar and energy costs through 1972 equal 42.44E9 dollars and 1,418E12 KC. The energies were obtained by using the appropriate energy to $ conversion ratio for that year. Estimating that overall of the years, approximately 50% of the AEC's activities are nuclear system related gives,

(1,418E12 KC)*(.5) = 709E12 KC

3. Construction of Power Plants

The long construction time associated with nuclear power plants means that society supplies the necessary energy over a 6 to 10 year period. It is assumed for this report that the energy is supplied uniformly over time during the construction period. Thus, both the ordering rate and completion rate of power plants are important.

Since the money paid for power plants flows throughout the nuclear supply and manufacturing industry, the material, labor operating, direct use of fossil fuels, and capital equipment dollar and energy costs can best be estimated by using the overall economy to dollar ratios.

a. 1970 Typical Flows

Completion rate in 1970 was 2,658 MWe of capacity. A value of 2,400 MWe is more representative of the trend during this period. Using a 1966 energy to dollar ratio of 28,200KC/$, as representative of the average energy cost over the construction period, yields

(2,400 MWe/yr)*(150E3$/MWe)*(28,200KC/$) = 10.1E12KC/yr

The ordering rate in 1970 was typically 15,400 MWe. Using an estimated 1975 energy/dollar ratio of 19,000KC/$ to represent the average energy cost of the construction time and an estimated $400/kw for the cost gives,

(15,400MWe/yr)*(400E3$/MW)*(19,000KC/yr) = 117E12KC/yr

This represents a 1.8 times greater energy cost per MWe for new orders versus completed plants. This seems like a large increase, yet the greater delays, legal entanglements, safety equipment requirements, AEC regulations, etc. are certainly adding to the energy cost of nuclear power plants.

b. 1970 Steady State Flow

If the reactors existing in 1970 were replaced with new plants at the depreciation rate, a steady state would exist. Power plant completions in 1970 total 59.35E12 KC of energy expended. Using 3.3% as the depreciation rate (30 yr lifetime) gives,

(59.35E12KC)*(3.3%/yr) = 1.96E12 KC/yr

c. 1972 Accumulated

Completion rates of power plants in 1972 total 87.9E12 KC of expended energy throughout the nuclear industry. Energy already expended for power plants under construction was estimated using the number of power plants under construction in early 1970 as 39,288 MWe. Assuming that 1/2 of the energy was expended by 1972, and using the same constants as in 3a, gives

(39,288MWe)*(.5)*(400E3$/MWe)*(19,000KC/$) = 150E12 KC
Thus the total accumulated is 237.9E12 KC

4. Operation and Maintenance
The operating and maintenance cost for supporting industry for power plants was included in item 3. For power plants direct operating and maintenance costs are estimated as 10% of the total production cost, or 1.5% of the total capital cost.

a. 1970 Typical and Steady State Flow
Using the total energy of 59.35E12KC as the stored energy in power plants in 1970, the operation and maintenance expenses were,

(0.15)*(59.35E12KC/y) =0.9E12 KC/yr

b. 1972 Accumulated Flow
The accumulated operation and maintenance flows were obtained from by multiplying accumulated structure for each year by 1.5%
and accumulating through 1972,

(560E12 KC-yr structure)*(0.15cost/yr struc.) = 8.4E12 KC

5. Fuel Cycle
The fuel cycle includes everything from the Uranium ore in the ground to the storage of radioactive waste, plus the recycling of spent fuel and plutonium and uranium. The direct AEC costs associated with fuel cycle were already included in item 2.

a. 1970 Typical year
The sum of the mining, milling, conversion, enrichment, and fabrication cost for 1970 was 98.23E12 KC/yr, producing 1,086E12 KC/yr of U-235 fuel. The other direct society costs were related to the actual use rate of U-235, of 102E12 KC/yr. These were the reprocessing costs of 1.83E12 KC/yr and the 1970 cost for radioactive waste disposal, of 4.3E12 KC/yr. Thus, the total fuel cycle costs were

[98.23 + 1.83 + 4.3]E12 = 104.36E12 KC/yr

b. 1970 Steady State
If the processing of uranium matched the 1970 consumption rate, the 98.23E12 KC/yr figure from item 5a above would be reduced to 9.23E12 KC/yr. The reprocessing and waste disposal costs would be the same. Thus, the total is

[9.23 + 1.83 + 4.3]E12 = 15.36E12 KC/yr

This value must be further reduced by the amount of plutonium produced and consumed in the reactor. Estimating that approximately 30% of power comes from plutonium yields 10.75E12 KC/yr.

c. 1972 Accumulated
Mining and milling costs were 1.4E16 KC/Kg of U3O8. 65,900 tons were mined for domestic power use by 1972.

(65.9E6 Kg)*(1.4E6KC/Kg) = 92E12 KC

Conversion, enrichment, and fabrication cost was 9.05E6 KC/Kg of U3O8, 43,500 tonnes were delivered to power companies by 1972.

(43.5E6 Kg)*(9.05E6 KC/kg) = 394E12 KC

Reprocessing costs were related to the total burn up or consumption of uranium. This was estimated from electrical production,

[(495 Accumulated)/77.8 (1970)]*(1.83E12) = 11.64E12 KC

Waste disposal costs were related to production, and thus were,

(495/77.8)*(4.3E12) = 27.35E12 KC/yr

Thus, total cumulative fuel cycle costs were

[92 + 394 + 11.6 + 27.4]E12 = 525E12 KC

TABLE B

Annual Nuclear Electrical Energy Production

Year	Nuclear 10^9kwhrs	Accumulated 10^9kwhrs
1960	1	1
1961	2	3
1962	2	5
1963	3	8
1964	3	11
1965	4	15
1966	6	21
1967	8	29
1968	13	42
1969	14	56
1970	22	78
1971	38	116
1972	54	170
1973	83	253
1974	114	367
1975	173	540
1976	191	731
1977	251	982
1978	276	1258
1979	255	1513
1980	251	1764
1981	273	2037
1982	283	2320
1983	294	2614
1984	328	2942
1985	384	3326
1986	414	3740
1987	455	4195
1988	527	4722
1989*	557	5279
1990*	606	5885
Steady State	606	
Total		5885

ref. Annual Energy Review, DOE/EIA-0384(88)
ref. Energy and Economic Data Base, DOE-NE-0091, Phase 9 Update

TABLE C

AEC, NRC Budget 1960-1990

Date	Raw Units A	$\$x10^6$ B	Transformity sej/$	Solar EMERGY E22sej/y
1960	1823	911.5	11.7E12	1.07
1961	1818	909	11.5E12	1.04
1962	1815	907	10.8E12	0.97
1963	2394	1197	10.5E12	1.20
1964	2017	1008	9.9E12	0.99
1965	2000	1000	9.4E12	0.94
1966	1916	958	8.9E12	0.85
1967	1761	880	8.4E12	0.73
1968	1983	991	7.9E12	0.78
1969	1964	982	7.6E12	0.74
1970	1685	842	7.3E12	0.61
1971	1758	879	6.8E12	0.59
1972	1741	871	6.4E12	0.55
1973*	1800	900	5.8E12	0.55
1974*	1800	900	5.3E12	0.48
1975	184.1	368	5.5E12	0.20
1976	199.3	398	4.4E12	0.17
	67.3	134	4.4E12	0.06
1977	253.9	507.8	4.1E12	0.21
1978	287.7	575.4	3.7E12	0.21
1979	326.4	575.4	3.2E12	0.21
1980	396.1	792.2	2.9E12	0.23
1981	448.7	897.4	2.5E12	0.22
1982	466.5	933	2.3E12	0.21
1983	467.1	934	2.2E12	0.21
1984	475.3	950	2.0E12	0.19
1985	445.4	891	1.9E12	0.17
1986	409.8	817	1.8E12	0.15
1987	406.9	813.8	1.7E12	0.14
1988	397.5	795	1.6E12	0.13
1989*	421.0	842	1.6E12	0.13
1990*	438.0	876	1.6E12	0.14
Total				15.07

*estimates

Note: values from 1960 to 1974 are AEC which were divided by 2 to account for civilian use giving the value in column B.
Note: values from 1975 to 1990 are NRC so it is doubled to account for budget in DOE used for civilian purposes in column B.
ref. AEC costs: Kystra,C.,Han,K., Energy Analysis of the U.S. Nuclear Power System, University of Florida, 1975, pg. 193
ref. NRC costs: Annual Costs DOE/EIA-0473(88), USCEA, Wash. D.C.

TABLE D

Nuclear Plant Construction Costs

The cost of construction is calculated by using the average cost of construction per kilowatt installed (mixed current$) in a given time period times number of kilowatts installed in that period. This is then multiplied by the average sej/$ in that period to get total EMERGY.

Time period	Ave Cost ($/kw)[1]	Kw built E6kw[2]	Cost E9$	Ratio sej/$	EMERGY E22sej/y
1960	1000	375	.38	11.7E12	0.44
1962	800	335	.27	10.8E12	0.29
1963	700	68.5	.05	10.5E12	0.05
1966	250	800	.20	8.9E12	0.18
1967	200	1045	.27	8.4E12	0.22
1968-71	161	7.32	1.2	7.4E12	0.89
1972-73	217	8.63	1.9	6.1E12	1.16
1974-75	404	16.3	6.6	5.4E12	3.56
1976-78	623	9.2	5.7	4.1E12	2.34
1979-84	1373	17.4	24.0	2.5E12	6.0
1985-86	2416	15.3	37.0	1.85E12	6.8
1987	4057	4.85	20.0	1.7E12	3.4
1988	3085	6.88	21.0	1.6E12	3.36
1989	2631	3.00	7.8	1.6E12	1.25
1990*	4000	3.00	12.0	1.6E12	1.92
Totals		91.88	137.2		31.86

ref. 1960-67, Kylstra,C., Han, K., Energy Analysis of the U.S. Nuclear Power System, University of Florida, 1975.
ref.1969-90, Nuclear Power Plant Construction Activity, Energy Information Administration, DOE/EIA-0473(88) Wash.
ref. Nuclear Plant Construction,Nuclear News/August 1989 pg.91
*estimate

TABLE E

Operation and Maintenance Calculations

1. Fixed Costs for installed capacity

Time period	Accum.Cost E9$	Ratio sej/$	EMERGY E22sej/y	O&M EMERGY @3% E22sej/y
1960	.38	11.7E12	0.44	0.013
1962	.65	10.8E12	0.70	0.021
1963	.70	10.5E12	0.74	0.022
1966	.90	8.9E12	0.80	0.024
1967	1.17	8.4E12	0.98	0.029
1968-71	2.37	7.4E12	1.75	0.053
1972-73	4.27	6.1E12	2.60	0.078
1974-75	10.87	5.4E12	5.87	0.176
1976-78	16.57	4.1E12	6.79	0.204
Total				0.62

Time Period	Kw Built E6kw	O&M Cost $/kwe	O&M Cost $E9	Ratio sej/$	O&M EMERGY E22sej/y
1979-84	61.45	41.8	2.56	2.5E12	0.64
1985-86	76.75	46.5	3.50	1.85E12	0.65
1987	81.6	51.0	4.2	1.7E12	0.71
1988	88.48	54.0	4.7	1.6E12	0.75
1989	91.48	57.0	5.2	1.6E12	0.83
1990*	94.48	61.1	5.8	1.6E12	0.93
Total					4.51

Total Fixed Operations & Maintenance EMERGY = 5.13E22 sej

ref. EPRI, Technical Assistance Guide, 1991

TABLE E Continued

Operation and Maintenance Calculations

2. Variable Cost

Year	Accumulated 10^9kwhrs	O&M Cost $E6	Ratio E22sej/$	O&M EMERGY E20 sej/y
1960	1	1.1	11.7	0.129
1961	3	3.3	11.5	0.253
1962	5	5.5	10.8	0.24
1963	8	8.8	10.5	0.35
1964	11	12.1	9.9	0.33
1965	15	16.5	9.4	0.42
1966	21	23.1	8.9	0.58
1967	29	31.9	8.4	0.74
1968	42	46.2	7.9	1.13
1969	56	61.6	7.6	1.17
1970	78	85.8	7.3	1.76
1971	116	127.6	6.8	2.8
1972	170	187	6.4	3.8
1973	253	287.3	5.8	5.2
1974	367	403.7	5.3	6.6
1975	540	590.4	5.5	10.4
1976	731	804.1	4.4	9.2
1977	982	1080	4.1	11.3
1978	1258	1383	3.7	11.2
1979	1513	1664	3.2	8.96
1980	1764	1904	2.9	8.0
1981	2037	2241	2.5	7.5
1982	2320	2552	2.3	7.1
1983	2614	2875	2.2	7.1
1984	2942	3236	2.0	7.2
1985	3326	3658	1.9	8.0
1986	3740	4114	1.8	8.2
1987	4195	4615	1.7	8.5
1988	4722	5194	1.6	9.2
1989*	5279	5807	1.6	9.8
1990*	5885	6774	1.6	10.6

Total Variable Operations and Maintenance EMERGY = 1.68E22 sej

Note: To obtain the variable O&M cost the production of electricity is multiplied by ($.0011/kwhe), a value for 1990 but used from 1960 to 1990 for a conservative estimate.

Total Operation and Maintenance EMERGY = 6.19E22 sej

ref. EPRI, Technical Assistance Guide, 1991

TABLE F

Fuel Cycle EMERGY Calculations

1960-1990

Year	Nuclear 10^9kwhrs	Energy Prod. (year/1990)	Fuel EMERGY E22sej(1990)	Fuel Cycle EMERGY E22sej/yr
1960	1	0.0016	2.48	0.004
1961	2	0.0033	2.48	0.0082
1962	2	0.0033	2.48	0.0082
1963	3	0.0049	2.48	0.0122
1964	3	0.0049	2.48	0.0122
1965	4	0.0066	2.48	0.0164
1966	6	0.0099	2.48	0.0246
1967	8	0.0132	2.48	0.0327
1968	13	0.021	2.48	0.0532
1969	14	0.023	2.48	0.0573
1970	22	0.036	2.48	0.0893
1971	38	0.063	2.48	0.155
1972	54	0.089	2.48	0.22
1973	83	0.137	2.48	0.34
1974	114	0.188	2.48	0.47
1975	173	0.285	2.48	0.71
1976	191	0.315	2.48	0.78
1977	251	0.414	2.48	1.027
1978	276	0.455	2.48	1.13
1979	255	0.42	2.48	1.043
1980	251	0.414	2.48	1.03
1981	273	0.45	2.48	1.12
1982	283	0.467	2.48	1.16
1983	294	0.485	2.48	1.20
1984	328	0.54	2.48	1.34
1985	384	0.63	2.48	1.57
1986	414	0.68	2.48	1.70
1987	455	0.75	2.48	1.86
1988	527	0.87	2.48	2.16
1989*	557	0.92	2.48	2.28
1990*	606	1.00	2.48	2.48
Total Fuel Cycle EMERGY				24.1E22 sej

Note: Fuel use for each year is based on the amount of power production as compared to the fuel use for the year 1990.

ref. Annual Energy Review, DOE/EIA-0384(88)
ref. Energy and Economic Data Base, DOE-NE-0091, Phase 9 Update

TABLE G

Chernobyl EMERGY Calculations

I. Land EMERGY Degradations

3 Zones

Zone	Area (km^2)	Degradation percent/100	Empower Density (sej/km^2/yr)	Solar EMERGY (sej/yr)
1. Closed	2520	-.90	4.13E17	-1.05E21
2. Permanent	10,000	-.60	4.13E17	-2.48E21
3. Periodic	24,060	-.30	4.13E17	-2.98E21
Total				-6.51E21

II. Economic EMERGY Calculation

Using 1) 3Rubles/$ commercial rate

1) 300E9Rubles x (1$/3Rubles) x 2E12 sej/$/15y = -1.3E22sej/y

III. Total EMERGY = Land + Economic

1) -6.51E21sej/yr - 1.3E22sej/yr =-7.81E22sej/yr until yr 2000

After year 2000 EMERGY loss = -6.51E21sej/yr

EMERGY loss per power plant (globally shared)

1) (-7.81E22sej/yr)/472 plants = 4E19 sej/yr/power plant

Cumulative EMERGY loss (300 years)
Assume linear recovery of region, so 1/2 of loss used

(-7.8E22sej/yr)*(15yrs)+(-6.51E21sej/yr)*(300yrs)*(.5) =
2.1E24 sej cumulative loss

ref. Ginzburg, H.M.,"Consequences of the Nuclear Plant Accident at Chernobyl," Public Health Reports, Vol. 106,No. 1,Jan-Feb 1991

ref. Nuclear News, World List of Nuclear Plants, Vol. 34 No. 2,feb. 1991.

TABLE H

Calculation of Environmental Degradation at Nuclear Sites due to Construction and Operation

I. EMERGY loss due to once-through cooling

Using 28 plants = 1/4 of U.S. Total

Natural Energies:(FFE, fossil fuel equivalents = KC)

(3.44E9 KC/yr)x(7.88E8sej/KC)x(28 plants) = 7.5E19 sej/yr

II. EMERGY loss due to cooling towers

Using 85 plants = 3/4 U.S. Total

Natural Energies:

(3.21E9 KC/yr)x(7.78E8 sej/KC)x(85 plants) = 2.1E20 sej/yr

Purchased Energies:

(276E9 KC/yr)x(7.78E sej/KC)x(85 plants) = 1.84E22 sej/yr

Total:

(1.84E22 + 2.1E20) = 1.85E22 sej/yr

Total EMERGY loss due to construction and operation = 1.85E22 sej/y

ref. Kemp, W.M., Odum, H.T.,"Ecosystem Modeling in Theory and Practice: Energy Cost-Benefit Analysis Applied to Power Plants Near Crystal River, Fl," John Wiley 1977, pg. 513.

TABLE I

Solar EMERGY/$ for the United States for 1947 to 1988
(Estimates based on 1983 Analysis changed according to GNP,Fuel)

Year	Fuel E19 J/yr+	Use E24sej/y*	Solar EMERGY use E24 sej/y	GNP E9$/y	Solar EMERGY/$ E12 sej/y
1947	3.47	1.84	5.23	231.3	22.6
1948	3.59	1.90	5.30	257.6	20.6
1949	3.33	1.76	5.16	256.5	20.1
1950	3.60	1.91	5.31	284.8	18.6
1951	3.89	2.06	6.54	328.4	16.6
1952	3.86	2.05	5.45	345.5	15.8
1953	3.97	2.10	5.50	364.6	15.1
1954	3.83	2.03	5.43	365.8	14.9
1955	4.22	2.24	5.64	398.0	14.2
1956	4.43	2.35	5.75	419.2	13.7
1957	4.42	2.34	5.74	441.1	13.0
1958	4.30	2.32	5.72	447.3	12.8
1959	4.58	2.43	5.82	483.7	12.1
1960	4.74	2.51	5.91	503.7	11.7
1961	4.82	2.55	5.95	520.1	11.5
1962	5.04	2.67	6.07	560.3	10.8
1963	5.24	2.77	6.18	590.5	10.5
1964	5.43	2.88	6.28	632.4	9.9
1965	5.69	3.02	6.42	684.9	9.4
1966	6.03	3.20	6.60	749.9	8.9
1967	6.14	3.25	6.65	793.9	8.4
1968	6.51	3.45	6.85	864.2	7.9
1969	6.85	3.63	7.03	930.3	7.6
1970	7.00	3.71	7.11	976.4	7.3
1971	7.16	3.79	7.19	1050.4	6.8
1972	7.58	4.02	7.42	1151.8	6.4
1973	7.84	4.15	7.55	1306.6	5.8
1974	7.65	4.05	7.45	1412.9	5.3
1975	7.44	3.94	7.34	1328.8	5.5
1976	7.85	4.16	7.56	1700.1	4.4
1977	8.05	4.26	7.66	1887.2	4.1
1978	8.24	4.37	7.77	2107.6	3.7
1979	8.32	4.41	7.81	2417.8	3.2
1980	8.00	4.24	7.64	2633.1	2.9
1981	7.81	4.13	7.53	3053.0	2.5
1982	7.47	3.96	7.36	3166.0	2.3
1983	7.44	3.94	7.34	3405.7	2.2
1984	7.82	4.15	7.55	3772.0	2.0
1985	7.80	4.13	7.53	4014.9	1.9
1986	7.82	4.14	7.54	4240.0	1.8
1987	8.10	4.29	7.69	4527.0	1.7
1988	8.43	4.46	7.86	4880.0	1.6

*Solar EMERGY of fuels used = Fuel Joules times 5.3E4sej/J

Ref. Odum, H.T.

+Fuels use in quads (E15 Btu/yr) from U.S. Statistical Abstract, 1990 times 1055 J/Btu

*Solar EMERGY of fuels used = Fuel Joules times 5.3E4 sej/J

$Total EMERGY for each year based on sum of Solar EMERGY in A+B+C
A. Fuels use in Column 3 plus
B. Renewables and soil use, 1.80 E24 sej/yr
C. Other continuing inputs, 1.60 E24 sej/yr

A. Fuels evaluated as oil equivalents (Fuel Joules * Solar Transformity of oil, 5.3 E4 sej/J)

B. U.S. Renewable EMERGY for and soil loss for 1983
(82.4 E22 + 97.6 E22) sej/yr = 180 E22 sej/yr

C. Other EMERGY for 1983 calculated as the total solar EMERGY use use by the U.S. analyzed in 1983 minus the solar EMERGY due to renewables, soil loss, and fuels for 1983;
Soil loss 97.6 E22 sej/yr
Fuel use in 1983
From U.S. sources: coal use 93.1 E22; Natural gas, 88.8 E2; oil use 185.0 E22 sej/yr; From Import, Natural gas, 4.8E22; Crude oil, 40.4 E22; Petrol production, 26.1 E22 sej/yr
(7.85 E24 -1.80 E24 -4.45 E24) = 1.60 E24 sej/yr

References Cited

1. Annual Energy Review, Table 85, Department of Energy/Energy Information Administration, DOE/EIA-0384(88), 1988.

2. Benedict, M., Pigford, T., and Levi, H.,"Nuclear Chemical Engineering,"McGraw-Hill, New York, 1981, pg 856.

3. Brown, M., University of Florida, Center for Wetlands

4. Chernobyl, New York Times Magazine, April 1991.

5. Energy and Economic Data Base (EEDB), Phase 9 update, DOE-NE-0091, July 1988.

6. Ginzburg, H.M., "Consequences of the Nuclear Plant Accident at Chernobyl," Public Health Reports, Vol. 106 No. 1, Jan-Feb 1991 pg. 32.

7. Greenwald, J.,"Time to Choose," Time, April 29,1991, pg 56.

8. Kemp, W.M., Odum, H.T.,"Ecosystem Modeling in Theory and Practice: Energy Cost-Benefit Analysis Applied to Power Plants Near Crystal River, Fl," John Wiley 1977, pg. 513.

9. Kylstra, C. & Han, K.,"Energy Analysis of the U.S. Nuclear Power System,"from Simulation of Macroenergetic Models for the Environment, Power and Society, Energy Research and Development Administration, Grant E-(40-1)-4398, 1975.

10. Lem, P., Energy Required to Develop Power in the U.S., Ph.D. Thesis, University of Florida, 1973.

11. Nuclear Regulatory Commission, Final Environmental Statement, Floating Nuclear Plants, Part II, Vol. 1 and 2, Sept. 1976.

12. Nuclear News, World List of Nuclear Plants, Vol. 34, No. 2 Feb., 1991.

13. Odum, H.T., Energy Analysis of Environmental Value, University of Florida, Center for Wetlands, Gainesville, FL 1987.

14. Perry, J.,Rotty, R., and Reister, D.,"Net Energy from Nuclear Power," in Nuclear Power and its Fuel Cycle Vol. 1, Vienna: IAEA, 1977.

15. Price, J.,"Dynamic Energy Analysis of Nuclear Power,Friends of the Earth (FOE), Earth Resources Ltd., London, 1976.

16. USCEA, An Analysis of the Cost of Electricity From Coal, Gas, Oil and Nuclear Energy Plants, in Advanced Design Nuclear Plants, USCEA, January 1991.

17. Wargo, J.R.,"Uranium: A Future Hinged on Factors Beyond its Control: Nuclear Ind. Vol. 33, no. 10, Dec. 1986, pg. 8.

18. World Nuclear Fuel Cycle, DOE/EIA -0436(90), Wash. D.C. 1990.

19. Wright, J., and Syrett, J., Energy Analysis of Nuclear Power New Scientist, January, 9, 1975.