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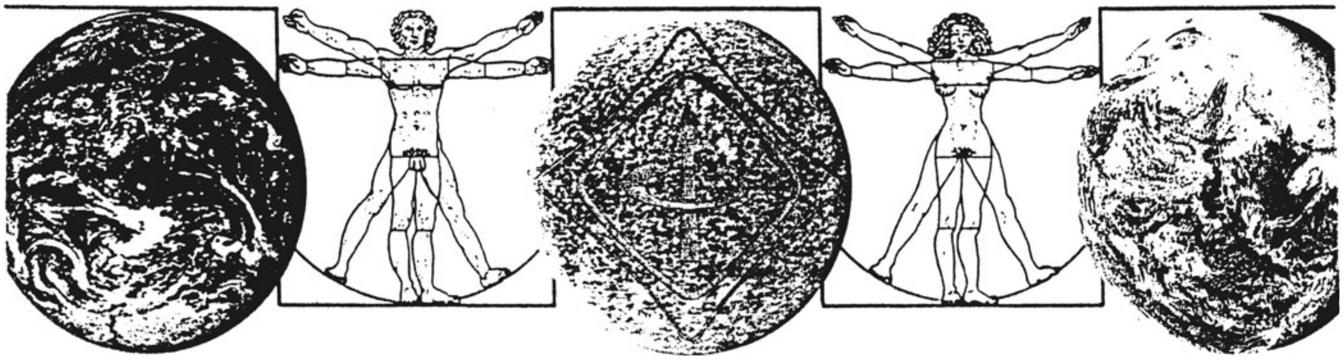

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"Economical Conversion of Unfueled Nuclear Generating Stations"

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(The authors are all members of the Southern California Federations of Scientists.)

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Economical Conversion of Unfueled Nuclear Generating Stations

MIGUEL A. PULIDO, JACK R. JENNINGS, SHELDON C. PLOTKIN, BARBARA MASTERS, AND COREY DZITZER

INTRODUCTION

A major problem has been confronting electric utilities. Large nuclear power plants are nearing completion at costs many times more than the original estimates. Billions of dollars more are required for actual completion. In the meantime, electricity demand is far below values projected at the time the plants were initiated. What to do?

The purpose of this study is to consider whether or not an already constructed, but not yet contaminated, nuclear power plant can be converted to gas without severe economic penalty. Specifically, must a utility company suffer a several billion dollar loss if the utility abandons nuclear power?

The study focusses on one particular plant, the San Onofre Nuclear Generating Station 2 (SONGS 2). The plant, located near San Clemente, California, was undergoing low-power testing at the time of this study in 1982. While this study used SONGS 2 as a prototype for assessing the economic feasibility of nuclear plant conversion, the conclusions are generally applicable to other nuclear plants at a similar stage of construction.

The study shows that, with reasonable increases in the future costs of natural gas, the cost for conversion and operation of a nuclear plant as a gas-burning facility would be comparable to the cost of its completion and operation as a nuclear plant.

METHODOLOGY

To determine the economics of conversion, this study first considers cost components common to all electric generating plants. Common costs include capital, fuel, and "operation and maintenance." However, the capital cost for a gas-burning plant includes the cost for the conversion process itself. Cost components unique to nuclear plants include fuel subsidies and decommissioning. The main cost unique to plants which burn natural gas is that for the control of airborne pollutants, particularly oxides of nitrogen.

Only costs associated with electricity generation are included. Second-order economic factors, such as profit and the cost of electric transmission are not considered. The study assumes that these factors would apply equally to both nuclear and natural gas plants, and would, therefore, not affect the relative costs of the two options.

Two types of inflation are considered in the study; namely, general inflation, and consumable resource inflation. General inflation is assumed to affect equally both types of electric generating plant. Accordingly, the effect of general inflation is treated by using constant 1981 dollars for each cost component.

Consumable resource inflation is separated from other costs of inflation because both uranium, the fuel for nuclear plants, and natural gas, our alternative fuel choice, are limited resources which become more valuable as reserves are used up. The possibly higher increases in the cost of these diminishing resources result in "added inflation." Unfortunately, there are no firm figures which can be used to determine the "added inflation" rate applicable to either fuel. Appendix A gives estimates of the comparative costs of fuel price inflation different from the general inflation rate. These figures can be used to adjust the final cost comparisons given at the end of the paper to account for fuel price increases or decreases.

All cost factors used in this study are expressed in cents per kilowatt-hour (¢/kWh). Each plant will produce a certain amount of useful power which can be estimated accurately. The price consumers must pay for this power reflects total overall costs and is generally expressed on the same basis of ¢/kWh.

CAPITAL COSTS

SONGS 2

Long term loans are used to finance the capital expenses of nuclear plants; these loans are then paid back with interest, generally over the lifetime of the plant. It is necessary, therefore, to compare interest rates to inflation rates in determining capital costs.

Interest rates on long-term loans are currently very close to the rate of general inflation. This is equivalent to a zero interest rate loan with a zero inflation rate. If interest rates should be greater over the next several years than the general inflation rate, the effect will be the same as that from the combination of an initial increase in capital costs plus no difference between interest and inflation rates. The converse also holds. Interest rates lower than the general inflation rate mean cheaper dollars will be used to pay off the capital investment, so that the effective initial capital investment is decreased. If the difference between inflation and interest were 2% for example, the effective initial capital cost, over thirty years, would be changed by a factor

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of nearly (0.02 x 30/(1 - exp (-0.02 *x* 30))) = 1.3298. Thus, the difference could be significant.

Without a "crystal ball," there is no way of knowing, a priori, which condition will prevail. However, it seems reasonably safe to conclude that the present long-term interest rate is very nearly what the general inflation rate will be in the future. This means that the present value of those dollars used to pay off the loans for capital investment will be the same as dollars now. Thus, we use current dollar investment as current effective value. In general, if the inflation rate will be less than the interest rate, then the effective capital costs will be larger than we have assumed. Because capital costs in ¢/kWh are larger for the nuclear plant, this factor would bias our study toward the nuclear facility. It is assumed that plant income for capital repayment varies as the general inflation rate.

The SONGS 2 plant will produce 1100 megawatts of electrical power (MWe). The overall capital cost for Southern California Edison (SCE) alone, a 76.55% partner, is currently estimated at \$1.5 billion [1]. Thus, the capital cost of SONG 2 is:

$$\$1.5E9 / 0.7655 = \$1.973E9 \qquad (1)$$

It is assumed, based on design projections, that the life time of a nuclear power plant is 30 years (and not the approximate 15 years which is the experience to date). It is also assumed that a completed plant operates 52% of the time [2]. Therefore, the capital cost to the rate payer in terms of cost/unit of electrical energy becomes:

$$\$1.973E9 \text{ x } 100¢/\$) / (1100MW \text{ x } 1000kW/MW \text{ x } 0.52 \text{ x } 30yrs \text{ x } 8760hrs/yr) = 1.31¢/Wh \qquad (2)$$

Converted Facilities

There are additional capital costs associated with equipment and design changes necessary for the natural gas conversion of the partially-constructed nuclear plant. These include the costs for the natural gas burners and the correction for design mismatch between nuclear and natural gas power plant turbines. Nuclear turbines typically operate at a lower temperature and pressure and with larger steam flow rates than do turbines associated with gas-fired boilers.

There are three options for redesigning the turbines:

1. The nuclear plant turbines could be modified by adding several input stages to accommodate higher temperatures and pressures; the power capacity may be kept the same by reducing the quantity of steam flow. This would be the least complicated and least expensive modification.
2. A second steam turbine-alternator could be added that would operate at the higher temperatures and pressures and with the same steam flow rate. This modification would lead to significant capacity increase and appears to be the most cost-effective.
3. A gas turbine alternator set could be added to nearly double the total power capacity by using cogeneration to supply the current steam flow to existing turbines at their required lower pressures and temperatures. When a separate gas turbine/alternator is installed, exhaust gas from the turbine will transfer heat to water which will provide steam for the existing turbo-alternator units.

Since option (3) is the only one for which reasonable cost numbers are available [3], that modification will be used in the calculation of capital costs. Specifically, it is estimated to cost \$85 million to convert the 250 MW Lingen Power Plant in Germany to natural gas [3]. The conversion process would nearly double the power capacity of the plant to 450 MW. For the purposes of this study, we intend to keep the total output of the converted SONGS 2 plant at 1100 MW. Therefore, in determining the cost of conversion, the resultant total output of each plant is used. Assuming a linear relationship, the cost is estimated to be:

$$\$85 \text{ million x } 1100 / 450 = \$210 \text{ million} \qquad (3)$$

Since these are 1979 figures, they must be adjusted to 1981 prices by the inflation rate which is obtained from the Consumer Price Index for 1979 to 1981.

$$\$210 \text{ million x } (1.13) \text{ x } (1.13) = \$268 \text{ million}$$

where

$$1.13 \text{ x } 1.13 = \text{inflation from 1979 to 1981.} \qquad (4)$$

Thus, the capital cost of the converted plant will be:

\$1.973E9 capital cost for SONGS 2
\$0.268E9 added cost for conversion

\$2.241E9

The capacity factor, that is, the actual energy generated divided by the rated energy capacity, of this redesigned natural gas power plant will be 0.741 [4]. Note that the comparable value for a nuclear power plant is 0.52 [2]. In addition, the design lifetime of a natural gas plant is 40 years, ten years longer than that for a nuclear plant [16].

Therefore, the capital cost of electricity to the ratepayer becomes:

$$\$2.241E9 \text{ x } 100¢/\$ / (1100 \text{ MW x } 1000kW/MW \text{ x } 0.741 \text{ x } 40 \text{ yrs x } 8760 \text{ hrs/yr}) = 0.78 ¢/kWh$$

Thus, even though the initial investment is greater for the gas-fired plant, the longer lifetime and the larger capacity factor result in a lower unit capital cost, 0.78¢/kWh, than for the nuclear-fired plant, 1.31¢Wh.

It must be emphasized that both capacity factors are experimental values. Thus, while some large nuclear power plants have operated at somewhat larger fractions of the time, the average is 0.52. This number was obtained by Komanoff by compiling available data and is independent of any engineering judgment. Likewise, the 0.741 gas plant capacity factor is a typical one for Southern California Edison to whom this study was directed. That company's data were more readily available to the authors than those of any other company. Some gas plants have higher capacity values.

As for lifetimes, design values were used in an attempt to be fair to the nuclear plant. While gas plants customarily last at least their 40 year anticipated lifetimes, large nuclear plants have not lasted any longer than 15 years to date.

Thus this study has a decided bias toward the nuclear plant. If gas plants customarily lasted 40 years in 1951, they would probably last at least that long today as well.

FUEL COSTS

Nuclear

there are a number of values of nuclear fuel costs in use by the utility companies and it is impossible at this time to determine which is the most valid. SCE projects, for 1982, fuel costs of 0.93¢/kWh [1]. The 1980 fuel cost. also according to SCE, was 0.899¢/kWh. To approximate 1981 fuel costs, the 1980 and the 1982 values were averaged, resulting in a value of 0.915¢/kWh.

For the sake of comparison, Boston-Edison estimated a cost of 1.42¢/kWh by 1991 based upon a 6% inflation rate from 1981 to 1985 and 10% inflation from 1985-1991 [17]. Thus. the 1981 fuel costs

$$1.42\text{¢/kWh} \ / \ (1.06\text{E}4 \times 1.10\text{E}6) = 0.635\text{¢/kWh} \qquad (7)$$

Thus. the SCE value for fuel costs may be somewhat high.*

Gas

SCE gives 1981 costs for natural gas as \$3.60 / 1000 cu. ft. [5]. In contrast, the Caifonia Energy Commission quotes a 1980 natural gas price for Southern California Gas (SCG) of \$3.10 / 1000 cu. ft. (allowing 1000 BTU / cu. ft., [6]). However, SCG lifeline customers were charged \$2.66 / 1000 cu. ft. during July/August of 1981. Since the California Public Utilities Commission claims that no class of service is subsidized by any other class, the \$2.66 / 1000 cu. ft. must be equal to, or greater than, the basic cost [7]. Thus, there is some evidence that the \$3.10 / 1000 cu. ft. is a high cost estimate. Using the same rationale, the \$3.60 / 1000 cu. ft. is probably quite high.

SONGS 2 is owned by two utility companies, SCE and San Diego Gas and Electric (SDGE). SDGE, a 20% owner of San Onofre, purchases gas from SCG at a lower price than does SCE. Thus, the price of gas for a converted nuclear plant could well be lower than \$3.60 / 1000 cu. ft. Nonetheless, for this study. \$3.60 / 1000 cu. ft. was used.

At 1000 BTU / cu. ft. and 10 BTU/Wh, \$3.60 / 1000 cu. ft. easily converts to 3.60¢/kWh.

Added Factors

Because fuel is a nonrenewable resource, its cost will increase faster than the general inflation rate. While it appears that this factor will not be effective in the next 40 or 50 years for either uranium or natural gas, Appendix A specifies how this factor could influence fuel costs.

OPERATION AND MAINTENANCE COSTS (O&M)

Nuclear

SCE data from 1982 indicate that the annual O&M costs for a 1100 MW nuclear plant are \$27.76 million [8].

Therefore, the yearly cost per unit of electricity is:

$$\$27.76\text{E}6/\text{yr} \times 100\text{¢}/\$ \ / \ (1100\text{MW} \times 1000\text{kW/MW} \times 0.52 \times 8760\text{hrs/yr}) = 0.55\ \text{¢/kWh} \qquad (8)$$

Gas

To determine the O&M costs for a gas burning plant, the SCE facility in Redondo Beach was used as a guide. O&M for 1980 was approximately \$10E6 [5] for effectively about 960Mw (the two larger and most efficient turbo generators). Using the same 0.741 SCE capacity factor as before, the cost to the rate payer becomes:

$$\$10\text{E}6/\text{yr} \times 100\text{¢}/\$ \ / \ (960\text{MW} \times 1000\text{kW/MW} \times 0.741 \times 8760\ \text{hrs/yr}) = 0.16\text{¢/kWh/yr} \qquad (9)$$

These calculated values are consistent with another independent study wherein it was determined that the O&M costs for nuclear power plants are nearly three times those for a natural gas plant [9].

UNIQUE COSTS

Nuclear

There are a number of cost factors for a nuclear power plant which are not applicable to a natural gas power plant. Specifically, these include decommissioning, fuel subsidies, and "crud" cleaning. The last is an insignificant cost and will not be considered further.

Although the NRC contemplates other decommissioning strategies than complete dismantling, e.g. mothballing and entombing [18], it can be shown that the only acceptable strategy is dismantling [10 and 11]. The factors that lead to this conclusion are as follows. Certain long-lived radionuclides produced in the reactor core are extremely toxic and must be kept out of the biosphere essentially forever. There will be about 170 Curies of Nickel-59 (Ni^{59}) in the SONGS 2 core after 30 years, plus even larger quantities of Niobium-94 (Nb^{94}). This is too much radioactivity to be left safely in one location. Ni^{59} has a half-life of about 80,000 years, while Nb^{94} has a half-line of nearly 20,000 years. Such half-lives make entombment or simple guarding unacceptable. Dismantling a nuclear reactor costs about 28% more than does the construction of the original plant [14]. For San Onofre, then, the decommissioning cost will be:

$$1.31\text{¢/kWh} \times 1.28 = 1.68\text{¢/kWh} \qquad (10)$$

For a more complete discussion of decommissioning, see Appendix B.

At present, nuclear fuel is subsidized in part by the federal government by an amount of 0.1¢/kWh [12]. If the government decides not to subsidize the fuel, then this cost will be passed on to the rate payer. Thus, total added nuclear costs are:

$$1.68\text{¢/kWh} + 0.1\text{¢/kWh} = 1.78\ \text{¢/kWh} \qquad (11)$$

Another unique cost not considered in this study is high level waste disposal. The Federal government has indicated that the cost of nuclear waste disposal will be borne by the entire society using public funds rather than monies

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* *Editor's note:* Since this study was made, gas prices have increased. This would be reflected in a higher per unit power cost for the gas option.

collected from the rate payers. Because this condition may change in the future, Appendix C is included to show how a future change in policy might affect the results of this study.

Gas

Reduction of nitrogen oxides can be achieved [13] by an ammonia catalytic technique for a cost of 0.4¢/gal of petroleum or about 0.3% of fuel costs. Applying the same technique to the gas plant exhaust, estimating that it would generally cost the same percentage, results in 0.003 x 6¢/kWh or 0.02¢/kWh being required for NOX reduction.

FINAL COST COMPARISONS

Assuming that general inflation alone is applicable and that interest rates equal inflation rates, component costs are given below.

Component	Nuclear (¢/kWh)	Gas (¢/kWh)
Capital	1.31	0.78
Fuel	0.92	3.60
O&M	0.55	0.16
Added Unique	1.78	0.02
Totals	4.56	4.56

CONCLUSIONS

Conversion of a nuclear power plant to natural gas before the primary loop has been contaminated with radioactive fission and activation products will probably result in about the same consumer electricity costs over the years. This conclusion derives from assumptions that 1) the fuel cost escalation is not very much above the general inflation rate over the planned 30-year nuclear plant lifetime (Appendix A); 2) the nuclear fuel plant will last the full 30 years as contemplated; 3) the nuclear fuel will be as cheap as originally thought; 4) high-level waste costs will not be included at any later date; and 5) dismantling costs will be no more than computed in this report (Appendix B). Should any of these assumptions prove to be incorrect, the nuclear plant convened to natural gas should be less expensive than the same plant nuclear-fueled.

With respect to natural gas costs, this study used a value somewhat higher than other such cost figures quoted in 1981. It was contemplated that important cost increases would be approximately at the normal inflation rate. However, natural gas has recently doubled in price while normal inflation has only increased about 20%. During this period, significant quantities of new natural gas have been discovered which would normally cause the price to drop. Thus, it may be concluded that the present high cost of natural gas will eventually fall in line with other important plant costs.

It has been argued that the *capacity* factor of 0.741 for a gas plant is merely an *availability* factor representing the possible use of a gas plant, not the actual use. The contention is that, after capital costs have been expended, the actual use of specific plants in a system is dictated by minimizing variable costs, regardless of the fixed costs. *If* there are plants with lower variable costs on a system, they would tend to be used more; hence, it is claimed, our 0.741 capacity factor may not be reached in practice. While there may be some validity to this point in the abstract, one would have to examine each particular utility system to verify the actual use. The 0.741 capacity factor used in this report is the *actual* gas plant utilization factor for Southern California Edison.

APPENDIX A

Fuel Cost Increases Above Those Due to General Inflation

Because fuel might increase in price above the general rate of inflation due to depletion of the fuel resource, an added inflation factor may be required. The following table shows the effect of a constant factor over the plant lifetime.

Fuel Cost with Added Inflation

f	A	Uranium (¢/kWh)	Incr. (¢/kWh)	Gas (¢/kWh)	Incr. (¢/kWh)
0.000	0.000	0.93	0.00	3.60	0.00
0.005	1.08	1.00	0.07	3.87	0.17
0.010	1.16	1.08	0.15	4.18	0.58
0.015	1.25	1.16	0.23	4.50	0.90
0.020	1.35	1.26	0.33	4.86	1.26

f = fuel escalation factor = fuel inflation - general inflation
$A = ((1 + f)^{30} - 1)/(30 \times f)$ = factor by which fuel costs must be multiplied to represent the effect of *"f"* over 30 years.

APPENDIX B

Nuclear Power Plant Decommissioning Costs

The only acceptable decommissioning technique will be total dismantlement because of Ni^{59} and Nb^{94} residue inventories. Hard cost data for such dismantlement are very difficult to find in the literature. To date, no large nuclear power plant has been decommissioned, although Humboldt Bay in California is expected to be decommissioned in the near future.

Published cost numbers have ranged from 100% to 166% of the original capital cost after scaling for the intervening inflation. However, these values are all estimates by their authors or are extrapolated from other estimated data.

The only firm cost figure found was for dismantling the UCLA nuclear reactor [14]. Rockwell, one of the few companies with dismantling experience, proposed a specific cost in 1980 for this project. The total quoted cost was \$752K (composed of three separate parts). Original cost for the UCLA reactor in 1958 was \$203K. Average inflation according to the Consumer Price Index from 1958 to 1980 was 4.95 %/year. The original cost of the reactor in 1980 dollars would be $\$203K \times 1.0495^{22} = \$588K$.

Thus, the relative cost for decommissioning is:

$752.000 / $588.000 = 1.28.
or 128% of initial construction cost for decommissioning after accounting for inflation.

Although the UCLA reactor is a small one, it seems apparent that any relative savings as a result of size would apply equally to both original construction and to dismantling. Thus, the 128% factor is probably as applicable to the dismantling of a large reactor as to the dismantling of the UCLA reactor. This result is also consistent with decommissioning estimates for Humboldt Bay [19] and TMI-2 [20].

It should be mentioned that the Humboldt Bay nuclear Power plant, owned by Pacific Gas and Electric, will probably be the first large facility to be decommissioned. However, actual figures for the cost of such decommissioning have not been obtained by PG&E. Their anticipated value as of September, 1983 was about equal to the original capital cost of construction in 1983 dollars. PG&E is very careful to point out that these are only preliminary estimates. Obviously, the fact that dismantling is the only accepted decommissioning technique is reflected in the PG&E estimate. This is also agreed to in the first two papers on decommissioning costs in Ref. [18].

APPENDIX C

High Level Radioactive Waste Disposal

1. A prototype system can never be tested, as good engineering practice dictates, because the test period required would be 1000 years for the high-heat-producing components, Sr^{90} and Cs^{137}, and 500.000 years for Pu^{239}. The EPA specifies 500,000 years as the required containment interval [15].

2. A disposal site will have to contain at least three barriers; 1) glass on ceramic matrix, 2) steel container and 3) surrounding geological material.

3. Because of 1) above, the disposal vault may have to allow for future retrieval as well as continuous monitoring.

Development of the disposal system will not be charged to rate payers because the identical research and development is required for nuclear weapons waste. However, it may be that the monitoring cost for the waste from each particular plant will be assigned to that plant. Thus, conceivably there could be an added nuclear power cost for the rate payers besides those listed in the body of this study.

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