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ESTIMATION OF CHEMONUCLEAR PRODUCTION COSTS

MORRIS BELLER AND MEYER STEINBERG

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

August 1966

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ESTIMATION OF CHEMONUCLEAR PRODUCTION COSTS

by

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Several capital and production cost estimates have been made in the past^(1,2) on fissiochemonuclear reactors and processes. These are all subject to review and revision as new information and cost reductions are achieved in the civilian power reactor programs in the U.S. and abroad. A generalized production cost analysis similar to one presented in reference (3) has been updated and expanded to include multipurpose and electrochemonuclear systems. This is presented below together with estimates for several single and multipurpose chemonuclear systems. These new estimates reflect the considerably lower reactor costs which were found possible by the nuclear power industry within the last several years.

A plant producing fissiochemicals will consist of a nuclear plant and a chemical plant. The nuclear plant includes

the nuclear reactor and the power generation equipment. The chemical plant serves the function of separating contamination from the process gas and separating the product from unreacted gas. In a multipurpose plant it also includes chemical processing equipment. Estimates for these units are required as a function of capacity. For the nuclear island cost, the following is assumed.

1. The chemonuclear plant investment cost is the same as for a light water reactor of equivalent thermal capacity. This assumes a well-developed chemonuclear reactor technology.

2. Large power reactor investment cost can be broken down as follows, based on Westinghouse⁽⁴⁾ and ORNL⁽⁵⁾ estimates for 1000 MW(e) plants:

<u>Component</u>	<u>% of Investment cost</u>
a. Nuclear boiler	30
b. Turbine generator	35
c. Indirect costs	20
d. Shielding, structures & containment	10
e. Miscellaneous equipment	3
f. Turbine bay	<u>2</u>
Total	100

From the GE Price Book for Boiling Water Reactors,⁽⁶⁾
the total plant cost is obtained as a function of the plant
thermal and electrical ratings as listed in the following Table.

<u>Plant rating</u>		<u>Total nuclear plant cost</u>	
<u>MW(t)</u>	<u>MW(e), net</u>	<u>10⁶ dollars</u>	<u>\$/KW(t)</u>
348	100	24.0	69.0
643	200	36.9	57.5
964	300	47.5	49.2
1286	400	56.7	44.1
1607	500	65.1	40.6
1928	600	73.0	37.9
2250	700	81.9	36.4
2571	800	90.6	35.2
2893	900	99.0	34.2
3214	1000	107.0	33.3

Note that net electrical output is 31.1% of the plant
thermal rating at 400 MW(t) and up.

I. Single Purpose Plants

To obtain the cost of the nuclear part of a single purpose chemonuclear plant (no power production), the cost of turbine-generators and accessories (i.e., condensers, etc.) and installation is subtracted from the total plant cost. Turbine-generator costs are the GE price book values. Installation and

auxiliaries are assumed to add 35%⁽⁷⁾ to the basic turbine-generator costs. The fraction of total nuclear plant cost represented by the turbine-generators is determined to be an average of 35% as shown in the Tables on page 5.

A log plot, shown in Figure 1, single purpose plant in \$/KW(t) vs Power in MW(t) gives the following scaling relationship for cost as a function of power in the above power range.

$$C_{NS} = \frac{500}{P^{0.4}} \quad (1)$$

Where:

C_{NS} = single purpose investment cost for nuclear
plant only, \$/KW(t), and,
 P = power, MW(t).

II. Dual-Purpose Plants

A dual-purpose plant (producing chemicals and power) was assumed equivalent to a power plant, except for the lowered electrical capacity due to conversion of a fraction of the thermal energy to chemical energy. Plotting the GE Price Book total plant cost vs power as shown in Figure 1 leads to the following.

$$C_{ND} = \frac{830}{P^{0.4}} \quad (2)$$

The fraction of thermal energy converted to chemical is $\frac{G_c}{G_{max}}$, and the turbine-generator installed cost is 35% of the

TURBINE-GENERATOR COST

Plant MW(t)	Rating MW(e)	Turbine-Generator (T-G) base prices, \$10 ⁶	T-G set XX1.35 incl. install. & aux.	Installed T-G set \$/KW(t)	Turbine bay \$/KW(t)
643	200	9.0	12.0	18.7	0.7
1286	400	14.0	19.0	14.8	1.1
1928	600	19.2	25.0	13.0	1.4
2571	800	23.5	31.0	12.8	1.7
3214	1000	31.2	40.0	12.4	2.0

Plant Rating MW(t)	Total T-G cost \$/KW(t)	Total plant cost \$/KW	T-G set installed % of total plant cost	Single Purpose Plant Cost (Total less T-G Cost incl. Bldg.) \$/KW(t)
200	19.4	57.5	32.5	38.1
400	15.9	44.1	33.4	28.2
600	14.4	37.9	34.2	23.5
800	14.5	35.2	36.1	20.7
1000	14.4	33.3	37.4	18.9

Average 35%

total plant cost. A list of the nomenclature appears at the end of this report. Therefore, credit must be taken for the reduced T-G requirement, and the dual-purpose plant cost is:

$$C_{ND} = \frac{830}{P^{0.4}} - 0.35 \frac{G_{\epsilon_o}}{G_{\max}} \left(\frac{830}{P^{0.4}} \right), \quad (3)$$

or

$$C_{ND} = \frac{830}{P^{0.4}} \left(1 - 0.35 \frac{G_{\epsilon_o}}{G_{\max}} \right). \quad (4)$$

III. Production Cost

The production cost for the chemical product consists of the sum of the following items.

1. Fixed charges.
2. Nuclear fuel cost.
3. Operating and maintenance costs.

1. Fixed charges

P = Reactor power, MW(t),

f = fixed charge rate, a fraction operating on unit capital investment,

C = unit capital cost, \$/KW(t),

L = load factor = 0.8.

Total yearly energy generation = $1000P \times 8760L \text{ kWh}(t)$

Gross income = $1000CfP$ dollars

Fixed charges = $\frac{1000CfP \times 1000 \frac{\text{mils}}{\$}}{1000P \times 8760 \times 0.8 \text{ kWh}} = 0.142Cf \frac{\text{mils}}{\text{kWh}} \quad (5)$

2. Fuel cost

a. Burnup

Assume $1.2 \text{ g U}^{235}/\text{MW-day}(t)$, and 3% enrichment.

Cost of U^{235} @ 3% enrichment = $\$8.48/\text{g U}^{235}$.

$1.2 \text{ g/MW-day}(t) \times 8.48/\text{g} \times \frac{1 \text{ day}}{24 \text{ hr}} = 0.42 \text{ mils/kWh}(t)$.

For certain chemonuclear thin foil fuels higher than 3% enrichment may be necessary. Fully enriched U^{235} has a value of $\$12.01/\text{g}$ which would increase the fuel cycle cost. However, in terms of total production cost the maximum increase is not significant for purposes of these estimates.

b. Use charge

1 kg U^{235} required for each $\text{MW}(t)$.

Use charge rate = $4.75\%/\text{yr}$.

Use charge = $1000 \text{ kg} \times 8.48 \times 0.0475 = 403P \text{ \$/yr}$.

$$\frac{403P \text{ \$/yr} \times 1000 \text{ mils/\$}}{1000P \text{ kW} \times 8760 \times 0.8} = 0.06 \text{ mils/kWh}$$

c. Reprocessing charge

0.4 kg/kg U^{235} is in processing.

Since 1 kg/MW is assumed, 0.4P kg/core cycle.

If S = core lifetime, months,

$0.4P \times \frac{12}{S}$ kg/yr is processed.

At reprocessing charge of \$600/kg (including transportation and insurance).

$$600 \times 0.4P \times \frac{12}{S} = 2880 \frac{P}{S} \text{ \$/yr.}$$

Assume S = 6 months.

$$2880 \times \frac{P}{6} = 480 P \text{ \$/yr} = 0.07 \text{ mils/kWh.}$$

d. Fabrication cost

Based on the analysis for the chemonuclear elements appearing in BNL 804, ⁽³⁾ 0.17 mils/kWh, is assumed, split evenly between power plant and chemical plant.

3. Labor and maintenance

Assume the following breakdown based on GE plant cost.

	<u>Power plant</u>	<u>Chemical plant</u>
Labor	0.09	0.06
Maintenance	<u>0.07</u>	<u>0.08</u>
	0.16 mils/kWh	0.14 mils/kWh

Total Production Cost

	<u>Power plant</u>	<u>Chemical plant</u>	
1. Fixed charges	0.142Cf		
2. Fuel costs mils/kWh(t)			
a. Burnup	0.42	-	
b. Use charge	0.06	-	
c. Reprocessing	0.07	-	
d. Fabrication	0.08	0.09	
3. Operation & maintenance	<u>0.16</u>	<u>0.14</u>	
Total of fuel, operating & maintenance	0.79	+ 0.23	= 1.02

Production Cost of Nuclear Thermal Energy, mils/kWh(t)

$$W = 0.142 \text{ Cf} + 1.02 \text{ mils/kWh(t)}. \quad (6)$$

A. Single-Purpose Plant

If V = chemical product cost, ¢/lb,

$$E = \text{Energy requirement} = \frac{1216}{G_{\epsilon} M_O} \text{ kWh(t)/lb}, \quad (7)$$

$$V = 0.1 E W, \quad (8)$$

and, The production cost for fissiochemical is thus,

$$V = \frac{1216}{G_{\epsilon} M_O} (.0142 C_{SP} f + 0.102) \text{ ¢/lb}. \quad (8a)$$

Chemical Island Cost

Cost of removal of radioactivity from the chemical product is known to a much smaller degree of certainty than the nuclear plant. However, it is related to the plant power capacity, since the activity release is a function of the rate of fuel burnup. In a single-purpose plant the investment cost was calculated as $500/P^{0.4}$ in \$/kWh(t). Because of similarity in shielding and taking into account conventional chemical equipment scaling factors, the assumption of a similar scaling function of the form $K/P^{0.4}$ should be valid here.

1. As a maximum, cost of the chemical island will equal the nuclear island investment cost. The total single-purpose plant cost (nuclear plus chemical plant) is then.

$$C_{SP} = \frac{500}{P^{0.4}} + \frac{500}{P^{0.4}} = \frac{1000}{P^{0.4}} \quad (9)$$

2. Cost of chemical cleanup may be smaller than the above assumed maximum and may even be negligible compared to the nuclear plant. A general equation then is:

$$C_{SP} = \frac{500}{P^{0.4}} + \frac{K}{P^{0.4}} \quad (10)$$

Where K is a constant greater than 0 and less than 500. A more detailed analysis for a nitrogen fixation plant indicates

K to be in the order of 50 to 170, depending on the G value (10).

B. Dual-Purpose Plant (chemical + power)

The production cost for a fissiochemical is given by Eq. (8), however, credit must be taken for value of power produced. Assume that the credit equals the equivalent cost of a plant producing the same amount of power as is available from the dual-purpose plant.

If F is the fraction of thermal energy utilized to produce saleable power, then

$$F \left(1 - \frac{G_{\epsilon_0}}{G_{\max}} \right) = \text{fraction of thermal power available for electricity.}$$

The equivalent nuclear electric plant cost that can be taken as a credit is:

$$C_E = \frac{830}{\left[F \left(1 - \frac{G_{\epsilon_0}}{G_{\max}} \right) P \right]^{0.4}} \quad (11)$$

The production cost for a fissiochemical, taking credit for the by-product power, is then:

$$V = \frac{1216}{GEM} \left[(0.0142C_{DP}^f + 1.02) - F \left(1 - \frac{G_{\epsilon_0}}{G_{\max}} \right) (0.0142C_E^f + 0.079) \right] \quad (12)$$

where:

$$C_{DP} = \frac{830}{P^{0.4}} \left(1 - 0.35 \frac{G_{\epsilon_o}}{G_{\max}} \right) + \frac{500}{P^{0.4}}$$

nuclear power + chemical cleanup

and

$$C_E = \frac{830}{\left[F \left(1 - \frac{G_{\epsilon_o}}{G_{\max}} \right) P \right]^{0.4}}$$

A useful plot of chemical production cost as a function of energy requirement for various $f/P^{0.4}$ ratios is given in Figure 2.

If decontamination cost is negligible, then:

$$C_{DP} = \frac{830}{P^{0.4}} \left(1 - 0.35 \frac{G_{\epsilon_o}}{G_{\max}} \right).$$

C. General Formulae for Estimation of Chemonuclear Production Cost in Multipurpose Plants

1. Fissiochemicals, power and electrochemicals

In a dual-purpose plant the power produced can be utilized to generate additional quantities of chemical an electro-chemical route. The most prominent example is the generation of hydrogen and oxygen by the decomposition of water. The hydrogen can be used for synthesizing ammonia, which is combined with fissiochemical nitrogen dioxide yielding an ammonium nitrate product. Thus a multipurpose plant can turn out a combination of fissiochemicals, power, and electrochemicals. Credit for by-product electrochemicals and fissiochemicals is

taken per unit of primary fissiochemical produced. The net production cost of the latter is given by the following Eq. (13).

$$\begin{aligned}
 v = & \frac{1216}{G_{\epsilon_O} M} \left[(0.0142 f C_{DP} + 0.102) - F \left(1 - \frac{G_{\epsilon_O}}{G_{max}} \right) (.0142 C_E + 0.079) \right. \\
 & + (1-F) \left(1 - \frac{G_{\epsilon_O}}{G_{max}} \right) - 0.0142 f C_E \left. \right] - (1-F) \left(1 - \frac{G_{\epsilon_O}}{G_{max}} \right) \sum_{n=1}^n \left(\frac{G_{BE} \epsilon_P^M BE^V}{G_{\epsilon_O} M} \right)_n \\
 & - \sum_{n=1}^n \left(\frac{G_{BF}^M BF^V}{GM} \right)_n \quad (13)
 \end{aligned}$$

The definitions of each of the terms are given in the nomenclature list. The subscript n refers to the identification of a number of different fissiochemicals and electrochemical by-products.

2. Desalination Plants

If in addition, desalinated water is to be produced from a plant producing power and/or chemicals, the following analysis can be made.

C_D = unit cost of desalination equipment, \$/kW(t),

S = fraction of reactor power utilized for desalination,

V_D = value of water sold, ¢/1000 gal,

D = water production, gal/MW(t).

The water costs or credits are at the plant site; thus no transportation cost is included.

The water credit in terms of $\phi/\text{kWh}(t)$,

$$= D \frac{\text{gal}}{\text{MW day} \times 24 \frac{\text{hr}}{\text{day}}} \times \frac{V_D \phi}{1000 \text{ gal}} \times \frac{1 \text{ MW}}{1000 \text{ kW}} = 4 \times 10^{-8} DV_D \phi/\text{kWh}(t).$$

In terms of chemical product, in ϕ/lb ,

$$= 4 \times 10^{-8} DV_D \phi/\text{kWh} \times \frac{1216 \text{ kWh}}{G_{\epsilon_O} \text{ M lb}}.$$

The general term for the desalinated water credit is

$$= \frac{1216}{G_{\epsilon_O} \text{ M}} \left[-S \left(1 - \frac{G_{\epsilon_O}}{G_{\text{max}}} \right) \left\{ (4 \times 10^{-8} DV_D) - 0.0142 C_{Df} \right\} \right].$$

The over-all equation for fissiochemicals, electrochemicals, power, and desalinated water,

$$\begin{aligned} V = & \frac{1216}{G_{\epsilon_O} \text{ M}} \left\{ (0.0142 f C_{DP} + .102) - F \left(1 - \frac{G_{\epsilon_O}}{G_{\text{max}}} \right) (0.0142 C_{Ef} + 0.079) \right. \\ & + (1-S-F) \left(1 - \frac{G_{\epsilon_O}}{G_{\text{max}}} \right) (0.0142 C_{cf}) - S \left(1 - \frac{G_{\epsilon_O}}{G_{\text{max}}} \right) \left[4 \times 10^{-8} DV_D - 0.0142 C_{Df} \right] \left. \right\} \\ & - (1-S-F) \left(1 - \frac{G_{\epsilon_O}}{G_{\text{max}}} \right) \sum_{n=1}^n \left(\frac{G_{BE} \epsilon_P^M \epsilon_{BE}^V}{G_{\epsilon_O} \text{ M}} \right)_n - \sum_{n=1}^n \left(\frac{G_{BE}^M \epsilon_{BF}^V}{G_M} \right)_n \quad (14) \end{aligned}$$

3. By-product Steam

If instead of desalinating water, steam is generated for process or other purposes,

Let, T = Fraction of reactor power to produce steam,
 H = steam production, lbs/MW(t),
 V_H = steam value, ¢/1000 lb,
 C_H = added cost of steam generation equipment, \$/kW(t),

then steam credit is:

$$\frac{1216}{G_{\epsilon_O} M} \left\{ -T \left(1 - \frac{G_{\epsilon_O}}{G_{\max}} \right) \left[4 \times 10^{-8} H V_H - 0.0142 C_H f \right] \right\}.$$

Then

$$\begin{aligned} V = & \frac{1216}{G_{\epsilon_O} M} \left\{ (0.0142 f C_{DP} + 0.102) - F \left(1 - \frac{G_{\epsilon_O}}{G_{\max}} \right) (0.0142 C_E f + 0.079) \right. \\ & - (1-T-F) \left(1 - \frac{G_{\epsilon_O}}{G_{\max}} \right) (0.0142 C_C f) - T \left(1 - \frac{G_{\epsilon_O}}{G_{\max}} \right) \left[4 \times 10^{-8} H V_H - 0.0142 C_H f \right] \left. \right\} \\ & - (1-T-F) \left(1 - \frac{G_{\epsilon_O}}{G_{\max}} \right) \sum_{n=1}^n \left(\frac{G_{BF} \epsilon_P^M \cdot V_{BE}}{G_{\epsilon_O} M} \right)_n - \sum_{n=1}^n \left(\frac{G_{BF}^M \cdot V_{BF}}{GM} \right)_n \quad (15) \end{aligned}$$

3. Electrochemonuclear Plants

Plants which require the least development at the present time are conventional nuclear power plants which feed power to electrochemical plants. Assuming the entire nuclear plant capacity is utilized to produce electrochemicals the following analysis is operative.

Let N = electrical energy required to produce an electrochemical product, kWh(t)/lb. Since thermal to electrical efficiency is 0.311,

Thermal energy required = $N/0.311$ kWh(t)/lb,

Fixed charges = $0.0142fC$ (\$/kW(t),

Fuel and operating cost was shown to be $0.079¢/\text{kWh}(t)$.

However, 0.079 is excessive since it assumed the chemo-nuclear fuel elements, which are not necessary for a power plant.

GE Cost Book Data for 1000 MW(e) or 3214 MW(t) plants, equilibrium core costs, are:

Fuel cost	0.0423

Operating and maintenance	<u>0.0069</u>

Total	0.0492

Therefore, $V_{EC} = \frac{N}{0.311}(0.0142fC_E + 0.0492)¢/\text{lb}$.

Let C_C = cost of cells and rectifiers and additional chemical equipment to produce the electrochemical,

$$\text{Then } V_{EC} = \frac{N}{0.311}[0.0142(C_E + C_C) + 0.0492] \quad (16)$$

where:

C_E = nuclear power plant cost, $830/P^{0.4}$, \$/kW(t)

C_C = additional investment, \$/kW(t).

4. Electrolytic Cells and Rectifier Costs

The several chemonuclear processes which appear of interest make use of the electrochemical decomposition of water for production of hydrogen. Electrolytic cell and rectifier

costs are specifically estimated for hydrogen production which is utilized for ammonia production.

Rectifier cost are estimated at a minimum of \$11/kW(e) = \$3.40/kW(t) based on contact with manufacturers.

Electrolytic cell data have been considered previously for well-advanced systems. (8,9)

For H_2 production, at an optimum current density of 800 amps/ft², power consumption is approximately 140 kWh(e)/1000 scf H_2 .

For a 1000 T/D NH_3 , the capital investment = \$8.5 MM using advanced-type cells. Since 66,700 scf H_2 are required per ton NH_3 , the size of the power plant is 1.25×10^6 kW(t) and the unit cell cost is \$6.80/kW(t).

For NH_3 plants, cost of converters and compressors adds another \$6/kW(t). (8,9) Nitrogen supply is provided from air liquefaction plant charged to the fissiochemical plant. Thus the total C_c for the hydrogen-ammonia system is as follows.

Rectifiers		\$3.40
Cells		6.80
Compressors and converters		<u>6.00</u>
Total,	C_c	= \$16.20

4. Application of the Production Cost Formulae

The above equations were used in determining reactor and plant capacities at production costs which are presently possible with competitive conventional processes and using fission-chemical G values which have already been experimentally demonstrated or which are believed to be reasonably achievable. Tables I to III show the results of this analysis. The processes fall into two categories: (1) high-volume, low-risk, utility-type chemical systems, and (2) low-volume, higher-risk, industrial chemical processes. For the highly competitive fixed nitrogen, and synthesis gas (carbon monoxide and hydrogen) cases, fixed charge rates comparable to public and private utility rates (7 and 14%) must be used to be reasonably competitive. This can be justified on the basis that fixed nitrogen for fertilizer and synthesis gas for pipeline distribution are fast becoming utility-type chemicals in the same sense as electric power and water are considered utilities today. However, the allowable fixed charge rates can increase to as high as 20% as indicated in Table I depending on the magnitude of the cost of the decontamination plant. The fixed nitrogen cases indicate that $G(N)$ values in the range of 6 to 11, in dual-cycle and dual-purpose plants, are competitive with \$25 to \$30 per ton of equivalent ammonia, which is in the range of the lowest production cost possible today. The capacities

are in existence today in single plant locations, and thus, the chemonuclear system is not unrealistic in this respect. A significant advantage of the chemonuclear plant is the long-term availability of fuel as plant sizes become larger. Consumption in conventional plants of fossil fuel becomes extraordinarily high and feed stocks are rapidly depleted with the result that costs increase. Larger chemonuclear plants can be shown to be more competitive, however, the equations for capital investment become less accurate. Credit for by-product oxygen under certain conditions is a significant factor. If electrical power is more valuable than turning it into fertilizer then the dual-purpose case becomes more interesting than the multicycle cases. At higher G values there is less need for crediting by-products to hold costs down.

The CO and H₂ gas product cases have been computed in Table II only for the dual-cycle process so that there is no credit for by-product power. All the power is internally consumed producing H₂ and O₂ electrochemically. The results indicate utility-type costs (7 to 11% fixed charge) of \$0.30 to 0.38/MSCF for G(CO) values between 10 and 20. The plant capacities have been limited to that which would be used in a steel mill for iron ore reduction. The reason for this is that the steel mills can also

use the by-product oxygen from the cells which can be credited at the low cost of \$4/ton O_2 . These costs are in the range of being competitive with gas produced from coal. Hydrogen produced from natural gas costs about \$0.30/MSCF but is geographically limited. It is possible to show, with the above equations, that CO , H_2 , and by-product O_2 can be produced in extremely large quantities for a minimum of 15¢/MSCF. These very large chemonuclear plants may be of use in providing gas supplies for distribution in the pipeline grids presently in existence. The CO_2 feed to the chemonuclear plant can be supplied, either by recovery from the consumer (i.e., iron ore reduction furnaces) or, if no other more concentrated source is available, from the atmosphere which contains a vast store of CO_2 even though it is at a low concentration. As the Table indicates, heavy capital investments will be required to achieve the returns expected in these high volume cases.

The other products shown in Table III which include ozone, hydrogen peroxide, and hydrazine have the potential of being produced at significantly lower than present conventional production costs at plant capacities which are quite reasonable. The ozone case is for large-scale water treatment and pollution control.

In every case, except for hydrazine, raw materials are air and/or water, thus raw material costs are negligible. In the case of hydrazine, the cost shown excludes the cost of ammonia and is thus a conversion cost. The largest plant in the tables is 5300 MW(t) which is roughly equivalent to a 1500 MW(e) plant, and is thus of a reasonable size within present day technology. Of the smaller plants, only the hydrazine case may be somewhat optimistic, since the 100 MW(t) size is somewhat below the intended range of the formula.

The tables also show the effects of decontamination cost factors on plant costs. By varying this factor, new fixed charge rates were calculated based upon typical cases. Product costs were also varied to determine their effect upon fixed charge rates.

Comparison of power costs from the formula with GE estimates for the same plant sizes show that the formula is approximately 15% higher, which indicates some amount of conservatism in the chemical cost estimates. This is shown in the following Table.

<u>Total Power Cost, mils/kWh(e)</u>			
<u>P-MW(e)</u>	<u>P-MW(t)</u>	<u>Formula</u>	<u>GE</u>
300	965	5.36	5.17
600	1930	4.76	4.17
750	2410	4.56	3.97
1000	3220	4.24	3.75

In making this comparison the GE fixed charge rate of 12% was used to obtain a common basis.

The whole point of this economic study was not to obtain high accuracy, but just to determine whether, under reasonably optimistic conditions, there is a chance for fission-chemonuclear processes to hold costs down in the future. It is certain that as the supply of natural fossil fuel decreases, the cost of production of materials based on these fuels will increase. The above analysis shows that even with present knowledge, in the long run, chemonuclear processes may be capable of producing large quantities of utility and industrial chemicals at costs which are not significantly higher than presently possible.

NOMENCLATURE

- C = General term for unit capital cost, $\$/kW(t)$,
- C_C = unit capital cost of electrochemical (cells and rectifiers) and additional chemical equipment to produce the by-product chemical, $\$/kW(t)$
- C_D = unit capital cost of desalination equipment, $\$/kW(t)$
- C_{DP} = unit capital cost of dual-purpose plant (nuclear + chemical), in $\$/kW(t)$,
- C_E = unit capital cost of equivalent nuclear electrical power plant, $\$/kW(t)$,
- C_H = added cost of steam generation equipment, $\$/kW(t)$,
- C_N = unit capital cost of nuclear reactor alone, $\$/kW(t)$,
- C_{NP} = unit capital cost of dual-purpose nuclear plant only (reactor and turbine-generator section), $\$/kW(t)$,
- C_{NS} = unit capital cost of single-purpose nuclear plant only (reactor section), $\$/kW(t)$,
- C_{SP} = unit capital cost of single-purpose plant (nuclear + chemical), $\$/kW(t)$,
- D = water production, gal/MW(t),

E = energy requirement per unit of chemical product,
           kWh(t)/lb of chemical product,
 f = fixed charge rate operating on investment fraction,
 F = fraction of reactor power used for electrical power production,
 G = G value of primary fissiochemical, molecules/100 eV,
 G_{BE} = G value of electrochemical by-product,
 G_{BF} = G value of by-product, fissiochemical,
 G_{max} = theoretical maximum or thermodynamic G value of
           primary fissiochemical,
 H = steam production, lbs/MW(t),
 K = constant factor for estimating cost of decontamination
           part of chemical plant,
 M = mol weight of primary fissiochemical,
 M_{BE} = mol weight of electrochemical by-product,
 M_{BF} = mol weight of fissiochemical by-product,
 N = electrical energy required to produce an electro-
           chemical product, kWh(e)/lb,
 P = reactor power, MW(t),
 S = fraction of reactor power utilized for desalination,
 T = fraction of reactor power to produce steam,
 V = production cost of primary fissiochemical product,
           ¢/lb,

V_{BE} = value of by-produce electrochemical, ¢/lb,

V_{BF} = value of by-product fissiochemical, ¢/lb,

V_D = value of desalinated water, ¢/1000 gal,

V_{EC} = cost of electrochemical product, ¢/lb,

V_H = value of steam, ¢/1000 lb,

W = production cost of nuclear thermal energy,
mils/kWh(t),

ϵ_O = fuel fission fragment energy deposition efficiency,

ϵ_P = efficiency of conversion of thermal to electrical
energy = 0.311.

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FIG. 1

Figure 2

Chemonuclear Production Cost Estimates

Table I

Fixed Nitrogen

Product ²⁾	Fixed Nitrogen as N in (NO ₂ + NH ₃) with O ₂ by-product ³⁾					Fixed Nitrogen as N in NO ₂ and electrical power by-product
System	dual-cycle					dual-purpose
G-value for fission fragment energy	6.0		11.0			6.0
Overall System G-value	7.8		10.3			6.0
Energy, kWh(t)/lb ¹⁾	11.1		8.5			29.0
Fixed charge rate	with de- contamination charge	without de- contamination charge	with de- contamination charge	without de- contamination charge		with decontamination charge
	.07	.10	.14	.20	.16	
Production cost	\$30/equiv. ton NH ₃	\$30/equiv. ton NH ₃	\$30/equiv. ton NH ₃	\$30/equiv. ton NH ₃	\$25/equiv. ton NH ₃	\$25/equiv. ton NH ₃ 4.0 mils/kWh(e)
Reactor power, MW(t)	2,000	2,000	3,700	3,700	5,300	1,300
Total plant cost - \$Million	160	112	241	172	224	98
Plant capacity-tons/day						
a. via fission fragments	825 N	825 N	2,320 N	2,820 N	4,000 N	540 N 400 MW (e)
b. via electrochemical cells	1,325 N 2,220 O ₂	1,325 N 2,220 O ₂	2,430 N 4,060 O ₂	2,430 N 4,060 O ₂	3,500 N 5,800 O ₂	

Notes: 1) Energy requirement is total for products and by-products, and includes fission fragment and electrical energy.

Basis: ϵ_o = f.f. energy deposition efficiency = 0.50 ϵ_p = Thermal to electrical power efficiency = .311Energy for H₂ electrolytic cells = 140 kWh(e)/MSCF H₂

2) Raw materials for all products are air and water.

3) O₂ by-product value taken as \$4.00/ton

Chemonuclear Production Cost Estimates

Table II
Synthesis Gas ($\text{CO} + \text{H}_2$)²⁾ Dual Cycle System With O_2 Byproduct

G - value for fission fragment energy	20			10	
Overall system G - value	15			11	
Energy, kWh(t)/MSCF	218			293	
Fixed charge rate	with decontamination charge	without decontamination charge		with decontamination charge	without decontamination charge
	.07	.07	.11	.07	.09
Production cost - ¢/MSCF($\text{H}_2 + \text{CO}$)	30	20	30	38	38
Reactor Power, MW(t)	1,380	5,000	1,380	1,880	1,880
Total plant cost - \$Million	105	158	67	133	88
Plant capacity - MMSCF/day of ($\text{CO} + \text{H}_2$)					
a. via fission fragments	100×10^6	363×10^6	100×10^6	68×10^6	58×10^6
b. via electrochem. cells	52×10^6	188×10^6	52×10^6	86×10^6	36×10^6
O_2 By-product-tons/day	3,280	11,900	3,280	3,290	3,290

Notes: 1) Energy requirement is total for products and by-products, and includes fission fragment and electrical energy.

Basis: ϵ_o = f.f. energy deposition efficiency = 0.50

ϵ_p = thermal to electrical power efficiency = .311

Energy for H_2 electrolytic cells = 140 kWh(e)/MSCF H_2

2) Raw materials for all products are air and water.

3) O_2 by-product value taken as \$4.00/ton.

Chemonuclear Production Cost Estimates³⁾

Table III
Single Purpose System Chemicals²⁾

Product	Ozone O ₃	Hydrogen Peroxide H ₂ O ₂	Hydrazine N ₂ H ₄
G-Value for fission fragment energy	6.0	1.7	2.0
Energy, kWh(t)/lb ¹⁾	8.5	42.0	38.0
Fixed charge rate	0.14	0.25	0.25
Production cost	\$47/ton	\$0.15/lb	\$0.25/lb (excludes NH ₃ cost)
Reactor power, MW(t)	423	700	100
Total plant cost - \$Million	38	51	16
Plant capacity - tons/day	600	200	30

- Notes:
- 1) Basis for energy requirement is f.f. energy deposition efficiency = 0.50.
  - 2) Raw materials for products are air and water.
  - 3) All estimates include maximum decontamination charge factor.