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Research and Economic Evaluation on Uranium Enrichment by Gaseous Diffusion Process in Japan

T. Aochi, Japan Atomic Energy Research Institute
R. Nakane, The Institute of Physical and Chemical Research
S. Takahashi, Mitsubishi Atomic Power Ind., Inc.

1. Introduction

A completion of a total fuel cycle system for light water power reactor is a current urgent problem. The technologies for construction and operation of power reactors and fuel fabrication are almost completed. The remaining problems are of uranium enrichment, reprocessing and waste management.

Research and development on Uranium enrichment by gaseous diffusion process were carried out by JAERI, IPCR, MAPI and others since 1965.

The accessment on gaseous diffusion plant were carried out under consideration of total techno-economical system. The scientific and engineering studies are carried out on main key components and/or problems such as barrier, compressor, sealing, corrosion, diffusor assembling, plant system design and so on.

Based on the experimental data, techno-economic evaluation on a uranium enrichment plant was carried out with regard to the optimization of separation efficiency, numbers of step and operating conditions of the plant. Financing planning to reduce the capital and operation cost to the minimum was studied.

2. Barrier

Tetrafluoroethylene, aluminum oxide and nickel were chosen as the source materials. Diameter and size distribution of tetrafluoroethylene particle were very important keys for barrier manufacturing. Polymerization test of monomer tetrafluoroethylene to obtain characteryzed powder showed γ-ray method much better than chemical one. The powders having diameter of particle from 0.04μm to 0.5μm was applied for manufacturing test of barrier. The size distribution range of the particle was narrow.

Tetrafluoroethylene powder consisted of characteryzed particle size and distribution was uniformly mixed with binder. The mixture was treated by roll machine, then immersed into solvent. The barrier was heated up to temperature of about 300°C. The size of a barrier sheet was about $5000cm^2$.

The aluminum oxide and nickel barriers were manufactured by pressing the fine powders under high temperature and pressure.

Evaluation test of barriers were conducted by measuring the isotope separation factor and permeability of Ar. The mean radius of pore was estimated from the observed values of separation efficiency, which were obtained at P_F = 1 atm and P_B = 0, and the Present-de Bethune Theory.[1] As shown in Fig. 1, the tetrafluoroethylene barrier showed the highest separation efficiency and then the smallest estimated value on the pore size. Permeability of the barrier decreased with increasing separation efficiency. The effect of operation pressure to separation efficiency was also observed. The separation efficiency decreased with increasing pressure as shown in Fig. 2. However, the decreasing of efficiency with pressure was not so marked as expected from the theory.[1]

U and Ar isotopes were separated by a 13-stage diffusion cascade using the tetrafluoroethylene barriers.[2] Good correlation for separation factor between both isotopes was found. No permeability change for tetrafluoroethylene barrier was observed after 3000 hr UF_6 corrosion test.

The tetrafluoroethylene barrier is considered to be the best from the points of cost and characters such as separation efficiency, chemical stability and so on.[3]

3. Compressor and others

Based on the experiences of small UF_6 loop using a 25KW centrifugal compressor, a large UF_6 loop using a 250KW axial compressor was constructed to get aerodynamic characteristics of UF_6 compressor. Long term operation test were conducted, which resulted in good agreement of tested values with these calculated by the design code of National Aerospace Lab. and adiabatic efficiency (shown in Fig. 3) was recognized as high as 90%. Fundamental design and manufacturing engineering have no special problems except sealing. Good results were also obrained for other components, such as heat exchanger, NaF trap, cold trap and shaft seal equipment, further, the handling techniques for large amount of UF_6 were established.

A shaft seal testing device was also constructed to determine leak rate for various kinds of seal mechanism. Several unit samples of contact and non-contact type seal showed good performances concerning with leak rate ($<10^{-4}$g/sec) and stabilities for UF_6.

4. Techno-Economical Studies

In economic evaluation on uranium enrichment by gaseous diffusion process, salient methods were developed by M. Martensson,[4] K. Higashi and H. Doi.[5] Two evaluation codes were developed by Mitsubishi Atomic Power Ind. Inc..[3][6] The cord "MIGAD-II" was advanced on the theory of barrier performance and cost functions. Optimizations scheme is same as the first one,[6] and characteryzed by following equation:

$$\begin{aligned} C_{pae} = {} & C_f F 10^3 + {}_{i+1} \left(N_{ei} + N_{si}\, 9.703 \times 10^{-6} F_o e^{-1} TL_i \ln \frac{P_{1i}}{P_{2i}} \right. \\ & + a F_1 F_2 F_3 F_4 \quad C_{oAj} \left(8.310 \times 10^{-6} \frac{TL_i}{P_{2i}}\right)^{K_{Aj}} \\ & + \quad C_{oBj} \left(1.479 \frac{L_i}{Q_i}\right)^{K_{Bj}} \\ & + \quad C_{oCj} \left(2.647 \times 10^{-4}\, TLi \ln \frac{P_{1i}}{P_{2i}}\right)^{K_{Cj}} \\ & + \quad C_{oDj} \left(2.958\, Li\right)^{K_{Dj}} \quad \left. \right) \\ & \qquad\qquad\qquad (\$ / yr) \qquad\qquad (1) \end{aligned}$$

where the meaning of symbols is given in Table I.

Typical factors and coefficients in the equation (1) are shown in Table II. Using the code "MIGAD-II", specific cost coefficient and cost exponents are shown in Table III, which is estimated from U.S.A.E.C. report.[7] An example of gaseous diffusion plant optimized on some assumptions is shown in Table IV. Some results are summarized as Figures. In Figs. 4 to 6, size of (3, 3) equi-step squared-off cascade and relative cost of separative work are shown as a function of production rate, separation factor and the unit cost of power.

Sensitivity analysis on the effects of many components factors were also studied. In Fig. 7, sensitivity of specific investment is shown as a function of barrier quality and compressor efficiency change. In Fig. 8, relative cost of separative work is shown as a function of various mean pore radius of the barrier. These results show that barrier quality is the most important key in the technology.

5. Financing Analysis

The assumed uranium enrichment gas diffusion facility for commercial use is a large and capital-intensive plant. The financing analysis shows that the following items are very important.

a) The financing plan must be established to reduce the cost of capital to the minimum and the risk to the practical minimum.

b) The construction schedule of plant and the operation schedule must be planned with consideration of the above-mentioned matters and minimized the cost for enrichment services.

c) The cash flow program study is the most important for this project.

d) Maximization of debt in a percentage of total capitalization.

e) Minimization of risks to equity and achievable cost of capital.

f) Off-take contracts to utilities and some organizations.

6. Political Problems

The living way of this century is considered as "energy consuming Human life". Oil was and is consumed as mathematical δ-function. Total energy system analysis is urgent matter which we must do.

If we consider the status of recent progress of technologies, uranium enrichment and reprocessing technologies are no-special fundamentally. On the other hand, there is uncertain possibility of abuse of enriched uranium. We must consider the use of enriched uranium for peaceful use only. This is very important matter of this century.

By the consideration of the present technologies status, their near future developments and future demands, the necessity of world agreements on uranium enrichment and plutonium is very important and urgent matter.

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[6] YAMADA, T., ISHII, B., Influence of Stage Separation Factor on Squared-off Cascades, J. of Nucl. Sci. and Techn., 11, 2 (1974)

[7] ORO-685, Data on New Gaseous Diffusion Plants. Oak Ridge, Tennessee, USAEC, April (1972)

Table I : Notation in Equation (1)

(see also Table II)

C_{pae} : Plants annual costs (\$/yr)
F : Supplied UF_6 quantity (Ton-U/yr)
M : Number of cascade steps (-)
N_{ei}, N_{si} : Number of stages of enriching step i and stripping step i respectively (-)
T : Process temperature (°K)
Li : Flow rate of step i (Ton-U/yr)
P_{1i}, P_{2i} : Fore and back pressure of step i, respectively (Torr)
C_{0j} : Cost coefficient (\$/stage)
j : Member of component element j
K_j : Cost exponent (-)
Q_i : Flow rate through barrier (Ton-UF_6/$m^2 \cdot$yr)
(Aj, Bj, Cj, Dj):
- A1 : Gas compressor
- A2 : Process piping and valves
- B1 : Gas diffuser
- B2 : Process buildings and enclosures
- C1 : Compressor drive motor
- C2 : Electrical system
- C3 : Heat Removal system
- D1 : Instrumentation
- D2 : Miscellaneous system
- D3 : Plant start-up support
- D4 : Process support facilities

Table II: Factors and Coefficients in Cost Function

Notation	Explanation	Value Used
F_o	Factor taking into account the electricity consumption for other purpose than the process main compression	1.45
F_1	Factor for the fee of engineering and design	1.045
F_2	Contingency factor	1.15
F_3	Factor of interest during construction	1.10
F_4	Factor for plants extra facilities	1.05
a	Plants annual capital charge rate	0.146
e	Unit cost of electricity (mills/kwh)	9.0
	Compressor efficiency	0.80
C_f	Unit cost of UF_6 feed (S/kg-U as UF_6)	23.5

Table III: Specific Cost Coefficient and Cost Exponent

	Cost coefficient ($/stage)	Cost exponent (-)
Gas Compressor	16,000	0.51
Process piping & valves	31,700	0.11
Gas diffuser	357	0.68
Process building & enclosures	1,030	0.53
Compressor drive motor	24.2	0.63
Electrical system	2,775	0.31
Heat removal system	29.3	0.58
Instrumentation	22,800	0.0
Miscellaneous system	13,200	0.05
Plant start-up support	8,900	0.0
Process support facilities	81,300	0.0

Note: These figures are estimated from ORO-685 using the cord "MIGAD-II".

Table IV: An Example of GDP Optimized on the Assumptions

Assumptions	Value Used
Product rate (ton-U/yr)	1,500
Enrichment (% 235U)	4
Type of cascade	(3.3) Equi step
Unit cost of electricity (mills/kwh)	9
Minimum pore radius (Angstron)	50
Minimum temperature ($^{\circ}$C)	30

Results	Value Obtained		
	Large stage	Medium stage	Small stage
Fore pressure (Torr)	382	441	469
Back pressure (Torr)	82	83	80
Pressure ratio (-)	4.7	5.3	5.9
Enrichment coefficient (-)	1.00418	1.00426	1.00435
Waste Assay (% ^{235}U)			0.285
Total number of stages			1,034
Equivalent separative work production (ton-SWU/yr)			8,152
Cascade efficiency (-)			0.93
Total construction cost. incl. indirect costs ($ million)			1,230
Specific investment ($/kg-SWU/yr)			151
Total electricity consumption (kwh/kg-SWU)			20.6 x 10^9
Specific electricity consumption (kwh/kg-SWU)			2,490
Cost of separative work ($/kg-SWU)			44.4

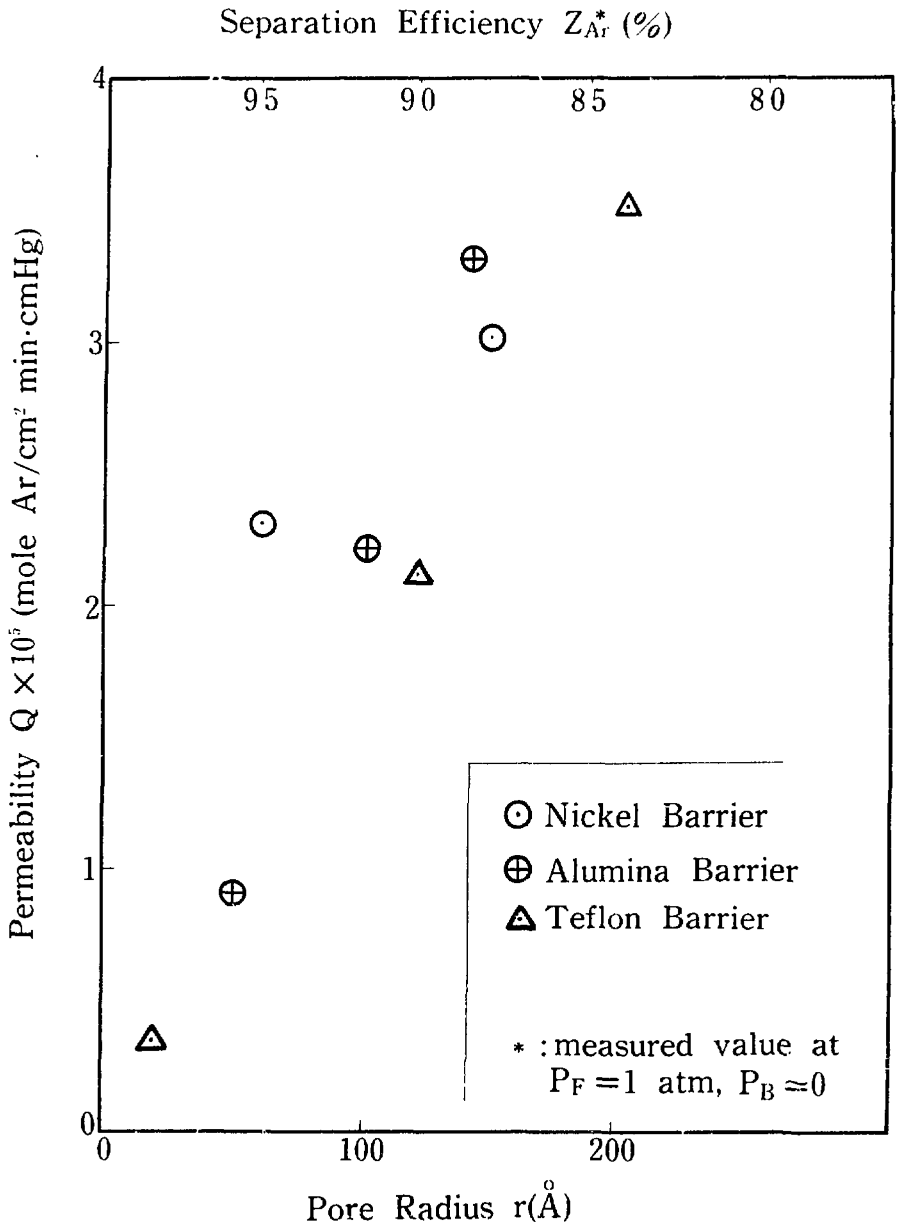

Fig.1 Charactaristics of Barriers

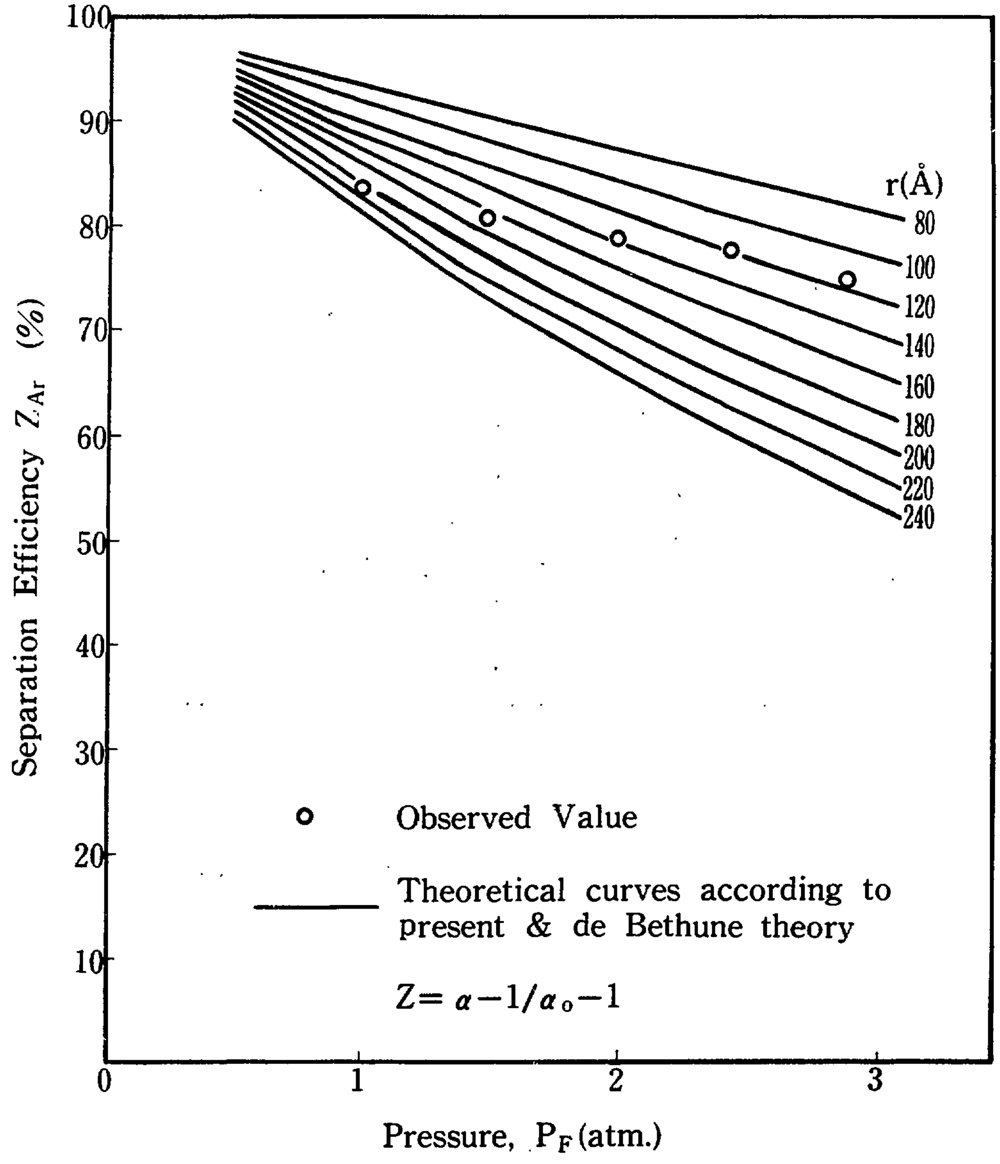

Fig.2 Effect of operation pressure to separation efficiency

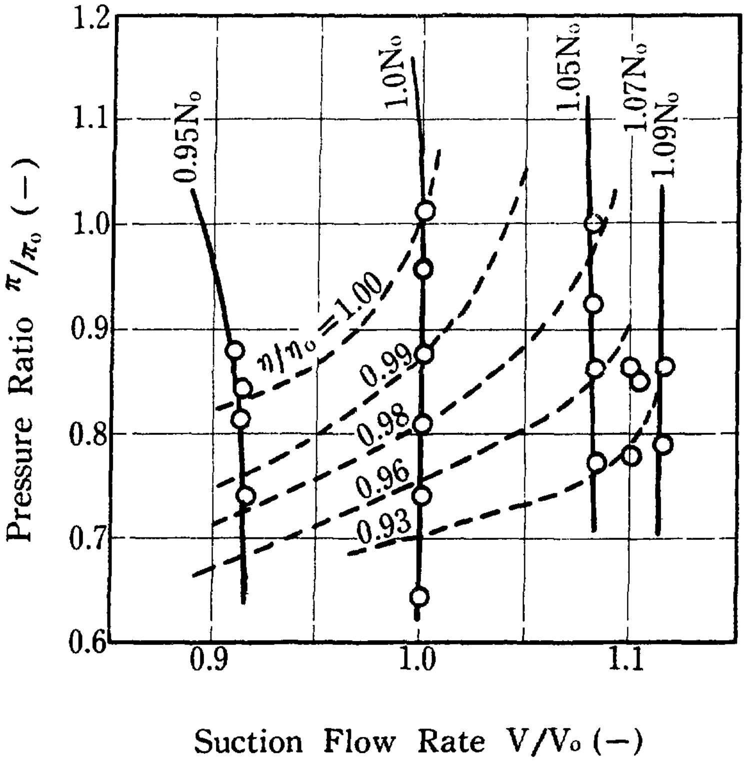

Fig.3 Performance Curve of Axial Compressor for Uranium Hexafluoride gas

π (=Pd/Ps) : Pressure Ratio of Compressor(−)
V : Suction Flow Rate (m^3/min)
N : Rotation Speed of Compressor Shaft(rpm)
η : Adiabatic Efficiency (%)
Suffix o : Designed Value

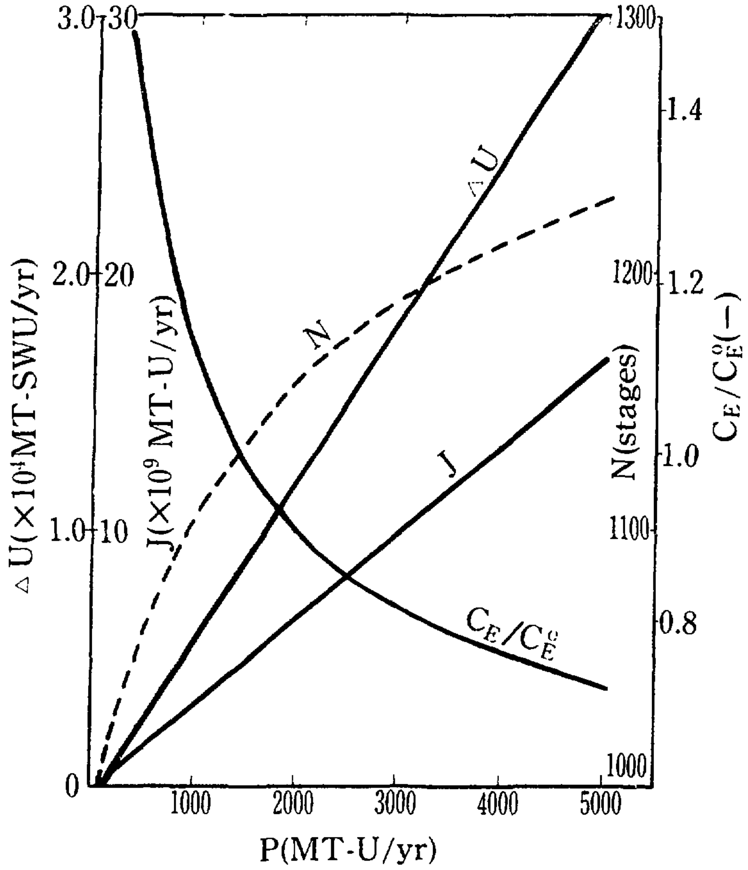

Fig.4 Required separative work (△U), total flow rate (J) and total stages (N) of the (3,3) equi-step squared-off cascade, and relative cost of separative work (C_E/C_E^0) as a function of the production rate (P). (product assay =4.0wt%, assumed separation factor=1.0040).

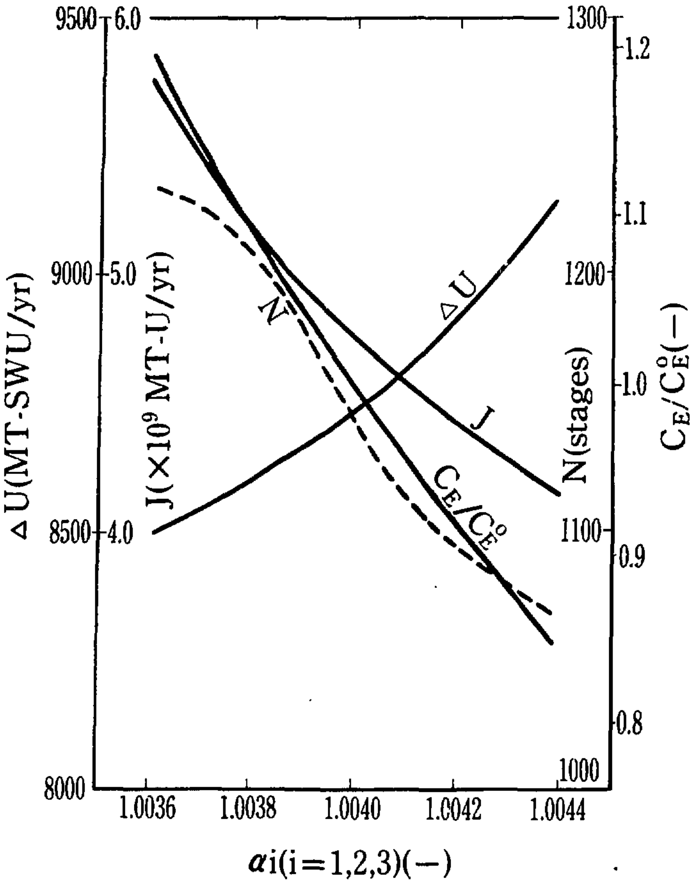

Fig.5 Required separative work (△U), total flow rate (J) and total stages (N) of the (3,3) equi-step squared-off cascade, and relative cost of separative work (C_E/C_E^0) as a function of the separation factor (αi). (production rate=1500MT-U/yr, product assay =4.0wt%).

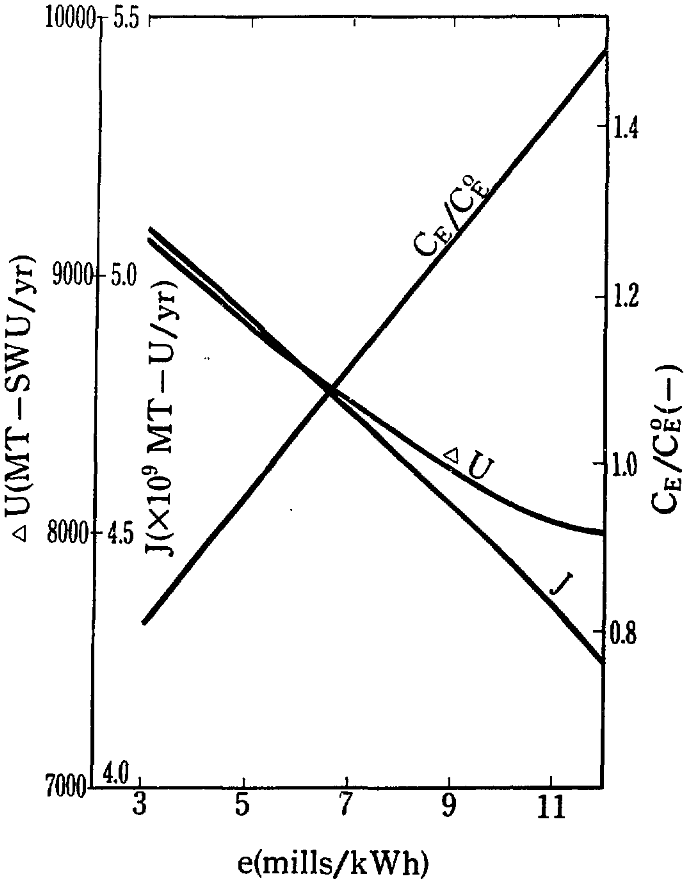

Fig.6 Required separative work (△U), total flow rate (J) of the (3,3) equi-step squared-off cascade, and relative cost of separative work (C_E/C_E^o) as a function of the unit power cost (e).
(production rate = 1500MT-U/yr, product assay = 4.0wt%,-assumed separation factor = 1.0040).

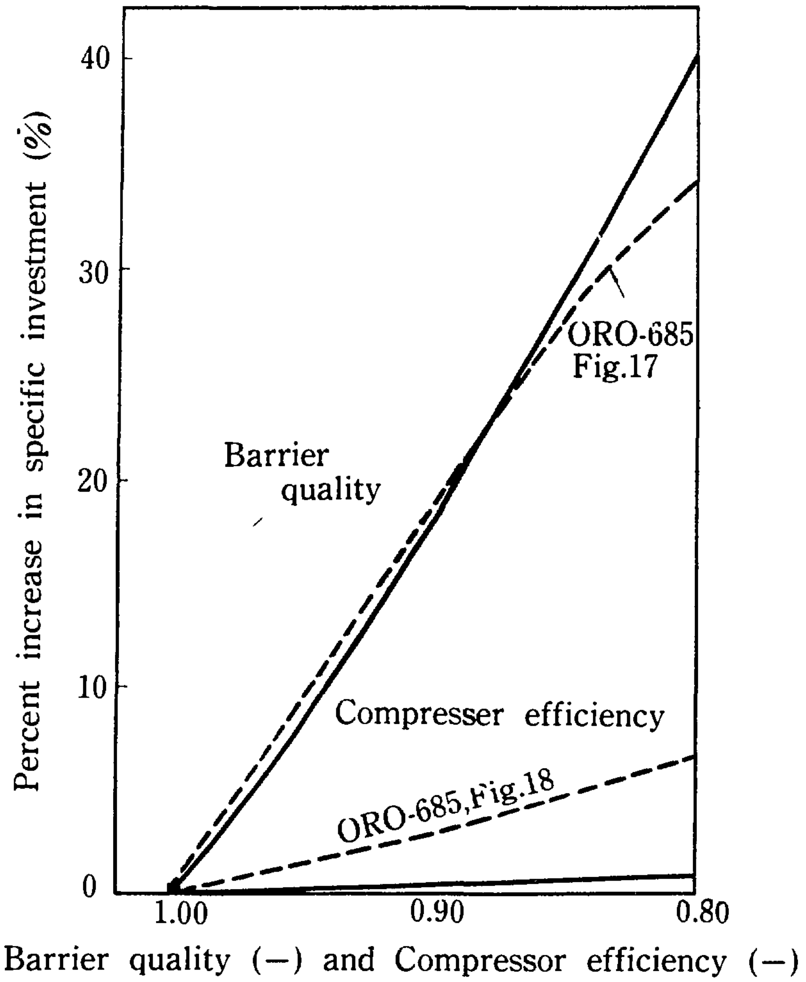

Fig.7 Percent increase in specific investment to barrier quality and compressor efficiency

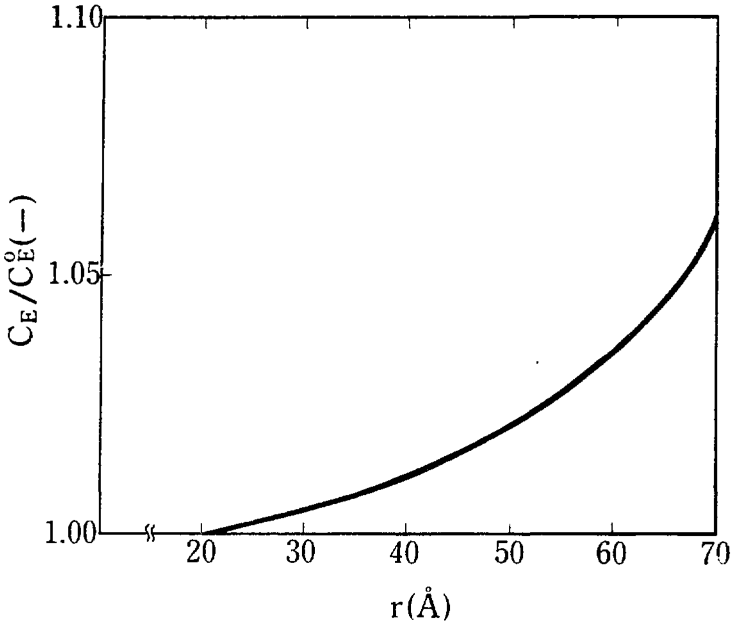

Fig.8 Estimated cost of separative work to mean pore radius of the barrier.