ECONOMIC ANALYSIS — PRELIMINARY CONSIDERATIONS FOR POWER GENERATION USING A DOWNHOLE COAXIAL HEAT EXCHANGER SYSTEM (Ⅳ)

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1. INTRODUCTION

A downhole coaxial heat exchanger (DCHE) system as illustrated in Fig. 1 was proposed as a new geothermal energy extraction system. A series of studies (Morita and Sugimoto, 1988; Sugimoto and Morita, 1988; Yamada et al., 1988) were carried out on power generation using the DCHEs for the specified well design and temperature distribution in the formation. The purpose of these studies is to clarify at what thermal output or effective thermal conductivity of the formation the system becomes economical.

The four effective thermal conductivities of the formation were assumed and thermal output of the DCHEs was estimated by computer simulation (Morita and Sugimoto, 1988). Assumed effective thermal conductivities are 2.7, 10.0, 20.0, and 30.0 kcal/mh℃. A combination of two-phase turbine and steam turbine was selected as a power generation system and the change of net power output was estimated (Sugimoto and Morita, 1988). The DCHEs and surface facilities were designed (Yamada et al., 1988).

In the present study, costs for prospect, DCHEs, power plants and related facilities were estimated. Then the power generation cost was estimated for each effective thermal conductivity of the formation.

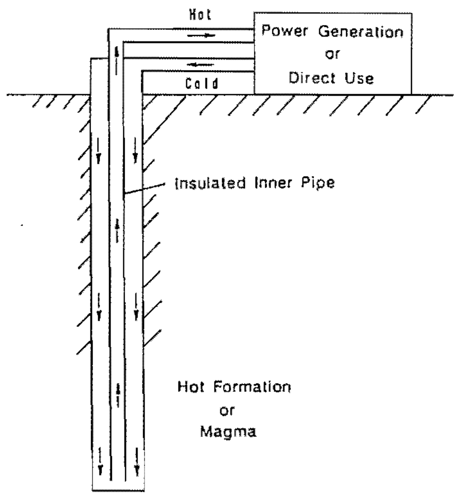

Fig. 1 Concept of the downhole coaxial heat exchanger system

2. OUTLINE OF THE POWER GENERATION SYSTEM

The outline of the power generation system is listed in Table 1. The power generation system mainly consists of 15 DCHEs and a power generation plant.

The length of the DCHEs is 3,000 m. It is assumed that 3 wells are completed every 4 months for the first 12 wells using 3 drilling rigs, then 3 wells are drilled one after another. It takes 28 months to drill 15 wells.

The design parameters of the power plants such as flow rates, reinjection temperatures and hot water temperatures were determined by Sugimoto and Morita (1988).

Table 1 Outline of the power generation system

Case	Case 1	Case 2	Case 3	Case 4
Eff. thermal cond. (kcal/mh℃)	2.7	10.0	20.0	30.0
Number of DCHEs	15			
Length of DCHEs (m)	3,000			
Plant capacity (MW)	3.5	12.8	25.7	37.2
Design flow rate (t/h)	180	540	1,080	1,260
Design reinjection temperature (℃)	90.0	90.0	90.0	80.0
Design hot water temperature (℃)	192.5	201.4	198.6	212.2

3. COST ESTIMATION

Total 18 wells are drilled for prospect. Nine of them are 400 m in depth, five of them are 1,000 m and five of them are 1,500 m. Costs for prospect wells, prospect on the surface, environmental survey and general analysis were estimated as listed in Table 2. Total prospect cost was estimated to be 1.83 billion Yen.

The DCHE system is applicable to any formation whose temperature is high, consequently to a wide variety of geothermal resources. The extent of hot formation is large in general. This indicates lower risk of prospect in comparison with conventional geothermal power generations or binary cycle power generations. Furthermore, the system is completely pollution free which results in very small environmental effects. The prospect cost including environmental survey cost might be reduced if proper prospect procedure for the DCHE power generation system is established.

Table 2 Prospect cost
(Unit: thousand Yen)

Item	Unit cost	Cost
Prospect wells		1,530,000
400 m (x9)	(40,000)	(360,000)
1,000 m (x5)	(102,000)	(510,000)
1,500 m (x4)	(165,000)	(660,000)
Prospect on the surface	—	130,000
Environmental survey	—	100,000
General analysis	—	70,000
Total	—	1,830,000

The construction cost of the DCHE was estimated for the specified design of well and inner pipe (Yamada et al., 1988). The results are listed in Table 3.

The construction cost per DCHE was estimated to be 965 million Yen (322 thousand Yen/m). Therefore, 14.48 billion Yen is necessary to construct 15 DCHEs.

Table 3 Cost for the DCHEs
(Unit: million Yen)

Item	Unit cost	Cost
Drilling and well completion	840	12,600
Inner pipe	125	1,875
Total	965	14,475

The construction costs of the power generation plant, transportation pipe line etc. were also estimated. The power plant construction costs were estimated to be 569, 1,539, 2,716 and 3,564 million Yen for Case 1 to 4, respectively.

All construction costs are listed in Table 4. "Others" in Table 4 includes cost for temporary structure, management and interest during construction period. The total construction costs are 18.6, 20.0, 22.1 and 23.5 billion Yen for Case 1 to 4, respectively. Construction cost per power plant capacity decreases significantly as effective thermal conductivity increases.

Table 4 All construction costs
(Unit: million Yen)

Item	Case 1	Case 2	Case 3	Case 4
Prospecting	1,830 (0.10)	1,830 (0.09)	1,830 (0.08)	1,830 (0.08)
DCHE	14,555 (0.78)	14,665 (0.73)	14,825 (0.67)	14,965 (0.64)
Transportation line	204 (0.01)	441 (0.02)	744 (0.04)	906 (0.04)
Power plant	569 (0.03)	1,539 (0.08)	2,716 (0.12)	3,564 (0.15)
Others	1,476 (0.08)	1,547 (0.08)	2,011 (0.09)	2,249 (0.09)
Total	18,634 (1.00)	20,022 (1.00)	22,126 (1.00)	23,514 (1.00)
Construction cost (Thousand Yen/kW)	5,002	1,530	1,000	657

The prospect cost corresponds 7 to 10 % of the total construction cost which is smaller than that of conventional geothermal power generation system.

The cost for DCHEs occupies 64 to 78 % of the total construction cost and the cost for surface facilities occupies 8 to 22 %. The cost for DCHEs occupies the major portion of the total construction cost and the percentage is greater than that of wells cost for conventional power generation systems. The reason is considered as follows:

1) Since net power output per well is smaller than that of conventional geothermal power generation system, more wells are required to produce the same net power output.
2) Insulated inner pipe is needed additionaly.
3) Since risk with prospect is less, prospect cost is smaller in comparison with conventional geothermal power genaration.
4) The hot water produced by DCHEs is quite clean. Consequently, the power generation plant is corrosion free and scale free which results in lower construction cost of the power plant.

4. POWER GENERATION COST

The change of annual power generation costs and adjusted mean power generation costs over 15years'plant operation were calculated. The same premises as used in economic analysis for conventional geothermal power generation were employed.

The premises used in this paper are as follows:

1) Interest rate : 6%
2) Inflation rate of personal and repairing cost : 2%
3) Repairing cost : 2% of initial construction cost
4) Life of equipments
   Well : 5 years, Power plant : 15years
   Transportation line : 8 years, Structure : 45 years

The change of annual power generation costs are shown in Fig. 2. The power generation costs of the first year are significantly high since net power outputs are small at that time. The costs decrease rapidly during from 5th year to 8th year of plant operation. In this period the depreciation of the wells ends in turn. The increase of the power generation costs after 8 years' plant operation is due to decrease of net power output and inflation of costs for personal, plant maintenance and management.

The power generation costs, after 14 years from the beginning of plant operation, are 31.3, 10.2, 6.8 and 5.2 Yen/kWh for Case 1 to 4, respectively.

The annual values of power generation costs over 15 years' plant operation were calculated according to the present value method which is usually used in evaluation of conventional power plant constructions. Table 5 shows an example of the results, in which each annual expense is converted into present value for Case 3.

The adjusted mean power generation costs are 119.0, 36.5, 20.2 and 14.7 Yen/kWh for Case 1 to 4, respectively as shown in Fig. 3. The cost decreases greatly as the effective thermal conductivity of the formation increases.

The result indicates that when effective thermal conductivity of the formation is 2.7 kcal/mh℃ (Case1), purely conductive case, the power generation system seems to be impractical. It can be used only in isolated islands or inlands. When effective thermal conductivity of the formation is 30 kcal/mh℃ (Case4), convective case, the power generation using the DCHEs is comparable to new geothermal power generation system such as binary cycle power generation system or Hot Dry Rock power generation systems.

It should be noted that a subsidy for well drilling is not taken into account in above cost estimation. Since well cost occupies major portion of the construction cost as described above, the subsidy reduces the power generation cost significantly.

5. CONCLUSIONS

The power generation costs of the DCHE system were estimated for the four effective thermal conductivities of the formation. The results obtained in this paper are summerized as follows:

1) When heat is transfered only by conduction in the formation as in the Hot Dry Rock, the power generation using DCHE seems to be not economical. It can be used only in isolated islands or inlands.
2) When effective thermal conductivity is greater than 30.0 kcal/mh℃, whieh means large contribution of convective heat transfer, the adjusted mean power generation cost becomes lower than 14.7 Yen/kWh. In this case, the power generation using the DCHE might be practical considering a subsidy for drilling of wells.

It has been clarified that the power generation using the DCHE becomes practical when effective thermal conductivity of the formation is greater than 30.0 kcal/mh℃. It suggests that the power generation using the DCHE is valuable to develop its technology.

On the other hand, in-situ effective thermal conductivity of the formation or magnitude of convective heat transfer in the formation has not been studied enough. It is important to evaluate in-situ effective thermal conductivity or, in other words, the effect of convective heat transfer on the thermal output of the DCHE to determine if this power generation system is realistic or not.

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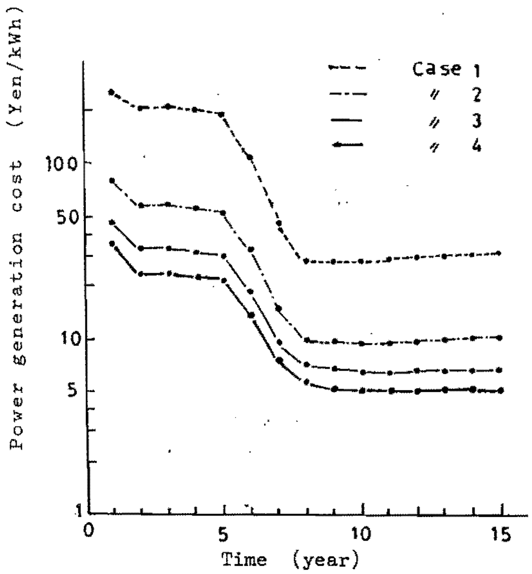

Fig 2 Change of power generation cost

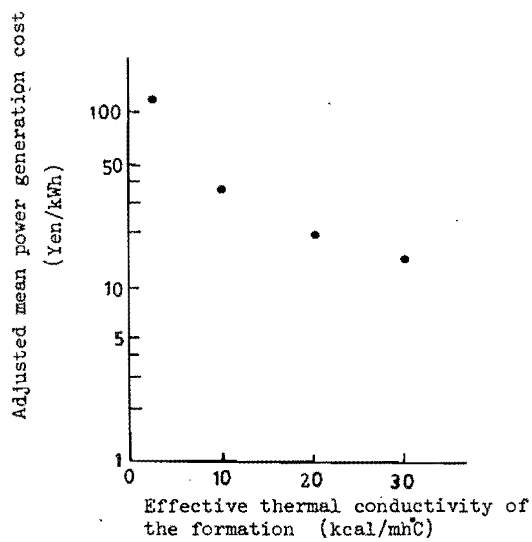

Fig 3 Relationship between effective thermal conductivity of the formation and adjusted mean power generation cost

Table 5 Adjusted mean power generation cost by present value method (Case 3)
(Unit; million Yen)

Capital recovery coefficient (0.102966)

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total	Averg. annual expenses
Book value	12,658	18,161	16,948	13,214	9,480	5,746	3,633	2,924	2,616	2,355	2,135	1,927	1,719	1,511	1,303		-
Additional well	7,020	2,005															
Additional transportation line	361	103															
(1)Capital 1+2+3	3,033	4,461	4,438	3,956	3,513	1,897	689	348	285	233	204	185	167	150	135	23,696	2,440
1 Interest 6%	980	1,088	905	656	451	258	154	117	98	84	72	61	51	43	35	5,060	521
Depreciation Well	1,621	2,854	3,049	2,877	2,714	1,349	283	0	0	0	0	0	0	0	0	14,746	1,518
Transportation line	47	83	89	84	79	75	70	67	33	7	0	0	0	0	0	634	65
Power generating plant	198	187	176	166	157	148	140	132	124	117	111	104	98	93	88	2,038	210
Structure	10	9	9	8	8	7	7	7	6	6	6	5	5	5	4	103	11
2 Total of depreciation	1,876	3,133	3,323	3,135	2,958	1,579	500	205	164	130	116	110	103	98	92	17,521	1,804
3 Fixed property tax	177	240	211	155	105	60	36	27	23	20	17	14	12	10	8	1,115	115
(2)Direct expenses	364	469	451	434	418	402	387	372	358	345	332	319	307	296	284	5,538	570
Personal expenses	60	58	56	53	51	50	48	46	44	42	41	39	38	36	35	697	72
Repairing expenses	253	343	330	317	305	294	283	272	262	252	242	233	224	216	208	4,034	415
Charges	51	69	66	63	61	59	57	54	52	50	48	47	45	43	42	807	83
(3)Indirect expenses	812	113	111	102	94	68	48	41	39	37	36	34	32	31	29	896	92
Management expenses (8% of direct expenses)	29	38	36	35	33	32	31	30	29	28	27	26	25	24	23	443	46
Enterprise tax	52	76	75	67	60	36	17	11	10	9	9	8	8	7	7	453	47
Total (1)+(2)+(3)	3,478	5,043	5,002	4,493	4,025	2,360	1,124	762	682	615	571	537	506	476	449	30,130	3,102
(4) Adjusted mean power generation cost Yen/kWh																	20.2