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DESIGN OF LAND-BASED, FOAM OTEC PLANTS FOR BOTTOMING CYCLES

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Abstract

Open cycle OTEC technology suggests new concepts for the embodiment of commercially feasible bottoming processes to recover energy from, and simultaneously minimize the environmental impact of, hot industrial effluents. The approach would make pollution abatement more economically attractive, yielding, clean, low temperature flue gases while recovering a large portion of their thermal energy as electricity. The technology opens the use of lower quality fuels without fear of air pollution caused by their flue gases. Scrubbing would clean and cool the gases, yielding a hot fluid which after proper treatment would serve as the working fluid for open cycle systems using ambient air as the heat sink.

Preparatory to demonstrating the Foam Energy Recovery Open Cycle System (FEROCS) at a 1 MW - 10 MW scale, a structural design was initiated for a unit 580 ft high visualized as an inverted, vertical, reinforced concrete U tube of 36 ft I.D. and walls 11 in. thick. The structure is feasible based on present construction practices with reinforced concrete in Puerto Rico. It would cost approximately \$1.4 MM and consume 3,800 yds^3 of concrete and 860 tons of reinforcing steel.

To accelerate the demonstration of FEROCS, it is proposed to utilize artificially created temperature differences that can be readily obtained between industrial thermal effluents, for example flue gases at > 250°F from fossil fuel fired steam generating plants, as the heat source and ambient air as the heat sink.

Results are presented of a study made conceptualizing the process using different scrubbing-working fluids.

Introduction

The technology being developed for the open cycle OTEC systems open new fields for the embodiment of commercially feasible processes to recover electric energy and simultaneously minimize the environmental impact of hot flue gases from fossil fuel fired furnaces. The approach would make their pollution abatement more economically attractive yielding "clean, low-temperature" flue gases while recovering a significant portion of their thermal energy as electricity. The ease with which the embodiment of the idea appears to be applicable would open for use lower quality fossil fuels, for example those of higher ash and higher sulfur content, without the fear of the air pollution caused by their flue gases. A relatively simple scrubbing step in properly modified commercially available scrubbing towers would clean and cool the gases, yielding a hot liquid which after proper cleaning would serve as the working fluid for open cycle systems using ambient air as the heat sink.

The Foam OTEC[1] system makes testing of this concept possible. The concept could be applicable just as well in a foam tower to raise the potential energy of the scrubbing fluid or in a convergent-divergent nozzle to increase the kinetic energy of the foam to move a water wheel that would drive a generator.

Contrary to the OTEC scheme which visualizes using the ocean surface waters as the heat source and the ocean deep waters as the heat sink, the approach described here visualizes utilizing the hot flue gases from fossil fuel fired furnaces and other industrial thermal effluents as the heat source and atmospheric air as the heat sink by the use of judiciously selected scrubbing fluids with presently known direct contact scrubbing and heat transfer technology.

A potential scrubbing fluid could be plain water. But, higher-boiling organic liquids or oils will probably permit higher energy recovery rates. Glycols or other high-boiling liquids like silicone oils and high boiling plasticizers might serve the purpose just as well if not better than water in the presence of small amounts of water to help the foaming, cooling tower operations and the separation of the phases. Because of the nature of the scrubbing-open cycle working fluids being considered, and the temperature levels of the process in addition to the foreign matter that the fluids will tend to accumulate, it is doubtful that it will be necessary to use a non-condensable gas and detergents to help generate the foam necessary to couple the vapour and liquid phases especially in convergent divergent nozzles.

Fig. 1 shows the embodiment of the process.

Description of the Process

The following description refers mainly to the recovery of energy from hot flue gases. The concept is equally applicable to other thermal effluents. The principal change would be in Unit I,

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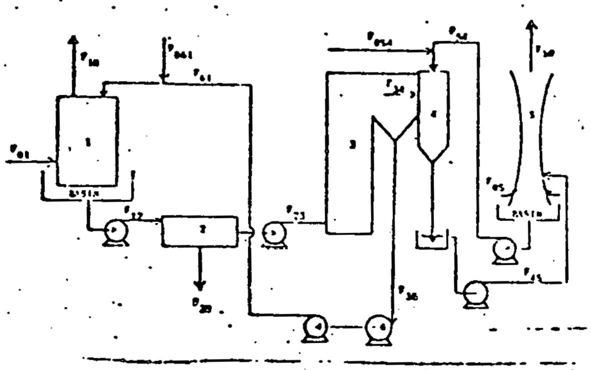
DISCLAIMER

Fig. 1

[illegible] CYCLE TO RECOVER ENERGY FROM HOT FLUE GASES AND TO REDUCE THEIR IMPACT UPON THE ENVIRONMENT



where the waste energy is transferred, preferably by direct contact, to the open cycle scrubbing-working fluid.

Unit I

A scrubbing/cooling tower where the hot flue gases F_{01} will be scrubbed of solid particles, sulfur and NO_x compounds and cooled to approximately 95°F - 100°F. The temperature of F_{01} will range upward from approximately 250°F depending upon the amount of sulfur in the fuel. Higher sulfur contents will call for higher F_{01} temperatures to prevent corrosion of the preheaters and economizers of the fossil fuel fired furnaces because of condensation of H_2SO_3 and H_2SO_4. F_{10} will leave the tower at 95°F - 100°F "cleansed of sulfur, NO_x compounds and solid particles" containing some water and a small amount of organic scrubbing liquid. The scrubbing agent F_{61}, plain water or higher-boiling liquids of the most thermally stable kinds, will enter the top of Unit 1 in a fashion counter-current to the flue gases and collect at the tower basin as a liquid at 212°F if water, or higher temperatures if higher boiling fluids are used. The flow F_{12} will contain the solid particles, H_2SO_3, H_2SO_4 and some of the NO_x compounds. F_{061} and F_{054} will be make up streams.

Unit 2

A system used to treat F_{12} to remove the sulfur compounds, solid particles and possibly NO_x compounds by sedimentation, filtration or a combination with other procedures. F_{20} could be treated to recover the high temperature scrubbing fluids.

Unit 3

This unit could be a foam tower to utilize the enthalpy released from F_{23} to raise the liquid, thereby increasing its potential energy. The raised liquid is used to drive the water wheel - Unit 6 to move an electric generator. Unit 3 could also be a convergent-divergent nozzle to "flash" the working fluid into a foam and utilize the enthalpy released from F_{23} to accelerate the foam and increase its kinetic energy, which could be used to drive the water wheel-generator, Unit 6. The foam density is much higher than the density of vapor so the size of the equipment will be greatly reduced from the large diameters being considered at present for the Claude-Westinghouse OTEC System.[2,3] This technology is available.

Unit 4

A direct contact spray condenser operating at 95°F - 100°F barometric leg.

Unit 5

A cooling tower to serve as heat sink. F_{50} will leave at 95°F - 100°F saturated with water and minute amounts of the high-boiling working fluid used. F_{05} will be air. F_{45} will be cooled by the evaporation of the water.

Energy Recovery Potential

Case 1

Basis. Low sulfur content liquid fossil fuel fired steam generating plant of 500MW.
Steam cycle and turbine efficiency of 37%.
Boiler efficiency of 86%.
Flue gases at 280°F.
Thermal energy content of F_{01}.

$$E_{01} = \frac{(500)}{.37} \cdot \frac{(1)}{.86} (.14) = 220 \text{ MW Heat}$$

Heat transferred to F_{61} at Unit 1 when using a "high boiling" scrubbing fluid, to be used as an open cycle working fluid.

$$E_{12} = 220 \; \frac{(280 - 95)}{280}$$

$$= 145.4 \text{ MW Heat}$$ (assuming the Cp of the gases remain essentially constant)

Which means:

% transferred = 66%

Assuming that 3% of the working fluid is "lost" with effluent F_{20}.

Energy available in F_{23}

E_{23} = 141 MW Heat

T_{F23} = 280°F

T_{F45} = 95°F

$$Eff_{cycle} = \frac{E_{released}}{E_{gained}} = \frac{C_p \Delta T^2 / 2T_H}{C_p \Delta T}$$

$$= \frac{185}{2(740)} = .125$$

A recovery of 50% of cycle is an extremely conservative value.

$$E_{recovered} = (141)(.125)(.50)$$

$$= 8.8 \text{ MW}$$

Mclean Fig A-5

which is equivalent to a recovery of 4% of the flue gas waste energy or a 1.8% increase in the over-all generating capacity of the power plant.

The results become more attractive in the case of power plants burning coal as Case 2 shows.

Case 2

Basis. Coal fired steam generating power plant of 1000 MW.
Steam cycle and turbine efficiency of 37%
Boiler efficiency of 30%.
Flue gases at 500°F.

Total energy content of F_{01}

$$E_{01} = \frac{(1000)\quad(1)}{(.37)\quad(.5)}(.20) = \underline{675 \text{ MW Heat}}$$

Heat transferred to F_{51} at Unit 1:

$$E_{12} = 675 \cdot \frac{(500 - 95)}{500} = 546.75 \text{ MW Heat}$$

% transferred = 81%

Energy available in F_{23}.

$$E_{23} = 531 \text{ MW Heat}$$

$$TF_{23} = 280°F$$

$$T_{F45} = 95°F$$

$$Eff_{cycle} = \frac{280 - 95}{2(740)} = .125$$

Assuming a recovery of 50% cycle,

$$E_{recovered} = (531)\quad(.125)(.50)$$

$$= 33.2 \text{ MW}$$

for a recovery equivalent to 4.9% of the flue gas waste energy or a 3.3% increase in the over-all generating capacity of the power plant. These results would be obtained with a scrubbing-open cycle working fluid with a thermal limitation of 280°F that limits the cycle efficiency to 14.1%. Using a fluid thermally stable at 500°F (260°C) would have a very marked effect on the cycle efficiency and possibly upon the percent of the waste energy recovered. In such a case:

$$Eff_{cycle} = \frac{500 - 95}{2(960)} = .211$$

Assuming again a recovery of 50% of cycle:

$$E_{recovered} = (531)(.211)(.50)$$

$$= 56 \text{ MW}$$

for a recovery equivalent to 8.3 % of the flue gas waste energy or [illegible] increase in the over-all generating capacity of the power plant. This would most probably make the pollution abatement of the flue gases more economically attractive. Also, it would open for use the lower quality fossil fuels, those with higher sulfur and ash contents, with less fear of the impact of their hot flue gases upon the environment.

Table 1 gives an idea of the economics involved, especially in Puerto Rico.

Table 1

ORDER OF MAGNITUDE OF VENTURE ECONOMICS WHEN APPLIED TO FLUE GASES OF A 500 MW THERMOELECTRIC POWER PLANT

Investment/kw	Investment $MM	Cost of $* hr.	Sales** hr.
$	$	$	$
250	2.49	49.8	696
500	4.97	99.4	696
750	7.46	149.0	696
1000	9.94	249.0	696
1500	14.90	298.0	696
2000	19.90	398.0	696

*Interest and finance-related factors = $\$2 \times 10^{-5}$/hr - $ invested.

**In Puerto Rico at $.07/kwh.

The results made it highly desirable to obtain a cost estimate of the structure required to apply the technology of the Foam OTEC system[1] as a bottoming cycle for a fossil fuel fired steam generating power plant. Since all the experimental work until now has dealt with converting the enthalpy released during the controlled flashing operation into potential energy it was deemed most proper to obtain the cost estimate for a foam tower.

A second study will be done soon to obtain a cost estimate of the structure required to apply the technology of the Foam OTEC system to the recovery of energy from low grade sources via convergent-divergent nozzles.

Design of the Foam Tower

The design of the foam tower was initiated as a step preparatory to demonstrating the Foam OTEC system in Puerto Rico at a scale of 1 MW. The size-up of the structure was based on initial experimental results[3] which indicated a power generating density or capacity of 1 KW per square foot of foam generating cross-sectional area when operated at temperature differences of ~ 12°C between the foam generator and the condenser. At these conditions the foam would rise ~ 340 ft where it would be broken and separated into its vapor and liquid phases. The vapor would continue down to the condenser and the liquid to a surge tank from which it would go to a water turbine to drive an electric generator. In August 1976 it was realized that the supply of the cold deep ocean water was years in the future. This realization dictated the need for artificially created temperature differences readily obtainable in the island, at the required water flow rates. These requirements fixed the site near one of the liquid fossil-fuel fired steam generating plants by the ocean. Such a site would provide process steam and ambient ocean water to create the temperature differences needed.

Since the unit was to be the tallest reinforced concrete structure in the island, the design was to incorporate all safety factors, especially seismic stresses. Fig. 2, Fig. 3 and Fig. 4 amply justify this design criteria.

Fig. 2 shows the topography of the ocean floor around Puerto Rico[4] showing the island to be the crest of a very steep mountain more than 5000 meters high.

Fig. 3 shows the location of earthquakes relative to Puerto Rico.

Fig. 4 shows the frequency of earthquakes that have affected Puerto Rico since 1915.

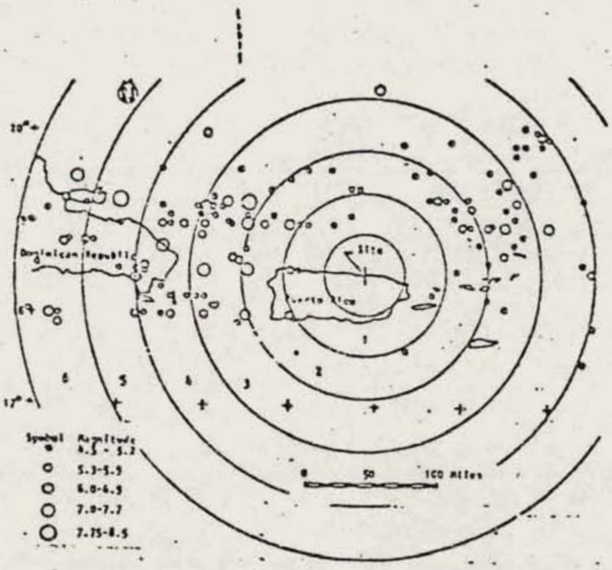


Fig. 3 Map of Epicenters for San Juan

Fig.2 Physiographic Diagram Around Puerto Rico

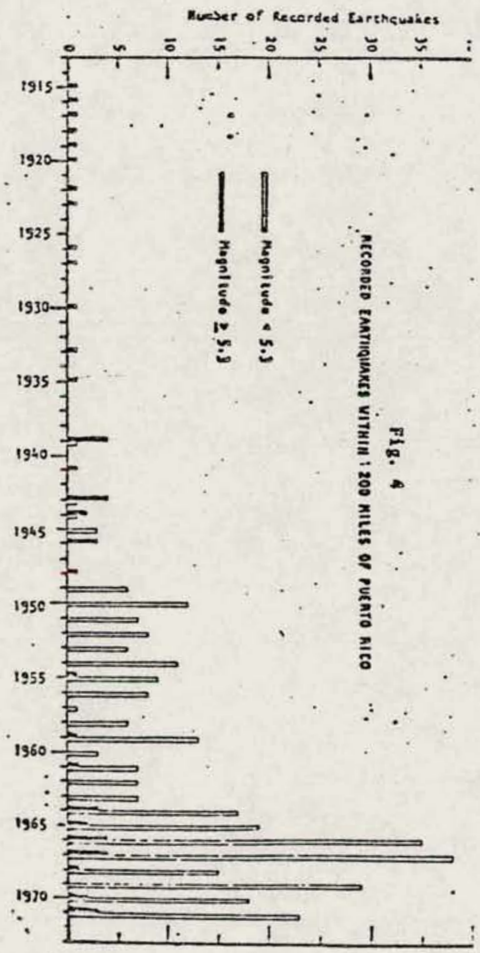


Fig. 4

In essence, the unit consisted of a structure 380 ft high visualized as an inverted, vertical, reinforced concrete U tube of 36 ft I. D. and walls 11 in thick. A water storage tank (surge tank) with a capacity of ~ 60,000 gals. was located at the top between the two vertical cylindrical at a height of 333 ft from ground level. Fig. 5 shows the elevation of the Foam Tower.

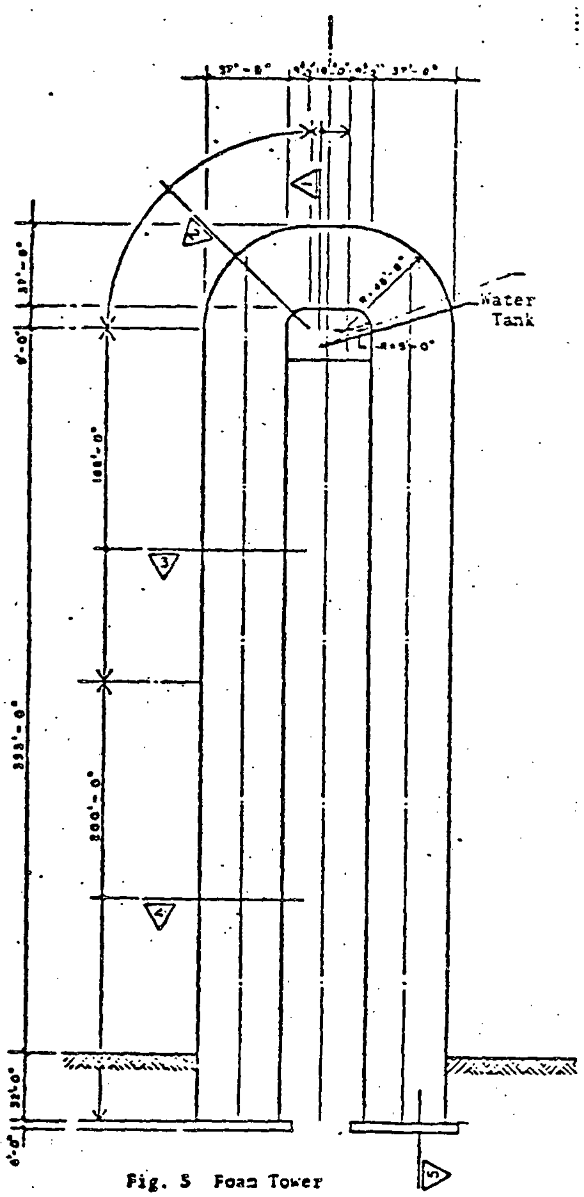


Fig. 5 Foam Tower

The structure is feasible based on present construction practices with reinforced concrete in Puerto Rico and would cost approximately $1.44 MM, consume 3,800 yds.^{3} of concrete and 860 tons of reinforcing steel for a construction cost of ~ $372/yd^3 of concrete and a capital investment of ~ $1440/KW. The high investment per unit of power is a reflection of the heavy reinforcement required to withstand the seismic stresses and the low power density achieved from the low ΔT of OTEC which we were initially trying to simulate. But, the application of the controlled foam flashing concept to the recovery of waste energy, or from flue gases, would be done at much larger ΔT which will result in a marked increase of the power generated per unit cross sectional area for foam generation. This will most probably place the investment/KW at a very attractive level in Table 1.

Summary

Application of the open cycle OTEC technology to the recovery of energy from poor thermal sources appears to be feasible. The concept proposed in this report would:

- Permit the use of the cheaper fuels without the fear of the environmental impact of their flue gases.
- Facilitate pollution abatement of the flue gases from fossil fuel fired furnaces.
- Eliminate the need for expensive, lined, tall smoke stacks.
- Result in the recovery of at least 5% of the energy presently lost in flue gases and/or augment the power output of steam-electric generating stations by at least 2%.
- Recover a large amount of energy from poor thermal sources.

Convergent-divergent nozzles appear to be more desirable than foam tower for the controlled foam flashing of the scrubbing-open cycle working fluids because of the much higher initial temperatures than originally envisioned for the Foam OTEC system demonstration.

Acknowledgements

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