Assessment of a Molten Salt System at 1000°F Reheat Steam

Feasibility, Economics, and Market Potential

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MASTER

AN ASSESSMENT OF FEASIBILITY, ECONOMICS, AND MARKET POTENTIAL FOR A MOLTEN SALT SYSTEM AT 1000°F REHEAT STEAM

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Prepared by

P. DeRienzo, M. Masaki, and P. Mathur

The Aerospace Corporation
El Segundo, California
Telephone: (213) 648-5333

FOREWORD

This report presents results of preliminary analyses to investigate the feasibility, performance, economics, and repowering market potential of a molten salt ACR system modified to provide 1000°F/1000°F steam conditions at the reheat turbine.

The study was conducted by The Aerospace Corporation under contract No. EY-76-03-1101 under the cognizance of Mr. R. Hughey, Director of the Division of Solar Energy, and Dr. S. D. Elliott and Mr. Larry Prince, Program Managers, DOE/SAN.

This document was prepared by P. DeRienzo of the Energy Projects Group in the Energy and Resources Division of The Aerospace Corporation. The work was conducted under the direction of Dr. P. N. Mathur, Manager of Advanced Central Power Projects. Mr. M. Masaki conducted the thermal and performance analyses.

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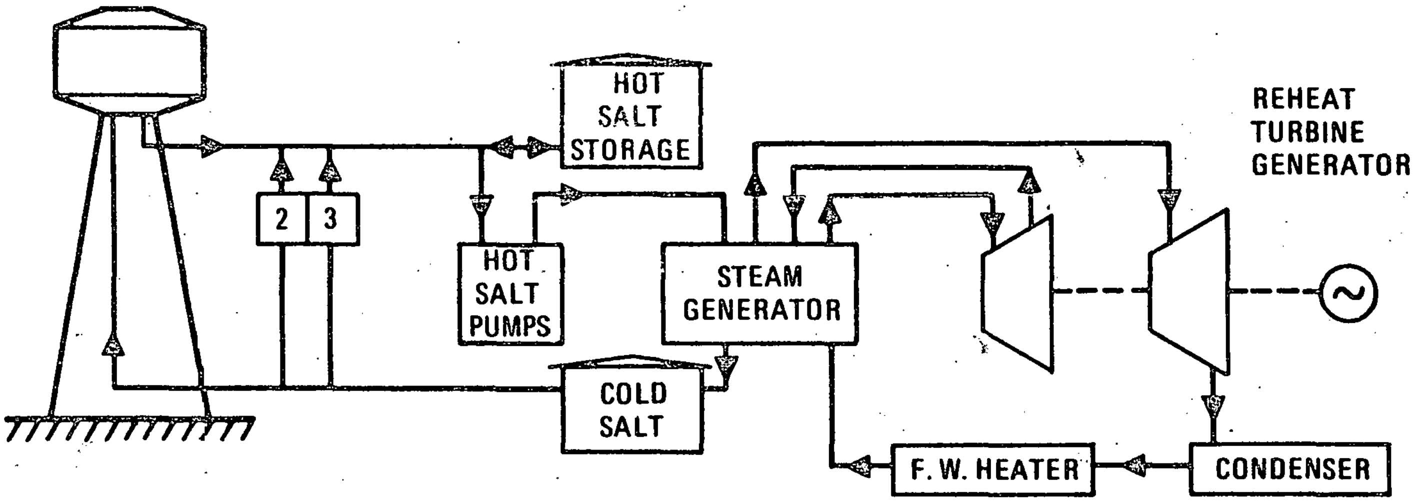
BACKGROUND AND TECHNICAL APPROACH

As a result of the Advanced Central Receiver (ACR) Phase I systems studies, Martin-Marietta Corporation (MMC) developed a conceptual design employing 1050°F molten salt and a 950°F/950°F reheat turbine as illustrated in Chart 1 on the opposite page. This concept appears to have the potential for providing higher steam conditions leading to higher performance and wider market application.

This report presents the results of a preliminary investigation of the above system to determine the feasibility of providing 1000°F/1000°F steam and the impact of the required design modifications on the system performance, cost, and market potential for solar repowering.

Two modified designs are investigated as noted in Chart 1. In the modified design-A, the temperature of the molten salt is the same as in the MMC baseline design (1050°F), but the steam generators have been modified to provide 1000°F/1000°F steam. In the modified design-B, the enhanced steam conditions are obtained using molten salt at a temperature of 1100°F.

MMC MOLTEN SALT SYSTEM DESIGN



0 BASELINE DESIGN

- o Molten Salt Receiver and Storage at 1050°F Salt Temperature
- o Reheat Steam Turbine at 2400 psi/950°F/950°F Steam

0 MODIFIED DESIGN-A

- o Molten Salt Receiver and Storage at 1050°F Salt Temperature
- o Reheat Steam Turbine at 2400 psi/1000°F Steam

0 MODIFIED DESIGN-B

- o Molten Salt Receiver and Storage at 1100°F Salt Temperature
- o Reheat Steam Turbine at 2400 psi/1000°F Steam

CHART 1

REPOWERING MARKET POTENTIAL

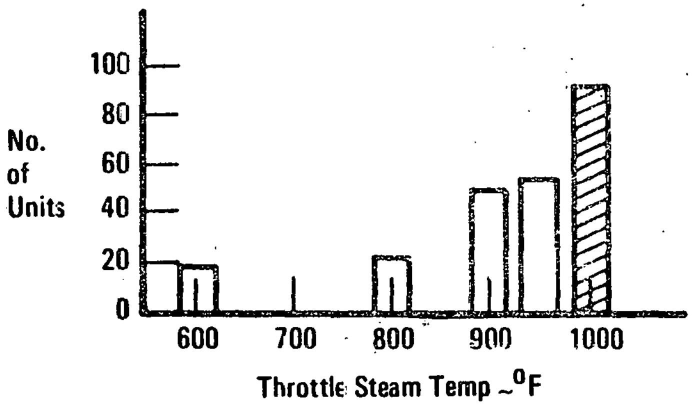
Results of various market surveys for solar repowering indicate that a large majority of the repowerable oil and gas-fired steam plants of interest utilize reheat turbines.

The opposite chart, based on data of Reference 1, presents a grouping of repowerable steam turbine units in terms of their corresponding operating steam conditions. For plant size ratings <200 MWe, 92 of the 244 units surveyed have 1000°F/1000°F reheat, as shown by the shaded area in Figure a. For a plant size rating >200 MWe, Figure b shows that 51 of the 61 units surveyed have 1000°F/1000°F reheat. Based on these observations, it appears that for widest application, the solar receiver should have the capability to match the steam generating requirements of the 1000°F/1000°F reheat turbines.

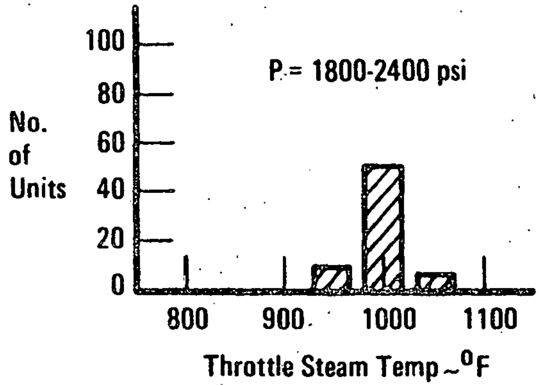
SOLAR REPOWERING MARKET POTENTIAL

CHARACTERISTICS OF REPOWERABLE STEAM TURBINE UNITS

a. Plant Rating < 200 MW_e



b. Plant Rating > 200 MW_e



Plant Rating, MWe	No. of Reheat Units < 200 MWe		
	1450 psi	1800 psi	2000 psi
	1000°F / 1000°F	1000°F / 1000°F	1000°F / 1000°F
0 to 10			
11 to 25	1		
26 to 50	3		
51 to 75	5	5	
76 to 100	15	3	
101 to 125	11	10	
126 to 150	1	8	3
151 to 200		25	2
	36	51	5

Reheat (hatched)

Non-Reheat (open)

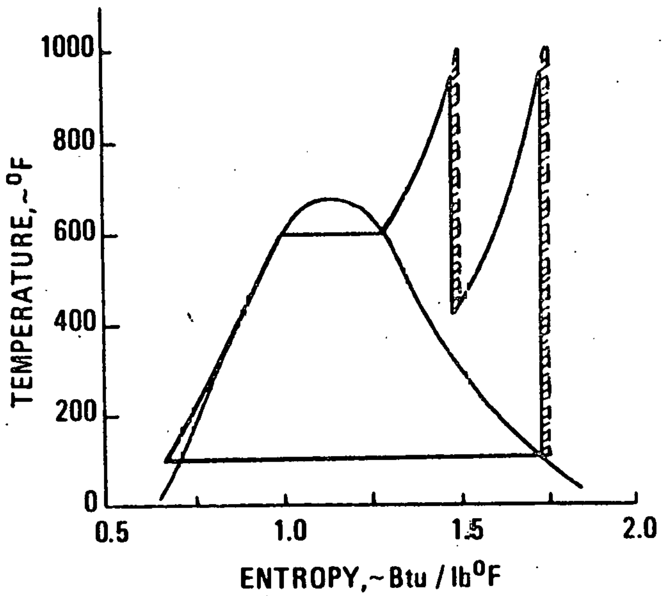
CHART 2

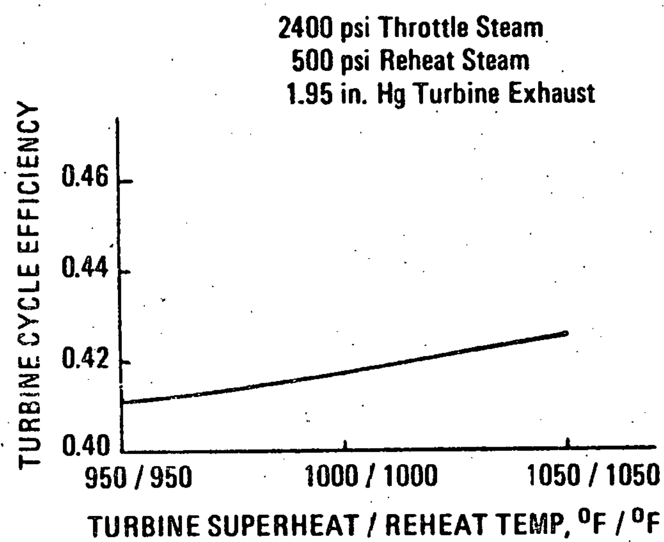
STEAM CYCLE AND TURBINE EFFICIENCY OF REHEAT TURBINES

For the two modified designs A and B, discussed above, the turbine inlet steam conditions have been upgraded from 2400 psi/950°F/950°F baseline to 2400 psi/1000°F/1000°F. Chart 3, Figure a, presents a temperature-entropy diagram comparing the baseline steam cycle to the upgraded cycle typical of most reheat turbines for repowering applications (1000°F/1000°F). The shaded area of Figure a represents extra work energy produced by the 1000°F/1000°F turbine which results in an additional net electrical energy output. If the turbine rating for both steam cycles of Figure a is the same, then the shaded area represents increased performance for the 1000°F/1000°F turbine.

The effects of throttle steam temperature on the turbine cycle efficiency is shown in Figure b. The gain in the efficiency when the temperature increases from 950°F/950°F to 1000°F/1000°F is approximately 0.7%, corresponding to the shaded area of Figure a.

STEAM CYCLE AND TURBINE EFFICIENCY OF REHEAT TURBINES





a. Temperature-entropy diagram for steam cycle of 950°F/950°F and 1000°F/1000°F reheat units

b. Effect of steam temperatures on turbine cycle efficiency

CHART 3

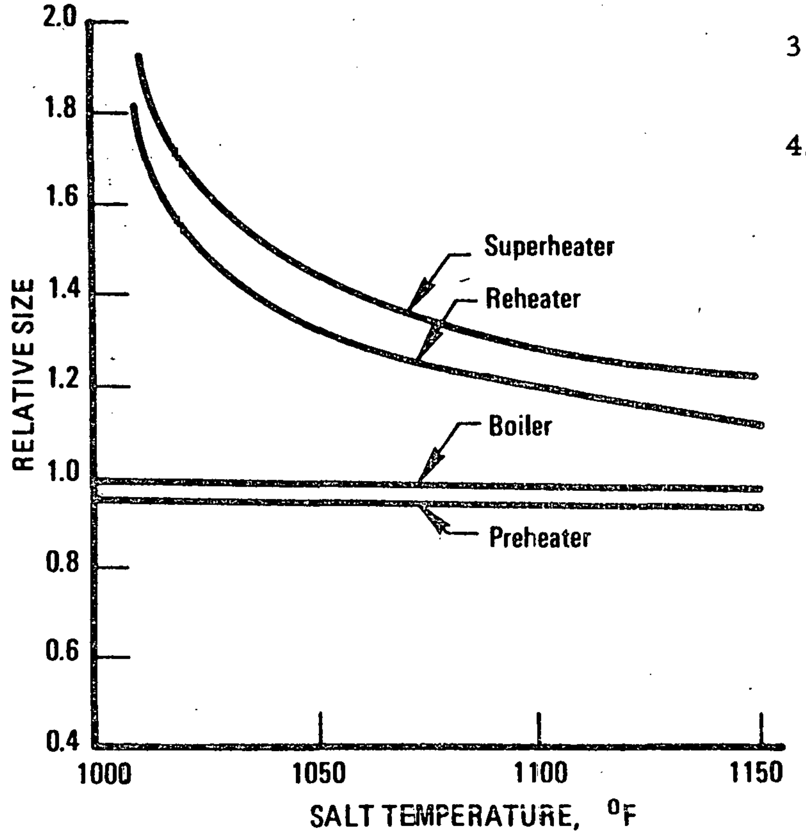
RELATIVE SIZES OF STEAM GENERATOR COMPONENTS

A parametric analysis was conducted to determine the required sizes of various steam generators (preheater, boiler, superheater, and reheater) as a function of inlet salt temperature for the particular pinch point temperature differential and other conditions noted in Chart 4. The curves of Chart 4 show relative increase in the areas of various heat exchangers over the baseline design to obtain 2400 psi/1000°F/1000°F reheat steam at different salt temperatures.

The boiler and preheater sizes do not change appreciably with salt temperature because the temperature increase from the feedwater temperature to the saturated vapor temperature is approximately the same for all steam cycles using the same turbine. The relative sizes of the boiler and preheater are < 1.0 at all salt inlet temperatures. This is a benefit resulting from the increased turbine cycle efficiency at the higher throttle temperatures, which permits using lower mass flow rates (~ 2% lower). With lower mass flow rates, the heat exchanger area is reduced.

At a salt temperature of 1050°F (modified design A), the superheater and reheater sizes, respectively, are 1.4 and 1.3 times the size of those for the baseline due mainly to the required increase in steam temperature. At salt temperatures of 1000°F, the exit steam temperature and entering salt temperature for the 1000°F/1000°F steam are equal, thereby requiring an infinite heat exchanger area. This is evident in Chart 3 where the curves for the superheater and reheater asymtotically approach the 1000°F salt temperature. Chart 4 shows that salt temperature should be as high as practical to minimize heat exchanger area. For the modified design B an upper limit 1100°F is assumed for salt due to material considerations.

RELATIVE SIZES OF STEAM GENERATOR COMPONENTS
FOR 1000°F/1000°F STEAM



1. Normalized by sizes of corresponding components for 950°F/950°F steam
2. Constant gross power output
3. Same salt temp drop through superheater and reheater
4. 20°F pinch point temp differential

	Heat Transfer Coeff., Btu / hft2°F	Tube Size	
		O.D., in.	I.D., in.
Preheater	461	0.625	0.407
Boiler	531	0.625	0.407
Superheater	371	0.625	0.407
Reheater	178	1.05	0.950

CHART 4

RELATIVE COST OF STEAM GENERATORS

Using the change in relative sizes of the steam generator components, as shown previously in Chart 4, and unit costs obtained from Reference 3, the generator cost increases were estimated for various inlet salt temperatures. Chart 5 shows the cost of the 1000°F/1000°F steam generator unit, normalized by the cost of the reference 950°F/950°F steam generator, as a function of salt inlet temperature.

It is seen that at the reference salt temperature of 1050°F, the steam generator for the 1000°F/1000°F steam cycle costs approximately 17% more (or $950,000) than that for the 950°F/950°F steam generator. For a given throttle steam temperature, cost decreases significantly with increase in salt temperature, mainly because of the improved efficiency of the heat exchanger, thereby requiring smaller incremental increases in area.

For a salt temperature of 1100°F the cost of the steam generator actually falls below that of the reference system, assuming that there is no major system impact due to the increase in salt temperature from 1050°F to 1100°F. It should be noted that continued operation of salt systems at temperatures above 950°F is currently not state of the art.

STEAM GENERATOR
COST COMPARISON

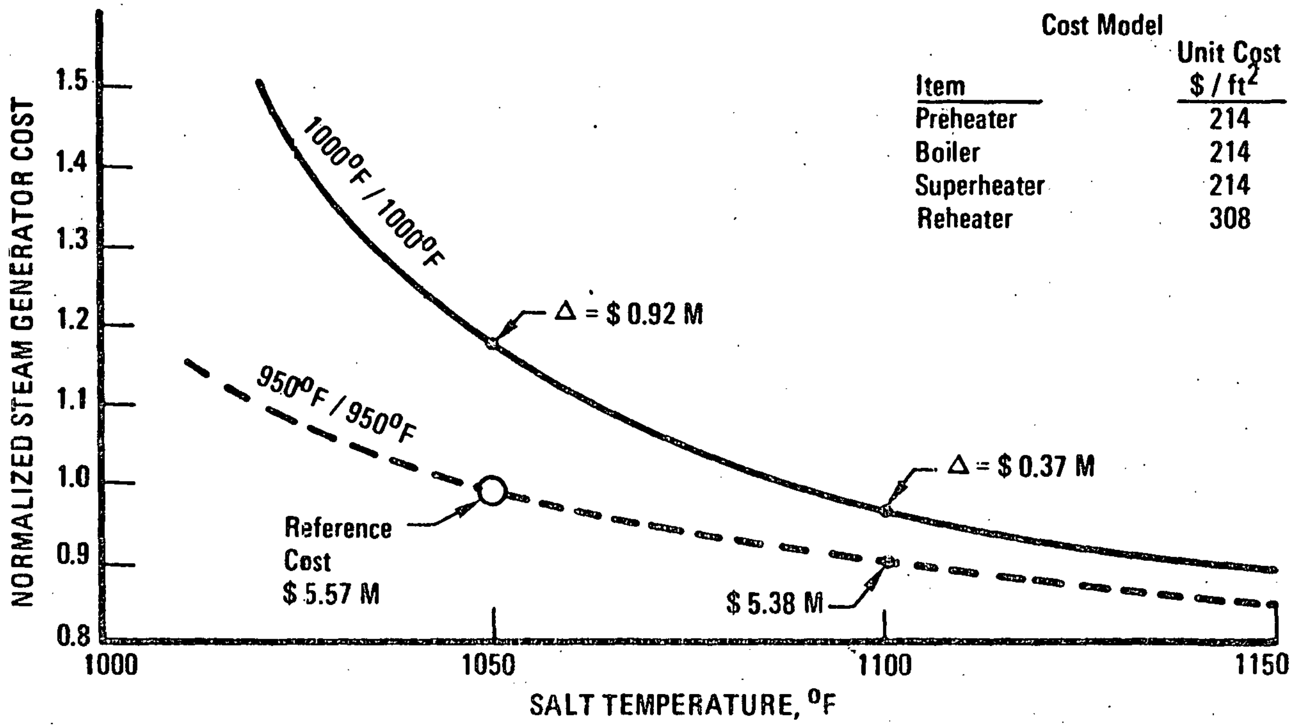


CHART 5

INCREMENTAL COSTS AND SAVINGS WITH 1000°F/1000°F STEAM CYCLE

A. Incremental Costs for Pumps and Turbine

Incremental costs due to resizing the pumps and associated piping to handle the temperature increase from 950°F to 1000°F were determined to be relatively small and were neglected for this study.

Data from Reference 2 were used to obtain estimates of the cost increases for a stand-alone solar plant due to required changes in the turbine to permit operation with 1000°F steam. The cost increase is relatively small ($40K-$90K) as shown in Table A, Chart 6.

B. Incremental Costs for Steam Generator Mods

Based on the cost curves of Chart 5, Table B of the opposite chart gives the estimated incremental costs to modify the steam generators of MMC's reference salt system (salt temperature 1050°F, steam conditions 2400 psi/950°F/950°F) for operation at 2400 psi/1000°F/1000°F and salt inlet temperatures of 1050°F and 1100°F corresponding to modified designs A and B, respectively. Incremental costs of equipment modifications due to changes in feedwater heating temperature were not accounted for.

C. Incremental Savings

Table C gives the incremental savings due to reductions in the heliostat area and the receiver/tower subsystem. The heliostat area reduction is a result of the improved turbine cycle efficiency which increased from the value of 0.4108 at 950°F to 0.4178 at 1000°F. For a given solar plant capacity, taken here as 110 MWe (gross), the increased turbine efficiency results in less thermal power required at the turbine inlet. This, in turn, permits a reduction in the number of heliostats, the size of the receiver/tower subsystem, and other equipment. For the purposes of this analysis, unit cost of the collectors was assumed to be $\$100/m^2$. The baseline cost of the receiver/tower subsystem was assumed to be $12.4M corresponding to 0.25 hours of storage and plant size 100 MWe. The incremental savings shown in the opposite chart result from the reduction in receiver/tower subsystem due to the reduced collector field.

INCREMENTAL COSTS AND SAVINGS FOR 1000°F/1000°F STEAM CYCLE

A. Incremental Costs for Turbines

throttle steam temp. , °F	Δ $ for turbine mods
950/950	0 (Baseline)
1000/1000	40 K
1050/1050	90 K

B. Incremental Costs

salt temp. °F	reference throttle steam temp. °F	cost of reference steam generator subsystem, $	modified throttle steam temp. °F	cost of steam generator mods $
1050	950/950	5.57M	1000/1000	.92M
1100	950/950	5.38M	1000/1000	.37M

C. Incremental Savings

Reduced turbine requirement = 4.5 MW_t

Reduced heliostat area = 7200 m^2

Savings due to reduced heliostat area = $0.72M

Savings due to reduced size of receiver/tower subsystem = $0.44M

Total system savings = $0.72M + 0.44M = 1.16M

D. Net savings = { $1.16M - $.96M = $.2M for 1050°F salt temperature
1.16 - $.41M = $.7M for 1100°F salt temperature

CHART 6

RESULTS AND CONCLUSIONS

1. Based upon the analyses and assumptions presented above, it is concluded that it is feasible to increase the steam outlet temperature from 950°F/950°F, 2400 psi (MMC baseline ACR design) to 1000°F/1000°F without increasing the baseline salt inlet temperature (design modification A). This can be accomplished by increasing the heat exchanger size (areas) of the baseline steam generator components--primarily the superheater and reheat steam generators. The sizes of the preheater and boiler are not changed because the feedwater temperature is not altered significantly. The required increase in the heat exchanger areas for the superheater and reheater are approximately 45% and 35%, respectively, relative to the baseline designs.

2. Steam generator efficiency is improved at a salt inlet temperature of 1100°F assumed for the design modification B. The increase in the heat exchanger areas for the superheater and reheater for this case are 30% and 20%, respectively.

3. It has been shown that a majority of the surveyed repowerable turbines are reheat at 1000°F. A design change in MMC's baseline system from a steam cycle of 950°F/950°F to 1000°F/1000°F would be compatible with the greatest number of repowerable turbines and, therefore, would maximize repowering applications.

4. Estimated incremental costs due to modifications of steam generators and estimated cost savings in system capital costs due to a higher performance cycle at 1000°F/1000°F for the two modified designs examined are shown in Chart 7. The net reduction in the system capital cost is relatively small with design modification B slightly better than the design modification A.

KEY RESULTS AND CONCLUSIONS

- Modified design A with 1050°F salt inlet temperature and 1000°F, 2400 psi reheat cycle is feasible.
- 35-45% increase in the superheater and reheater size is required to provide 1000°F reheat cycle.
- 1000°F/1000°F reheat cycle significantly enhances the repowering market potential for salt system.
- Net cost advantage of modified reference steam cycle is a small percentage of system capital cost.

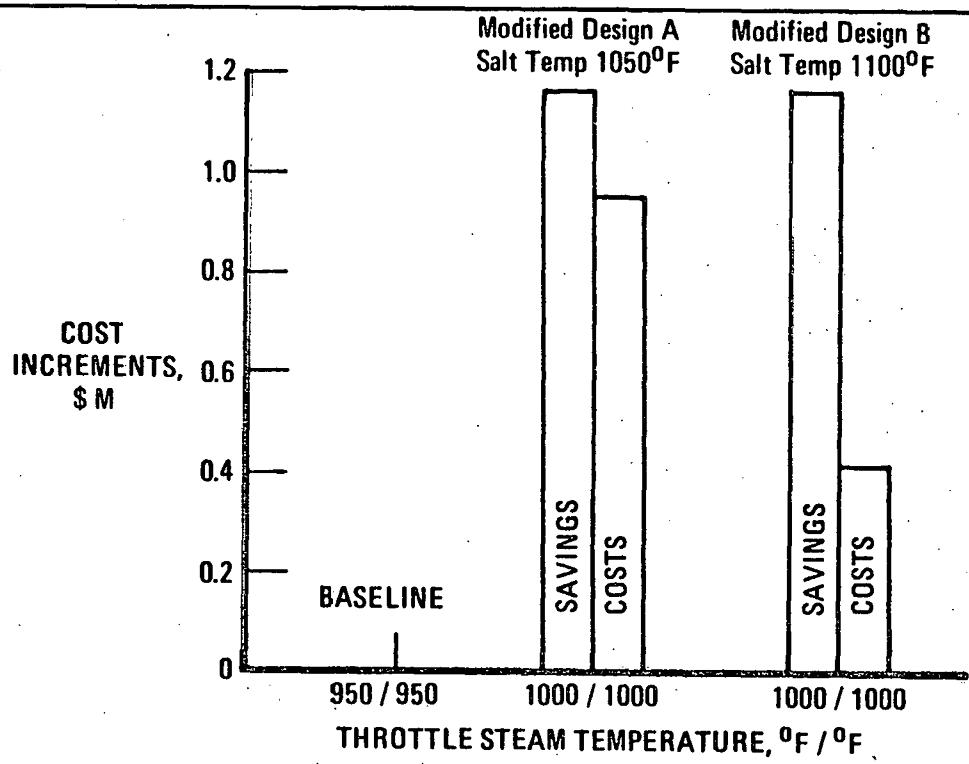


CHART 7

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