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Comparison of High Temperature Salt Thermal Storage Concepts for Line Focus Solar Thermal Power Systems

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COMPARISON OF HIGH TEMPERATURE SALT THERMAL STORAGE CONCEPTS FOR LINE FOCUS SOLAR THERMAL POWER SYSTEMS

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FOREWORD

This report is written as a partial account of work performed for the Department of Energy, on the Advanced Central Power Project, under Letter Contract Number EY-76-C-03-1101 (PA 14).

OBJECTIVES AND SCOPE

The objective of this study is to determine the most cost-effective means of storing thermal energy for high temperature salt-cooled line focus solar thermal power systems. The system selection will be based on capital and operating cost, performance, technical risk and operational factors.

This evaluation was based on the data available from the line focus contractors to date (March, 1979). The results of this study will be used to support contractor activities in the thermal storage parametric analysis and system design effort. As additional data becomes available from the contractors, the results of this study will be updated.

- OBJECTIVE
  - TO SELECT MOST COST EFFECTIVE SALT THERMAL STORAGE CONCEPT
  - SUPPORT TECHNICAL MANAGEMENT ACTIVITIES

- SCOPE
  - THIS EVALUATION IS BASED ON TECHNICAL AND COST DATA AVAILABLE FROM CONTRACTOR DESIGN REVIEWS AND MONTHLY REPORTS

THERMAL STORAGE OPTIONS

This chart presents a matrix of possible salt thermal storage options for storage-coupled solar thermal power plants. The matrix lists the storage combinations deemed technically possible at the capacity and temperature conditions imposed by the system design. Fabrication materials and tank sizing conditions are noted in the last column of the chart.

SALT THERMAL STORAGE OPTIONS

TSS OPTION	REMARKS
THERMOCLINE SINGLE TANK ALL SALT	INTERNAL INSULATION (24 in. salt internal insulation) CARBON STEEL CONTAINMENT LENGTH TO DIAMETER RATIO EQUAL TO 1.0
THERMOCLINE SINGLE TANK SALT - TACONITE	STAINLESS STEEL CONTAINMENT EXTERNAL INSULATION (12 in. calcium silicate) LENGTH TO DIAMETER RATIO EQUAL TO 0.5
TWO-TANK ALL SALT	STAINLESS STEEL HOT TANK EXTERNAL INSULATION (12 in. calcium silicate) CARBON STEEL COLD TANK EXTERNAL INSULATION (6 in. calcium silicate) LENGTH TO DIAMETER RATIO EQUAL TO 0.5

STUDY GROUNDRULES

This chart presents the study groundrules used as a basis for system sizing and temperature distribution calculations. The results are not expected to change with increasing storage size.

STUDY GROUNDRULES

THERMAL STORAGE SIZE = 420 MWe-hrs.

80 Mwt-hrs. used for STARTUP and SHUTDOWN

HEAT RECOVERY EFFICIENCY = 96%

TEMPERATURE DIFFERENCE: 550°F to 1050°F = 500°F

THERMO-PHYSICAL PROPERTIES AT T_{ave} = 800°F

PROPERTY	SALT	TACONITE
Specific Heat-Btu/lb°F	.373	.23
Density -lb/ft^3	113	237
Thermal Conductivity-Btu/hr-ft°F	.23	--

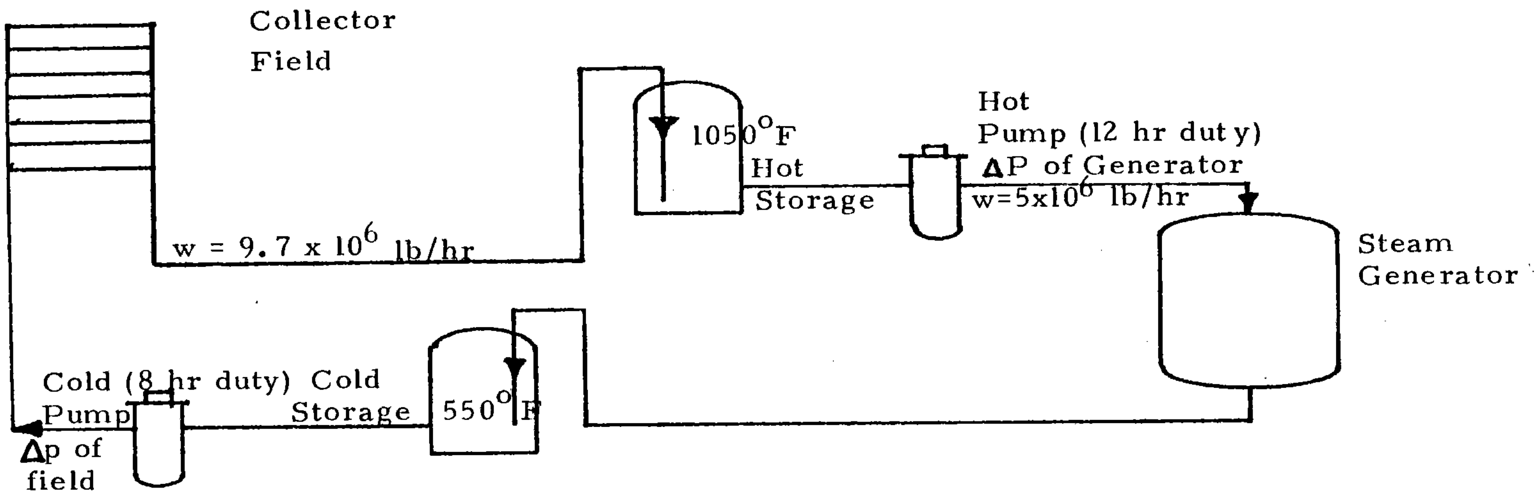
POWER CONVERSION EFFICIENCY VARIES WITH TSS EFFLUENT TEMPERATURE

This chart presents the basic characteristics of the candidate thermal storage options. The all salt and salt-taconite thermocline concepts are generally similar and are represented by the same diagram. For reference and comparison of subsystem design and operational characteristics some basic performance factors and duty cycles have been identified for each concept.

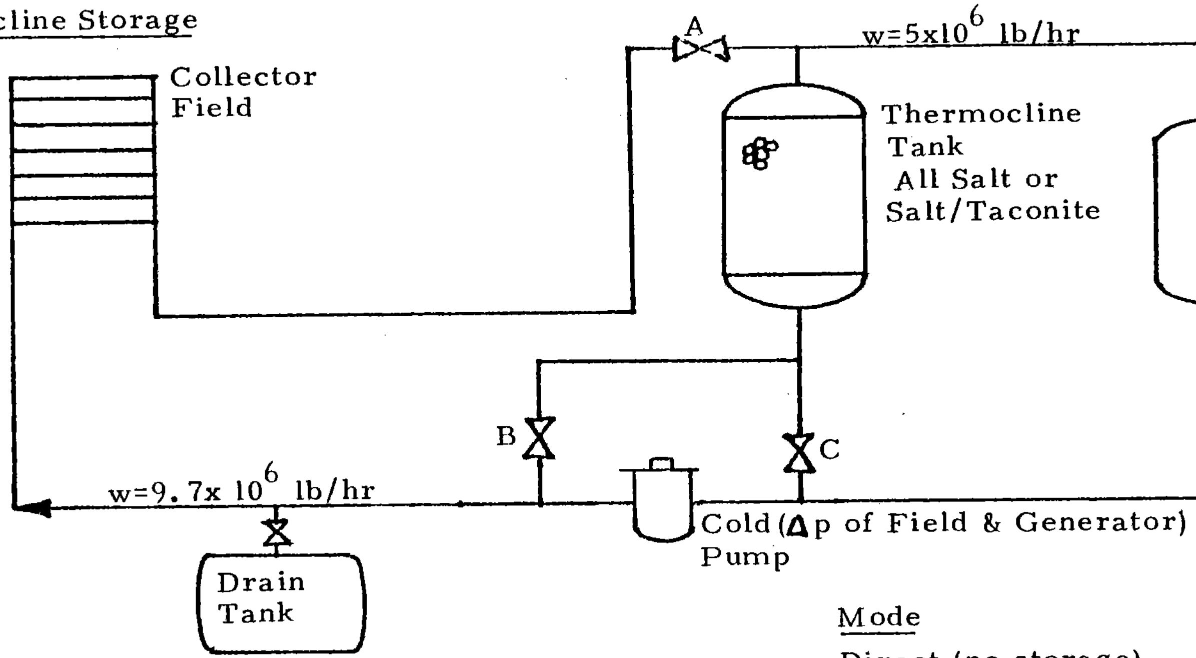
The two tank system requires two tanks of equal size, each rated for the full storage energy requirement. The system also requires an additional hot pump to deliver the hot salt from the storage tank to the steam generators. The thermocline system requires one less pump with higher head requirement; however, there is some flow switching required when changing from a charging to discharging mode. The pressure drops through the two systems are not available at this time; the assumption is made that the two tank system has a 15 percent higher total loop pressure drop.

SYSTEM SCHEMATICS

Two-Tank Storage



Thermocline Storage



Mode	Valve Position A	B	C
Direct (no storage)	Open	Closed	Closed
Direct + Storage	Open	Closed	Open
Operation from storage	Closed	Open	Closed

A parametric analysis for the thermal energy storage system was performed comparing molten salt/Taconite thermocline, all-salt thermocline, and all-salt single hot/single cold tank system alternatives. All systems were sized based on the groundrules noted previously. The thermocline systems were sized for assumed utilizations ranging from 60% to 100%. Thermocline performance was based on models developed by the Energy Systems Group of Rockwell. The volume of thermal storage was calculated using the following relation:

$$\text{Volume} = \frac{Q_{mwe} \times HRS \times 3.412 \times 10^{6}}{PCE \times HRE \times U \times \Delta TEMP \times \rho c_p}$$

Where:

$Q_{mwe} \times HRS$ - Required stored energy

PCE = power conversion efficiency

HRE = heat recovery efficiency

U = utilization (percent of stored energy which can be drained effectively from thermocline tank)

ΔTEMP = temperature difference

ρc_p = mass specific heat of storage

A summary of key TSS characteristics is shown in the accompanying Table. There are reduced volume requirements with higher utilizations for both thermocline systems; however, this is achieved with a severe penalty in the final exit temperature of the salt as the energy is drained. The thermocline system will require an additional tank to drain both the heat transport and collector subsystems as well as the thermocline tank should that tank have a failure.

TSS SUBSYSTEM CHARACTERISTICS

Characteristic	Salt/Taconite Thermocline			Salt Thermocline		Salt Two-Tank
	U= 60	U=65	U= 100	U= 60	U = 100	
Storage Volume (ft^3)	256,093	236,394	153,656	300,365	180,000	-
Hot Tank	-	-	-	-	-	195,000
Cold Tank	-	-	-	-	-	195,000
Salt Weight ($lb \times 10^6$)	11.6	10.7	6.95	33.8	20.3	-
Hot Tank	-	-	-	-	-	22
Cold Tank	-	-	-	-	-	22
Taconite Weight ($lb \times 10^6$)	36.4	33.6	21.85	-	-	-
Tank Material	SS	SS	SS	CS	CS	SS hot tank Carbon steel cold tank
Temperature Drop due to utilization (^oF)	80	100	> 200	70	> 200	0
Drain Tank Volume (ft^3)	102,400*	94,500*	61,500*	75,000**	45,000**	-

* Adequate volume to drain Thermocline tank

** Assume 25% redundancy

This table presents the cost data for the candidate concept identified in the previous table. Cost studies were based on draw salt costs of 15¢/lb. and Taconite costs of 3¢/lb., including shipping.

The costs enclosed in the boxes are additional cost items identified by Aerospace as being important in the concept trade-off. All the thermocline systems require an additional tank to drain the heat transport and collector fields and to drain the thermocline tank when that tank requires service. The taconite thermocline contains an additional cost factor for taconite cleanup and preparation prior to commissioning. This system should also have a cost penalty for purification of taconite particles in the fluid loop, however, the extent of this problem and associated cost isn't known at this time. The two-tank system requires an additional hot pump with its accompanying capital and operating cost.

The cost algorithm for the tank was based on the following relation:

$$\text{COST} = \text{CONSTANT} \times V^{0.8}$$

where V is the tank volume

The constant depends on the tank material and mode of insulation.

These costs are preliminary in nature, and intended for use only in trade-off studies. As the subsystem becomes better defined, the total cost will certainly increase.

COST SUMMARY
(Costs quoted in millions)

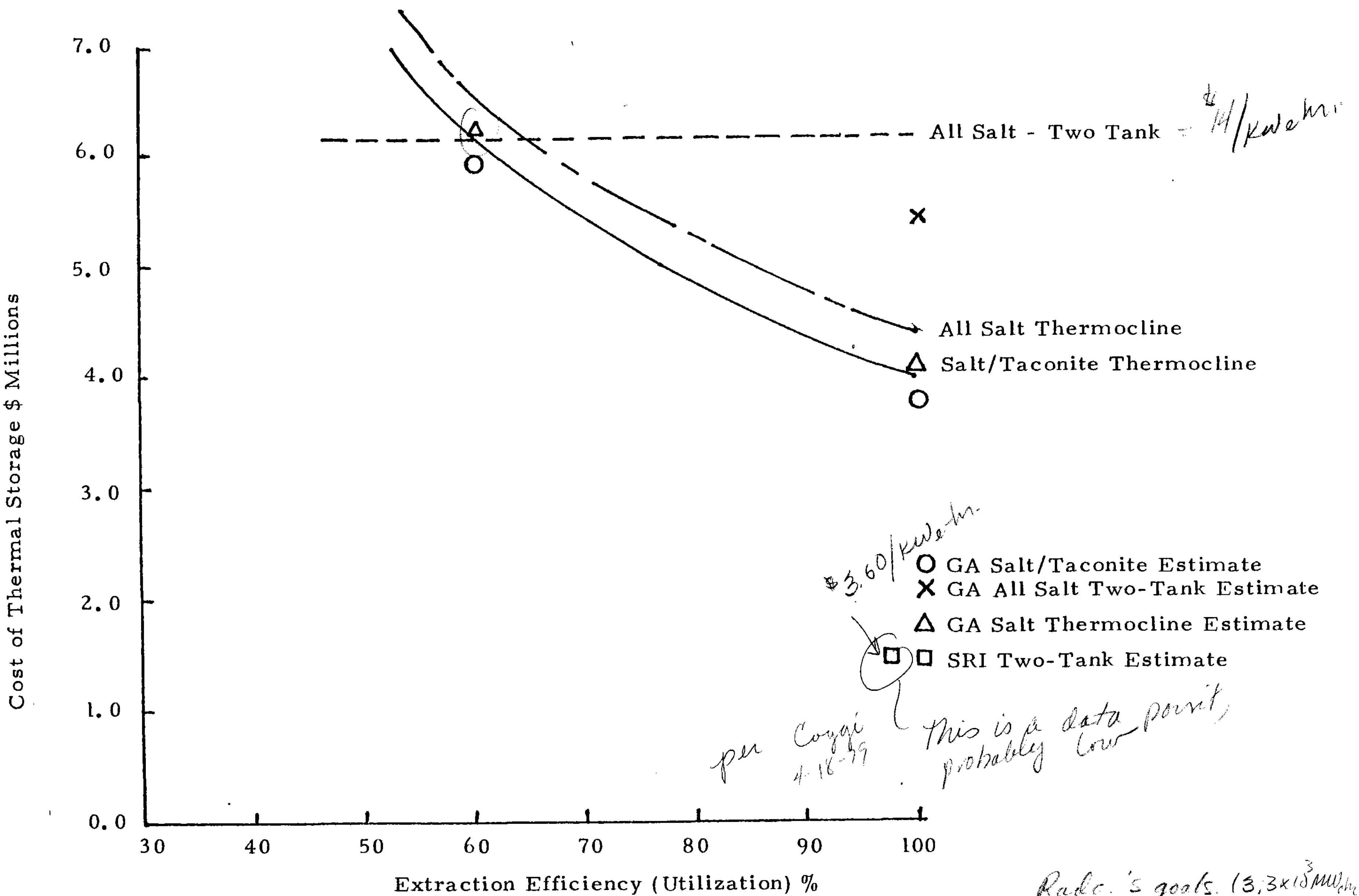
Cost Elements	Salt/Taconite Thermocline			Salt Thermocline		Salt Two Tank
	U = 60%	U= 65%	U = 100%	U = 60	U = 100%	
Salt Cost (15¢/lb)	1.74	1.61	1.04	5.2	3.3	1.44
Taconite (3¢/lb)	1.1	1.01	0.65	-	-	-
Containment	2.16	2.03	1.44	1.0	0.8	4.01
Field Drain & TSS Drain Tank	1.04	0.97	0.69	0.3	0.27	
Additional Pumps	-	-	-	-	-	.242
Additional Pumping Power	-	-	-	-	-	.45
Taconite Preparation	0.27	0.25	0.16			
Purification & Makeup System	TBD	TBD	TBD	TBD	TBD	TBD
Cost Summary	6.07	5.87	3.98	6.5	4.37	6.14

U = utilization

This Figure compares the costs for the taconite/salt and all-salt thermoclines to an all-salt two-tank system, as a function of assumed thermocline extraction efficiency. The all salt thermocline does not become competitive until the utilization is on the order of 65%. The cost breakeven point for the taconite system is at a utilization of 60%.

The maximum useful utilization of a thermocline system is unknown. At high utilizations the concept has an inherent temperature degradation during discharge which can seriously lower the efficiency of the conversion efficiency. The cost savings at higher utilizations might also be used up in the additional design and fabrication expenses of an inlet/outlet manifold system to minimize mixing and promote stratification.

THERMAL STORAGE SYSTEM COST COMPARISONS



Rade's goals (3.3×10³ MWt hr)

D.C.*	Total
$10/kwe-hr	$14/kwe-hr

*EXCLUDES HOME OFFICE CONTINGENCY

TABLE OF ADVANTAGES/DISADVANTAGES

The advantages and disadvantages of the three candidate storage concept are summarized in this Table. These items can be classified under cost, performance, development risk, design and operational factors.

CONCEPT ADVANTAGES AND DISADVANTAGES

TSS CONCEPT	ADVANTAGES	DISADVANTAGES
Salt/Taconite Thermocline	1. Cost advantages at utilizations greater than 60% 2. Preliminary tests indicate stable salt taconite combination 3. Requires only one cold pump	1. There is an EPGS and system performance and cost penalty associated with a temperature decay during discharge of the thermocline. 2. Requires drain tank in case of TSS leaks or HTS drain. 3. No experimental data on salt-taconite systems. 4. Development problems associated with inlet and outlet manifolds to prevent loss of stratification. This may be a heavy cost penalty. 5. Long term stability of salt taconite unknown. 6. Requires 2.5 times the weight of an all-salt system which may impose severe foundation problems and cost. 7. Taconite particles in salt will require filters and may deposit on generation equipment resulting in damage. 8. Operationally more complex

TSS CONCEPTS	ADVANTAGES	DISADVANTAGES
All Salt Thermocline	1. Cost advantages at utilizations greater than 65% 2. Minimum container-salt compatibility problems 3. Requires only one cold pump 4. Clean system 5. Cheaper carbon steel container 6. Common development with another DOE program	1. See Salt/Taconite items 1, 2, 4, 8 2. Internal insulation is a development item 3. Performance is questionable since all experimental work has been limited to small size systems. 4. Temperature cycling on tank wall will induce cyclic stresses.
Two Tank Salt System	1. Known technology 2. Tanks may be used to drain field 3. Eliminates transients due to cloud cover or load fluctuations 4. Operationally simpler	1. Requires development of high temperature pump 2. Larger tank required 3. There may be an initial cost penalty

SUMMARY AND RECOMMENDATIONS

A comparison of the subsystem level attributes of the three thermal storage concepts has been completed. The salt/taconite thermocline concept does not offer a significant cost advantage over the all-salt thermocline to compensate for the development risk and operational constraints imposed by the taconite. This concept should be deemphasized. The all-salt thermocline displays cost advantages over the two tank system at high utilizations, however, the ability to achieve these utilizations is still unproven. It is likely the choice between these latter two concepts will be based on important non-economic factors including user preference for a given technology.

Two Line Focus contractors indicate a preference for the two-tank system although only one, to date, has completed a parametric analysis. It is in the interest of DOE that both concepts be pursued to a finer system definition. If both contractors still select the two tank concept, then they should be directed to continuously review the salt thermocline work sponsored by DOE on other programs.

This study indicates that the contractor tradeoffs are not complete and must be refined to insure that comparisons are made on concepts of equal capability. Additional data are also required on the following items:

(1) Single versus multiple tanks for operational advantages
(2) Distributed versus centralized storage
(3) Salt/container compatibility
(4) Thermocline stability and tank manifolds

RECOMMENDATIONS

- PROCEED WITH EMPHASIS ON SALT TWO-TANK STORAGE CONCEPT
- CONTINUE REVIEW OF DOE SALT THERMOCLINE RESEARCH WITH SPECIAL ATTENTION TO:
  - VALIDATION OF STORAGE THERMOCLINE AND INTERNAL INSULATION DESIGN WITH LARGE TANKS
  - DESIGN OF INLET AND OUTLET MANIFOLDS
- CONTINUE TO RESOLVE THE IDENTIFIED SUBSYSTEM ISSUES