INTERNALLY INSULATED THERMAL STORAGE SYSTEM DEVELOPMENT PROGRAM*

Owen L. Scott
Martin Marietta Corporation

INTRODUCTION

The purpose of the program is to define a cost effective thermal storage system for a solar central receiver power system using molten salt stored in internally insulated carbon steel tanks. The program is divided into four tasks: testing of internal insulation materials in molten salt; preliminary design of storage tanks, including insulation and liner installation; optimization of the storage configuration; and definition of a subsystem research experiment to demonstrate the system.

The purpose of the materials tests was to determine which materials could be used in contact with the molten salt as an insulating material. The material long-life compatibility with the molten salt had to be determined, and the thermal properties of the salt-saturated material needed to be known. The approach of the materials tests was to place fifteen or more representative samples into test for 500 hours and select the five best candidate materials. These selected materials would then be tested for 5000 hours and evaluated at several points throughout the test. The effect of thermal cycling on the salt-saturated material also needed to be evaluated.

The analytical evaluation leads up to a cost optimization for various storage systems. The design and costing of tank insulation and foundation was necessary. The three types of thermal storage systems evaluated were thermocline, dual tank, and cascade (see Figures 1 to 3). A thermocline tank system stores both the hot and cold fluid in the same tank and depends on the fluid density difference to prevent fluid mixing. An analytical computer model was developed to analyze the thermocline tank. The dual tank system stores the hot fluid and cold fluid in separate tanks. As the hot fluid is used and cooled, it is stored in the cold tanks, so half of the tankage is always empty. The cascade system allows a tank to be used either as a cold tank or a hot tank. It is possible with this system to reduce the number of empty tanks as compared to the dual tank system.

The safety study is a separate document which addresses the safety considerations of using molten draw salt along with utility company evaluation.

The design of a small scale test program for demonstrating molten salt thermal storage is presented along with estimated program cost. The system is of sufficient size that representative insulation thicknesses can be used. The

---

*Sandia Laboratories, Livermore Contract 83-3638 to Martin Marietta Corporation, T. R. Tracey, Program Manager.

object of the test is to satisfactorily answer questions about a molten salt storage and system operation such that confidence to build a full-scale system is achieved.

SUMMARY

The material compatibility tests showed that none of the materials tested would be acceptable as internal tank insulation when in contact with the molten salt. Since a wide range of materials were tested, it is unlikely that any insulation material will be compatible with molten salt. Since the use of internal insulation is extremely advantageous in reducing tank shell cost, a metal liner is recommended to protect the internal insulation from the molten salt. It is also cost effective to use a metal liner because the low thermal conductivity of dry insulation is much less than the conductivity of insulation wet with salt. A commercial stainless steel liner that is orthogonally folded to allow for expansion can be used for this application. Only minor liner development is considered necessary. These liners have seen many years of commercial service with exceptional reliability.

The most economical tanks are large, cylindrical, carbon steel ones with externally supported umbrella roofs. Tank wall thickness in this study was limited to 0.041 m (1.63 in.) to eliminate the need for post-weld heat treatment. Tanks storing hot salt (839 K (1050°F)) are internally and externally insulated to maintain a shell temperature of 588 K (600°F). The internal insulation separated from the salt by a metal liner is a lightweight refractory brick for the floor and walls and a fiberous insulation for the ceiling. The external insulation is a fiberous insulation for the walls and a load-bearing mineral block for the roof; both are covered with lagging for weather protection. The internal and external insulation is balanced to maintain the tank shell at a uniform temperature of 589 K (600°F). The cold tank (561 K (550°F)) requires external insulation only.

The tank foundation design is a water-cooled concrete slab that prevents the soil from reaching the boiling point of water, and also eliminates the necessity for a stainless steel tank bottom. Placing the tank directly on the ground (whether insulated or not) is not recommended, as very little is known of soil properties at elevated temperatures and boiling water trapped in the soil can produce unpredictable results.

A thermal analytical model and analysis of a thermocline tank was performed. Data from a present thermocline test tank was compared to gain confidence in the analytical approach. The thickness of the temperature-degraded fluid between the hot and cold temperatures (the thermocline) was determined for salt tanks. Small tanks, large heat losses, and large heat capacity of the wall insulation will all increase the thickness of the thermocline. Limiting the thermocline thickness is best achieved by outflowing some of the thermocline fluid at both the low and high temperature ends.

A computer analysis of the various storage system parameters (insulation thickness, number of tanks, tank geometry, etc.) showed that 1) the most cost-effective configuration was a small number of large cylindrical tanks, and

2) the optimum is set by the mechanical constraints of the system, such as soil bearing strength and tank hoop stress, not by the economics. Figure 4 shows a cost comparison of the three different storage concepts studied. Capital cost refers to the cost of the system components, effective cost is capital cost plus the cost of the extra heliostats, etc., necessary to compensate for the system's energy losses.

The cost of the tankage system with internal insulation is less than one half the cost of comparable salt storage system without internal insulation. Using a cascade system instead of a dual tank system introduces the technical problem of thermal cycling of the internal insulation, but reduces the cost very little. It is important to note that this cost-of-storage comparison is limited to storage system/central receiver combinations that have been proposed.

The design suggested for the tank development program is a dual tank system with tank sizes of 4.6 m (15 ft) by 4.6 m (15 ft) high. The system includes an air cooler and a fossil fuel heater necessary to vary the salt temperature. Included in the tank development program is liner verification.

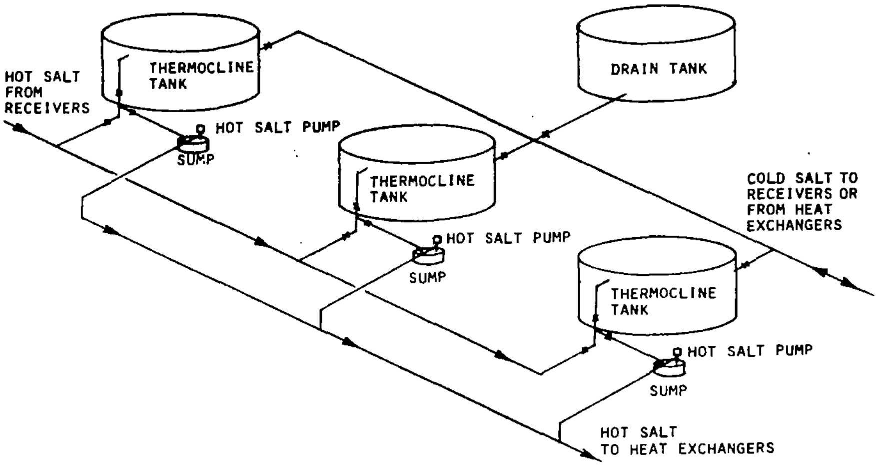


Figure 1 Thermocline Storage System Schematic

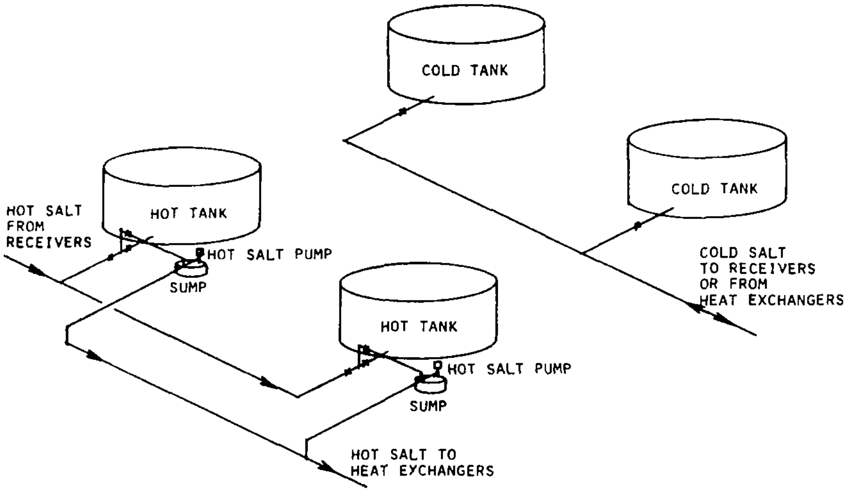


Figure 2 Dual Tank Storage System Schematic

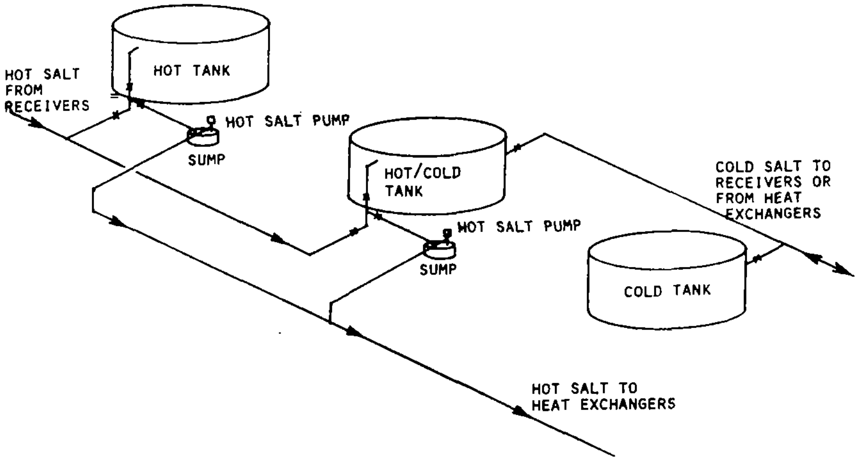


Figure 3 Cascade Storage System Schematic

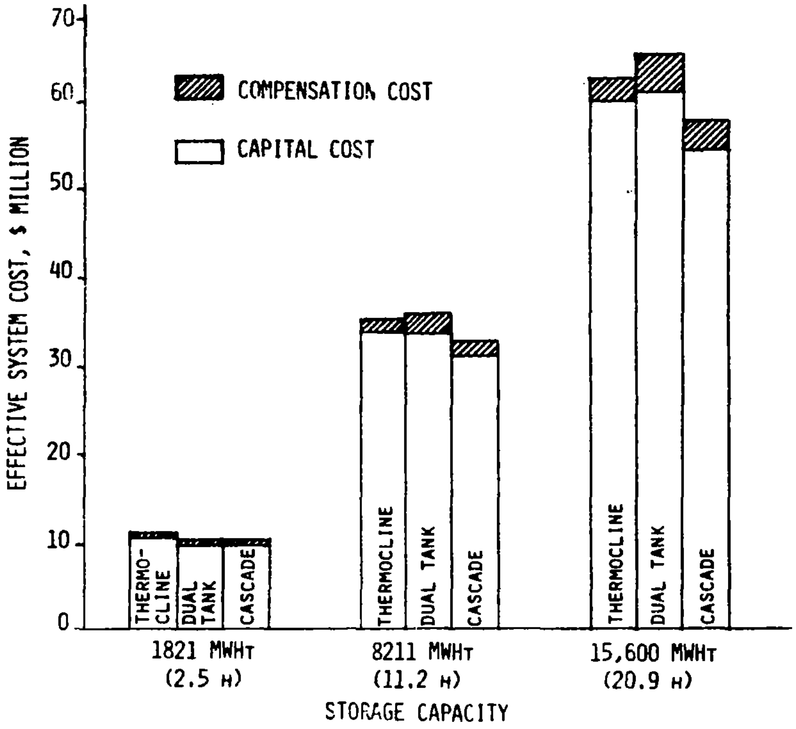


Figure 4 Effective Storage System Cost Vs Storage Size (300 MWe Plant)

CONTRACT FOR:	SANDIA LABORATORIES LIVERMORE, CALIFORNIA
CONTRACT NO.:	83-3638
PERIOD OF PERFORMANCE:	MARCH 1979 - DECEMBER 1979
FUNDING LEVEL:	$216,500
LEVEL OF COMPLETION:	95%

PURPOSE OF CONTRACT

DETERMINE COST OPTIMUM OF STORAGE SYSTEM USING MOLTEN SALT FOR SOLAR SYSTEMS

- TYPE, NUMBER, SIZE OF TANK
- INSULATIONS
- FOUNDATION
- MATERIAL

DETERMINE COMPATIBILITY OF INSULATION MATERIAL WITH MOLTEN SALT

ANALYZE THERMOCLINE TANKS BY DEVELOPING A COMPUTER MODEL

EVALUATE SAFETY ASPECT OF SALT

TESTED MATERIALS

MANUFACTURER AND MATERIAL		DENSITY		COMPOSITION PRODUCTS IN PERCENT								
		lb/ft^3	gm/cm^3	Al_2O_3	SiO_2	Fe_2O_3	TiO_2	CaO	MgO	ALKALIES Na_2O;B_2O_3 K_2O	OTHERS	IGNITION LOSS
Brick												
Maximul	KR	142-146	2.27-2.34	42.76	53.15	1.07	1.11	0.47	0.57	0.87		
Lo Erode	KR	135-143	2.16-2.29	57.94	32.06	0.91	1.29	6.67	0.22	0.59		
Hi Strength	KR	126-133	2.02-2.13	43.64	38.31	3.68	1.06	11.11	0.41	1.39		
Krilite 30	KR	30	.48	55.5	38.2	1.6	1.4	2.2	0.2	1.2		
Krilite 60	KR	60	.96	55.5	38.2	1.6	1.4	2.2	0.2	1.2		
K-30	B&W	51	.82	46.0	52.0	0.9	1.4	0.5	0.1	0.4		
Firebrick 80-D	B&W	151	2.42	45.0	52.0	1.4	1.7	0.1	+	0.3		
Visil	HW	116-120	1.86-1.92	0.5	98.9	0.3	0.02	0.02	0.1	0.2		
Krimax CS-124	KR	150-154	2.40-2.47	46.2	49.7	1.6	1.9	0.06	0.17	0.23		
Semacid	SE	137	2.2	36.30[3]	57.88	2.74		0.82	0.54	1.38		.38
Castable												
IRC 24LI	KR	56-58	.90-.93	40.55	36.15	1.65	1.30	16.39	0.37	1.93		1.63
Coreline	KR	176	2.82	87.1	6.2	0.4	0.2	0.1	0.2	6.2[4]		
Firelite 2100	KM	65	1.04	38.4	31.2	4.8	1.5	22.4	0.5	0.2		0.8
Firecrete 2800	JM	123	1.97	50.3	39.3	4.0	2.0	4.0			0.4	
KAO TAB 95	B&W	166	2.66	95.0	0.1	0.1	+[2]	4.6	+	0.1		

TESTED MATERIALS (CONCLUDED)

MANUFACTURER AND MATERIAL		DENSITY		COMPOSITION PRODUCTS IN PERCENT								
		lb/ft^3	gm/cm^3	Al_2O_3	SiO_2	Fe_2O_3	TiO_2	CaO	MgO	ALKALIES Na_2O;B_2O_3 K_2O	OTHERS	IGNITION LOSS
Foamglass												
Foamsil-12	PC	25	.40	4.0	88.0					8.9[1]	0.1	
Fibreous Board												
Duraboard	CC	28-30	.45-.48	43.5	45.6	0.9		1.4		0.3		
Other												
T-Bond KT	KR	194.5	3.12	0.2	0.6	0.2		1.9	97.1			

Manufacturer

KR - Kaiser Refractories
B&W - Babcock & Wilcox
HW - Harbison-Walker Refractories
SE - Stebbins Engineering
JM - Johns-Manville
PC - Pittsburgh Corning
CC - Carborundum Co.

[1] B_2O_3 7.0
K_2O 1.0
Sb_2O_3 0.2
Na_2O_7 0.4-0.7

[2] + = Trace

[3] Includes a small amount of TiO_2

[4] Na_2O 0.2
K_2O 0.1
P_2O_5 5.9

TEST CONDITIONS

PRESCREENING

TIME = 500 HOURS

TEMPERATURE = 593 C (1100°F)

LONGEVITY

TIME = 500, 1000, 3000, 5000 HOURS

TEMPERATURE = 566 C (1050°F)

SUMMARY MATERIAL COMPATIBILITY RESULTS

SEM SHOWS ALTERATION OF STRUCTURE AND NEW COMPOUNDS BEING FORMED.

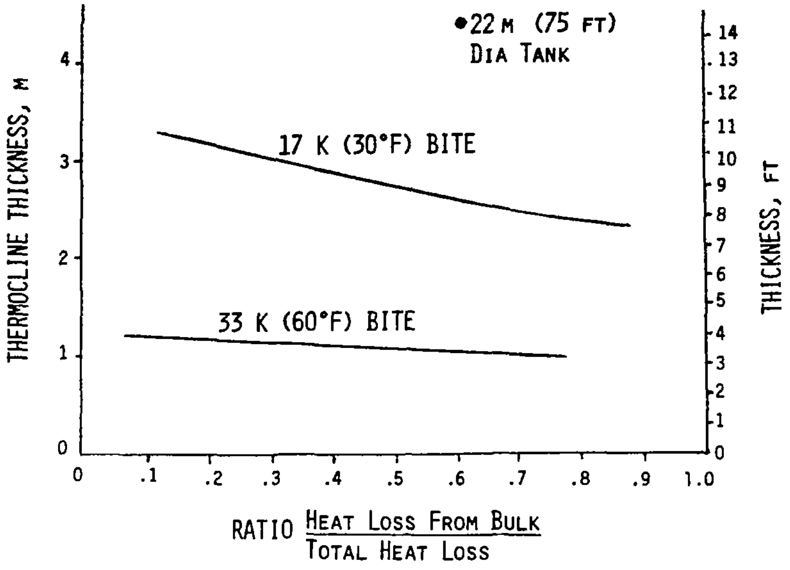
K/R PETROGRAPHIC ANALYSIS AND X-RAY DEFRACTION SHOWS MATERIAL BEING ATTACKED AT VARIOUS RATES BUT ALL BEING ATTACKED.

SALT EVALUATION SHOWS ALUMINUM AND SILICON BEING LEACHED FROM ALL PRODUCTS.

K/R ACKNOWLEDGES NEW COMPOUND WILL FREEZE ABOVE 288 C (550°F).

CONCLUSION: IT IS UNLIKELY THAT PRODUCT WILL SURVIVE A MOLTEN SALT ENVIRONMENT FOR 30 YEARS.

THERMOCLINE THICKNESS vs RATIO AND BITE



THERMOCLINE SUMMARY

A THERMAL ANALYTICAL MODEL WAS DEVELOPED WHICH SIMULATES A THERMOCLINE TANK

COMPARISON MADE WITH A FRENCH OIL TANK TEST SHOWED GOOD AGREEMENT

THE THERMOCLINE THICKNESS IS SENSITIVE TO:

- THERMOCLINE TEMPERATURE BITE
- TANK SIZE
- HEAT CAPACITY OF WALL

THE EFFECT OF BULK FLUID CIRCULATION ON THERMOCLINE THICKNESS IS MUCH LESS THAN THE EFFECTS OF BITE AND WALL HEAT CAPACITY

THERMOCLINE THICKNESS FOR THE OPTIMUM SYSTEM STUDY WAS 2.62 M (8.6 FT) BASED ON A 16.6 K (30°F) TEMPERATURE BITE

TANK BEARING ON HOT SOIL

- EXTENSIVE TELEPHONE SURVEY OF COMPANIES, FEDERAL BUREAUS AND COLLEGE PROFESSORS SHOW THIS IS A NEW TECHNICAL AREA
- SOIL PROPERTIES REQUIRED AT TEMPERATURE

BEARING	CREEP
THERMAL EXPANSION	COHESION
DEFORMATION	SHEAR

- GROUND WATER

  SOURCE - DIRECT SOIL PERCULATION
  - UPSTREAM STORMS THROUGH **PERVIOUS** SOIL LAYER

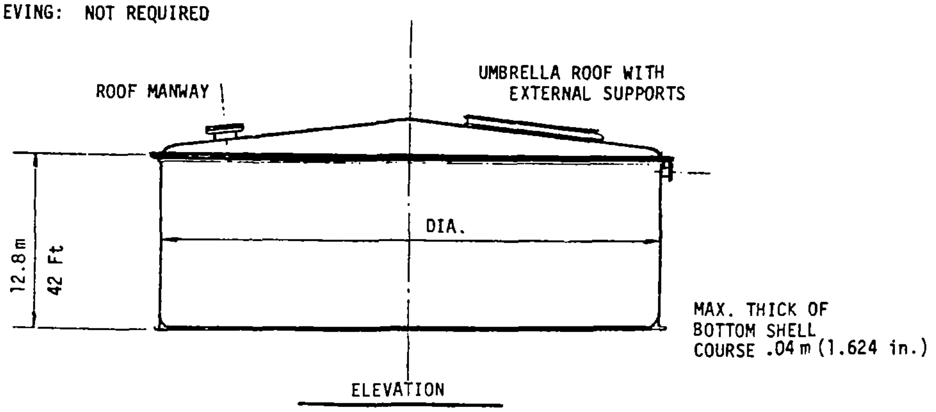
  RESULT - LIFTING OF SOIL OVERBURDEN AND TANK WHEN STEAM IN SOIL PORES EXCEED LITHOSTATIC SOIL LOAD

- PRESENT PRACTICES

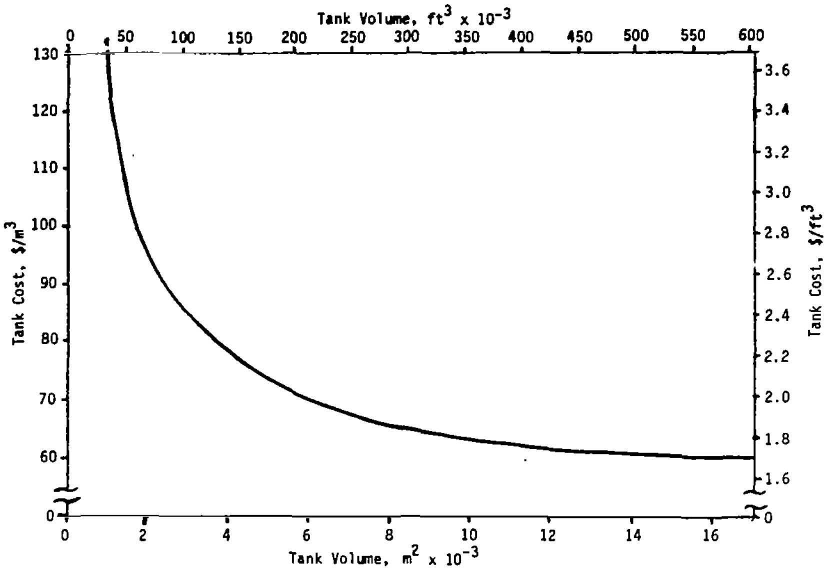
  PHTHALIC ANHYDRIDE TANKS, 422 K (300°F) ON GROUND - INSULATING CONCRETE
  ASPHALT TANKS, 561 K (550°F) - COOLED FROM GROUND
  FURNACES - PLACED ABOVE GROUND

MOLTEN SALT STORAGE TANK - CYLINDRICAL

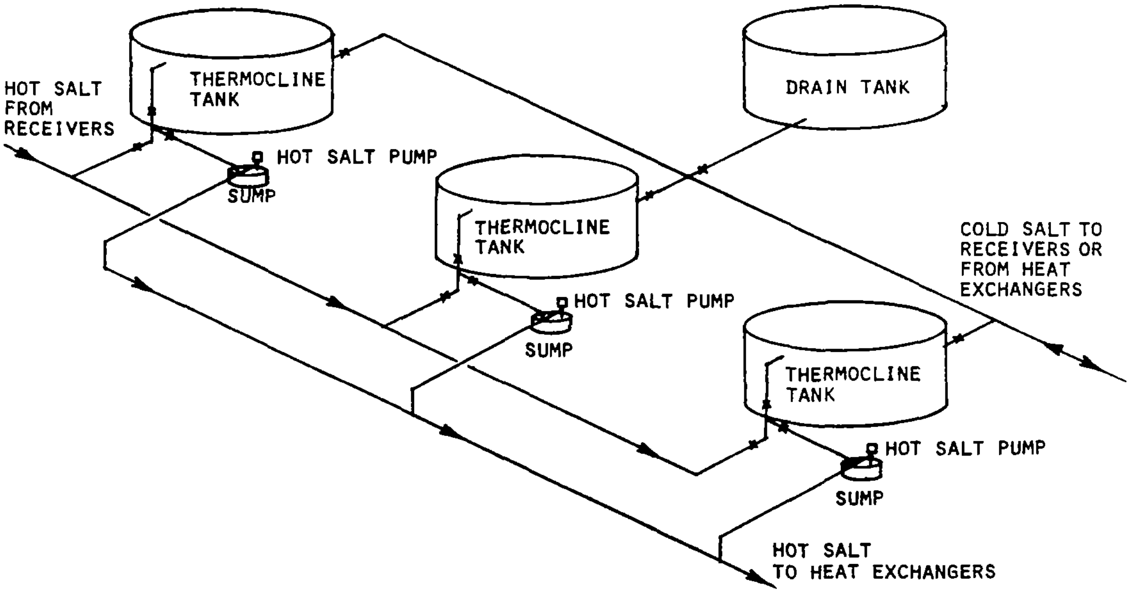
DESIGN: ATMOSPHERIC
SHELL DESIGN TEMPERATURE: 600°F
MATERIAL: SA-516, GR. 70
CORROSION ALLOWANCE: .003m (.125 in.)
CODE: API-650 CONSTRUCTION, NO STAMP.
MAX. SPECIFIC GRAVITY (COLD) 1.907
EARTHQUAKE: ZONE 3
SPOT X-RAY
STRESS RELIEVING: NOT REQUIRED



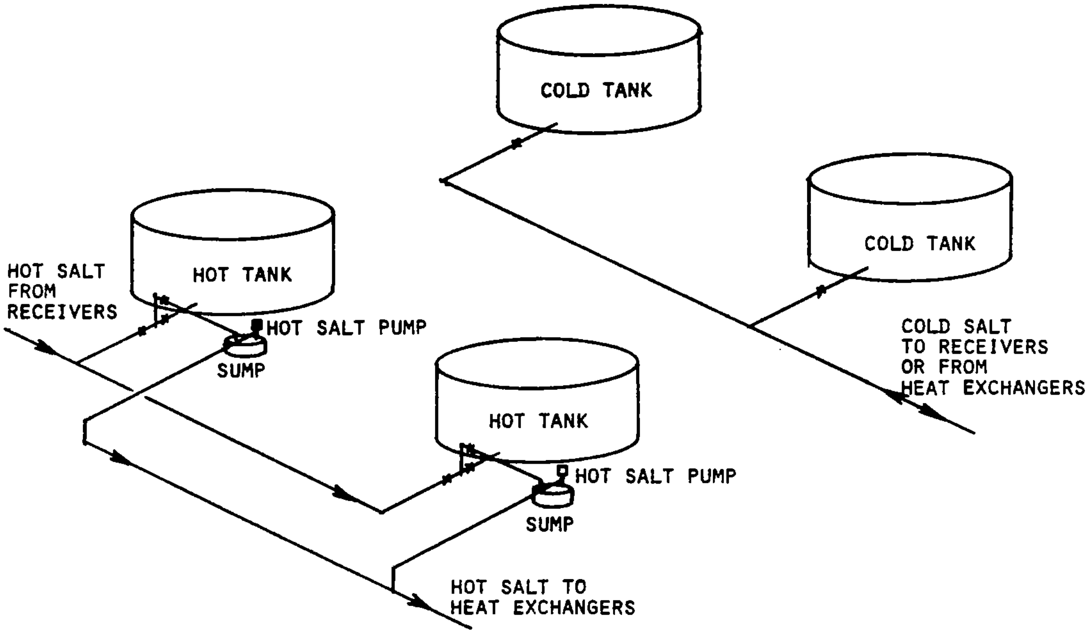
CYLINDRICAL TANK COST vs SIZE



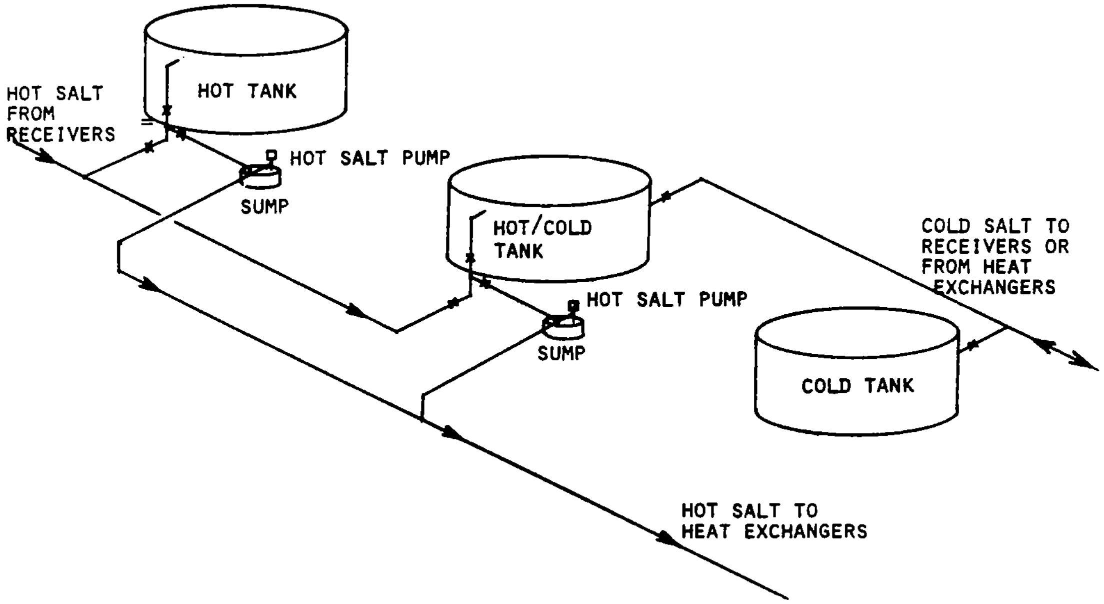
THERMOCLINE STORAGE SYSTEM



DUAL TANK STORAGE SYSTEM



CASCADE STORAGE SYSTEM



SPAM - STORAGE PARAMETRIC ANALYSIS MODEL

GOALS OF PROGRAM

- FIND THE CAPITAL AND EFFECTIVE* COSTS OF MOLTEN SALT STORAGE SYSTEMS DEFINED BY THE USER
- FIND THE SENSITIVITIES OF THESE COSTS TO VARIOUS SYSTEM PARAMETERS
- DETERMINE THE OPTIMUM STORAGE SYSTEM CONFIGURATION

APPROACH

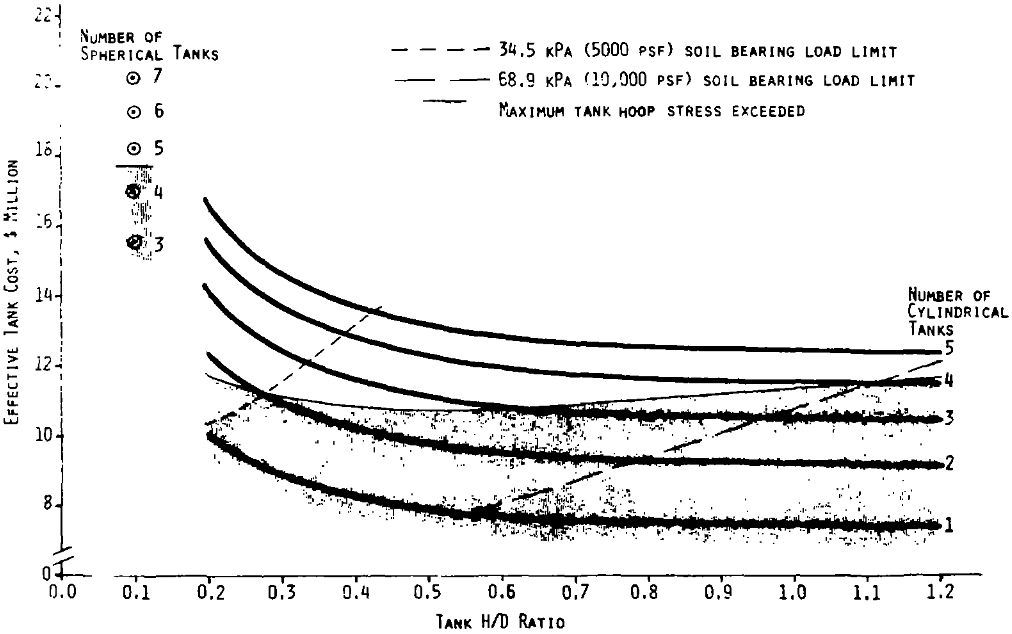
CALCULATE THE SUBSYSTEM AND SYSTEM COSTS FOR EACH USER-DEFINED CONFIGURATION, VARYING SUCH THINGS AS INSULATION THICKNESS, H/D RATIO, AND NUMBER OF TANKS.

PRINT OUT ALL COMBINATIONS, ALLOWING USER TO SEE SENSITIVITY TO A GIVEN PARAMETER, AND TO CHOOSE THE OPTIMUM CONFIGURATION.

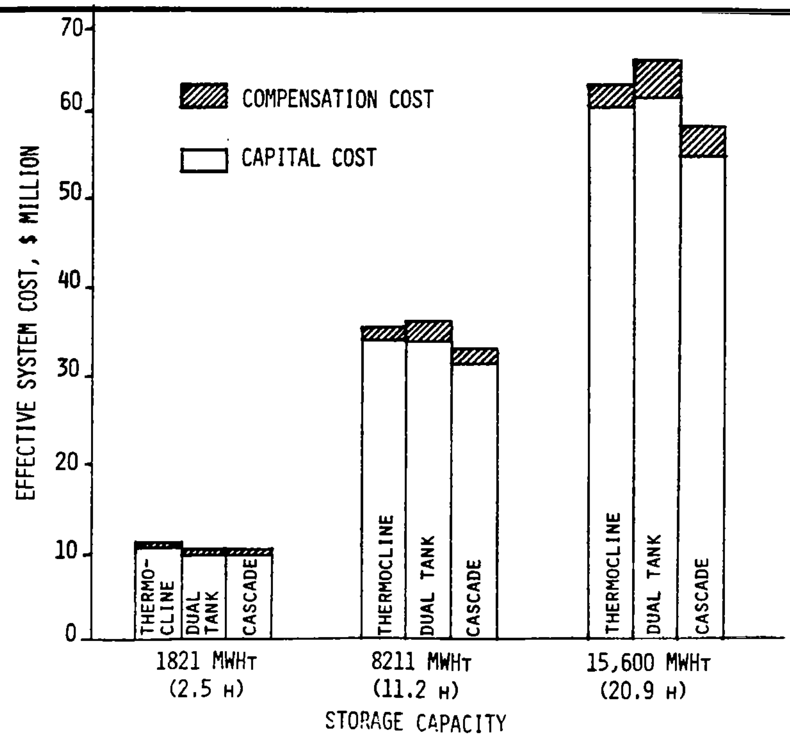
---

*EFFECTIVE COST TAKES INTO ACCOUNT THE COST OF EXTRA HELIOSTATS, ETC., NEEDED TO COMPENSATE FOR THE STORAGE SYSTEM HEAT LOSS.

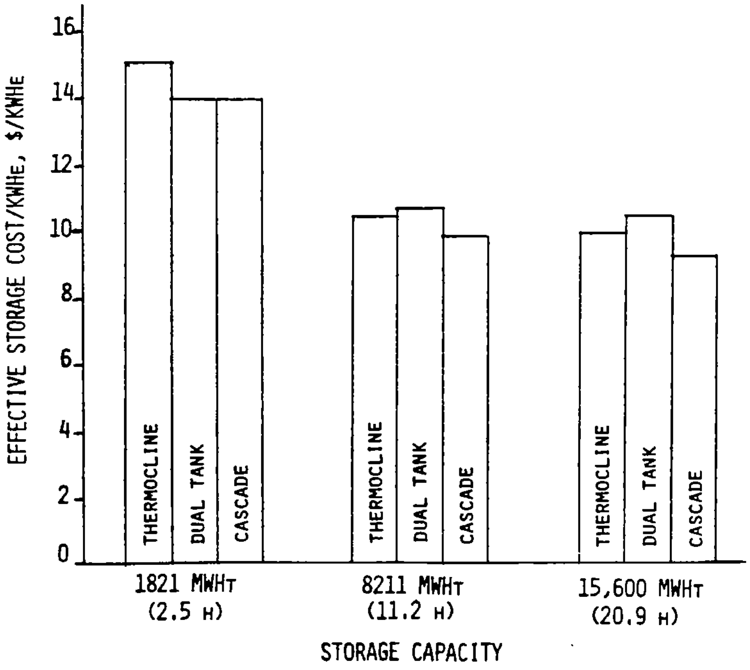
HOT TANK OPTIMIZATION (8200 MWHT STORAGE)



EFFECTIVE SOLAR STORAGE SYSTEM COST vs STORAGE SIZE (300 MWE PLANT)



EFFECTIVE COST OF SOLAR STORAGE vs STORAGE SIZE



CONCLUSIONS AND RECOMMENDATIONS

- THE OPTIMUM TANK CONFIGURATION FOR EACH SYSTEM IS THE SMALLEST NUMBER OF LARGE TANKS POSSIBLE WITHIN THE MECHANICAL CONSTRAINTS (SOIL BEARING LOAD, TANK HOOP STRESS).
- FOR SMALL STORAGE SYSTEMS WHERE ALL THE SALT CAN BE STORED IN ONE TANK (<3000 MWHT), THE DUAL TANK SYSTEM IS THE MOST ECONOMICAL SYSTEM.
- FOR INTERMEDIATE STORAGE SYSTEMS (≈10,000 MWHT), THE DUAL TANK SYSTEM IS RECOMMENDED AS THE COST ADVANTAGES OF THE THERMOCLINE AND CASCADE SYSTEMS DO NOT WARRANT THE ADDED TECHNICAL RISK.
- FOR LARGE STORAGE SYSTEMS (>15,000 MWHT), THE COST ADVANTAGE OF THE CASCADE SYSTEM IS ATTRACTIVE ENOUGH TO ENCOURAGE A SOLUTION TO THE THERMAL CYCLING PROBLEM. IN LIGHT OF THE CURRENT INFORMATION, THOUGH, A DUAL TANK SYSTEM IS STILL RECOMMENDED.

SYSTEM SCHEMATIC