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Thermal Energy Storage for Advanced Solar Central Receiver Power Systems

L. G. Radosevich

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THERMAL ENERGY STORAGE FOR ADVANCED SOLAR CENTRAL RECEIVER POWER SYSTEMS

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Abstract

Thermal energy storage is used in the advanced solar central receiver power systems currently being studied under Department of Energy sponsorship. This report describes: 1) the storage operating requirements imposed by interface constraints between energy storage and the receiver and electrical power generation systems, 2) several storage concept candidates which may meet these requirements, 3) potential cost differences between each of the storage concepts, and 4) the technical uncertainties associated with each storage concept.

Table of Contents

Illustrations

Figure | Page

Tables

Page

THERMAL ENERGY STORAGE FOR ADVANCED SOLAR CENTRAL RECEIVER POWER SYSTEMS

Introduction

The Department of Energy (DOE) is currently funding several studies designed to develop solar central receiver power systems which are economically competitive with conventional power generation energy sources (References 1 to 4)*. These systems under consideration include the water/steam receiver technology selected for the 10-MW(e) Barstow pilot plant and several advanced systems. Selection of storage concepts for the candidate systems is affected by several issues. First, storage operating requirements are imposed by interface constraints between the energy storage, receiver, and electrical power generation subsystems. In contrast to the first-generation central receiver systems, which use water/steam as the working fluid in both the receiver and electrical power generation subsystems, the proposed receiver subsystems use sensible heat working fluids (liquid sodium, molten salt, or air). The electrical power generation subsystems employ either steam Rankine reheat cycles or Brayton cycles compared to the steam Rankine non-reheat cycle used in the first-generation systems. Secondly, because the advanced systems operate at high temperatures technical performance uncertainties are an important consideration. Third, there will be important cost differences between each of the candidate storage concepts.

The purpose of this report is to:

- Describe storage operating requirements for the different advanced central receiver concepts.
- Indicate several candidate storage concepts which are most applicable to meeting the requirements.
- Describe potential cost differences between each of the storage concepts.
- Define the areas associated with each storage concept that require further analysis and experimentation.

It is hoped that this information can be used to develop a plan for future thermal energy storage research.

*The rationale for the advanced central receiver system studies is given in the Appendix.

Storage Operating Requirements

The interfaces between the energy storage system and the receiver and electrical power generation subsystems for each proposed advanced central receiver concept are defined in Tables I-III in terms of the type of working fluid and its temperature and pressure. As shown, the operating temperatures of the receiver working fluids at the receiver/storage interface are somewhat higher than that of the current water/steam receiver. For the sodium and salt systems, the use of a pressure reducing device (PRD) to reduce the tower hydrostatic head at this interface results in identical receiver and storage working fluid temperatures and allows a lower pressure storage containment design. These advantages may be offset by increased pumping power requirements. An alternative approach is the use of an intermediate heat exchanger (IHX) which reduces the storage fluid temperature but also the receiver pumping power. For the Brayton cycle system, the receiver and storage temperatures are the same but a high-pressure storage containment vessel is needed. At the storage/electrical power generation system (EPGS) interface, the operating temperatures and pressure of the EPGS working fluid are significantly different from those obtainable with the oil/rock storage system to be used in the 10-MW_e pilot plant at Barstow, CA. For the salt and sodium system, a steam generator heat exchanger is required; for the Brayton cycle system, the storage and EPGS working fluids are the same.

The net effect of the interface temperatures and pressures is a requirement for a storage system which can operate at temperatures significantly higher than that of the Barstow pilot plant. The operating pressure of the storage system can also be an important consideration depending on the design selected.

The charge rate, discharge rate, and capacity requirements for the advanced storage subsystems are being studied. Per DOE requirements, storage is being sized to accept the maximum power available from the receiver while the discharge rate is that required to produce the full plant nameplate rating. Storage capacity is a parameter and will be studied as part of the total plant cost/performance analyses. For plant sizes of 100 to 150 MW_e, typical charging rates are in the range of 400 to 700 MW(t), discharging rates are in the range of 250 to 400 MW(t), and storage capacities are in the range of 1 to 24 hours.

Storage Concept Candidates

Several candidate storage concepts and materials for presently proposed advanced central receivers are shown in Tables IV and V respectively. Additional concepts which may be compatible with the advanced central receivers are being studied under DOE contracts funded through the Division of Energy Storage (Reference 5).

The following sections present further details on the advantages, disadvantages, and technical uncertainties associated with the storage concepts summarized in Table IV.

TABLE I

ADVANCED CENTRAL RECEIVER PROJECTS

PRELIMINARY ENERGY STORAGE/RECEIVER INTERFACE REQUIREMENTS

	ATOMICS INTERNATIONAL	GENERAL ELECTRIC	MARTIN MARIETTA
RECEIVER WORKING FLUID	SODIUM	SODIUM	DRAW SALT
RECEIVER WORKING FLUID TEMPERATURE AT STORAGE INTERFACE, OUTLET/INLET	288°/593°C (550°/1100°F)	371°/704°C (700°/1300°F)	288°/566°C (550°/1050°F)
RECEIVER WORKING FLUID PRESSURE AT STORAGE INTERFACE	2.4 MPa (350 PSI) FOR A RECEIVER MID-POINT ELEVATION OF 258 m (846 ft)	2.4 - 3.4 MPa (350 - 500 PSI) DEPENDING ON RECEIVER ELEVATION	4.9 MPa (719 psi) FOR A RECEIVER MID-POINT ELEVATION OF 295 m (968 ft)

NOTE: CHARGING STEAM CONDITIONS FROM THE RECEIVER FOR THE BARSTOW PILOT PLANT ARE 510°C (950°F) AND 10.1 MPa (1465 PSI)

TABLE I (Continued)

ADVANCED CENTRAL RECEIVER PROJECTS

PRELIMINARY ENERGY STORAGE/RECEIVER INTERFACE REQUIREMENTS

	SANDERS	DYNATHERM	BOEING
RECEIVER WORKING FLUID	AIR	AIR	AIR
RECEIVER WORKING FLUID TEMPERATURE AT STORAGE INTERFACE, OUTLET/INLET	649°/1093°C (1200°/2000°F)	412°/816°C (775°/1500°F)	518°/816°C (1000°/1500°F)
RECEIVER WORKING FLUID PRESSURE AT STORAGE INTERFACE	0.1 MPa (15 PSI)	0.6 MPa (90 PSI)	3.4 MPa (500 PSI)

TABLE II

ADVANCED CENTRAL RECEIVER PROJECTS

PRELIMINARY ENERGY STORAGE/EPGS INTERFACE REQUIREMENTS

	ATOMICS INTERNATIONAL	GENERAL ELECTRIC	MARTIN MARIETTA
EPGS WORKING FLUID	WATER/STEAM	WATER/STEAM	WATER/STEAM
EPGS WORKING FLUID TEMPERATURE AT STORAGE INTERFACE, INLET/OUTLET	205°/538°C (400°/1000°F)	257°/538°C (495°/1000°F)	233°/510°C (450°/950°F)
EPGS WORKING FLUID PRESSURE AT STORAGE INTERFACE	INTIAL -12.4 MPa (1800 PSI) REHEAT - 3.0 MPa (440 PSI)	INTIAL - 16.4 MPa (2400 PSI) REHEAT - 3.3 MPa (477 PSI)	INITIAL - 12.4 MPa (1800 PSI) REHEAT - 2.8 MPa (402 PSI)

NOTE: DISCHARGING STEAM CONDITIONS FROM STORAGE FOR THE BARSTOW PILOT PLANT ARE 277°C (530°F) and 2.76 MPa (400 PSI).

TABLE II (Continued)

ADVANCED CENTRAL RECEIVER PROJECTS

PRELIMINARY ENERGY STORAGE/EPGS INTERFACE REQUIREMENTS

	SANDERS	DYNATHERM	BOEING
EPGS WORKING FLUID	AIR	AIR	AIR
EPGS WORKING FLUID TEMPERATURE AT STORAGE INTERFACE, INLET/OUTLET	204°/1093°C (400°/2000°F)	412°/816°C (775°/1500°F)	518°/816°C (1000°/1500°F)
EPGS WORKING FLUID PRESSURE AT STORAGE INTERFACE	0.4 MPa (60 PSI)	0.6 MPa (90 PSI)	3.4 MPa (500 PSI)

TABLE III

ADVANCED CENTRAL RECEIVER PROJECTS

PRELIMINARY ENERGY STORAGE OPERATING REQUIREMENTS

	ATOMICS INTERNATIONAL	GENERAL ELECTRIC	MARTIN MARIETTA
RECEIVER WORKING FLUID	SODIUM	SODIUM	DRAW SALT
RECEIVER/STORAGE INTERFACE DEVICE	PRESSURE REDUCING DEVICE	INTERMEDIATE HEAT EXCHANGER	PRESSURE REDUCING DEVICE
STORAGE MAXIMUM OPERATING TEMPERATURE	593°C (1100°F)	682°C (1260°F)	566°C (1050°F)
STORAGE MINIMUM OPERATING TEMPERATURE	288°C (550°F)	332°C (630°F)	288°C (550°F)
STORAGE/EPGS INTERFACE DEVICE	STEAM GENERATOR	STEAM GENERATOR	STEAM GENERATOR
EPGS WORKING FLUID	WATER/STEAM	WATER/STEAM	WATER/STEAM

NOTE: STORAGE MAXIMUM AND MINIMUM OPERATING TEMPERATURES FOR THE BARSTOW PILOT PLANT ARE 302°C (575°F) and 218°C (425°F), RESPECTIVELY

TABLE III (Continued)

ADVANCED CENTRAL RECEIVER PROJECTS

PRELIMINARY ENERGY STORAGE OPERATING REQUIREMENTS

	SANDERS	DYNATHERM	BOEING
RECEIVER WORKING FLUID	AIR	AIR	AIR
RECEIVER/STORAGE INTERFACE DEVICE	NONE	NONE	NONE
STORAGE MAXIMUM OPERATING TEMPERATURE	1093°C (2000°F)	816°C (1500°F)	816°C (1500°F)
STORAGE MINIMUM OPERATING TEMPERATURE	204°C (400°F)	412°C (775°F)	518°C (1000°F)
STORAGE/EPGS INTERFACE DEVICE	NONE	NONE	NONE
EPGS WORKING FLUID	AIR	AIR	AIR

TABLE IV
ADVANCED CENTRAL RECEIVER ENERGY STORAGE CONCEPTS

CONCEPT	RECEIVER WORKING FLUIDS	ADVANTAGES	DISADVANTAGES	TECHNICAL UNCERTAINTIES
(A) All-Sodium Sensible Heat With Hot and Cold Storage Tanks	Sodium	Potentially simple operation if (1) storage and receiver fluids are the same; (2) separate hot and cold tanks are used.	(1) Sodium tower pressure requires pressure reducing device or intermediate heat exchanger. (2) Sodium material and tank costs are high.	(1) Containment material lifetime. (2) Safety. (3) Pressure reducing device.
(B) Sodium/Cast Iron Sensible Heat Using Thermocline Principle	Sodium	(1) Potentially simple operation if storage and receiver fluids are the same. (2) Reduced tankage cost using thermocline and high density filler.	(1) Sodium tower pressure requires pressure reducing device or intermediate heat exchanger. (2) Storage material costs are high.	(1) Storage material. (2) Thermocline performance. (3) Containment material lifetime. (4) Safety. (5) Pressure reducing device.
(C) Air/Rock Sensible Heat Using Thermocline Principle	Air Sodium Salt	(1) Potentially simple operation if storage and receiver fluids are the same. (2) Reduced material costs using rocks.	(1) High pressure tankage is needed with air receiver.	(1) Storage material lifetime. (2) Thermocline performance. (3) Containment material lifetime. (4) Safety (with sodium receiver).
(D) Air/MgO Sensible Heat Using Thermocline Principle	Air Sodium Salt	Same as (B)	(1) Storage material costs are high.	Same as (C)
(E) Air/Cast Iron Sensible Heat Using Thermocline Principle	Air Sodium Salt	Same as (B)	Same as (D)	Same as (C)

TABLE IV (cont'd)
ADVANCED CENTRAL RECEIVER ENERGY STORAGE CONCEPTS

	CONCEPT	RECEIVER WORKING FLUIDS	ADVANTAGES	DISADVANTAGES	TECHNICAL UNCERTAINTIES
(F)	Molten Salt Sensible Heat Using Thermocline Principle	Salt Sodium	(1) Potentially simple operation if storage and receiver fluids are the same.	(1) Salt tower pressure requires pressure reducing device or intermediate heat exchanger.	Same as (B)
(G)	Molten Salt Sensible Heat With Hot and Cold Storage Tanks	Salt Sodium	Same as (A)	(1) Salt tower pressure requires pressure reducing device or intermediate heat exchanger. (2) Salt tank costs are high.	(1) Storage material lifetime. (2) Containment material lifetime. (3) Safety. (4) Pressure reducing device.
(H)	Molten Salt/Rock Sensible Heat Using Thermocline Principle	Salt Sodium	Same as (C)	Same as (F)	Same as (B)

TABLE V
STORAGE MATERIAL DATA

MATERIAL/ TEMPERATURE SWING	DENSITY kg/m^3(lb/ft^3)	SPECIFIC HEAT J/kg-°C(BTU/lb-°F)	STORAGE DENSITY MJ/m^3-°C(BTU/ft^3-°F)	THERMAL CONDUCTIVITY (W/m-°C(BTU/hr-ft-°F)	THERMAL DIFFUSIVITY m^2/sx10^{-7}(ft^2/hr)	COST* $/MBTU
CALORIA HT-43 132°-316°C (450°-600°F)	690 (43)	2760 (0.66)	1.9 (28.4)	0.12 (0.07)	0.65 (0.0025)	1413 ($.14/lb)
ROCK 232°-316°C (450°-600°F)	2660 (166)	1000 (0.24)	2.66 (39.8)	2.60 (1.5)	9.8 (0.038)	139 ($10/ton)
288°-566°C (550°-1050°F)	2640 (165)	1050 (0.25)	2.77 (41.3)	2.60 (1.5)	9.8 (0.038)	40 ($10/ton)
DRAW SALT 288°-566°C (550°-1050°F)	1840 (115)	1550 (0.37)	2.85 (42.6)	0.57 (0.33)	2.0 (0.0078)	811 ($.15/lb)
HITEC 288°-566°C (550°-1050°F)	1780 (111)	1550 (0.37)	2.76 (41.4)	0.61 (0.35)	2.2 (0.0085)	1620 ($.30/lb)
MgO 538°-816°C (1000°-1500°F)	3000 (187)	1130 (0.27)	3.39 (50.5)	5.07 (2.93)	15 (0.058)	1111 ($.15/lb)
CAST IRON 538°-816°C (1000°-1500°F)	7880 (492)	840 (0.20)	6.62 (73.8)	42.9 (24.8)	65 (0.25)	2143 ($.30/lb)
316°-704°C (600°-1300°F)	7880 (492)	840 (0.2)	6.62 (73.8)	42.9 (24.8)	65 (0.25)	3000 ($.30/lb)
SODIUM 316°-704°C (600°-1300°F)	960 (60)	1260 (0.30)	1.21 (18)	67.5 (39)	570 (2.2)	1428 ($.30/lb)

*Cost is based on the temperature swing shown in the first column and material cost shown in parentheses.

All Sodium Sensible Heat With Hot and Cold Storage Tanks

In this concept, the storage is charged by pumping cold sodium from a cold storage tank to the receiver where it is heated and returns to the hot storage tank. Alternatively, if an intermediate heat exchanger is used, separate receiver and storage sodium loops are required with the sodium heated in the heat exchanger. During discharge, sodium is pumped from the hot storage tank through a steam generator heat exchanger and then returned to the cold storage tank.

The main advantage of this design is simple operation: the storage and receiver working fluids are the same and separate hot and cold storage tanks are used. The steam generator is also decoupled from those receiver transients that are caused by rapidly varying insolation conditions. A disadvantage which applies to all the sodium or salt receiver concepts is that if the sodium tower pressure is transmitted to storage tanks tank costs increase. This pressure constraint can be eliminated with an intermediate heat exchanger or pressure reducing device. An intermediate heat exchanger lowers the maximum operating temperature of the storage fluid while a pressure reducing device increases pumping power requirements. A second disadvantage is high material and tankage costs due to the low volumetric energy density of sodium and the need for separate hot and cold storage tanks.

The technical uncertainties associated with this concept are the tankage material lifetime due to high temperature operation, cycling over a large temperature swing (typically 278°C (500°F)) and containment of a chemically active storage material. Safety at the sodium/water interface and technical feasibility of a pressure reducing device for a variable charge rate should also be determined.

Sodium/Cast Iron Sensible Heat Using Thermocline Principle

This concept uses dual liquid (sodium) and solid (cast iron) storage media with the thermocline principle applied to store both hot and cold media in the same tank. In operation, the media is heated by removing cold fluid from the bottom of the tank, heating it either directly in the receiver or through an IHX, and returning the fluid to the top of the tank. For heat extraction, the process is reversed and steam is generated by passing the hot sodium through a steam generator heat exchanger.

The advantage of simple operation applies to this design since the receiver and storage working fluids are the same. Use of a thermocline with a high density filler (cast iron) reduces the tankage volume and results in a lower cost compared to the hot and cold tank concept. Disadvantages include transmitting the tower pressure to the storage tanks and the high cost of sodium and cast iron.

Technical uncertainties for this concept are the possible reductions in the lifetime of the tankage material caused by high-temperature operation, cycling over a large temperature swing, and containment of both cast iron and a chemically active storage material. Sodium/cast iron compatibility in the temperature range of interest needs to be established. An analytical and experimental verification of thermocline performance is required because the thermal diffusivity of liquid sodium is several hundred times greater than that of water or oil. The same concerns over the safety and feasibility of a pressure-reducing device mentioned previously also apply.

Air/rock Sensible Heat Using Thermocline Principle

This storage concept can be used with the air, sodium, or salt receiver working fluids. The concept uses dual air and rock storage media with the thermocline principle employed. The rocks are heated by removing cold air from the tank, heating it either directly in the receiver or through an intermediate heat exchanger, and returning the air to the tank. For heat extraction, the process is reversed and the hot air passes directly to the turbine or through a steam generator heat exchanger.

For the Brayton cycle system, the operation of this design is simple because the receiver and storage working fluids are the same; an intermediate heat exchanger is required for other receiver working fluids. Use of rock as the storage media results in the lowest media cost. A disadvantage of this concept when applied to the Brayton cycle receiver is the need for a high-pressure containment vessel (3.4 MPa (500 psi)).

Technical uncertainties are the tankage material lifetime due to high temperature operation, cycling over a large temperature swing and containment of the rock at high pressures. The stability of rocks when thermal cycling at temperatures up to 816°C (1500°F) and thermocline performance as a function of rock particle size and air velocity should be verified. For sodium receivers, safety at the sodium/air interface should be established.

Air/MgO Sensible Heat Using Thermocline Principle

This concept is identical to the air/rock system with the exception of the solid storage media. Rock and MgO thermal properties are similar but the cost of MgO refractory material is much higher than that of rock since the media is fabricated into spheres or bricks. Other refractory material, such as firebrick and Al_2O_3, could be used for this concept.

Air/Cast Iron Sensible Heat Using Thermocline Principle

The concept is similar to the air/MgO system with the exception of the solid storage media. Cast iron has a much higher density but slightly lower heat capacity than MgO, which results in reduced pressure vessel costs. However, the cost of cast iron material cost, is at least double that of MgO and much higher than rock.

Molten Salt Sensible Heat Using Thermocline Principle

This concept uses molten salt (draw salt) with the thermocline principle used to store hot and cold molten salt in the same tank. In operation the concept is similar to the sodium/cast iron system, except that solid storage media is employed.

The volumetric energy density of an all-salt system is more than double that of an all-sodium system. This high energy density, along with use of a thermocline, results in lower pressure vessel costs than those associated with the all-sodium concept.

The cost of draw salt is much less than sodium or iron, and thermocline degradation should be less severe because the thermal diffusivity of draw salt is only slightly greater than water but much less than sodium or iron.

Technical issues for this concept are similar to those for the sodium/cast iron concept. Salt stability is a critical issue since any cost advantages could be negated by a high salt makeup requirement. Spherical containment vessels are under consideration for this concept; both analytic and experimental studies of thermocline performance in spherical containment vessels will be required.

Molten Salt Sensible Heat With Hot and Cold Storage Tanks

This concept is similar in operation to the all-sodium system except that molten salt is used as the storage media. Pressure vessel costs are greater than for the previous single tank molten salt system because separate hot and cold storage tanks are employed. Salt stability is again a critical issue.

Molten Salt/Rock Sensible Heat Using Thermocline Principle

This concept uses dual liquid (molten salt) and solid (rock) storage media with the thermocline principle applied to store hot and cold media in the same tank. In operation the concept is similar to the sodium/cast iron system.

The molten salt/rock concept has the potential for low material costs if salt makeup rates are not excessive. Salt thermal stability and salt/rock compatibility are major technical issues, along with containment material lifetime and thermocline performance.

Summary of Major Technical Uncertainties

The requirement for operation at high temperatures and possibly high pressures raises several questions regarding the technical feasibility of the proposed storage systems. These questions, which were discussed earlier for each concept, are summarized in Table VI. They include storage and containment material lifetime, thermocline performance, safety, and the feasibility of pressure reducing devices.

TABLE VI

ADVANCED CENTRAL RECEIVER PROJECTS

ENERGY STORAGE TECHNICAL UNCERTAINTIES

ISSUE	STUDY AREAS	CONCEPTS REQUIRING STUDY
STORAGE MATERIAL LIFETIME	THERMAL STABILITY	B, C, D, E, F, G, H
	COMPATIBILITY	
	REFURBISHMENT	
CONTAINMENT MATERIAL LIFETIME	FATIGUE	ALL
	CORROSION	
THERMOCLINE PERFORMANCE	PARTICLE SIZE	B, C, D, E, F, H
	FLUID VELOCITY	
	SOLID AND FLUID PROPERTIES	
SAFETY	SODIUM/WATER INTERFACE	ALL
	SALT/WATER INTERFACE	
	SODIUM/SALT INTERFACE	
PRESSURE REDUCING DEVICE DEVICE	VARIABLE CHARGE RATE	A, B, F, G, H

High-temperature operation requires a verification of salt stability and compatibility, particularly in the case of molten salts. Enhancement of salt lifetime through refurbishment requires study. Containment material corrosion is a major issue for salt storage due to their oxidizing nature and operation at high temperatures. Containment material fatigue is an important issue for all storage concepts due to operation at high temperatures, temperature cycling, and large temperature gradients (particularly for thermoclines). Currently, studies are being conducted on molten salts at Sandia and Martin Marietta. Oak Ridge National Laboratory has recently proposed additional studies on salt stability. The objectives and status of this ongoing and proposed work are summarized in Figures 1 through 3.

Thermocline performance requires analytical and experimental verification of thermocline shape under expected plant operating conditions because the storage material's physical properties, particle size, fluid velocity, and tank geometry can differ significantly from those of the present oil/rock system. Finally, studies to verify the safety of sodium/salt/water interfaces are needed, and the technical feasibility of a salt or sodium pressure reducing device for variable charge rates must be established.

FIGURE 1

SANDIA SALT STUDIES

OBJECTIVES

INVESTIGATE THERMAL STABILITY OF MOLTEN SALT ALKALI NITRATES AND NITRITES IN AIR AND OTHER ENVIRONMENTS

STUDY CORROSION BEHAVIOR OF VARIOUS IRON ALLOYS IN THE MOLTEN SALT ENVIRONMENTS

INVESTIGATE COMPATIBILITY OF MOLTEN SALT (DRAW SALT AND HITEC) WITH ROCK AND METAL IN SEALED CONTAINERS

STATUS

PRELIMINARY RESULTS OBTAINED WITH DRAW SALT IN AIR AT 550°C (1022°F)

CONTINUING STUDIES ON BEHAVIOR OF SINGLE AND BINARY SALTS

ONE SIX MONTH CORROSION TEST (SIX ALLOYS) COMPLETED WITH HITEC IN AIR AT 550°C (1022°F)

FIGURE 2

MARTIN MARIETTA SALT STUDIES

OBJECTIVES

- INVESTIGATE THERMAL STABILITY OF MOLTEN SALT (DRAW SALT AND HITEC) IN SEALED CONTAINERS

- STUDY CORROSION BEHAVIOR OF SELECTED ALLOYS IN THE MOLTEN SALT ENVIRONMENTS USING IMMERSION AND FLOW LOOP TESTS

STATUS

- PRELIMINARY STABILITY RESULTS OBTAINED WITH DRAW SALT IN SS304 CONTAINER AT 593°C (110°F) FOR 5000 HOURS

- IMMERSION TESTS CONDUCTED WITH SEVEN ALLOYS AT TEMPERATURES RANGING FROM 482°C (900°F) TO 621°C (1150°F) FOR 400 HOURS

FIGURE 3

ORNL SALT STUDIES

OBJECTIVES

INVESTIGATE CHEMICAL STABILITY OF ALKALI NITRATES AND REACTIONS WITH CARBON DIOXIDE

DETERMINE MELTING TEMPERATURES OF ALKALI NITRATE MIXTURES WITH AND WITHOUT THEIR REACTION PRODUCTS WITH CARBON DIOXIDE

ASSESS ALTERNATIVE MOLTEN SALT MIXTURES FOR THE SOLAR CENTRAL RECEIVR CONCEPT

STATUS

ORNL DRAFT PROPOSAL FOR 18 MONTH STUDY UNDER REVIEW

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APPENDIX A

ADVANTAGES OF ADVANCED TECHNOLOGIES

The energy storage design proposed for the 10-MW_e pilot plant (Reference 3) uses the sensible heat concept for storing thermal energy (see Table A-I). A major constraint of the first-generation water/steam solar central receiver technology is the reduction in the temperature and pressure of steam generated from storage compared to that which is available directly from the receiver. This constraint results in a need for a dual-admission turbine to accept both steam conditions and reduces the plant thermal efficiency and electrical output when operating from storage.

An increase in thermal efficiency can be obtained by increasing the temperature and/or pressure of the steam generated from storage. This is accomplished either by reducing the temperature swing in the storage fluid (difference in the maximum and minimum operating temperature) or by adding stages. In Figure A-1, for example, an increase in pressure of the steam generated from storage moves the vertical portion of the solid curve for discharging flow to the right. Since the dashed curve cannot cross either the discharging or charging solid curves without violating the Second Law of Thermodynamics the temperature swing of the storage fluid must become increasingly smaller. A reduced temperature swing leads to increased heat exchanger, storage material, and tankage cost.

Staging increases the thermal efficiency when operating from storage somewhat but also results in increased storage material, tankage, and piping costs compared to the single stage concept. This result is best illustrated by use of an example (Table A-II). Constraints introduced by the need to interface with a phase change working fluid (i.e., water/steam) reduce the temperature swing in the main stage of the two-stage system. The storage material volume required in the main stage of the two-stage design is therefore about the same as that needed for the single-stage design. Since the two-stage system also requires storage material for the high-temperature stage its total material requirement exceeds that of the single-stage system in spite of its higher efficiency. The increase in material, tankage, and piping costs which results was sufficient to offset any gain in thermal efficiency and was a factor in the selection of the single-stage design for the 10 MW_e pilot plant energy storage subsystem.

TABLE A-I

BARSTOW $10MW_e$ PILOT PLANT ENERGY STORAGE CONCEPT

CHARACTERISTIC	
STORAGE CONCEPT	SINGLE-STAGE SENSIBLE HEAT USING AN OIL/ROCK THERMOCLINE
NET ELECTRICAL OUTPUT/DURATION	7 MW(e)/3 HOURS
DISCHARGING STEAM CONDITIONS FROM STORAGE	2,760 KPa (400 PSIA) 277°C (530°F)
STORAGE MEDIA	CALORIA HT-43 OIL WITH CRUSHED GRANITE AND COARSE SAND
STORAGE MEDIA OPERATING TEMPERATURES	218 to 302°C (425 TO 575°F)

PILOT PLANT ENERGY STORAGE OPERATING CONDITIONS

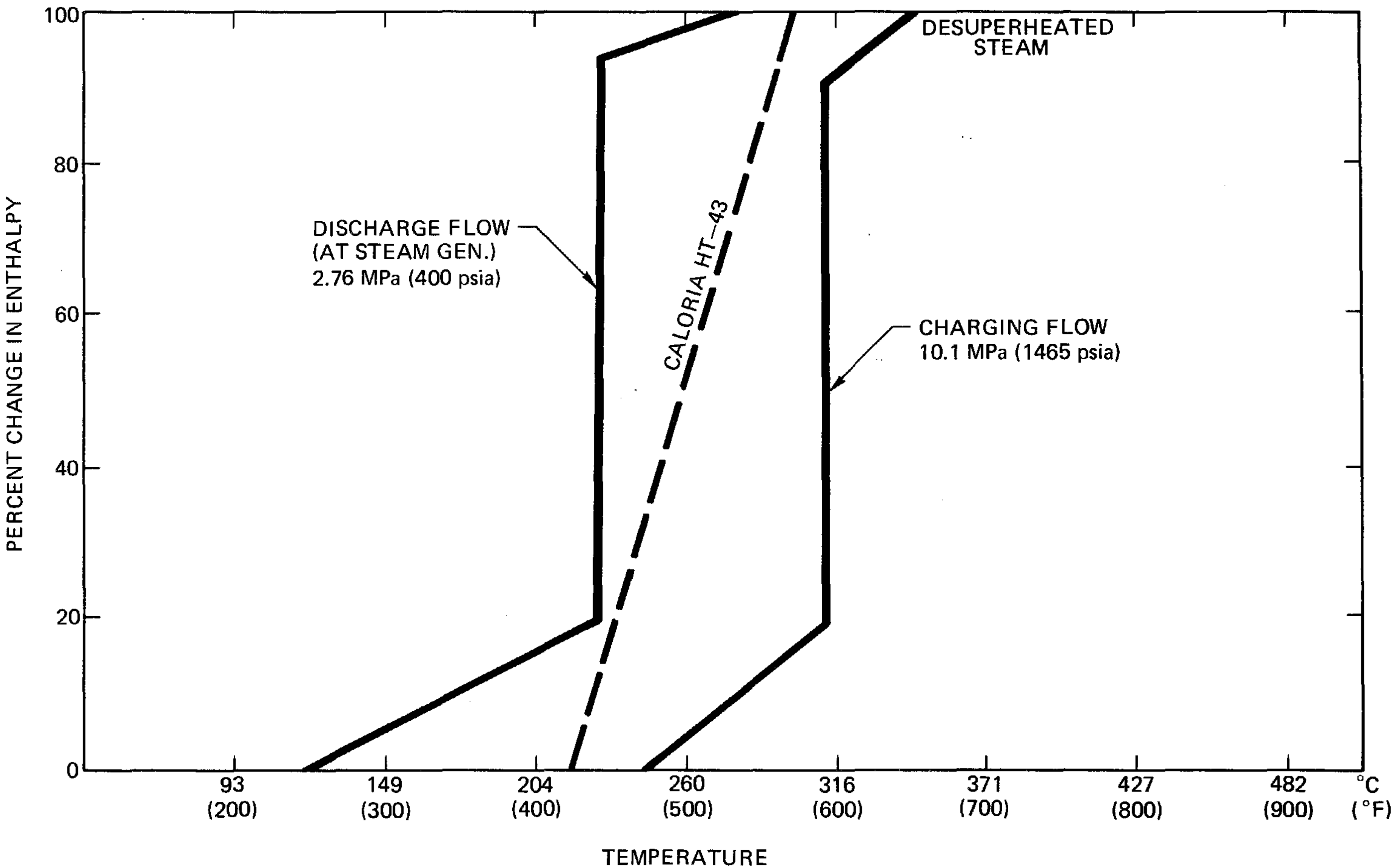

FIGURE A-1

TABLE A-II

COMPARISON OF STORAGE MATERIAL QUANTITIES

FOR SINGLE- AND TWO-STAGE DESIGNS

	Single-Stage	Two-Stage
Net Efficiency (Typical)	0.24	0.29
Output (100 MW_e Commercial Plant)	70 MW_e	70 MW_e
Duration	3 hr	3 hr
Required Thermal Capacity	875 MWHt	724 MWHt
Main-Stage Fraction	100%	80%
Second-Stage Fraction	Not Applicable	20%
Main-Stage Temperature Swing	83°C (150°F)	56°C (100°F)
Normalized Main-Stage Material Volume	1.01	1.00

These limitations and constraints along with other factors have led to consideration of advanced concepts. Advantages of these advanced central receiver concepts over the current water/steam system are high cycle efficiencies (typically 0.4) due to increased receiver operating temperatures and pressures, capability to generate the full plant electrical output when operating from storage, elimination of the need for a dual admission turbine, and complete decoupling of the turbine from receiver transients caused by rapidly varying insolation conditions. Finally, the concepts have potentially lower system cost due to the need for fewer heliostats, smaller receiver, a shorter tower, and reduced storage material and tankage volume requirements although these cost advantages may be offset somewhat by increased receiver and energy storage component costs introduced by the requirement for operating at higher temperatures. Studies, such as Reference 4, have shown that it may be possible to reduce the cost of electricity relative to the current pilot plant technology by the use of advanced receiver concepts.

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