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Thermal Energy Storage for Solar Thermal Applications Program Progress Report (Oct 1979-Mar 1980)

L. G. Radosevich

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THERMAL ENERGY STORAGE FOR SOLAR THERMAL APPLICATIONS
PROGRAM PROGRESS REPORT

(October 1979 - March 1980)

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Thermal Subsystems Division
Sandia National Laboratories, Livermore

ABSTRACT

This report summarizes the progress made by the Thermal Energy Storage for Solar Thermal Applications (TESSTA) Program in the period October 1979 - March 1980.

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THERMAL ENERGY STORAGE FOR SOLAR THERMAL APPLICATIONS
PROGRAM PROGRESS REPORT

I. Introduction

General Program Description

Recognizing thermal energy storage as potentially critical to the successful commercialization of solar thermal power systems, the DOE Divisions of Energy Storage Systems (STOR) and Central Solar Technologies (CST) have established a comprehensive and aggressive thermal energy storage technology development program in direct support of solar thermal power applications. The program concentrates on storage subsystem development in the FY80 to 85 time period with emphasis on the more near-term solar thermal power system applications.

The overall objective of this storage development program is to develop general solar thermal energy storage technologies that provide:

- Second-generation storage subsystems offering cost/performance improvements over the first-generation storage subsystems currently being developed for solar thermal power applications.

- First-generation storage subsystems for those solar thermal applications that presently have no storage subsystems under development.

- A technology base to support storage subsystem development for future solar thermal power applications.

Implementation of the first two program elements, which are application oriented, is the responsibility of the Field Lead Laboratory, Sandia National Laboratories. The Field Lead Laboratory for implementation of the technology base goal is the Solar Energy Research Institute (SERI). Private industry and universities, competitively selected, perform the implementation as operating contractors with Sandia and SERI performing that generic R&D appropriate to a national laboratory and necessary for management of the program.

Applications Program Description

The applications portion of the program is organized through a work breakdown structure which includes the development of thermal storage technologies matched to solar thermal power system requirements for several near-term applications. Solar thermal power systems of interest to this program include concentrating troughs, dishes, and central receivers with working fluids at various operating conditions. Storage development for central receivers and generic storage development are directed by Sandia National Laboratories Livermore (SNLL), who also performs overall program management and coordination functions. Storage development for trough and dish collectors is directed by Sandia National Laboratories Albuquerque (SNLA) and Jet Propulsion Laboratory (JPL), respectively. Based on current direction of the Thermal Power Systems (TPS) Branch, Central Solar Technology (CST), the early portion of the program is stressing storage for repowering/industrial retrofit, total energy,* and small community system applications.

The applications program has been divided into seven major elements according to the tasks outlined in Figure 1. The first element represents generic activities required to support program management functions; the remaining six elements are keyed to storage development for specific collector/receiver technologies. Several tasks have been further divided into subtasks which represent specific concepts being pursued. Project applications** for the six major elements have been identified to provide a development focus for the storage technology development. The relation between the elements and the project applications is shown in Figure 2.*** A summary description of each application is given in Table I.

Report Outline

In the next section the application program goals are described. Representative cost and performance goals have been developed for both first and second generation systems. Section III describes the approach used for implementation of the program goals. This includes a discussion of the program five-year plan and the FY80 program developed in support of that plan. Section IV summarizes accomplishments since the start of the program, October, 1979. This includes achievements of both program and project goals and highlights of accomplishments for each major task element. Detailed discussions of current projects are summarized in the Appendix.

---

*The terms, "total energy" and "cogeneration," are used interchangeably in this report. They refer to systems which provide for the combined production of electrical and other useful thermal energy.

**The repowering/industrial retrofit program may result in two system applications: repowering of an existing electric power generating plant and retrofitting of an existing industrial process heat plant. Storage requirements, which may differ significantly for the two applications, will be further defined pending completion of conceptual design studies in FY80.

***The solar interface operating conditions and candidate applications are representative cases only. For example, several water/steam collector/receivers at various operating conditions are under consideration for the repowering/industrial retrofit system application.

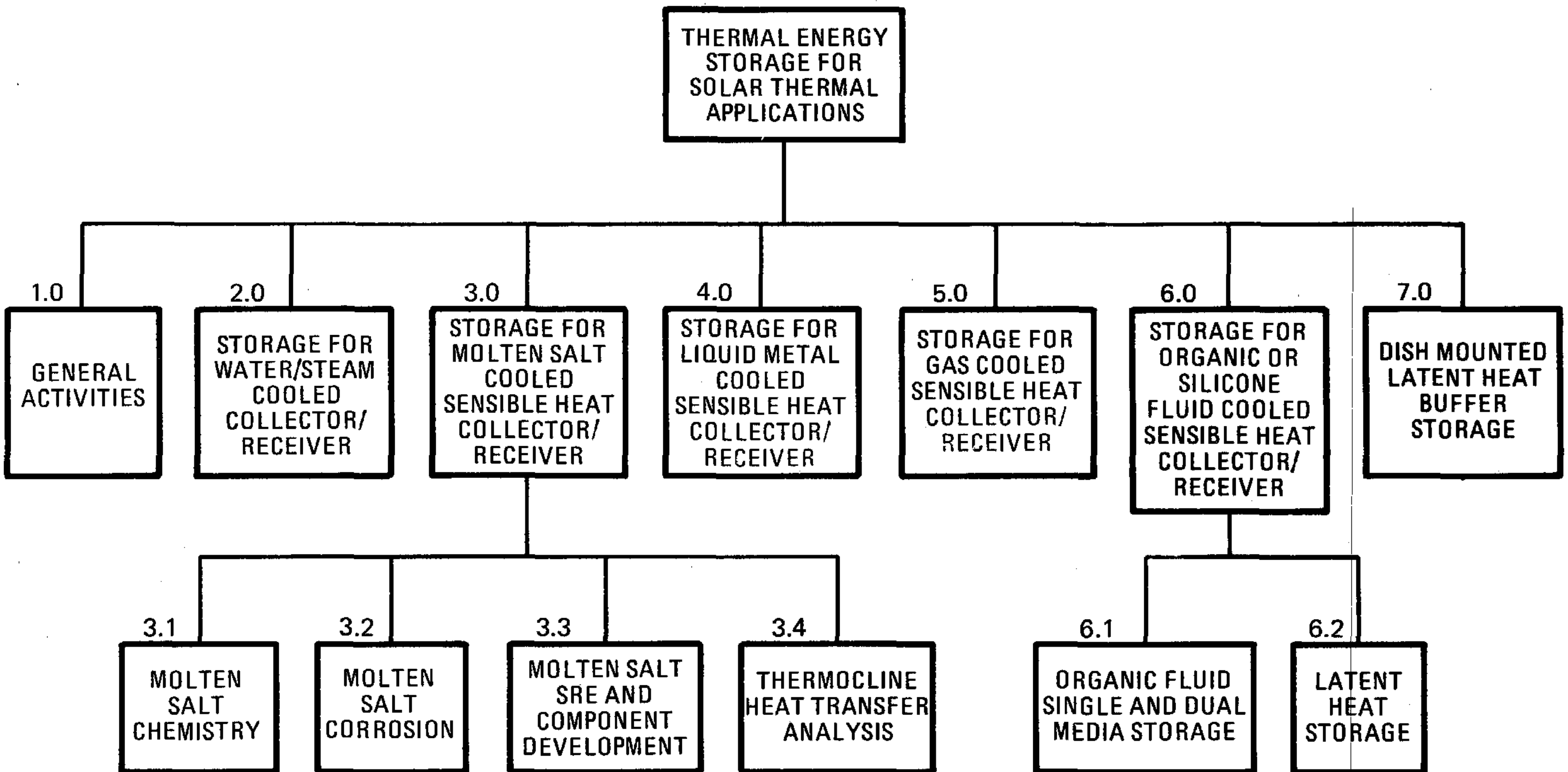


Figure 1 - Task Outline

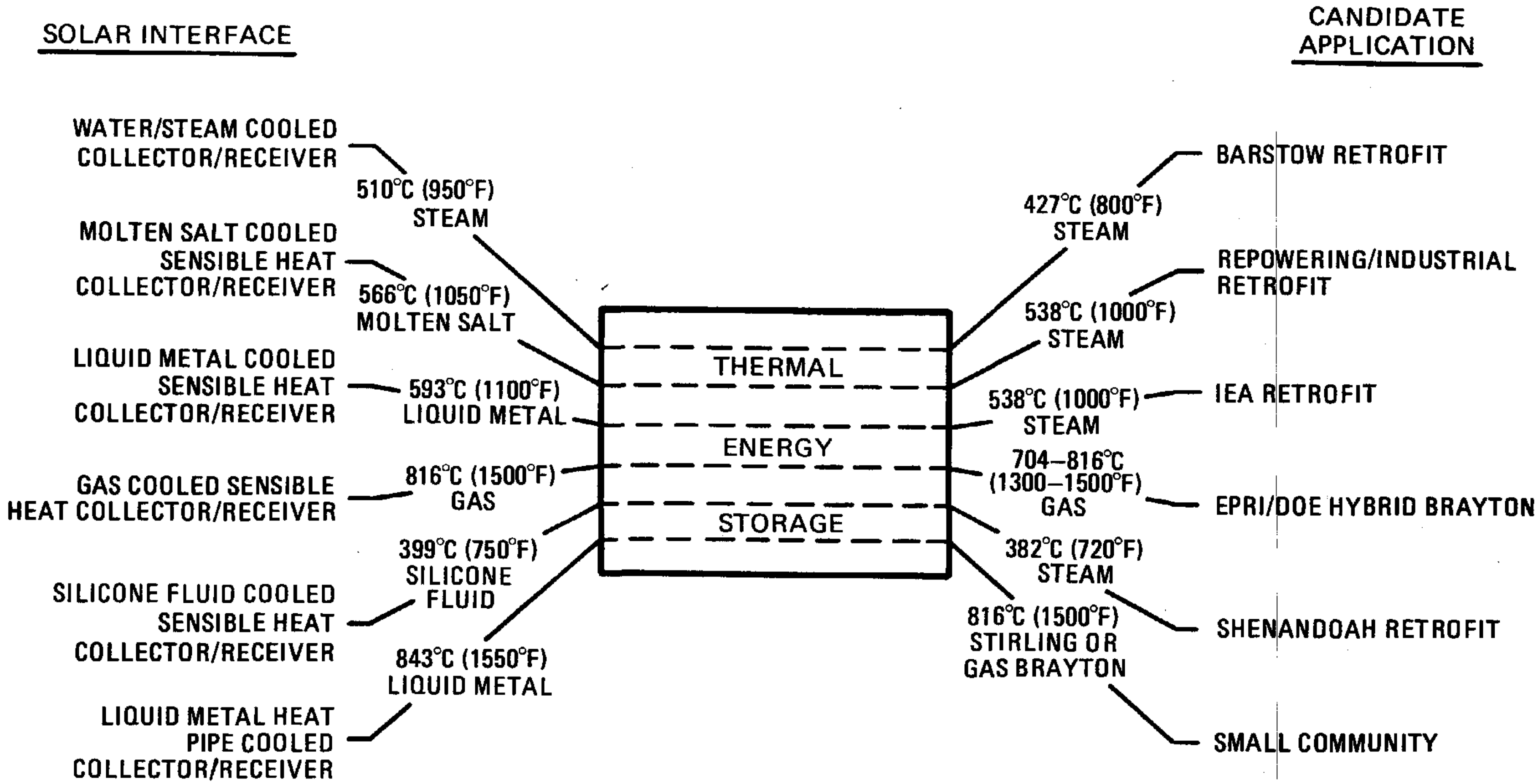


Figure 2 - Focused Elements

TABLE I

DESCRIPTION OF PROJECT APPLICATIONS

NAME	LOCATION	SIZE	STATUS
BARSTOW	BARSTOW, CA	10 MW_e	UNDER CONSTRUCTION
REPOWERING/ INDUSTRIAL RETROFIT	TBD	TBD	CONCEPTUAL DESIGNS BEING PERFORMED ON SEVEN REPOWERING AND SIX INDUSTRIAL APPLICATIONS. SEVERAL PROJECTS MAY BE SELECTED FOR DEMONSTRATION
IEA	ALMERIA, SPAIN	0.5 MW_e	UNDER CONSTRUCTION
EPRI/DOE HYBRID	TBD	TBD	CONCEPTUAL DESIGN TO BEGIN IN 1981
SHENANDOAH	SHENANDOAH, GA	0.4 MW_e ELECTRIC, 2.6 MW_t PEAK THERMAL	UNDER CONSTRUCTION
SMALL COMMUNITY	TBD	1 MW_e	SITE SELECTION UNDERWAY

II. Applications Program Goals

Cost and Performance Goal Summary

Representative cost and performance goals for each solar thermal system application have been developed for both first and second generation systems. A description of first and second generation thermal energy storage technologies for each application is given in Table II; the corresponding cost and performance goals are shown in Tables III and IV, respectively. These goals, which assume fully developed storage technologies incorporated in large commercial systems, represent the lowest achievable total capital cost consistent with system performance requirements. They were based on the results of studies of commercial solar and conventional power systems that incorporate thermal energy storage.

Cost Goals

When developing a cost goal for a storage subsystem, both power-related and capacity-related costs must be considered. The power component corresponds to the capability of the storage subsystem to accept and deliver thermal energy at a given rate and includes items such as manifolds, pumps, piping, and heat exchangers. The capacity component reflects the maximum amount of energy to be contained within storage at any time and includes containment and media expenses.

Power related costs (C_p) are a function of the special application. In some systems the same equipment is used for charging and discharging storage. Other systems may require separate heat exchangers for charging and discharging while still other systems may require no additional heat exchangers for integration of a storage subsystem. Only in detailed analyses of specific system applications can these power-related costs be determined.

The unit cost of a storage subsystem capable of containing h hours at the rated system load is:

$$C_t = (C_p + C_c \times h)/h$$

where C_t = Total storage subsystem cost ($/KWH),

C_p = Power related costs ($/KW),

C_c = Capacity related costs ($/KWH).

Performance Goals

There are two major considerations to the performance of a storage subsystem: the recoverable energy efficiency and the power cycle conversion efficiency when the system is operated from storage. High recoverable energy efficiency, that is, the energy out of storage divided by the energy in, is important in that it minimizes the required collector area. Furthermore, it

TABLE II

DESCRIPTION OF FIRST AND SECOND GENERATION THERMAL ENERGY STORAGE TECHNOLOGIES

CANDIDATE APPLICATION*	SOLAR INTERFACE	STORAGE TECHNOLOGY FIRST GENERATION	SECOND GENERATION
BARSTOW	WATER/STEAM COLLECTOR/RECEIVER	OIL/ROCK THERMOCLINE	SALT, TRICKLE OIL
REPOWERING	MOLTEN SALT COLLECTOR/RECEIVER	MOLTEN SALT WITH EXTERNAL INSULATION	MOLTEN SALT WITH INTERNAL INSULATION
IEA	LIQUID METAL COLLECTOR/RECEIVER	LIQUID METAL WITH EXTERNAL INSULATION	MOLTEN SALT OR LIQUID METAL WITH INTERNAL INSULATION, AIR/ROCK
EPRI/DOE HYBRID	GAS COLLECTOR/RECEIVER	REFRACTORY BRICK WITH WELDED STEEL TANK	REFRACTORY BRICK WITH PRESTRESSED CAST IRON VESSELS
SHENANDOAH	SILICONE FLUID COLLECTOR/RECEIVER	SILICONE/TACONITE THERMOCLINE	SALT, TRICKLE OIL
SMALL COMMUNITY	LIQUID METAL HEAT PIPE COLLECTOR/ RECEIVER	REFRACTORY WITH WELDED STEEL TANK-GROUND BASED	LATENT HEAT SALT-DISH MOUNTED

*Storage development for these representative applications is emphasizing second generation technology development. First generation technology development will be initiated during FY80 on additional applications, such as industrial retrofit process heat.

TABLE III

THERMAL ENERGY STORAGE CAPITAL COST GOAL SUMMARY (FY79 DOLLARS)

CANDIDATE APPLICATION*	SOLAR INTERFACE	REFERENCE PLANT SIZE (MWe)	REFERENCE STORAGE DURATION (HOURS)	POWER RELATED FIRST GENERATION ($/KW)	POWER RELATED SECOND GENERATION ($/KW)	CAPACITY RELATED FIRST GENERATION ($KWH)	CAPACITY RELATED SECOND GENERATION ($/KWH)	TOTAL FIRST GENERATION ($/KWH)	TOTAL SECOND GENERATION ($/KWH)
BARSTOW	WATER/STEAM COLLECTOR/RECEIVER	100	6	100	86	29	21	46	35
REPOWERING	MOLTEN SALT COLLECTOR/RECEIVER	300	11	10	10	27	13	28	14
IEA	LIQUID METAL COLLECTOR/RECEIVER	100	3	43	86	86	14	100	43
EPRI/DOE HYBRID	GAS COLLECTOR/RECEIVER	100	3	83	83	60	33	88	61
SHENANDOAH**	ORGANIC FLUID COLLECTOR/RECEIVER	4	14.5	46	46	48	22	51	25
SMALL COMMUNITY	LIQUID METAL HEAT PIPE COLLECTOR/ RECEIVER	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD

* Applications shown are all electrical power generating systems except for the cogeneration Shenandoah system. Cost goals will be established for process heat applications pending completion of conceptual design studies in FY80.

** Cost goals are based on $\$/KW_t$ or $\$/KWH_t$; cost goals for other applications are based on $\$/KW_e$ or $\$/KWH_e$

TABLE IV

THERMAL ENERGY STORAGE PERFORMANCE GOAL SUMMARY

CANDIDATE APPLICATION*	SOLAR INTERFACE	ROUND TRIP EFFICIENCY FIRST GENERATION (%)	ROUND TRIP EFFICIENCY SECOND GENERATION (%)
BARSTOW	WATER/STEAM COLLECTOR/RECEIVER	70	80
REPOWERING	MOLTEN SALT COLLECTOR/RECEIVER	98	98
IEA	LIQUID METAL COLLECTOR/RECEIVER	98	98
EPRI/DOE HYBRID	GAS COLLECTOR/RECEIVER	80	80
SHENANDOAH	ORGANIC FLUID COLLECTOR/RECEIVER	96	96
SMALL COMMUNITY	LIQUID METAL HEAT PIPE COLLECTOR/RECEIVER	TBD	TBD

*Applications shown are all electrical power generating systems except for the cogeneration Shenandoah system. Performance goals will be established for process heat applications pending completion of conceptual design studies in FY80.

is the primary criterion when the recovered energy is utilized for industrial process heat. Power conversion cycle efficiency will vary depending on the conditions of the working fluid input to the power conversion subsystem from storage. Ideally, the conditions of the working fluid coming from storage would be identical to the conditions of the working fluid input directly from the solar collection subsystem. In this case, no modifications in operation of the power conversion subsystem are necessary, nor is there any loss in the ability to generate rated load.

When the recoverable energy and power cycle conversion efficiencies of the storage subsystem are combined with other system efficiencies, the "round-trip" efficiency for operation from storage can be defined. A general goal for performance of a storage subsystem then is to maximize this efficiency, that is, maximize system performance when operating from storage. From a different viewpoint, the goal is to minimize differences in system operation when storage is used, within the constraint of minimal capital and operating costs.

The round-trip efficiency of a storage subsystem is defined as:

$$N_{r.t.} = \frac{E_{out}}{E_{in}} \times \frac{N_{TES}}{N_{solar}}$$

where E_{out} = Thermal energy out of storage

E_{in} = Thermal energy into storage

N_{TES} = Power conversion efficiency when operating from storage

N_{solar} = Power conversion efficiency when operating directly from solar

III. Approach

General

In order to initiate the required development activites for achieving cost and performance goals a comprehensive five-year plan has been prepared. In describing the plan the Task Breakdown Structure in Figure 1 will be used. A description of each major task element is provided here in order to provide a framework for discussion of the FY80 program.

The basic development flow, shown in Figure 3, consists of three phases:

1. Storage concept development--concept feasibility and lab experiments,
2. Storage subsystem development, and
3. System applications including new projects or retrofits.

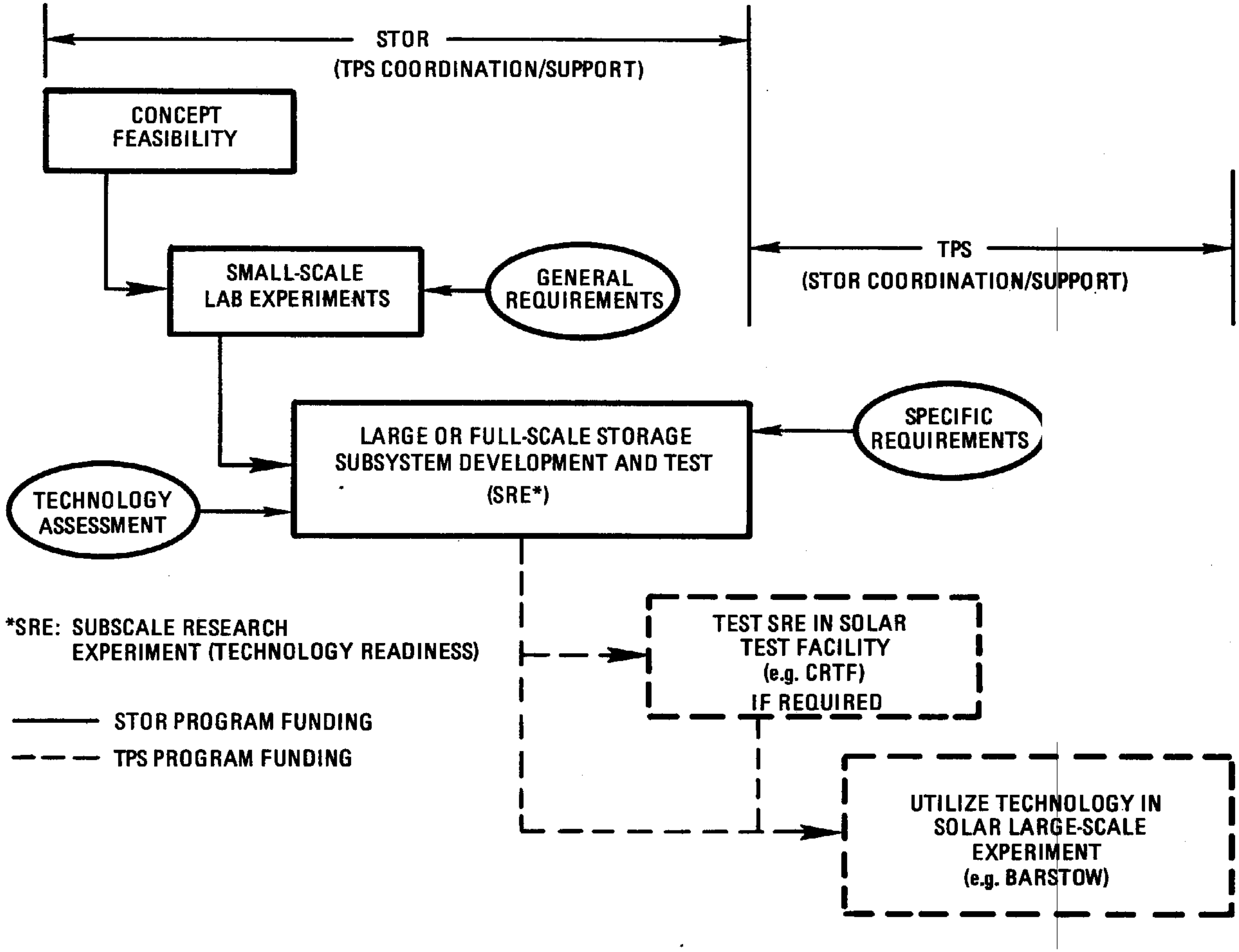


Figure 3. Detailed Approach

Concept development activities include development of storage concepts to the point of establishing the technical feasibility and assessing the concepts based on general solar thermal system requirements. Establishing technical feasibility involves both concept feasibility studies and small-scale laboratory experiments. Many of the feasibility studies have been completed, and a number of the experiments are under way. Assessments of the technically feasible concepts will be performed to reduce the number of the options based on appropriateness to the anticipated solar application.

The subsystem development phases culminates with technology readiness for the storage subsystem. Activities include subsystem definition, engineering development, and subscale research experiments (SRE's).*

The final step entails storage subsystem/solar system integration at an online or new solar thermal power plant or test facility. At the completion of this step, the storage subsystem will be a proven alternative available for retrofit to existing solar systems or for use in future solar systems.

The first two phases, which will advance a storage subsystem to technology readiness, are STOR-led activities. Program activities for the final step is primarily a TPS responsibility.

Five Year Plan

Task 2.0 Storage for Water/Steam Cooled Collector/Receiver--The goal for this element is to develop a second generation storage subsystem for a Barstow retrofit application. This development will also find application in other sectors such as repowering/industrial retrofit and cogeneration projects.

The first generation storage subsystem for the 10 MW_e Barstow pilot plant is a sensible heat oil/rock thermocline storage concept. A major constraint of this 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 reduces the plant thermal efficiency and electrical output when operating from storage. An additional concern is high fluid maintenance costs (replacement of fluid lost by thermal decomposition) dictated by the need to operate the storage media at or near its maximum operating temperature.

Subsystem development tests for the first generation Barstow storage technology are virtually complete. They have included long-term stability, compatibility, and fouling tests on various oil storage media candidates and a 4 MWH_t subscale research experiment (SRE). Work to be completed early in FY80 includes investigations of fluid maintenance (sidestream processor) techniques and a small effort to study the effect of temperature cycling on rock strength.

Second-generation storage development will emphasize the study of higher temperature storage media with low initial and replacement costs. The plan also provides for the study of storage techniques to reduce the required

*These are also often called subsystem research experiments. They refer to experiments of sufficient scale to insure operation of the full size subsystem.

quantities of components which may have desirable high-temperature properties but are costly. The storage development plan leading to a completed Barstow retrofit project by mid FY86 is shown in Figure 4. The key milestones are:

• TPS/STOR recommendations on candidate technologies	FEB 1981
• Complete SRE; technology readiness	NOV 1983
• Complete Barstow retrofit	MAY 1986

Task 3.0 Storage for Molten Salt Cooled Sensible Heat Collector/Receiver--This element will provide support for and advanced alternatives to the molten salt storage subsystems under development for a repowering/industrial retrofit application. Other potential applications include IEA and Barstow retrofit projects.

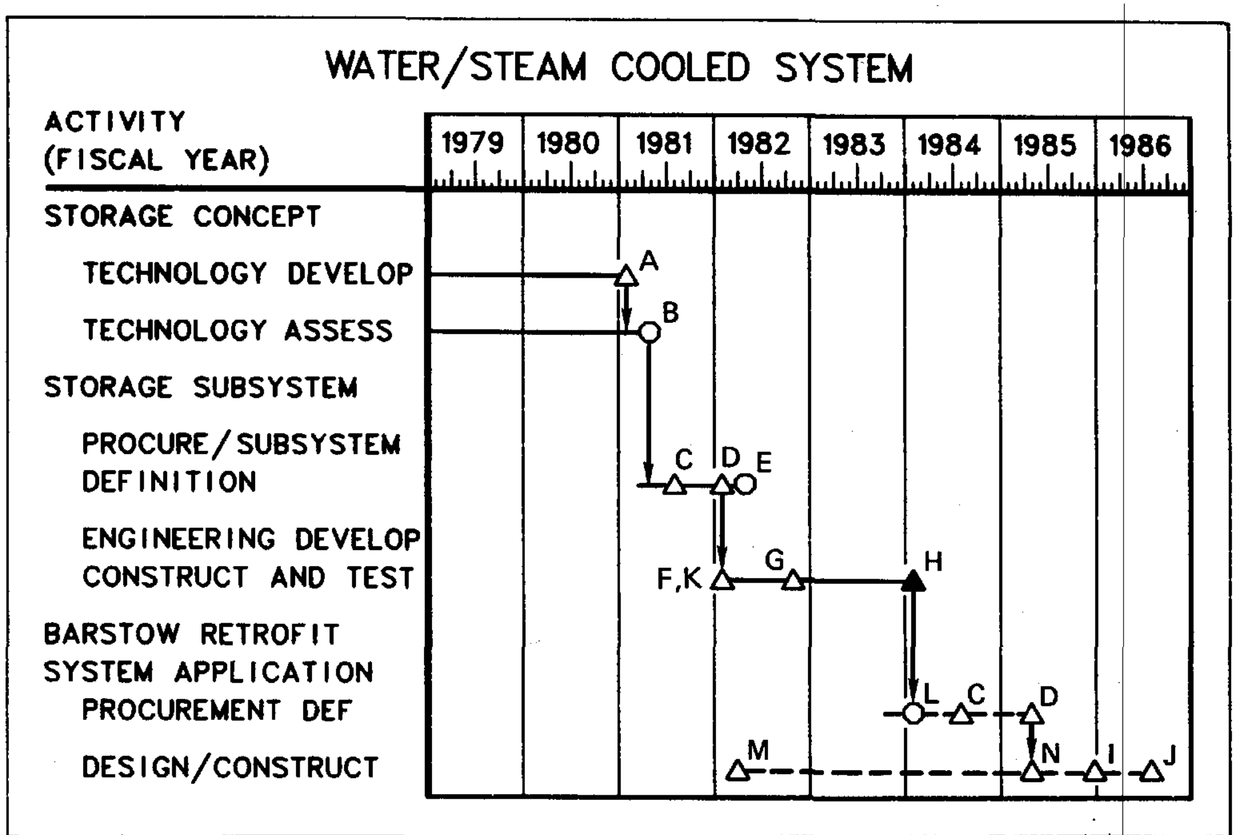
The first generation storage subsystem for an advanced central receiver system as studied by the TPS/Large Power Systems Branch used a molten nitrate salt ($NaNO_3$/KNO_3 mixture*) storage media with externally insulated hot and cold tanks. A number of technical issues have been raised in the development of the first generation systems. Containment materials lifetime issues are currently being addressed by the TPS advanced central receiver system development team; storage media lifetime/maintenance issues are being studied to a much lesser extent by TPS. Additional efforts directed at the resolution of the remaining technical issues will be performed within the framework of this element.

The high storage media operating temperature of this application [566°C (1050°F)] requires expensive containment materials. Second-generation storage development will therefore be directed toward low-cost containment techniques, in particular, internally insulated containment vessels. Compatibility tests of molten nitrate salt and insulation materials are already under way as part of the advanced central receiver development program. Additional studies of candidate materials will be performed, if required; pending identification of a suitable material an SRE will be designed, fabricated, and tested.

The storage development plan leading to a repowering/industrial retrofit application late in FY85 is shown in Figure 5. Identification of a technically feasible low cost containment technique by early FY80 is required if it is to be considered for this application; otherwise the first-generation storage subsystem technology will be used. Storage for an industrial process heat application may require additional development as previous work emphasized electrical power applications with steam Rankine conversion cycles that operate at about 540°C (1000°F). Key milestones are:

• TPS/STOR recommendations on candidate technologies	JAN 1980
• Complete SRE; technology readiness	SEP 1981
• Complete repowering/industrial retrofit	JUL 1985

*A 50/50 molar mixture is often referred to as "draw salt."



A – ESTABLISH FEASIBILITY
B – RECOMMEND CANDIDATE TECHNOLOGIES FOR DEVELOPMENT
C – ISSUE RFP
D – AWARD CONTRACT(S)
E – SELECT CONCEPT(S)
F – BEGIN ENGINEERING DEVELOPMENT
G – BEGIN CONSTRUCTION
H – TESTING COMPLETE
I – BEGIN INSTALLATION
J – OPERATIONAL
K – SELECT SRE SITE
L – DECISION TO PROCEED
M – BARSTOW OPERATIONAL
N – BEGIN DETAILED DESIGN/CONSTRUCTION

△ PROGRAM CONTROLLED
○ TPS/ST OR DECISION
▲ TECHNOLOGY READINESS
——— STORAGE SUBSYSTEM DEVELOPMENT
– – – SOLAR THERMAL DEVELOPMENT
——► TRANSFER RESULTS/TECHNOLOGY

Figure 4. Storage Development Program Milestones (Barstow Retrofit Application)

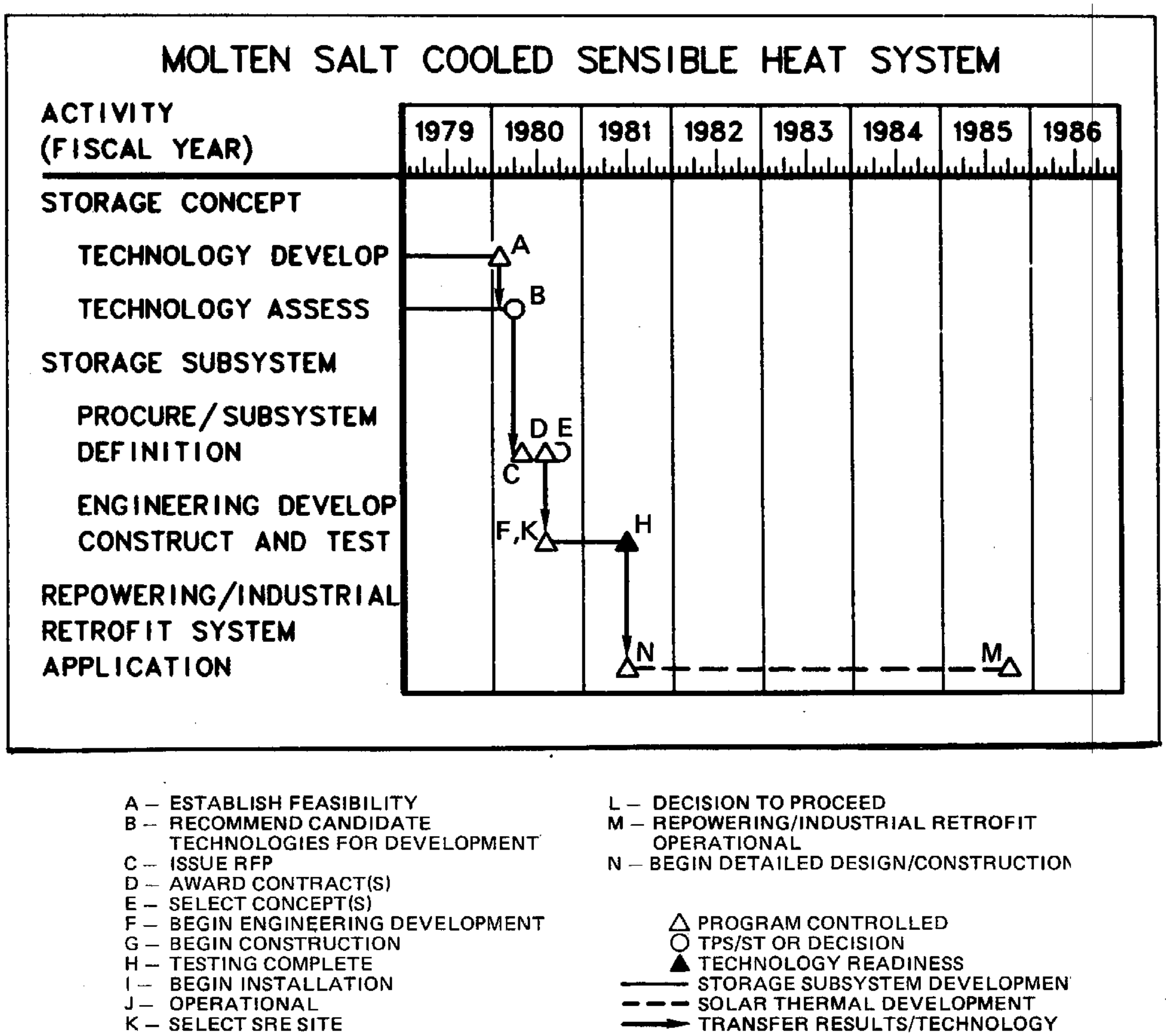


Figure 5. Storage Development Program Milestones (Repowering/Industrial Retrofit Application)

Task 4.0 Storage for Liquid Metal Cooled Sensible Heat Collector/Receiver--The goal of this element is to develop a second-generation storage subsystem for an IEA retrofit application. Another potential application is the repowering/industrial retrofit project. The first-generation storage subsystem for advanced central receiver systems as studied by TPS/Large Power System Branch uses liquid sodium as the storage media with externally insulated hot and cold tanks. Subsystem development for the first generation system has emphasized electrical power applications with steam Rankine conversion cycles that operate at about 540°C (1000°F). This development is complete with no additional work required.

The first generation storage subsystem, because of the low density and heat capacity and high media cost of sodium, has a high capacity-related cost. As was the case with the molten salt system, a high operating temperature [593°C (1100°F)] requires expensive containment materials to minimize thermal fatigue due to temperature cycling. Development of second-generation systems will therefore emphasize low-cost containment techniques, such as internal insulation. In addition,this study will include the technical and economic feasibility of interfacing storage subsystems of lower capacity cost, such as molten salt or air/rock, with a liquid metal collector/receiver via an intermediate heat exchanger.

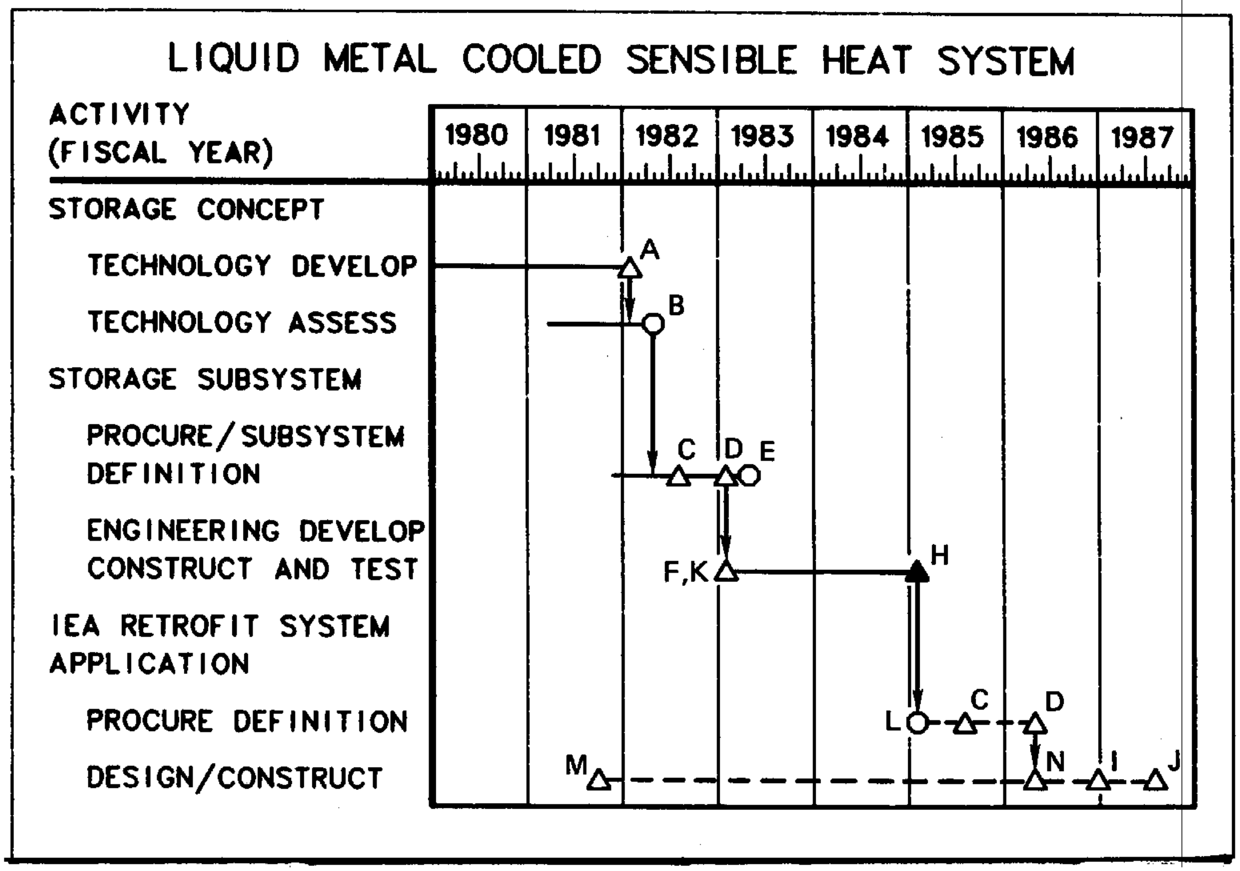
The storage development plan leading to an IEA retrofit application by mid FY87* is shown in Figure 6. Second-generation storage technology may also be available for the first repowering/industrial retrofit application if a large scale SRE is not required. Key milestones are:

- TPS/STOR recommendations on candidate technologies FEB 1982
- Complete SRE, technology readiness NOV 1985
- Complete IEA retrofit MAY 1987

Task 5.0 Storage for Gas Cooled Sensible Heat Collector/Receiver--This element addresses the development of a storage subsystem for a EPRI/DOE hybrid Brayton system retrofit. Other applications include the TPS/Large Power Systems Branch repowering/industrial retrofit project and TPS/Small Power Systems Branch small community system project.

The first-generation EPRI/DOE system concept uses a fossil energy source but has no energy storage. The primary goal of this element is to develop an energy storage subsystem capable of operating at temperatures up to 816°C (1500°F) and compatible with the existing subsystems. A conceptual design of a refractory brick thermocline storage subsystem has been completed as part of the Large Power Systems Branch advanced central receiver program. This concept is a candidate for the retrofit project but may require experimental verification. The concept uses welded steel containment vessels, which due to the high temperature [816°C (1500°F)] and high pressure [3.4 MPa (500 psi)] operation, are very costly. Development will emphasize verification of

*It should be noted that the present IEA agreement and funding extends to approximately FY85. Additional extensions provided for in the working agreement will be needed.



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——— STORAGE SUBSYSTEM DEVELOPMENT
– – – SOLAR THERMAL DEVELOPMENT
——► TRANSFER RESULTS/TECHNOLOGY

Figure 6. Storage Development Program Milestones (IEA Retrofit Application)

thermocline performance, low cost storage media, e.g., rocks, and low cost containment techniques, in particular internally insulated, prestressed cast iron containment vessels.

A small scale storage system for a dish mounted collector is also under development. A conceptual design of a refractory brick thermocline system has been completed as part of the Small Power Systems branch small community systems program. Fabrication of a test module is scheduled for completion by the end of FY79 with testing completed by mid FY80.

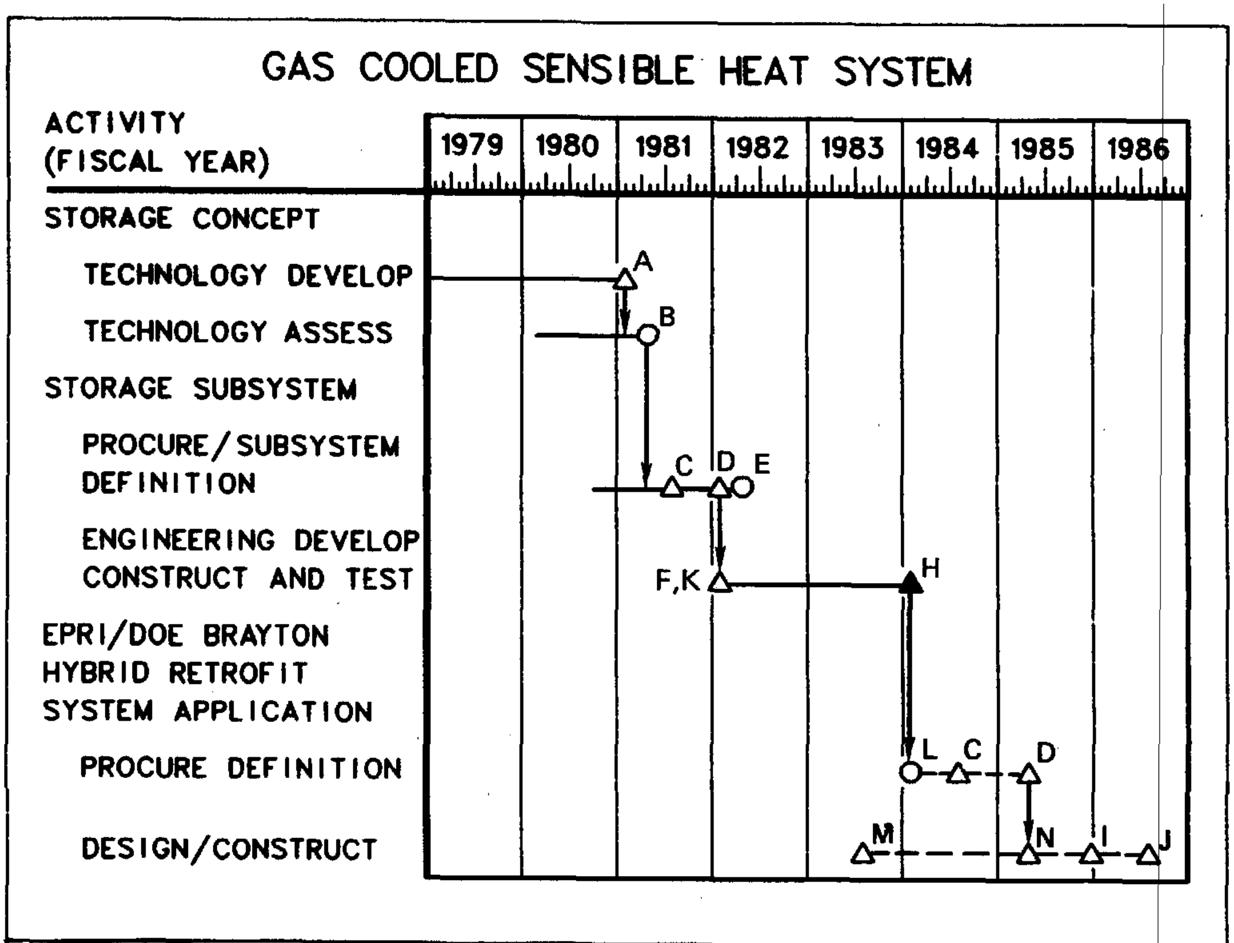
The storage development plan leading to an EPRI/DOE hybrid Brayton retrofit by the middle of FY86 is shown in Figure 7. Key milestones are:

- TPS/STOR recommendations on candidate technologies FEB 1981
- Complete SRE; technology readiness NOV 1883
- Complete EPRI/DOE retrofit MAY 1986

Task 6.0 Storage for Organic or Silicone Fluid Cooled Sensible Heat Collector/Receiver--This element will provide support for and advanced alternatives to storage subsystems under development for midtemperature solar thermal applications, such as irrigation, cogeneration, and repowering/industrial retrofit. In addition, the dual media (oil/rock) thermocline system development for Barstow, which was described under Task 2.0, is applicable to this element. First generation organic fluid thermocline systems have been designed and built for irrigation applications (Willard, NM and Coolidge, AR). Operational testing indicates the need for further development before an acceptably efficient system can be considered ready for commercial deployment. Analyses, laboratory and field scale testing will therefore include thermocline stability in large tanks, fluid inlet and outlet diffuser designs, feasibility of a driven piston separating hot and cold regions, storage subsystem control, and the effect of system off-design performance on the thermocline storage subsystem and its subsequent effect on the performance of other components and subsystems with which it interfaces. This activity will be completed by the end of FY81, at which time concept characterization of the dual media (rock/oil) thermocline systems will be initiated. Concept characterizations similar to those for the oil thermocline system will be performed with completion scheduled for mid FY83. Storage subsystem application handbooks for use by system designers as implementation tools for each concept judged feasible is a principal output of each activity. This work will be performed at the Sandia Midtemperature Solar Systems Test Facility (MSSTF), Albuquerque, New Mexico.

The first generation storage subsystem for the Shenandoah cogeneration project employs a silicone oil/taconite* thermocline storage concept with operating temperatures up to 399°C (750°F). Because the silicones are expensive fluids, a trickle storage concept is under consideration. This is a modification of the dual-media concept in which, by modularizing small rock or taconite and oil units within a single container and following a sequential

*Taconite is a pelletized iron ore which is almost entirely Fe_2O_3. The Fe_3O_4 in the ore is removed magnetically, pelletized, and then roasted in air to produce Fe_2O_3.



A – ESTABLISH FEASIBILITY
B – RECOMMEND CANDIDATE TECHNOLOGIES FOR DEVELOPMENT
C – ISSUE RFP
D – AWARD CONTRACT(S)
E – SELECT CONCEPT(S)
F – BEGIN ENGINEERING DEVELOPMENT
G – BEGIN CONSTRUCTION
H – TESTING COMPLETE
I – BEGIN INSTALLATION
J – OPERATIONAL
K – SELECT SRE SITE
L – DECISION TO PROCEED
M – EPRI/DOE BRAYTON OPERATIONAL
N – BEGIN DETAILED DESIGN/CONSTRUCTION

△ PROGRAM CONTROLLED
○ TPS/ST OR DECISION
▲ TECHNOLOGY READINESS
—— STORAGE SUBSYSTEM DEVELOPMENT
– – – SOLAR THERMAL DEVELOPMENT
——→ TRANSFER RESULTS/TECHNOLOGY

Figure 7. Storage Development Program Milestone (EPRI/DOE Brayton Hybrid Retrofit Application)

mode of operation with these modules during charge and discharge cycles, the quantity and therefore the cost of the required silicone fluid is a small fraction of that required in a nonmodified configuration.

Development tests for these applications have emphasized stability and compatibility of heat transfer fluids and solid storage media, such as taconite or rocks. A laboratory test of the trickle storage concept has been performed. Testing to assess the effects of operating the storage media at elevated temperatures for long periods of time are ongoing and will continue into the first quarter of FY80. Consideration is being given to providing Shenandoah with a storage subsystem capable of operating in either the trickle or dual-media mode.

The aim of second-generation storage development will be to provide an improved storage subsystem for a Shenandoah retrofit application. Emphasis will be placed on an evaluation of alternative, less costly, organic fluid candidates and alternate storage concepts, in particular, latent heat storage.

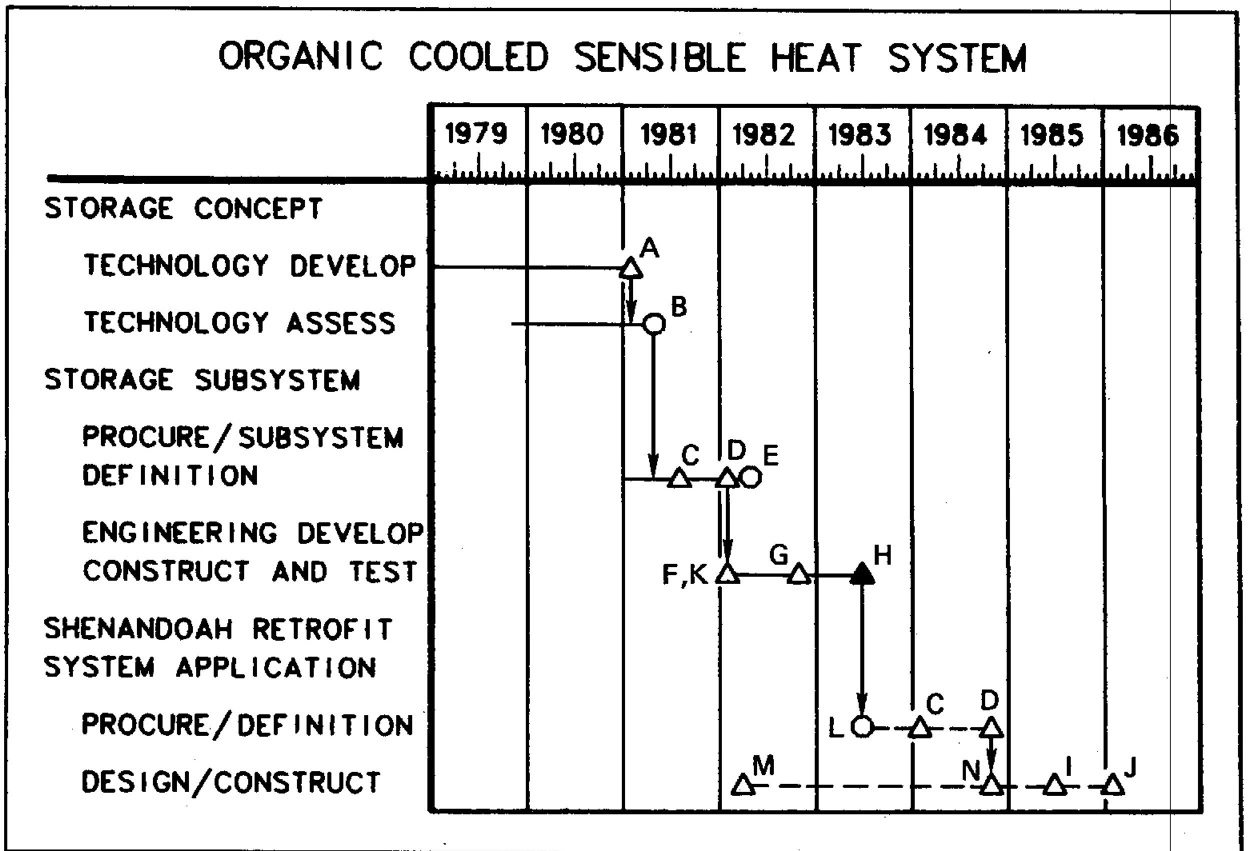
The storage development plan leading to a completed Shenandoah retrofit by early FY86 is shown in Figure 8. Key milestones are:

- TPS/STOR recommendations on candidate technologies FEB 1981
- Complete SRE; technology readiness APR 1983
- Complete Shenandoah retrofit NOV 1985

Task 7.0 Dish Mounted Latent Heat Buffer Storage--This element addresses the development of a storage subsystem for a small community system using a dish-mounted power conversion cycle. A storage subsystem under consideration for the small community system project uses a storage module mounted directly on a collector dish or in the counterweight position. A liquid metal heat pipe receiver transfers thermal energy to the storage module. This concept requires that the modules be small, lightweight, and configured to cast minimum shadow. Storage durations are necessarily limited to a few hours even with a high density latent heat technology, such as NaF-MgF_2.

Activities in the development of the concept will focus on an evaluation of latent heat storage media. Media stability and containment materials compatibility will be studied in the temperature range, 649 to 816°C (1200 to 1500°F) to match present Stirling and Brayton system requirements. The storage development plan leading to a small community system is shown in Figure 9. Key milestones are:

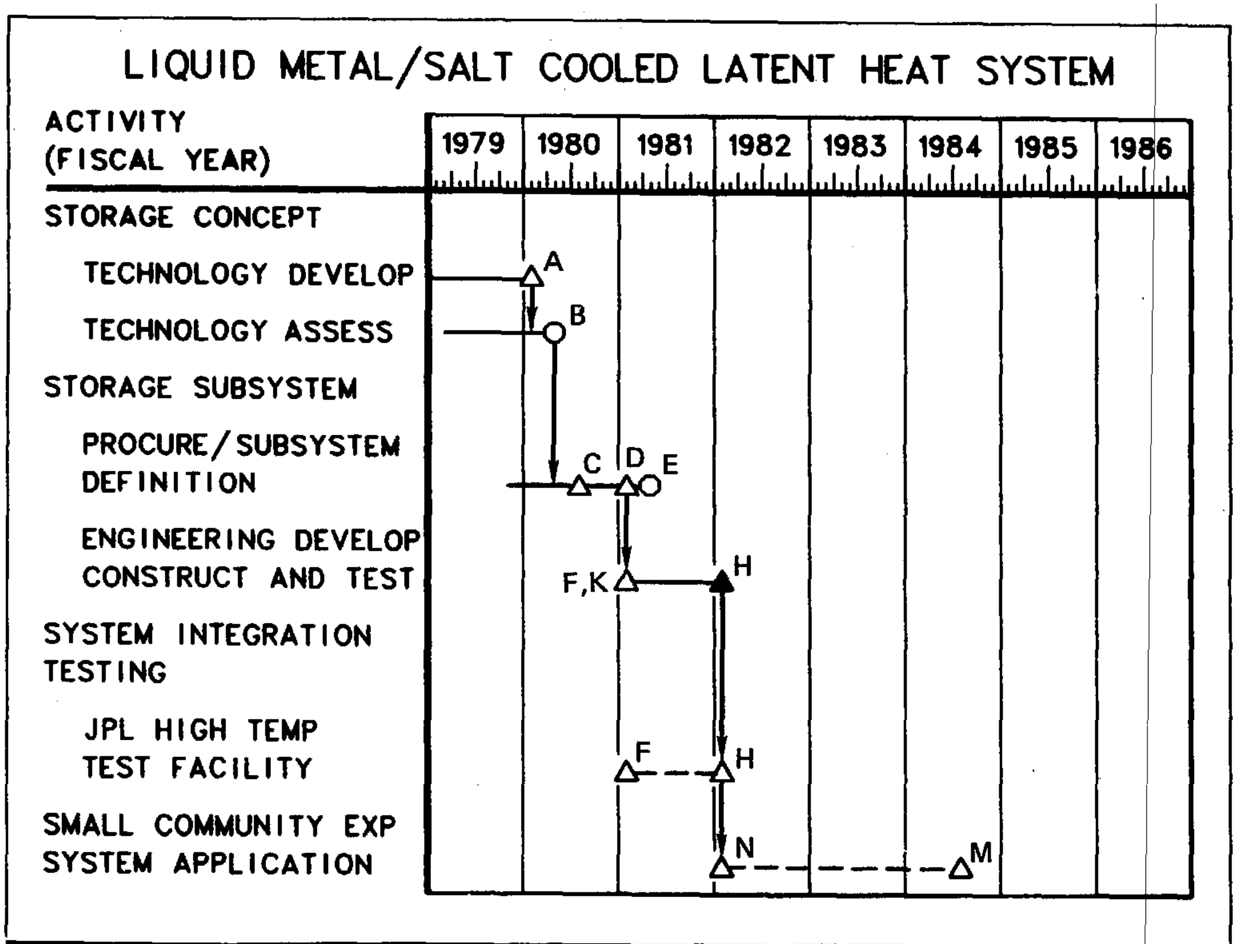
- TPS/STOR recommendations on candidate technologies FEB 1980
- Complete SRE; technology readiness NOV 1981
- Complete small community system MAY 1984



A – ESTABLISH FEASIBILITY
B – RECOMMEND CANDIDATE TECHNOLOGIES FOR DEVELOPMENT
C – ISSUE RFP
D – AWARD CONTRACT(S)
E – SELECT CONCEPT(S)
F – BEGIN ENGINEERING DEVELOPMENT
G – BEGIN CONSTRUCTION
H – TESTING COMPLETE
I – BEGIN INSTALLATION
J – OPERATIONAL
K – SELECT SRE SITE
L – DECISION TO PROCEED
M – SHENANDOAH OPERATIONAL
N – BEGIN DETAILED DESIGN/CONSTRUCTION

△ PROGRAM CONTROLLED
○ TPS/ST OR DECISION
▲ TECHNOLOGY READINESS
——— STORAGE SUBSYSTEM DEVELOPMENT
– – – SOLAR THERMAL DEVELOPMENT
———► TRANSFER RESULTS/TECHNOLOGY

Figure 8. Storage Development Program Milestones (Shenandoah Retrofit Application)



A – ESTABLISH FEASIBILITY
B – RECOMMEND CANDIDATE TECHNOLOGIES FOR DEVELOPMENT
C – ISSUE RFP
D – AWARD CONTRACT(S)
E – SELECT CONCEPT(S)
F – BEGIN ENGINEERING DEVELOPMENT
G – BEGIN CONSTRUCTION
H – TESTING COMPLETE
I – BEGIN INSTALLATION
J – OPERATIONAL
K – SELECT SRE SITE
L – DECISION TO PROCEED
M – SMALL COMMUNITY EXP'T OPERATIONAL
N – BEGIN DETAILED DESIGN/CONSTRUCTION

△ PROGRAM CONTROLLED
○ TPS/ST OR DECISION
▲ TECHNOLOGY READINESS
——— STORAGE SUBSYSTEM DEVELOPMENT
– – – SOLAR THERMAL DEVELOPMENT
——► TRANSFER RESULTS/TECHNOLOGY

Figure 9. Storage Development Program Milestones (Small Community Expt Application)

FY80 Program

Task 2.0 Storage for Water/Steam Cooled Collector/Receiver--The objective of this task is to develop second generation storage subsystems for Barstow retrofit and repowering/industrial retrofit applications. This development will also find application in other sectors such as cogeneration projects.

A preliminary study conducted by Martin-Marietta at the end of the Barstow pilot plant conceptual design identified molten salt sensible heat storage as a storage subsystem candidate for a water/steam central receiver. During FY80 additional studies will be performed to assess this concept and others for Barstow retrofit and repowering applications.

Reflecting an increasing interest in industrial retrofit (process heat) the task also provides for storage concept development including storage media screening studies, engineering analyses, conceptual design, and cost estimates for a latent heat storage concept for mid-temperature applications.

This task will be closely coordinated with Task 6.2 through issuance of a single RFP (two categories) in FY80 for latent heat storage concept development for process heat applications and sensible and/or latent heat storage concept development for Barstow retrofit and repowering applications. Subsystem research experiment design, fabrication, testing, and evaluation will follow in later years.

Task 3.0 Storage for Molten Salt Cooled Sensible Heat Collector/Receiver--This task will provide for the development of a second generation storage subsytem for a repowering/industrial retrofit application. Other potential applicaitons include IEA and Barstow retrofit projects. Material studies and analyses to resolve technical issues for first generation molten nitrate salt storage systems will also be performed.

This task is composed for four subtasks:

3.1 Molten Salt Chemistry--The objectives of this subtask are to study changes in molten nitrate salt composition with time of operation, investigate techniques for preventing or reversing changes, and provide thermophysical property data. Molten nitrate salt material studies to be conducted in FY80 include salt decomposition,* phase equilibrium, atmospheric interactions, and thermophysical property measurements of surface tension,* viscosity,* density* and thermal conductivity.

3.2 Molten Salt Corrosion--This subtask will investigate the general corrosion behavior of candidate containment alloys in a molten nitrate salt environment. Molten nitrate salt material studies to be conducted in FY80 include alloy immersion tests,* closed and breathing* thermal convection loops, and electrochemical analyses to study the effects of temperature, oxygen, and impurities on the salt melt* and the formation of a passivating film on I800. Studies of alternative alloy-salt combinations will also be initiated in FY80.

*Indicates in-house SNLL studies. Others will be studied via outside contracts.

3.3 Molten Draw Salt Storage Subsystem Research Experiment (SRE) and Component Development--This subtask will demonstrate a molten nitrate salt storage subsystem using low cost containment techniques. A subscale research experiment scaleable to a full size system will be designed, fabricated, and tested.

3.4 Thermocline Heat Transfer Analysis--This subtask will provide for thermocline analyses and laboratory testing to predict thermocline performance as a function of time under various operational modes. The effects of side wall heat capacity, conduction, and convection will be studied. Generic studies to be carried out during the early part of this study will be applicable to both organic (see Task 6.1) and molten salt storage systems.

Task 4.0 Storage for Liquid Metal Cooled Sensible Heat Collector/Receiver--The objective of this task is to develop a second generation storage subsystem for an IEA retrofit application. Another potential application is the repowering/industrial retrofit project. The task provides for laboratory experiments, engineering analyses, conceptual design and cost of low-cost liquid sodium containment techniques and liquid sodium to molten salt heat exchangers.

Development of a first-generation liquid sodium storage subsystem is complete with no additional work required. No work is planned on second-generation storage development during FY80 unless a change in program priorities occurs. It should be noted that low cost containment techniques to be demonstrated under Task 3.3 may also be applicable to liquid metal storage.

Task 5.0 Storage for Gas Cooled Sensible Heat Collector/Receiver--This task addresses the development of a storage subsystem for a EPRI/DOE hybrid Brayton retrofit project. Other applications include the small community system and repowering/ industrial retrofit projects.

Storage concept development for a refractory brick thermocline storage system has been completed as part of the TPS advanced central receiver program. This concept, which is a candidate for the retrofit project, may require experimental verification. Sensible heat storage subsystem development for an EPRI/DOE retrofit will not be undertaken in FY80, however, unless a change in program priorities occurs.

Sensible heat storage subsystem development for a small community system is underway. A ground based storage test module for a gas cooled dish mounted collector has been designed and fabricated with testing to be completed in FY80. Latent heat storage concept development will be initiated in FY80 and coordinated with work under Task 7.

Task 6.0 Storage for Organic or Silicone Fluid Cooled Sensible Heat Collector/Receiver--The objective of this task is to provide support for and advanced alternatives to storage subsystems under development for midtemperature solar thermal applications, such as irrigation, cogeneration, and repowering/industrial retrofit. The task includes analyses and testing of organic fluid single and dual media storage systems leading to the preparation of a design handbook. The task also provides for the development of a second generation latent heat storage subsystem for a Shenandoah midtemperature solar thermal application.

This task is composed of two subtasks:.

6.1 Organic Fluid Single and Dual Media Storage--The objective of this subtask is to perform testing and analyses to resolve technical issues for oil multitank and single and dual media thermocline systems. Studies include thermocline stability, fluid diffuser design, feasibility of a moving piston for single media storage, storage subsystem control, and system off-design performance. A design handbook will be prepared and issued. Studies to be performed in FY80 include control strategies for a multitank storage subsystem, thermocline performance of single media systems for buffer or diurnal operation, feasibility of a moving piston, and design and fabrication of a dual media system for installation and testing during FY81. These tests will be performed at the Sandia Mid-Temperature Solar System Test Facility (MSSTF), Albuquerque, New Mexico.

6.2 Latent Heat Storage--The objective of this subtask is to develop a latent heat storage subsystem for midtemperature solar applications. Studies include storage media screening, engineering analyses, conceptual design, and cost estimates. This subtask will be closely coordinated with Task 2 through issuance of a single RFP in FY80 for storage concept development. Subsystem research experiment design, fabrication, and testing will follow in later years.

7.0 Dish Mounted Latent Heat Buffer Storage--The objective of this task is the development of a dish mounted latent heat storage subsystem for three small community system applications. Power conversion cycles under consideration include Rankine, Brayton, and Stirling. The task provides for storage requirements definition, conceptual design, media stability and compatibility tests, thermal performance analyses, cost estimates, and a SRE. During FY80 storage requirements definition, concept development and SRE design studies will be initiated for each of the above power conversion cycles.

IV. Summary

This section summarizes activities for the current reporting period, the first half FY80. Achievements toward meeting both program and project goals are presented. A summary of accomplishments for the major program elements is also described.

Achievement of Program Goals

The following program milestones were reached during this reporting period:

1. Concept development of internally insulated thermal storage containment completed.

2. Concept development of organic fluid maintenance unit completed.

3. Concept development of ground-based refractory thermal storage for dish collectors completed.

4. TESSTA Multiyear Program Plan prepared and approved.

Achievement of Project Goals

Table V summarizes the status of the projects which were active during this reporting period. More detailed discussions and an assessment of results to date are given in the Appendix.

Summary of Accomplishments

The following list summarizes the major accomplishments for this reporting period.

Task 2.0 Storage for Water/Steam Cooled Collector/Receiver--A RFP for storage concept development for second generation storage for saturated steam and superheated steam receivers was prepared and issued. Contracts will be awarded during the third quarter of FY80.

Storage concept development for an organic fluid maintenance unit was completed. Hydrocarbon-based oils at or near 316°C (600°F) are being used in solar thermal power plant development, such as the 10 MW_e Barstow pilot plant. An experimental and analytical research program has been conducted by Martin-Marietta and SNLL to develop an understanding of Exxon's Caloria HT-43 oil thermal decomposition process, predict fluid replenishment requirements, and develop methods to reduce its degradation rate.

Task 3.0 Storage for Molten Salt Cooled Sensible Heat Collector/Receiver--Concept development of internally insulated thermal storage containment was completed. The purpose of this program which was conducted by Martin Marietta was 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 was divided into six tasks--testing of internal insulation materials in molten salt; preliminary design of storage tanks, including insulation and liner installation; thermal analysis of internally insulated thermocline tanks; optimization of the storage configuration; definition of a subscale research experiment to demonstrate the system, and a salt safety study.

Molten nitrate salt storage subsystem development was initiated. RFP's were prepared and issued for molten nitrate salt chemistry studies and the design, construction, testing, and evaluation of a molten salt subscale research experiment. Salt material studies were started at Oak Ridge National Laboratory to establish the long-term corrosion behavior of molten nitrate salts at elevated temperatures. Salt material studies are also underway at SNLL to complement the planned and ongoing contracted activities.

Table V
FY 80 PROJECT SUMMARY AND STATUS

Program Element/ Subelement	Project	Contractor	Contractor Principal Investigator	Contract Period	Sandia or JPL Technical Manager	Status
1. Storage for Water/Steam Cooled Collector/Receiver						
1.1 Advanced Solar Thermal Storage Concept Development	Same Title	TBD	TBD	July 1980-- December 1980	S. Faas 415-422-2287 FTS-532-2287	RFP issued
2. Storage for Molten Salt Cooled Sensible Heat Collector/Receiver						
2.1 Molten Salt Chemistry	2.1.1 Molten Nitrate Salt Interaction with CO_2 and H_2O	TBD	TBD	June 1980-- June 1981	R. Carling 415-422-2206 FTS-532-2206	RFP issued
	2.1.2 Molten Nitrate Salt Stability	Sandia	C. Kramer 415-422-2907 FTS-532-2907	October 1979-- September 1980	R. Carling	In progress
2.2 Molten Salt Thermophysical Properties	2.2.1 Molten Nitrate Salt Thermal Conductivity	TBD	TBD	June 1980-- June 1982	R. Carling	RFP issued
	2.2.2 Molten Nitrate Salt Density, Viscosity and Surface Tension	Sandia	D. Nissen 415-422-2767 FTS-532-2767	October 1979-- September 1980	R. Carling	In progress
	2.2.3 Molten Nitrate Salt Heat Capacity	Sandia	R. Carling	October 1979-- September 1980	R. Carling	In progress
2.3 Molten Salt Corrosion	2.3.1 Molten Nitrate Salt Breathing Thermal Convection Loops	Sandia	R. Bradshaw 415-422-3229 FTS-532-3229	October 1979-- September 1980	R. Carling	In progress
	2.3.2 Molten Nitrate Salt Closed Thermal Convection Loops	Oak Ridge National Lab	J. H. DeVan 615-483-4451 FTS-624-4451	January 1980-- January 1981	R. Carling	In progress
	2.3.3 Molten Nitrate Salt Electrochemical Corrosion Studies	TBD	TBD	May 1980-- May 1981	R. Carling	Contract in negotiation

Table V con't.
FY 80 PROJECT SUMMARY AND STATUS

Program Element/ Subelement	Project	Contractor	Contractor Principal Investigator	Contract Period	Sandia or JPL Technical Manager	Status
	2.3.4 Electro-chemistry in Molten Nitrate Salts	Sandia	D. Nissen	October 1979--September 1980	R. Carling	In progress
2.4 Molten Nitrate Salt Subsystem Research Experiment and Component Development	2.4.1 Internally Insulated Thermal Storage Concept Development	Martin Marietta	O. Scott 303-973-5750 FTS-329-5750	March 1979--December 1979	W. Winters, Jr. 415-422-2367 FTS-532-2367	Complete
	2.4.2 Molten Nitrate Salt Subsystem Research Experiment	TBD	TBD	July 1980--December 1981	S. Faas	RFP issued
2.5 Experimental and Theoretical Study of Thermocline Degradation	Same Title	Univ. of California, Berkeley	J. Humphrey 415-642-6460	October 1979--September 1980	W. Winters, Jr.	In progress
3. <u>Storage for Liquid Metal Cooled Sensible Heat Collector/Receiver</u>						
3.1 Air/Rock Thermal Cycling Testing	Same Title	Sandia	V. Burolla 415-422-3002 FTS-532-3002	October 1979--September 1980	S. Faas	In progress
4. <u>Storage for Gas Cooled Sensible Heat Collector/Receiver</u>						
4.1 Checker Stove Power Module Design, Fabrication, and Testing	Same Title	Sanders Associates, Inc.	A. Poirier	April 1979--February 1980	E. Hanseth 213-577-9493 FTS-792-9493	Final report in preparation
5. <u>Storage for Organic or Silicone Fluid Cooled Sensible Heat Collector/Receiver</u>						
5.1 Advanced Solar Thermal Storage Concept Development	Same Title	TBD	TBD	July 1980--December 1980	S. Faas	RFP issued
5.2 Organic Fluid Storage Thermocline Testing at the MSSTF	Same Title	Sandia	R. Harrigan 505-264-3004 FTS-844-3004	October 1979--September 1980	R. Harrigar	In progress
5.3 Organic Fluid Storage Multitank Testing at the MSSTF	Same Title	Sandia	R. Harrigan	October 1979--September 1980	R. Harrigar	In progress

Table V con't.
FY 80 PROJECT SUMMARY AND STATUS

Program Element/ Subelement	Project	Contractor	Contractor Principal Investigator	Contract Period	Sandia or JPL Technical Manager	Status
5.4 Storage Fluid Maintenance Study Using Caloria HT-43 Hydrocarbon Oil	Same Title	Martin Marietta	D. Beshore 303-973-4339 FTS-329-4339	December 1978-- November 1979	W. Winters, Jr.	Complete
5.5 Thermal Storage Fluid Stability and Compatibility Tests	Same Title	Sandia	V. Burolla	October 1979-- September 1980	V. Burolla	In progress
6. Dish-Mounted Latent Heat Buffer Storage						
6.1 Storage Requirements Definition and SRE Design for Rankine, Brayton, and Stirling Power Conversion Cycles	Same Title	TBD	TBD	Rankine: May 1980-- January 1981 Brayton: July 1980-- March 1981 Stirling: April 1980-- December 1980	Y. Won 213-577-9233 FTS-792-9233	Contracts for Rankine and Stirling studies in negotiation
6.2 Latent Heat Storage Media Chemistry and Corrosion Studies	Same Title	TBD	TBD	July 1980-- March 1981	Y. Won	Contract in negotiation
6.3 Latent Heat Storage Solidification Control	Same Title	TBD	TBD	August 1980-- April 1981	Y. Won	RFP prepared
6.4 Advanced Concepts	Same Title	TBD	TBD	August 1980-- April 1981	D. Young 213-577-9313 FTS-792-9313	RFP prepared
6.5 Latent Heat Storage In-house Studies (JPL)	Same Title	Jet Propulsion Laboratory	R. Manvi 213-577-9349 FTS-792-9349	January 1980-- January 1981	R. Manvi	In progress
6.6 Heat Pipe Receiver Module Design, Fabrication, and Testing	Same Title	General Electric	W. Zimmerman 513-243-2000	April 1978-- January 1980	P. Poon 213-577-9426 FTS-792-9426	Final report in preparation

A contract was awarded to the University of California, Berkeley for analytical and experimental thermocline heat transfer studies.

Task 4.0 Storage for Liquid Metal Cooled Sensible Heat Collector/Receiver--Energy Systems Group (ESG) of Rockwell International performed a conceptual design of an air/rock thermocline storage system as part of the TPS Advanced Central Receiver Program. This system has potential for low cost but requires experimental verification. Prior to the consideration of any contracted large-scale development effort SNLL is performing laboratory tests to study the effect of thermal cycling on rock strength. The preliminary data show little evidence of rock fracture when thermally cycled (approximately 600 cycles) from 316°C (600°F) to 593°C (1100°F) while under a mechanical load. Additional tests are planned to allow a greater number of samples to be simultaneously tested.

Task 5.0 Storage for Gas Cooled Sensible Heat Collector/Receiver--Concept development of a ground-based checker stove thermal storage system for a dish collector was completed. A small scale storage module was designed, fabricated, and tested by Sanders.

Task 6.0 Storage for Organic or Silicone Fluid Cooled Sensible Heat Collector/Receiver--Fabrication and installation of the organic fluid single media thermocline tank was completed at the Midtemperature Solar Systems Test Facility (MSSTF).

Second generation storage development activities were initiated for mid-temperature applications. The RFP for storage concept development, which was described under Task 2.0, provides for an assessment of latent heat storage for organic or silicone fluid cooled collector/receivers.

Task 7.0 Dish Mounted Latent Heat Buffer Storage--Concept development of a dish mounted latent heat buffer storage system was completed. A thermal storage modular heat pipe experiment using a sodium heat pipe and a latent heat salt storage material (a eutectic mixture of NaF and MgF_2) was fabricated and tested at a temperature of 827°C (1520°F) by General Electric.

Contractors were selected for storage requirements definition and SRE design studies. The major emphasis is the development of a dish mounted latent heat storage subsystem for three small community system applications. Power conversion cycles under consideration include Rankine, Brayton, and Stirling.

APPENDIX--THERMAL ENERGY STORAGE FOR SOLAR THERMAL APPLICATIONS PROJECTS

In this section detailed discussions are given of the individual projects which comprised the TESSTA program during this reporting period. Topics discussed are: (1) Project Objectives, (2) Project Tasks, (3) Technical Progress, (4) Technical Problems, and (5) Publications. The projects are organized according to the outline shown below. Projects labeled with an asterisk (*) were initiated in previous fiscal years with Central Solar Technology (CST) funding. Since any follow-on activity will be funded by STOR they are listed here for completeness.

Thermal Energy Storage for Solar Thermal Applications Project Outline

1. Storage for Water/Steam Cooled Collector/Receiver

    1.1 Advanced Solar Thermal Storage Concept Development

2. Storage for Molten Salt Cooled Sensible Heat Collector/Receiver

    2.1 Molten Salt Chemistry

        2.1.1 Molten Nitrate Salt Interaction with CO_2 and H_2O
        2.1.2 Molten Nitrate Salt Stability

    2.2 Molten Salt Thermophysical Properties

        2.2.1 Molten Nitrate Salt Thermal Conductivity
        2.2.2 Molten Nitrate Salt Density, Viscosity, and Surface Tension
        2.2.3 Molten Nitrate Salt Heat Capacity

    2.3 Molten Salt Corrosion

        2.3.1 Molten Nitrate Salt Breathing Thermal Convection Loops
        2.3.2 Molten Nitrate Salt Closed Thermal Convection Loops
        2.3.3 Molten Nitrate Salt Electrochemical Corrosion Studies
        2.3.4 Electrochemistry in Molten Nitrate Salts

2.4 Molten Salt Subsystem Research Experiment and Component Development

2.4.1 Internally Insulated Thermal Storage Concept Development*

2.4.2 Molten Nitrate Salt Subsystem Research Experiment

2.5 Experimental and Theoretical Study of Thermocline Degradation

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3. Storage for Liquid Metal Cooled Sensible Heat Collector/Receiver

3.1 Air/Rock Thermal Cycling Testing

4. Storage for Gas Cooled Sensible Heat Collector/Receiver

4.1 Checker Stove Power Module Design, Fabrication and Testing*

5. Storage for Organic or Silicone Fluid Cooled Sensible Heat Collector/Receiver

5.1 Advanced Solar Thermal Storage Concept Development

5.2 Organic Fluid Storage Thermocline Testing at the MSSTF

5.3 Organic Fluid Storage Multitank Testing at the MSSTF

5.4 Storage Fluid Maintenance Study Using Caloria HT-43 Hydrocarbon Oil*

5.5 Thermal Storage Fluid Stability and Compatibility Tests

6. Dish-Mounted Latent Heat Buffer Storage

6.1 Storage Requirements Definition and SRE Design for Rankine, Brayton, and Stirling Power Conversion Cycles

6.2 Latent Heat Storage Media Chemistry and Corrosion Studies

6.3 Latent Heat Storage Solidification Control

6.4 Advanced Concepts

6.5 Latent Heat Storage In-house Studies (JPL)

6.6 Heat Pipe Receiver Module Design, Fabrication, and Testing*

1.1 Advanced Solar Thermal Storage Concept Development - Contractor TBD

Objectives

This project, which provides for advanced storage development for water/steam receivers, has two major objectives. The first objective is to produce a commercial-scale conceptual thermal energy storage design offering cost and performance improvements over the oil/rock dual media concept selected ~~for the Barstow Pilot Plant. Storage subsystems utilizing sensible and~~ latent heat storage or a combination thereof will be considered. Although the storage concept development will focus on commercial-scale Barstow Pilot Plant design requirements, a secondary objective is to assess the applicability of the proposed advanced storage concept for Barstow to storage in solar repowered power plants.

The second major objective is to produce a mid-temperature 304-316°C (400-600°F) latent heat thermal energy storage conceptual design for saturated steam receivers offering advantages over systems currently being investigated for mid-temperature storage such as oil or oil/rock sensible heat storage.

Work on this project has been divided into three phases. Phase I, the subject of this discussion, consists of conceptual design activities, which are to be completed by the end of CY80. Phase II, the design, construction, and testing of a subsystem research experiment (SRE), and Phase III, the final design and system retrofit, will follow in later years.

Tasks

The Phase I project is divided into six tasks:

Task 1. Engineering Analysis--The contractor shall review the existing literature on thermal energy storage systems utilizing sensible and latent heat storage. The contractor, on the basis of this review, analyses, and parametric studies shall select several thermal energy storage systems (sensible and/or latent heat storage) having superior qualities for the applicable receiver (superheated or saturated steam). The contractor is not constrained to previous concepts and is urged to create new system concepts. At least one of the concepts to be considered for the superheated steam receiver should be a molten salt sensible heat storage concept.

Task 2. Selection of Preferred System--The contractor shall review the concepts selected in Task 1 and select the one concept which is most promising on an overall basis and best suited for further investigation. The selection criteria and method of selection shall be clearly described.

Task 3. Conceptual Design and Cost/Performance Estimates--The contractor shall prepare a commercial scale conceptual design and cost estimate for the selected thermal energy storage system. The conceptual design shall be of sufficient detail to 1) permit a more definitive assessment of technical feasibility of the concept and the development requirements for later phases of the project, and 2) support estimation of the capital cost and operating and maintenance costs, as necessary for assessment of economic feasibility.

Task 4. Assessment of Commercial Scale, Thermal Energy Storage Subsystem--The contractor shall assess the conceptual design. The assessment shall address, as a minimum, the following topics: potential future improvements of the conceptual design including performance improvements, cost improvements, and economics of scale, and potential limitations including status of material and heat exchanger technology, commercial availability of storage material, equipment, and instrumentation, safety and environmental constraints, and land use constraints.

Task 5. Assessment of the Preferred Storage System for Other Receiver Working Fluid Conditions--The contractor shall assess the preferred storage system concept for other receiver working fluid conditions. The assessment shall address, as a minimum, the effect of increased receiver steam operating pressure and temperature, and receivers with organic or silicone sensible heat working fluids (saturated steam receivers only) on storage system cost/performance, status of material and heat exchanger technology, and safety and environmental constraints.

Task 6. Development Activities for Conceptual Design--The purpose of this task is to delineate the developmental activities required during subsequent phases to bring the conceptual design of Task 3 to a state of readiness for final design and construction.

The contractor shall define any additional analyses and experiments which may be required prior to production of a finalized design. Such analyses and experiments may be directed toward, but not limited to, resolving performance uncertainties of components, material properties, and heat and mass transfer. Activities required to support the detailed design, construction, and testing of the SRE shall also be identified.

Technical Progress

The RFP for this activity has been issued. Storage development for receivers producing superheated steam and saturated steam will be conducted under separate contracts. Contract awards are expected in July, 1980 with contract completion to occur in December, 1980 (5 month study).

Technical Problems

None.

Publications

None.

2.1.1 Molten Nitrate Salt Chemistry Studies - Contractor TBD

Objectives

The objective of this study is to develop a thorough understanding of the interactions of molten $NaNO_3$ - KNO_3 mixtures with water vapor and carbon dioxide in the air. The results of this study will help to determine whether an opened, closed, or breathing system is needed for salt storage.

Tasks

This study is divided into six tasks:

Task 1. Literature Review--A literature search and critical review of the relevant phase diagrams and thermodynamic data shall be made. This review should include the nitrate-carbonate and nitrate-hydroxide systems of Na and K.

Task 2. Nature and Rates of Interaction with CO_2--The nature and the rates of interaction between CO_2 and the following 3 salts shall be investigated: KNO_3, $NaNO_3$, and 50 KNO_3/50$NaNO_3$ (molar ratio). The important parameters affecting the rates of interaction will be defined and quantified (e.g., partial pressure of CO_2, temperature, and surface area of the salt.)

Task 3. Nature and Rates of Interaction with H_2O--Similar determinations shall be made for H_2O with the same three salts.

Task 4. Interactive Effects of Both H_2O and CO_2 with the Nitrates--The interactive effects of both H_2O and CO_2 on the chemistry of the nitrate salt melts must be determined.

Task 5. Interactive Effects of Both H_2O and CO_2 with the Decomposition Products of Nitrates--The experiments must distinguish between interaction of CO_2 and H_2O with nitrates and interaction of CO_2 and H_2O with the thermal decomposition products of nitrates (e.g., nitrites, oxides).

Task 6. Temperature Dependence of Reactions--The temperature dependence of these reactions must be determined for the temperature range 350 - 600°C (662 - 1112°F).

Technical Progress

The RFP for this activity has been issued. A contract award is expected in June, 1980 with contract completion to occur in June, 1981.

Technical Problems

None.

Publications

None.

2.1.2 Molten Nitrate Salt Stability - Sandia National Laboratories, Livermore

Objectives

The objective of this project is to study the thermal stability of molten sodium nitrate and potassium nitrate in order to obtain a precise and comprehensive understanding of the factors affecting salt decomposition.

Tasks

Two tasks have been defined for thermal stability studies.

Task 1. Atmospheric Screening Tests of Nitrate Salt--This task will study the thermal decomposition of nitrate and nitrite salts in air using a statistical screening test matrix designed to identify significant variables.

Task 2. In-depth Kinetic Studies of Nitrate Salt Decomposition--This task will develop a quantative description of the thermal decomposition of $NaNO_3$, KNO_3, and $(Na,K)NO_3$ from 350 to 650°C (662 to 1202°F).

Technical Progress

Task 1. Atmospheric Screening Tests of Nitrate Salt--Two series of twenty experiments have been performed to evaluate the effects of the following variables on the chemistry of the nitrate and nitrite salts: composition over the salt (specifically O_2, N_2, CO_2, and H_2O contents and its flow rate), salt sample size, sample purity, and composition (K/Na). The experimental test matrices were of a Plackett-Burman statistical design and were performed with the nitrates and nitrites. Various physical responses and chemical changes were evaluated using a statistical analysis. The dominate variable was in all cases the temperature of the experiment. All the variables were observed to affect at least one of the measured experimental responses. Reactions to form carbonate in the nitrate and nitrite salts were significantly enhanced at high temperature, 600-650°C (1112-1202°F). The same factors that enhanced carbonate formations were observed to be the factors that decreased the nitrate content. The details of the experiments and in-depth analysis of the results are being documented in a Sandia report.

Task 2. In-depth Kinetic Studies of Nitrate Salt Decomposition--A thermal microbalance and a mass spectrometer (TGA/MS) system has been designed and built to study the decomposition of nitrate salts. The TGA/MS system has been successfully tested for operating with experiments at 1 atm pressure and in vacuum.

Experiments with $NaNO_3$ and $(Na,K)NO_3$ have been performed with the TGA/MS. The salts decompose linearly with time and the rates increase with temperature. The rate of decomposition appears to be proportional to the surface to volume ratio of the salt. The extent of the weight losses indicate that as the salts decompose to metal oxides, some of the oxides volatilize. The gas analyses show that O_2, NO, and N_2 are decomposition products at 400°C (752°F) in vacuum. In addition to these gases, NO_2 appears to be a decomposition product at 600°C (1112°F) in vacuum. The gas analyses support that multiple reactions are occurring over the temperature range of interest.

Technical Problems

Due to the low viscosity and low surface energies of the nitrate salts, they have a strong propensity to spread, cover and creep out of any container. This wetting behavior interfered with the accuracy of the chemical analyses for the screening tests and with the measurement of the surface area of the salt in the kinetic investigations. No container material or crucible configuration could be found to alleviate this problem. A possible solution to this problem for kinetic studies involves the use of adherent salt films on gold substrates.

Publications

1. C. M. Kramer and C. J. Wilson, "The Phase Diagram of $NaNO_3$-KNO_3," SAND80-8502, Sandia Laboratories Livermore, April, 1980.

2.2.1 Molten Nitrate Salt Thermal Conductivity - Contractor TBD

Objective

The objective of this project is to measure the thermal conductivity of molten $NaNO_3$ - KNO_3 mixtures, to determine the effect of impurities upon the thermal conductivity of these mixtures, and to use these data to construct a predictive model for the thermal conductivity. No conductivity data exist for the mixtures at the temperatures of interest or for the effect of impurities. The experimental data will be used for engineering design studies of thermal storage and heat transfer systems and the development of better thermal models to predict salt performance as a heat transfer medium.

Tasks

The project has been divided into three tasks.

Task 1. Experimental Measurements of Uncontaminated Mixtures--The thermal conductivity of the following uncontaminated mixtures of molten nitrate salts will be measured over the temperature range, 350-600°C (662-1112°F).

a) $50KNO_3$-50 $NaNO_3$ (molar ratio)

b) $60KNO_3$-$40NaNO_3$

c) $40KNO_3$-$60NaNO_3$

d) $45KNO_3$-$45NaNO_3$-$10KNO_2$

Task 2. Experimental Measurements of Mixtures with Impurities--The effect on the thermal conductivity of small additions of $CO_3^{=}$, and OH^- will be determined for each salt listed in Task 1. The suggested maximum additions of contaminants are:

a) $CO_3^{=}$ (5 wt%)

b) OH^- (0.1 wt%)

Task 3. Development and Verification of Predictive Models--The results of the molten nitrate thermal conductivity studies are to be used to develop and verify a predictive method for determining the thermal conductivity of molten salts.

Technical progress

The RFP for this activity has been issued. A contract award is expected in July, 1980 with contract completion to occur in July, 1982.

Technical Problems

None.

Publications

None.

2.2.2 Molten Nitrate Salt Density, Viscosity, and Surface Tension - Sandia National Laboratories, Livermore

Objectives

The objective of this project is to provide data on thermophysical properties, e.g. viscosity, surface tension, and density of molten salts. These data are required for engineering design studies of thermal storage and heat transfer systems and verification of predictive models. By comparing experimental values for the various thermophysical properties to those calculated on the basis of various models of molten salt solutions it is possible to gain a better understanding of the structure and properties of ionic solutions.

Tasks

Two tasks have been defined to meet the objectives of this study.

Tasks 1. Development of Measurement Equipment--This task provides for fabrication of the necessary instrumentation, performance checks and construction of calibration curves.

Task 2. Experimental Measurements--Thermophysical property data will be obtained for the $NaNO_3$-KNO_3 system as a function of temperature and composition of the atmosphere.

Technical Progress

Task 1. Development of Measurement Equipment--Appropriate instrumentation has been built to measure viscosity, surface tension, and density over a temperature range of 25-900°C (77-1652°F) and a pressure range of 1 to 10 atmospheres. The measurement can also be made in vacuum. A microprocessor, designed to control the instrument and collect and reduce the data has been installed and completely checked out. A calibration curve for the viscosity determination has been constructed.

Task 2. Experimental Measurements--The viscosity of $NaNo_3$-KNO_3 has been measured over the temperature range 275-600°C (527-1112°F) in argon. The experiment will be repeated in an oxygen atmosphere and with additions of potassium nitrite.

Technical Problems

None.

Publications

1. Nissen, D. A., "The Physical Properties of $NH_4Cl \cdot 3NH_3$," SAND79-8049, Sandia Laboratories, Livermore, CA, August 1979.

2.2.3 Molten Nitrate Salt Heat Capacity - Sandia National Laboratories, Livermore

Objectives

The objective of this project is to measure the heat capacities of $NaNO_3$, KNO_3, and $NaNO_3$-KNO_3 mixtures up to 577°C (1070°F) using a differential scanning calorimeter. A second objective is to study the effect of impurities (e.g. nitrite) on the heat capacity. These data are required for engineering design studies of thermal storage and heat transfer systems and development of a model to predict the effect of impurities on heat capacity.

Tasks

The project is divided into three tasks:

Task 1. Experimental Measurements of Uncontaminated Mixtures--The heat capacity of $NaNO_3$, KNO_3 and a 50/50 molar mixture of $NaNO_3$ and KNO_3 will be measured over the temperature range 77-577°C (170-1070°F).

Task 2. Experimental Measurements of Mixtures with Impurities--The effect of impurities (e.g., NO_2^-, $CO_3^=$, and OH^-) on the heat capacity of the 50/50 molar mixture of $NaNO_3$ and KNO_3 will be determined.

Task 3. Development of Predictive Model--A model to predict the effect of different impurity levels on the heat capacity of the salt mixtures will be developed.

Technical Progress

Task 1. Experimental Measurements of Uncontaminated Mixtures--The heat capacities of $NaNO_3$ and KNO_3 have been measured from 77°C (170°F) to 477°C (891°F) and 527°C (981°F), respectively.

Technical Problems

The gold capsules that contain the salts have ruptured at the upper temperature limits causing the molten salt to creep out of the sample capsules. Ways to prevent this are being investigated.

Publications

None.

2.3.1 Molten Nitrate Salt Breathing Thermal Convection Loops - Sandia National Laboratories, Livermore

Objectives

The objectives of this study are to evaluate the corrosion behavior of high temperature structural alloys in molten nitrate salts and to ascertain if thermal gradient mass transfer phenomena significantly affect corrosion behavior. Two aspects of corrosion are to be considered, formation of surface scales and depletion of chromium. Thermal convection loops were chosen as the research tool since corrosion data can be acquired over a wide range of temperatures in a single experiment. The loops operate in the breathing configuration, simulating one possible mode of storage operation.

Tasks

Three tasks have been defined for this project:

Task 1. Loop Design and Construction--This task provides for the design and construction of three thermal convection loops from Incoloy 800, 316 SS and 304 SS.

Task 2. Loop Operation and Alloy Corrosion Analysis--Under this task the loops will be operated for at least 5000 hours. The corrosion behavior of the alloys will be evaluated over this period by removal and analysis of sample specimens.

Task 3. Salt Analysis--The chemical composition of the salt will be analyzed during the test to determine the amount of chromium depleted from the alloys.

Technical Progress

Task 1. Loop Design and Construction--Convection loops were constructed from Incoloy 800, 316 SS, and 304 SS, the primary candidates for use in the high temperature sections of advanced central receivers (ACR). The temperature distribution was adjusted to match the full operational range of ACR systems, 350 to 600°C (662 to 1112°F). The Incoloy 800 and 316 SS loops were set at 630°C (1166°F) to accelerate the corrosion process. Weldments of the test alloys were also placed in the loops for corrosion testing along with the standard wrought material.

Task 2. Loop Operation and Alloy Corrosion Analyses--The corrosion behavior of the alloys has been evaluated gravimetrically and metallographically at intervals during the course of the loop tests. Surface scales have been analyzed by scanning electron microscopy and Auger microscopy as well as optically. The primary corrosion products observed are magnetite and iron-chromium spinels. Corrosion is relatively benign below 600°C (1112°F) although samples lose weight due to chromium depletion. At the highest temperature, corrosion and depletion rates are several times faster. Further experiments are needed to clarify the temperature limit for acceptable corrosion rates.

Task 3. Salt Analysis--Samples of molten salt were removed from the loops periodically and analyzed for metal content by atomic absorption spectroscopy. Chromium contents appeared to increase linearly with time and had reached 200 ppm in the Incoloy 800 and 316 SS loops after 2000 hours. Relatively little iron or nickel were found. A UV-VIS spectrophotometric technique is being used to distinguish between Cr^{6+} and Cr^{3+} to make a first step toward understanding the fluxing mechanism of chromium.

Technical Problems

A malfunction of the furnace used on the 304 SS loop led to freezing at 2000 hours. The loop was not damaged but the inserted samples were not retrievable. The loop was restarted with new samples, however, additional time will be needed to accumulate the desired number of hours on these samples.

An operator error caused the Incoloy 800 loop to overheat considerably after 4000 hours. The hot leg and corresponding samples were severely corroded and the test could not be continued. Several samples of the tube were removed from areas not affected by overheating for metallographic analysis. A new loop is being constructed to repeat the experiment.

Publications

1. W. S. Winters, R. W. Bradshaw, and F. W. Hart, "Design and Construction of Thermal Convection Loops for Corrosion Testing in Molten $NaNO_3$-KNO_3," Sandia Laboratories, in preparation.

2.3.2 Molten Nitrate Salt Closed Thermal Convection Loops - Oak Ridge National Laboratory

Objectives

The objectives of this study are to evaluate the corrosion behavior of high temperature structural alloys in molten nitrate salts and to ascertain if thermal gradient mass transfer phenomena significantly affect corrosion behavior. Two aspects of corrosion are to be considered, formation of surface scales and depletion of chromium. Thermal convection loops were chosen as the research tool since corrosion data can be acquired over a wide range of temperatures in a single experiment. The loops will operate under an inert atmosphere to learn the effects, if any, of a cover gas on alloy corrosion or salt decomposition rates.

Tasks

Four tasks have been defined for this project:

Task 1. Loop Construction--ORNL will construct one 304 SS and one Incoloy 800 thermal convection loop. A 316 SS loop has already been constructed by ORNL and will be consigned to the subject program.

Task 2. Salt Preparation--The salt will be vacuum outgassed while heating it to just above the melting point, then further heated under argon to approximately 300°C (572°F) for transfer to the loop. An archive specimen of the salt will be collected during each loop fill.

Task 3. Loop Operation--The molten salt will be transferred at approximately 300°C (572°F) from the 304 SS vessel to the loop under a protective argon atmosphere, and the loop temperature will be held at approximately 300°C (572°F) during filling. Natural circulation of the salt will then be induced to achieve maximum and minimum temperatures of approximately 595°C (1103°F) and 360°C (680°F) respectively. The insert specimens in the loop will be removed at intervals of 500, 1500, and 4500 h, respectively. Salt samples will also be taken each time the inserts are removed.

Task 4. Specimen Examination--After removal, insert specimens will be washed in warm water, dried, and weighed. Corners of the specimens will be clipped for metallographic examination, and nondestructive x-ray fluorescence analyses of specimen surfaces will be performed if weight changes are significant.

After 4500 h, all specimens in the loop will be examined metallographically, and selected metallographic specimens will also be examined by ion and electron beam spectroscopy. Oxide films on the specimens will be examined in place by x-ray diffraction and will be stripped for more exhaustive chemical and diffraction analyses as required.

Technical Progress

The project is on schedule. To date technical progress has been achieved on the first two tasks.

Task 1. Loop Construction--The materials to build the 304 SS and Incoloy 800 loops have been received and construction is under way.

Task 2. Salt Preparation--The salt for the 316 SS loop was outgassed at about 300°C (572°F). The salt was transferred to the loop and held at 540°C (1004°F) to further outgas the salt. A sample of the gas evolved by the salt was taken for analysis.

Technical Problems

None.

Publications

None.

2.3.3 Molten Nitrate Salt Electrochemical Corrosion Studies - Contractor TBD

Objectives

The objective of this project is to develop an understanding of the phenomena ascribed to Incoloy 800 that inhibits the corrosion of the metal by molten nitrates. Available experimental evidence indicates that the formation of thin passivating oxide layers is responsible for the negligible corrosion rates of certain structural alloys in molten nitrates. However, nothing is known about either the kinetics or mechanism of the formation of this passivating film in molten nitrates or of the corrosion mechanism in general. Neither the effect of temperature nor the effect of oxygen partial pressure on these processes is understood. A thorough appreciation of these effects is critical because this passivating film will be subjected to disruptive forces developed during the heating and cooling cycles experienced in solar receiver and thermal storage applications. It is the purpose of this program to develop a thorough understanding of the corrosion mechanism of Incoloy 800, as a representative structural alloy, and of the mechanism of formation of these passivating films so that conditions leading to catastrophic failure of this protective layer can be avoided.

Tasks

The project is divided into two tasks:

Task 1.--In order to understand the corrosion behavior of Fe-Cr based alloys, the behavior of metallic iron and chromium and the species that are formed at 450 to 550°C (842 to 1022°F) in molten $NaNO_3$-KNO_3 will be investigated. The kinetics and mechanism of the formation of the passivating film on Incoloy 800 will be made in molten 50 mole percent $NaNO_3$-KNO_3 over the temperature range, 450 to 550°C (842 to 1022°F). The effect of oxygen partial pressure and the role of impurities, such as NO_2^-, OH^-, and Cl^- on the stability of these species, and the rate and mode of formation of the passivating film will be included in the investigation.

Task 2.--The chemical identity of the passivating film will be determined as well as the dependence of composition upon the conditions of formation. Since studies of the corrosion of stainless steel in molten sulfates have shown that corrosion behavior is very strongly influenced by the quantity of liquid phase present and it is anticipated that a similar situation would be observed in molten nitrates, consideration should be given to this phenomenon in the design of the experiment. The experimental methodology shall be selected by the contractor; however, the contactor shall consider electrochemical techniques.

Technical Progress

The University of New York at Buffalo has been selected to perform this study. Contract award is expected during the third quarter of FY80.

Technical Problems

None.

Publications

None.

2.3.4 Electrochemistry in Molten Nitrate Salts - Sandia National Laboratories, Livermore

Objectives

The objectives of this project are to identify the various chemical species present in nitrate melts and develop an understanding of the relationship between the concentration of these species and such variables as temperature and composition of the gas phase. It is intended that these data will provide a foundation for a fundamental understanding of corrosion processes in molten nitrates. Appropriate electrochemical techniques will be used to accomplish these objectives.

Tasks

The project is divided into two principal phases: (1) development of species specific indicator electrodes which can serve as on-line salt monitors, (2) identification and study of the chemical species present in nitrate melts by appropriate electrochemical methods. Each of these phases is composed of specific tasks as follows.

Phase 1

Task 1. Identification of Appropriate Specific Ion Electrodes--A combination of literature studies and experimentation will be used to identify those electrode systems which can be expected to function best under actual test conditions.

Task 2. Fabrication of Electrodes--A number of different fabrication schemes, compatible with the electrode system of choice, will be tested to try to optimize response and lifetime.

Task 3. Determination of Electrode Response to Environmental Changes--The electrode response to concentration changes and temperature will be evaluated.

Phase 2

Task 1.--Selection of appropriate electrochemical technique and fabrication of electrodes and electrochemical cells.

Task 2.--Preliminary experiment designed to measure electrode response to various chemical species.

Task 3.--In-depth investigation of individual chemical species.

Technical Progress

A combination of literature surveys and screening studies have identified the electrode system Pb, $PbO/ZrO_2(Y_2O_3)$ as being responsive to the oxide ion in molten nitrates. Extensive tests of this electrode have been completed. They have shown that this electrode will respond in a rapid, predictable and reproducible manner to the oxide ion concentration in $NaNO_3$-KNO_3 melts over the

resistant to any corrosion in these melts. There is a linear relationship between the electrode potential and temperature over the temperature range, 330-410°C (626-770°F).

An electrochemical cell and appropriate electrodes have been fabricated and appropriate instrumentation assembled for the study of chemical species in nitrate melts. Cyclic voltammetry has been chosen as the experimental technique that will be used in these studies. Current emphasis is on the NO_2^- ion. Peaks corresponding to the NO_2^-/NO_2 couple have been found at + 0.425 V vs $Ag/AgNO_3$, and + 0.325V for the reduction step at 350°C (662°F). The peak separation of 0.10 V is in reasonable agreement with the theoretical value of 0.118 V. There is a linear relationship between NO_2^- concentration and peak current up to at least 4×10^{-2} molal. From these data, the intrinsic NO_2^- concentration resulting from the thermal decomposition of NO_3^-, at 350°C (662°F) in an inert atmosphere is $\sim 5 \times 10^{-3}$ molal. How this intrinsic NO_2^- concentration changes with temperature and atmosphere is now under study.

Technical Problems

None.

Publications

None.

2.4.1 Internally Insulated Thermal Storage Concept Development* - Martin Marietta Aerospace, Denver Division

Objectives

The primary objective of this project is to define a cost effective thermal storage system for a solar central receiver power system using molten nitrate salt stored in internally insulated carbon steel tanks.

Tasks

The project is divided into six tasks:

Task 1. Internal Insulation Materials Test Program--Laboratory experiments and analyses will be conducted for the purpose of developing effective and economical internal tank insulation(s) compatible with high temperature molten nitrate salt. This task will focus on the following: materials compatibility with molten nitrate salt, structural integrity, performance, economics (i.e., low material costs, ease of construction and installation, etc.), and durability under long term thermal cycling (including freeze-thaw effects when appropriate).

Task 2. Internally Insulated Thermocline Storage Tank Analysis--A thermal analysis of internally insulated thermocline storage tanks will be performed to study thermocline behavior under various operational strategies.

Task 3. Storage Tank Parametric Design and Optimization Study--This task provides for preliminary designs and cost estimates of externally insulated low temperature, 288°C (550°F) tanks and internally/externally insulated high temperature, 566°C (1050°F) tanks over a capacity range of 142 m^3 (5×10^3 ft^3) to 5.7×10^4 m^3 (2×10^6 ft^3). Insulation and foundation parametric studies will be performed to define the optimum design.

Task 4. Storage System Parametric Analysis--A systems analysis will be conducted which compares three energy storage options for solar thermal central receiver power plants: internally insulated thermocline tanks, internally insulated hot/cold tanks of identical design, i.e., one cold tank with cascading strategy for charging and discharging storage, and internally insulated hot tanks with an identical number of conventionally designed cold tanks.

Task 5. Safety Study--A safety study of molten salts shall be conducted. The study shall document safety hazards and precautions which must be considered in the storage, handling, and use of solid and high temperature molten nitrate salt mixtures.

Task 6. Development Plan--A development plan for the storage system(s) shall be provided. The plan will describe the development issues, define alternative plans to commercialize the system(s), and provide a rationale for the selection of a recommended plan considering cost and schedule versus risk.

Technical Progress

All of the tasks described above have been completed and the final report has been published (References 1 and 2). Several important results from the study are summarized as follows:

1. Materials/salt compatibility testing indicates that currently available salt wetting internal tank insulation materials will not withstand the molten nitrate salt environment for 30 years.

2. Even if a compatible wet insulation could be identified, costing studies indicate that it would be less economical than a dry internal insulation design consisting of a leak-proof, thermally expandable, steel liner backed by conventional, load-bearing, lower conductivity, dry insulation.

3. The lack of data on soil properties at elevated temperatures makes it impossible to confidently design a conventional concrete tank foundation in thermal contact with the ground. Tanks containing 538°C (1000°F) molten salt must either be elevated or placed on ground foundations which are passively or actively cooled.

4. For storage capacities up to 15,600 MWHT storage system optimization studies indicate that there is little to be gained from a cost effectiveness standpoint in employing internally insulated thermocline or cascading tankage methods in place of more conventional internally insulated hot and cold tanks. The "marginal" decrease in system cost does not appear to justify the technical risk associated with thermocline and cascading tank development. For amounts of thermal energy storage in excess of 15,600 MWHT the cascade and thermocline strategies begin to look more attractive.

5. Carbon steel cylindrical hot tanks insulated both internally and externally with an actively cooled ground foundation have the potential of reducing molten salt thermal energy storage costs by 50% (\$10/KWH_e). Martin Marietta proposes to employ the dry insulation concept for internal insulation with a liner manufactured and installed by Technigaz, Inc.

6. Safety procedures for handling both dry and molten nitrate salts are well established and have contributed to accident-free plant operations for up to 60 years. Potential hazards can be avoided by recognizing the salt as an oxidizing agent and by treating the molten salt like any hot liquid. The use of molten nitrate salt in a solar thermal power plant represents nothing new in this respect except for the quantity of salt involved.

Technical Problems

None

Publications

1. "Internally Insulated Thermal Storage System Development Program," Final Report, Sandia Contract 83-3638, SAND80-8175, Martin Marietta, December, 1979.

2. "Molten Salt Safety Study," Final Report, Sandia Contract 83-3638, Martin Marietta, January, 1980.

2.4.2 Molten Salt Thermal Energy Storage Subsystem Research Experiment - Contractor TBD

Objectives

The objective of this study is to develop (i.e., design and demonstrate) a lower cost molten nitrate salt (draw salt) sensible heat Thermal Energy Storage (TES) subsystem for solar thermal plants. Molten salt TES development will be accomplished through the following:

1. Preliminary design of a TES subsystem for a solar central receiver facility.

2. Design, construction, testing, and evaluation of a Subsystem Research Experiment (SRE) of sufficient scale to insure successful operation of the full size subsystem - the SRE will employ appropriate full scale fabrication techniques and all aspects of the actual subsystem startup, operation, and shut-down will be investigated. The purpose of the SRE is to resolve all design, fabrication, operational, and performance uncertainties associated with the full scale system.

A primary project goal is the reduction in salt TES costs and advancement of the state-of-the-art in high temperature containment. Practical and cost effective methods for tank construction and insulation will be emphasized.

Tasks

The project is divided into four tasks:

Task 1. Critical Component Development--The contractor will review the existing literature on molten draw salt and TES. Critical components (e.g. internal tank insulation, tank foundations, etc.) requiring further development will be identified and a plan will be formulated and executed to resolve the important technical uncertainties. Component development under this task may require detailed design, analysis, experimentation, and testing before finalizing the subsystem and SRE designs.

Task 2. TES Subsystem Preliminary Design--The contractor will re-evaluate the proposed concept in light of the literature reviews and component development activities of Task 1. A preliminary design shall be made for the molten draw salt TES subsystem. The subsystem design should maximize the potential worth to the user of molten salt TES for solar electric power or process heat generation. This shall include but is not limited to: maximizing roundtrip TES efficiency, providing acceptable reliability, minimizing the cost of molten salt TES, and advancing the state-of-the-art in high temperature containment.

Task 3. Subsystem Research Experiment--The contractor shall establish a rational approach for sizing a Subsystem Research Experiment of sufficient scale to resolve all design, fabrication, operational, and performance uncertainties associated with the full scale TES subsystem. The SRE should employ full scale fabrication techniques and demonstrate startup, operation, emergency shut-down, and normal maintenance activities associated with the subsystem. A detailed SRE test plan shall be written. The contractor shall build and test the SRE in accordance with the test plan. Although a storage/EPGS heat exchanger will not be designed and demonstrated as part of the current SRE, the SRE configuration should be flexible enough to permit the addition of such a heat exchanger (salt/water-steam) at a later date.

Task 4. Evaluation of SRE Test Results and Assessment of TES Subsystem--The contractor shall perform a detailed evaluation of the SRE test results ~~and determine the impact on the full scale subsystem. The contractor shall~~ make an assessment of the preliminary TES system design. This assessment shall include but is not limited to the following:

a. Cost and performance estimates of the TES subsystem.

b. Potential future improvements in the energy storage system:

   1) Performance improvements

   2) Cost reductions

   3) Economies of scale, with consideration of plant power ratings and thermal energy storage capacities less than or greater than that specified by the TES Subsystem Definition and Specifications.

c. Potential limitations to widespread implementation of the TES Subsystem.

d. Application to a storage subsystem utilizing liquid sodium in place of molten draw salt as an energy storage media.

Technical Progress

The RFP for this activity has been issued. A contract award is expected in September, 1980 with contract completion to occur in March, 1982 (18 month program).

Publications

None

2.5 Experimental and Theoretical Study of Thermocline Degradation - University of California, Berkeley

Objectives

Thermoclines have been proposed for storing solar thermal energy as sensible heat in liquids. In thermocline heat storage systems thermally induced density variations provide a means of storing both hot and cold fluids in a single reservoir. Efficiency of storage depends to a large extent on the rate at which the thermocline separating the hot and cold fluids degrades with time. The objective of the present effort is to study the mechanisms involved in thermocline degradation through analysis and laboratory experimentation. Emphasis is being placed on obtaining engineering estimates of long term thermocline storage performance using a simplified analysis which does not rely on detailed, complex, and prohibitively time consuming fine mesh computer calculations. Generic studies to be carried out during the early part of this study will be applicable to both organic and molten salt storage systems.

Tasks

Work in this study has been divided into the following areas:

Literature Review--The literature review consists of two search periods: one at the start of the project (preliminary) and one at the end (final). In this way an up-to-date report of all relevant work can be made available upon completion of the study.

Experimental Work--The experimental work consists of temperature measurement and two dimensional flow visualization on a laboratory scale parallelpiped enclosure. The enclosure has inner dimensions of 40 cm (height), 40 cm (depth) and 120 cm (maximum width). The tank width is a variable in the experiment and allows an exploration of H/W over the range $1/3 < H/W < 20$.

The variation in container width is accomplished by having displaceable internal channels within the container. The walls of the displaceable channels in contact with thermocline fluid will be metal or plexiglass, depending on the boundary condition of interest (constant temperature or adiabatic). A constant temperature wall condition will be achieved by pumping a thermostatic fluid through the channels. The adiabatic condition will be enforced by trapping a stagnant layer of air within each channel, with the metallic panel on each channel replaced by a plexiglass wall.

To allow for the homogeneous displacement of the thermocline interface as a function of time, two specially designed pipe-like diffusers will be placed at the top and bottom walls of the container.

For the experimental program, the following parameters or effects will be investigated qualitatively and quantitatively:

1. Effect of constant temperature and adiabatic wall conditions (including variation of wall thickness) on the degradation of a non-displacing thermocline.

2. Displacement of thermocline interface and its effect on degradation as a function of time for conducting and adiabatic wall conditions.

3. Effect of the variation in H/W over the range $1/3 < H/W < 20$. Careful search for waves and turbulence characteristics at the thermocline interface under a variety of conditions including wall boundary conditions for temperature and rate of thermocline displacement.

4. Measurements of temperature using thermocouples, and of velocity components using particle-based flow visualization techniques. If appropriate, laser-Doppler velocimetry (LDV) measurements will also be performed for conditions of special interest and relevance to the thermocline degradation process.

Analytical Work--Two simultaneous avenues of research will be explored, guided by the experimental results. One will be to assess the cost and accuracy of coarse grid numerical calculations based on time-dependent fully-elliptic forms of the conservation equations governing thermocline behavior. There is no doubt that grid refinement will yield increasingly accurate results, but at a considerable computational expense. The question to be answered here is whether or not results of sufficient accuracy for engineering purposes can be attained on relatively coarse, unequally spaced, computational meshes.

In parallel with the above, the necessary requirements for the development and application of a simple theoretical model predicting thermocline degradation sufficiently accurately for purposes of design will be established. The model will be based on simplified forms of the transport equations using boundary layer integral techniques in accordance with the guidance provided by the experimental results. The present work will consider also an approach involving numerical calculations based on simplified forms of the partial differential transport equations. The later approach is quite distinct from the fully-elliptic coarse-grid work proposed above.

Development of the simplified model will proceed independently of the experiment but must subsequently be guided by and tested against the measurements as they become available. In this way, limitations imposed by the model, especially in relation to its application to the design of prototype systems, will be established. Similarly, the data will serve to test the adequacy of coarse-grid numerical predictions.

Technical Progress

The preliminary literature review is now complete. The experimental apparatus has to be designed and submitted to the machine shop for construction. Analytical work has been initiated to investigate one dimensional convection - conduction in thermocline systems. A two-dimensional version of the TEACH code, including time dependence and buoyant effects, has been completed. This code will be used for coarse grid calculations for comparison with the experiment and with the one-dimensional model.

Technical Problems

None

Publications

None

3.1 Air/Rock Thermal Cycling Tests - Sandia National Laboratories, Livermore

Objectives

Rock bed storage systems are under consideration for several system applications using gas or liquid metal cooled (via an intermediate heat exchanger) central receivers. They are also being studied for compressed air thermal storage applications. The objective of this project is to determine if a rock bed used for sensible heat storage with air as the heat transfer medium would be reduced to sand sized particles over a period of time, due to continued thermal cycling. The temperature span considered for this project is between 300 to 600°C (572 to 1112°F). To simulate the loading of the rock bed and the loading of steel tank walls during expansion and contraction, the rocks tested will have several different loads applied. The entire project is designed to develop 30 year equivalent cycles in several months of testing.

Tasks

This project is divided into three tasks:

Task 1. Data Assimilation--The first task is to assemble as much literature as possible on 1) the nature of rocks and minerals, in general, relating to crack propagation, 2) the fracture mechanics of rock under thermal loads and 3) the availability and cost of minerals that would be candidates for long term survivability under thermal cycling.

Task 2. Preliminary Measurements--This task is to provide a preliminary estimate of the ability of common river gravel to survive thermal cycling. A one rock test cell will be assembled with appropriate spring loading to simulate the forces exerted by the rock bed and the steel tank wall on a typical rock located at the bottom center of the bed. The test conditions are varied to determine reasonable cycle times and to measure the heat transfer rate into a 1" nominal size granite rock. Also, these first tests are used to screen several mineralogically and granularly different rocks to see if there would be any relationship between grain size, mineral content and susceptibility to fracturing.

Task 3. Statistical Sampling--This task will generate confidence in the preliminary data by subjecting as many as 6 rock types simultaneously to the thermal cycling stresses. The rock types chosen will be as varied in as many parameters as possible, in order to predict how an average mixture of rocks would behave in a thermal storage bed. This task is expected to involve several months of data collection unless there is evidence of rock fracture in some types of rock. In this case, the tests would be extended to further evaluate the fracturing rocks.

Technical Progress

Task 1. Data Assimilation--This task has been completed with no firm evidence found on the continued fracturing of rock due to thermal cycling. Several fairly low cost minerals have been identified as potential long term thermal storage media. Although this task is essentially complete, samples of new materials are being considered for testing.

Task 2. Preliminary Measurements--This task is also completed indicating that even very angular, large grain, non-homogeneous rocks do not exhibit significant fracturing. Rounded, small grain, homogeneous rocks (granite) show no fracturing whatsoever even when drilled to the center for insertion of a thermocouple probe. These observations were made after 600 cycles between 300° (572°F) and 600°C (1112°F).

Task 3. Statistical Sampling--The equipment for this task is on hand and being assembled at present. Tests are expected to begin at the end of April, 1980, with some preliminary results by mid-June, 1980.

Technical Problems

The only problem that has surfaced to date is the availability of high temperature springs capable of providing the loads required for the test. Methods have been developed to limit exposure of the springs to the maximum temperature to minimize damage.

Publications

None

4.1 Checker Stove Power Module Design, Fabrication and Testing*- Sanders Associates, Inc.

Objectives

The objectives of this project were to verify the performance of the selected components listed below and to demonstrate that the checker stove concept represents a viable candidate for dispersed power systems applications.

- Ceramic checker stove as a heat exchanger/storage device
- An open cycle Brayton turbine
- Alternator
- Valving and manifolds
- Associated controls for use in a 20 kWe Brayton cycle solar power system

Tasks

A three-phase program was designed to meet the objectives. During Phase I, a design point analysis was performed on a checker stove of approximately 50 kWt rating appropriate to the application. Phases II and III provided for the design, fabrication, and testing of a checker stove power module.

Phase I. Preliminary Design and Analysis

Task 1. Design Point Analysis--A design point analysis will be performed on a checker stove of approximately 50 kWt rating appropriate to the proposed application. The analysis will include but not be limited to the following: (1) physical properties of checker brick candidate materials, (2) thermocline propagation characteristics for each operating mode (stove position), (3) thermal efficiencies of the stove while functioning and during charging, discharging, and recuperative cycles, and (4) pressure drop for each operating mode.

Task 2. Design Point Analysis Review--The results and findings of the design point analysis delineated in Phase I will be presented to JPL personnel. Contingent upon the JPL review and evaluation of the Task 1 data, approval will be issued by JPL to continue with the Phase II activities.

Phase II. Power Module Design

Task 1. Power Module Design--A prototype checker stove of approximately 50 kWt rating will be designed based on the results of the design point analysis of the checker stove, Task 1, Phase I. Departures from or the refinement of the data from the Task 1, Phase I might be necessary depending on the validity of original assumptions and rationale, engineering considerations and stove configuration. Design activities will include storage material selection, thermal and fluid flow analyses, containment structure, manifolding, upper and lower valve modules, interconnecting ducting, support structure, instrumentation and controls.

Task 2. System Definition--A preliminary system analysis will be performed to define design requirements for the checker stove power module. A review of available turbo-machinery applicable to this system will be conducted and a system cost estimate commensurate with the Task 2, Phase II system analysis effort will be provided.

Task 3. Design Review--The results and findings of Phases I and II will be presented to JPL personnel. Contingent upon the results of the JPL design review and evaluation, approval will be issued by JPL to continue with the Phase III activities.

Phase III. Power Module Fabrication, Test and Evaluation

Task 1. Prototype Checker Stove Fabrication--One prototype checker stove will be fabricated and instrumented in accordance with Task 1, Phase II.

Task 2. Prototype Valve Module and Manifold Fabrication--One prototype valve module and manifold will be fabricated. The prototype will be instrumented to enable observation of temperature gradients, pressure drops, etc.

Task 3. Heat Source Unit Fabrication--A heat source unit will be fabricated to provide energy input(s) to the checker stove which will be capable of performing the following functions: collector/receiver output simulation, compressor outlet condition simulation, turbine outlet condition simulation, and startup/shutdown transients for all of the above.

Task 4. Control System Fabrication--A control system will be fabricated for checker stove operation according to the following requirements: The control system shall allow the checker stove to be exercised in any of the expected modes.

Task 5. Prototype Testing--A document delineating operating, testing and safety procedures shall be prepared for review and evaluation. Testing of the checker stove and valve module will be performed in accordance with these testing and safety procedures.

Technical Progress

Phases I-II. Both Phase I and Phase II have been completed. A high performance and optimized design was specified for fabrication.

Phase III. Power Module Fabrication, Test, and Evaluation: Tasks 1 through 4 have been completed resulting in a power module, valving and manifolding, heat source unit, and control system for characterizing power module performance.

Task 5. Prototype Testing--The prototype power module is presently undergoing tests. Test plans include 32 runs of various flow rates, temperatures, and pressures. Preliminary results show the thermocline to be much sharper than analytical estimates. This will result in significant module performance gains as both a heat storage and heat transfer component.

Technical Problems

In initial system checkout testing, it was found that inadequate clearance was provided in bellows sleeves and shaft bushing of the high temperature valve. The clearances were reevaluated and proper operation has resulted. Presently it appears that some leakage is occurring in the storage tank insulation resulting in excessive pressure vessel temperature in at least one location. This problem is now being investigated.

Publications

A final report documenting the entire technical effort is expected in April 1980.

5.1 Advanced Solar Thermal Energy Storage Concept Development - Contractor TBD

Objectives

The objective of this project is to develop second generation thermal storage systems for system applications with organic or silicone fluid, sensible heat receivers such as the Shenandoah cogeneration system.

Tasks

Work performed in FY 80 will evolve from Task 5 as described under project 1.1, Advanced Solar Thermal Storage Concept Development for Water/Steam Receivers. The latent heat storage concept developed for a saturated steam receiver will be assessed by the contractor for use in organic or silicone fluid, sensible heat receivers. Key points of the assessment are storage cost and performance, status of material and heat exchanger technology, and safety and environmental constraints.

Technical Progress

The RFP for this activity has been issued. This work is part of the contract to be awarded for storage development for saturated steam receivers (see section 1.1). Contract awards are expected in July, 1980 with contract completion to occur in December, 1980 (5 month study).

Technical Problems

None

Publications

None

5.2 Organic Fluid Thermocline Storage Testing - Sandia National Laboratories, Albuquerque

Objectives

The objective of this project is to develop a design handbook which allows the design and efficient operation of both single media and mixed-media (oil/rock) thermocline storage systems operating in conjunction with parabolic trough collector fields. This will be done through the construction and test of thermocline storage tanks both at the engineering prototype (1200 gallons) and laboratory scale (less than 100 gallons) levels. Development of analytical computer models will accompany testing of model systems.

Tasks

Work on the testing of organic fluid thermocline systems is divided into two major tasks - single media thermocline systems (i.e. straight oil systems) and mixed media thermocline systems where rock or some other inert material is used to displace expensive oil in the storage tank. Under each major area are subtasks which result in the fabrication of the test equipment, testing of the storage system concept and issuance of a report which serves as a design handbook for potential users of the technology.

Task 1. Single Media Thermocline

1.1 Design and Fabrication--A single 1200 gallon storage tank will be designed under this subtask. Constraints are that the tank be representative of standard commercial fabrication techniques, fit into an existing location within the MSSTF located at SNLA, and be compatible with the desired test program for single media thermocline storage systems.

1.2 Development of Storage Test Program--A detailed test program will be prepared under this subtask. The test program influences tank design as well as instrumentation.

1.3 Installation and Instrumentation--This subtask provides for installation (including insulation) and instrumentation of the thermocline storage tank at the MSSTF. Proper instrumentation is particularly important to allow accurate interpretation of test results.

1.4 Laboratory Scale Testing--The subtask executes small scale tests to provide guidance on the design and testing of the 1200 gallon MSSTF engineering prototype thermocline tank. Laboratory experiments extend testing capability to areas (i.e. diffuser design) not easily examined at the engineering prototype level.

1.5 Prototype Scale Testing--This subtask provides for testing of the 1200 gallon engineering prototype storage tank. Principle areas of interest are diffuser effectiveness, heat loss mechanisms, thermocline stability in both static and dynamic situations, and response of the thermocline to variations in collector field operation.

1.6 Design Handbook Publication--The publication of a handbook for the design and operation of organic fluid single media thermocline storage systems satisfy a major objective of this project.

Task 2. Dual Media Thermocline--The execution of Task 2 involves the same subtasks outline in Task 1 - Single Media Thermoclines. An additional area of concern under Task 2 will be an examination of the stability of oil in the presence of rock or other media. This will fall under Laboratory Scale Testing and will build upon existing knowledge of oil/rock compatability.

Technical Progress

Task 1. Single Media Thermocline--Subtasks 1.1 through 1.3 have been completed. A 1200 gallon engineering prototype tank is in place at the MSSTF with testing scheduled to start in late March 1980. In addition, subtask 1.4, Laboratory Scale Testing, has been initiated. Small scale tests were conducted to choose the diffuser design to be used in the prototype tank. Further diffuser design options will be tested shortly.

Technical Problems

None

Publications

None

5.3 Organic Fluid Multitank Storage Testing - Sandia National Laboratories, Albuquerque

Objectives

The objective of this project is the development of a design handbook for the design and efficient operation of a multitank thermal energy storage system interfaced with a parabolic trough solar collector field. Of primary interest is identification of the control strategies which minimize instrumentation requirements (both accuracy and complexity) while allowing energy efficient utilization of the storage system.

Tasks

This project utilizes a three tank storage system already in place within the MSSTF at Sandia National Laboratories, Albuquerque. This system, which interfaces both with a field of parabolic trough collectors and an organic Rankine cycle turbine generator, has a total storage capacity of about 6000 gallons of oil (assuming two tanks full and one empty). It is described in detail in a recent report (see Publications below). There are three separate tasks associated with this project.

Task 1. Identification of Thermal Heat Loss Mechanisms--In order to assess and improve upon, if possible, the thermal efficiency of the multitank thermal energy storage system it is necessary to measure the heat losses from the system. Possible mechanisms for heat loss include conduction through the insulation, conduction down tank legs to the ground, and thermal syphoning to remote heat sinks. Laboratory scale testing will be conducted to aid in evaluating the different potential mechanisms.

Task 2. Control Strategies--The control strategy for a three tank storage system in a solar energy application can be rather complex. Testing of different control strategy will be performed with a goal of maintaining peak thermal availability within storage (i.e. minimum mixing of hot and cold fluids).

Task 3. Design Handbook--A design handbook will be published at the conclusion of this project. The handbook will describe tank and plumbing configurations together with a preferred control strategy for the multitank storage system.

Technical Progress

Task 1. Identification of Thermal Heat Loss Mechanisms--Testing to date with the MSSTF multitank storage system has indicated far greater thermal losses from the tanks than anticipated. The heat loss mechanisms have yet to be completely identified. Thermal syphoning from the bottom of a hot storage tank to a heat sink has been noted. Flow visualization tests in laboratory scale models indicate that thermal syphoning between hot and cold sinks is relatively efficient in a two inch horizontal pipe. Study of this phenomenon is continuing with emphasis on exploring methods to eliminate heat loss by this mechanism.

Publications

Robert A. Randall, "Summary Report: Multiple - Tank High-Temperature Storage Subsystem," SAND79-2056, Sandia Laboratories, Albuquerque, New Mexico, January 1980.

5.4 Storage Fluid Maintenance Study Using Caloria HT-43 Hydrocarbon Oil* - Martin Marietta Aerospace, Denver Division

Objectives

Organic fluid thermal storage systems are being designed and built for several system applications which use water/stream or organic fluid cooled collector/receivers. The objective of this program was to investigate the thermal degradation characteristics of Exxon's Caloria HT-43 oil. Phase I studied the thermophysical effects of oil degradation in a partially vented storage tank at 316°C (600°F) for a period of 1000 hours. Phase II examined the effect of a sidestream processor (vacuum distillation column) on oil degradation in a vented storage tank. Phase III, the subject of the current study, has examined the effects of a continuously vented storage tank (without the sidestream processor) on degradation rate.

Results and analyses were performed in Phases I and II under separate contract with DOE (Contract No. DE-AC03-76ET20422) and can be found in Reference 1.

Tasks

The Phase III project is divided into three tasks:

Task 1. Oil Testing--Laboratory tests on Caloria HT-43 in a 379 liter (100 gallon) storage tank will be conducted in a vented condition for 1000 hours at a constant temperature of 316°C (600°F). Samples of the oil will be extracted periodically for chemical analysis during the test period.

Task 2. Model Development and Performance Evaluation--Mathematical models will be developed and used to simulate the oil decomposition process and determine the effects of a processor on reduction of oil degradation. Test results will be used to verify and direct the modeling effort. A literature search will be performed to develop a practical kinetic reaction rate mechanism scheme to describe the oil degradation process. Using the rate mechanism, a general degradation rate model will be developed to predict such effects as system pressure and oil temperature on degradation rate.

A computer model will be employed to assess the performance of an oil processor. The results of this model will be used with the degradation model to evaluate the effects of a procesor on oil degradation rate. Single and multistage distillation processes will be examined for processor performance. The degradation model and the processor model will aid in the evaluation of modes of processor operation and development of conceptual processor flow schematics. The flow schematics will indicate processor location in relationship to the thermal storage subsystem components (tank, pipelines, etc.).

Task 3. Economic Evaluation--An economic evaluation of oil replenishment costs will be conducted considering an applicable range of degradation rates for a 30 year thermal storage system lifetime. Parametric analyses will be conducted by varying degradation rates, quantity of oil in storage, and oil price escalation rates to determine life cycle costs of oil replenishment. Analyses will be directed toward commercial size systems.

Technical Progress

All of the tasks described above have been completed, and the final report has been published (Reference 2). Several important conclusions from the study are:

Task 1. Oil Testing--Results indicate that the thermal decomposition process results from a combination of both thermal cracking and autocatalysis. That is, the initial components in the fresh hydrocarbon oil are reduced to lower boiling components due to molecular splitting at a high energy state (thermal cracking) and from the existence of low molecular weight active radical species which catalyze the further breakdown of hydrocarbons into lower molecular weight species (autocatalysis). Therefore, the existence of decomposition products in the liquid oil accelerates the degradation rate. The chemical analyses performed on the tank bulk oil samples further indicate that the decomposition of the oil was not due to oxidation of the oil used in these tests. No polymerization of initial hydrocarbon components to higher molecular weight species was evident.

Task 2. Model Development and Performance Evaluation--The replenishment and degradation rates of the oil at 316°C (600°F) for all three phases of tests are summarized below:

	Phase I	Phase II	Phase III
Degradation Rate (Wt %/week)	2.4	0.1	2.4
Replenishment Rate (Wt %/week)	1.1	0.8	1.3

The fluid replenishment rate is the rate at which makeup oil must be added to the storage vessel to maintain a constant mass. The oil degradation rate, however, is defined as the amount of decomposition products which formed in the oil or escaped from solution below the initial boiling point and above the final boiling point of the original oil.

In Phases I and III the replenishment rate was less than the degradation rate resulting form some decomposition products remaining in solution. Conversely, the Phase II replenishment rate was greater than the degradation rate because the processor extracted non-degraded oil in addition to decomposition products. A comparison of Phase I and Phase III results shows that partial or complete venting of the oil storage system has no discernable effect on oil degradation rates. The larger scale tests performed in this study reveal that larger scale oil storage systems may produce higher degradation rates than the laboratory and small engineering scale tests have provided thus far. The results of these tests indicate that degradation reductions can be expected with reprocessing (Phase II vs Phases I and III). Analyses indicate that with processor improvements the degradation and replenishment rates can potentially be reduced by over 90%.

Task 3. Economic Evaluation--A conceptual design of a new processor was developed. Preliminary costs were developed for the processor unit based on capital, operating, and maintenance expenditures. A cost-to-oil savings analysis was performed on the processing unit for two plant sizes--pilot plant scale (oil and rock) and commercial scale size (oil only). Results from this analysis show cost-to-savings ratios ranging from 0.21 to 0.50 for a processor installation at the pilot plant scale and cost-to-savings ratios from 0.12 to 0.38 for the commercial plant scale for systems operating at 316°C (600°F).

Technical Problems

None

Publications

1. D. G. Beshore, J. E. Myers, W. R. Morgan, and M. G. Barth, "Storage Fluid Maintenance Study using Caloria HT-43 Hydrocarbon Oil," Final Report, DOE Contract DE-AC03-76ET20422, Martin Marietta, April, 1979.

2. D. G. Beshore, D. G. Raynor, and M. G. Barth, "Storage Fluid Maintenance Study Using Caloria HT-43 Hydrocarbon Oil," Final Report, Sandia Contract 83-2754, Martin Marietta, November, 1979.

5.5 Thermal Storage Fluid Stability and Compatibility Tests - Sandia National Laboratories, Livermore

Objectives

The objective of this project is to develop a large data base for the selection of organic or silicone fluids for use in sensible heat thermal storage systems. The specific data sought is fluid loss as a function of bulk storage temperature and time. In addition, data are needed on the compatability of these fluids with various filler media that could be used to cut down fluid inventory and hence system costs.

Tasks

The project initially concentrated on only one fluid proposed for use in the Barstow Pilot Plant, but was later expanded to include fluids with higher temperature capabilities for central receivers and also silicone fluids for distributed collectors. Specific tasks are summarized below.

Task 1. Evaluation of Caloria HT-43--The parameters investigated include fluid loss as a function of temperature between 288°C (550°F) and 316°F (600°F), rock and sand surface area, and metal surface area. The latter parameter is to be studied to examine the effect of large piping systems and subsequently higher metal surface area to fluid volume ratios. Much of the work is to verify data generated previously but in a system that had significant differences from an operating thermal storage unit.

Task 2. Evaluation of Sun 21--The parameters investigated include fluid loss as a function of temperature between 260°C (500°F) and 316°C (600°F) and metal type. Sun 21 is essentially Caloria HT-43 without an anti-oxidant.

Task 3. Evaluation of Therminol 55 and Therminol 66--These tests will be performed with variations of the same parameters used in testing Caloria HT-43. Much of the work is again to verify data previously generated in a substantially different test cell.

Task 4. Evaluation of a Dow Corning Silicone Fluid--These tests will be performed with several experimental arrangements: fluid alone or in contact with granite rock, scrap metal, virgin metals, several iron ores, and sodium sulfate pellets for use in a high temperature, 400°C (752°F) distributed collector system to be built in Shenandoah, Georgia. The parameters studied include pressure and variations in test vessel design to better simulate the trickle storage mode to be used in the system.

Task 5. Evaluation of Proprietary Heat Transfer Fluids--Several proprietary fluids obtained from industrial suppliers will be tested as alternatives to the silicone fluid. The temperature range in consideration here is between 372°C (702°F) and 400°C (752°F) and compatibility is centered on metals and iron ore.

Technical Progress

All tasks except Task 4 have been completed. This task is evaluating the silicone fluid loss effects of simulating a trickle storage mode in a static vessel design. Correlations have been developed for all parameters investigated for all other fluids including estimated cost comparisons for yearly fluid makeup.

Technical Problems

Problems were encountered in testing the silicone fluid because of its unique properties. Test vessels had to be redesigned several times in order to prevent inordinate fluid losses.

Publications

V. P. Burolla, "Analysis of Thermally Degraded Sensible Heat Storage Hydrocarbons," SAND77-8264, Sandia Laboratories, Livermore, CA, December, 1977.

V. P. Burolla, "Prediction of Yearly Fluid Replenishment Rates for Hydrocarbon Fluids in Thermal Energy Storage Systems," SAND79-8209, Sandia Laboratories, Livermore, CA, April, 1979.

6.1 Storage Requirements Definition and SRE Design for Rankine, Brayton, and Stirling Power Conversion Cycles - Contractors TBD

Objectives

As a first step toward commercialization of the modular point focusing distributed receiver (PFDR) solar thermal electric systems, the U.S. Department of Energy is planning a series of experiments to help establish their technical, operation and economic aspects. In these experiments small heat engines with attached electrical generators will be mounted adjacent to the receivers located at the focal point of each parabolic dish concentrator. The power conversion system rquirements are:

- Rankine Cycle - 15kW$_e$ Organic engine, operating at ~ 427°C (800°F)
- Brayton Cycle - 18kW$_e$ Open cycle Brayton engine, operating at ~ 816°C (1500°F)
- Stirling Cycle - 15kW$_e$ Kinematic Stirling engine, operating at ~ 816°C (1500°F)

The objectives of this project are to define the requirements for latent heat thermal energy buffer storage subsystems and the subsystem research experiments for the point focusing distributed receivers equipped with Rankine, Brayton, and Stirling power conversion cycles. The storage requirement definition includes thermodynamic and economic performance analysis to determine the need of thermal energy buffer storage and, if needed, its optimum size, identification of candidate storage concepts which meet JPL specified cost and weight goals, and recommendations for specific component and subsystem development needs. Separate contracts of each of the above power conversion cycles will be awarded to meet the objectives of this effort.

Tasks

The following tasks have been identified for establishing storage requirements and Subscale Research Experiment (SRE) design for each power conversion cycle.

Task 1. Thermal Buffer Storage Requirement--Dynamic performance, cost, weight, control, and structural design characteristics of the dish mounted heat engine in the absence and presence of a buffer storage shall be generated to explore the utilization opportunity, advantages, and the required capacities of latent heat buffer thermal energy storage (TES). The thermodynamic and economic performance of the integral system with and without buffer storage will be established by simulating the behavior of the system under time varying insolation and meteorological conditions of a specified geographical location over an entire year.

Task 2. Parametric Evaluation--The contractor shall perform system integration and trade-off studies for various buffer TES options, which are different in concept, material, and capacity, to quantitatively assess the technical and economic advantages of the conceptual designs of latent heat buffer TES of Task 1. Three conceptual designs of the receiver-TES-engine integral system shall be developed which will meet the receiver/TES cost goal of \$10 to \$15 per KW_t (1980 Dollars), and a total weight goal of 680kg (1500 lb) at the dish focal point.

Task 3. Development Requirements--The contractor shall identify the development requirements which include system analyses, materials, components, fabrication, assembly, testing and control required to carry the conceptual designs into successful hardware demonstration and eventual mass production.

Task 4. Subscale Experiment Design--The contractor shall perform a detailed subscale experiment design of one of the three conceptual designs developed in Task 2 which will be selected by JPL. The subscale experiment design will include drawings of sufficient detail for complete fabrication and testing, frabication costs and schedule, required instrumentation and test plan, material lists, and test data to be collected and the associated costs.

Technical Progress

Effort is underway to award the three contracts - on Dish Rankine to Ford Aerospace and Communications Corporation, on Dish Brayton to a system contractor yet to be selected, and Dish Stirling to the General Electric Company. Ford Aerospace and Communications Corporation and General Electric Company have existing contracts with JPL that involve the respective heat engine-receiver system development for the engineering experiments. Hence, the proposed effort on the integration of thermal buffer storage in their heat engine receiver system is an extension of the already contracted effort. Contract awards to General Electric Company and Ford Aerospace and Communications corporation are expected at the end of April, 1980, and May, 1980, respectively. Procurement activities for Dish Brayton storage requirement definition and SRE design will begin after the system contractor for the engineering experiment is selected by JPL.

Technical Problems

None.

Publications

None.

6.2 Latent Heat Storage Media Chemistry and Corrosion Studies - Contractor TBD

Objectives

The development of latent heat storage systems requires the knowledge of relevant properties of latent heat storage materials, such as latent heat of fusion, melting point, thermal conductivity, thermal expansion coefficient, molten phase viscosity, as well as the freezing behavior and the temperature range in which phase change takes place. Along with the knowledge of such physical data two other crucial considerations for the actual design of a latent heat storage system are corrosion resistant container materials and thermodynamic stability under thermal cycling.

The objectives of this project are: (1) define the thermophysical properties of certain specified salt eutectics that are relevant to the latent heat storage requirements at or about 441°C (825°F), 552°C (1025°F) and 829°C (1525°F); (2) conduct a large number of heating and cooling cycles of specified eutectic salts - containment materials combinations with and without corrosion inhibitors and impurities to determine the thermodynamic stability and corrosion characteristics of the selected salt eutectic.

Tasks

This project is divided into three tasks:

Task 1. Candidate Material Screening--The contractor shall conduct a preliminary screening of nine JPL specified phase change materials on the basis of thermophysical properties, availbility, and containment to select three candidates with melting points at or around 441°C (825°F), 552°C (1025°F), and 829°C (1525°F), for in-depth study of life-cycle performance.

Task 2. Salt Properties Definition--The contractor shall prepare four sample capsules for each recommended and JPL-approved composition with and without impurities, with getter (aluminum, zirconium or hafnium), and with impurities and getter. Each sample will be thermally cycled across its melting point minimum ten times in a Differential Scanning Calorimeter (DSC) to investigate the completeness of mixing and the possible leakage at the crimped holder pans. The history of the melt-freeze temperature profile during the cycling will be reproduced to detect any gross supercooling, component separation, or component interaction. Also specific heat, heat of fusion, and any heat of solid-solid transitions will be measured during these cycles to reveal any changes during cycling.

Task 3. Life-Cycle Simulation--The contractor shall conduct two sets of experiments to produce accelerated performance data. In the first set, extensive thermal cycling of small quantities of three selected compositions will be carried out in the automatic cycling mode of the DSC to investigate mainly the thermal performance. In the second set of experiments, larger quantities of selected salts will be sealed in specified container materials and cycled repeatedly for months in an electrically heated oven to produce corrosion data in addition to thermal performance data. Replicate samples will be used so that periodic removal and analysis may produce the kinetic data.

Technical Progress

Effort is underway to award a contract to Pennwalt Corporation, King of Prussia, Pa. A contract start date at the end of June, 1980 is expected.

Technical Problems

None.

Publications

None

6.3 Latent Heat Storage Solidification Control-
Contractor TBD

Objectives

In a latent heat storage system, the heat transfer area required for a given quantity of heat depends strongly on thermal conductivity, particularly near the heat transfer walls where solidification occurs. High heat transfer rates result in reduced heat transfer areas and the corresponding energy storage system costs can be achieved if suitable techniques are developed for the solidification control of the latent heat materials. Such techniques include active and passive control of the solids build-up on the heat transfer surface, and bulk additives as conductivity parameters. Since the present thrust is on the development of dish mounted, receiver integrated buffer energy storage systems, no active control techniques such as scraping, agitation, or electromagnetic field application are considered. The emphasis is on passive techniqes such as wall configurations, surface coatings along with the addition of bulk additives as conductivity promoters.

The objectives of this project are to experimentally determine (1) the effects of Phase Change Material (PCM) containment wall geometry and configuration including concave and convex external and internal surfaces, (2) thermal conductivity enhancing additives, (3) various types of surface finishing and coating of heat exchanger surfaces on PCM solidification, and (4) to identify some attractive solidification control options which will promote heat transfer in a dish mounted latent heat thermal energy storage system.

Tasks

This project is divided into three tasks:

Task 1. Experiment Design--The contractor shall investigate the solidification control techniques of a specified phase change material (PCM) used in a small scale thermal energy storage experiment of about 1 kW_t capacity. The PCM to be studied is 66.9 weight percent NaF - 33.1 weight percent MgF_2 eutectic mixture, melting at ~832°C (1530°F). The objective of this effort is to experimentally determine the effects of PCM containment wall configuration including concave and convex external and internal surfaces, conductivity enhancing additives, and finishing and coating of heat exchanger surfaces, and to identfy attractive solidification control options which will promote heat transfer. The contractor shall design the experimental components and laboratory test setup including instrumentation and data log system to investigate the three above mentioned techniques for solidification control and their effects on heat transfer. Also, the contractor shall prepare a detailed test plan including the specification of the data to be collected, test procedure, schedule, and safety. The hardware design and test plan are subject to review and approval by JPL.

Task 2. Fabrication and Testing--The contractor shall fabricate the experimental hardware and conduct tests in accordance with the plan and procedure prepared and approved in Task 1. Both qualitative and quantitative evaluation of the test results will be made to determine the solidification characteristics and rate-limiting process of heat transfer.

Task 3. Recommendations--The contractor shall recommend future investigative programs that are necessary to expand the experimental work accomplished under the present contract to the improved design of small-scale prototype TES devices.

Technical Progress

The RFP for this activity has been issued. A contract award is expected in July, 1980.

Technical Problems

None

Publications

None

6.4 Advanced Concepts - Contractor TBD

Objectives

Advanced Stirling, Brayton, and combined cycle energy conversion systems will require temperatures as high as 1371°C (2500°F) with buffer thermal storage requirements of 30 minutes to 2 hours. The solar fuels and chemical program has identified some thermal process applications for temperatures, 1371°C (2500°F) and higher, which also will require dish mounted buffer thermal storage.

The objective of this project is to identify concepts, perform some limited bench scale tests, and recommend buffer thermal storage systems which are parabolic dish receiver integrated, for applications at temperatures, 1010°C (1850°F), 1149°C (2100°F) and 1371°C (2500°F).

Tasks

This project is divided into three tasks:

Task 1. Candidate Materials Screening--The contractor shall screen potential materials for thermal buffer storage for dish-mounted receivers and select two each for the temperatures of 1010°C (1850°F), 1149°C (2100°F) and 1371°C (2500°F). The contractor shall select containment materials for the selected materials and shall provide JPL with the rationale for their selection. The operating conditions for the buffer storage device will be specified by JPL. The contractor shall supply thermophysical property data for the buffer storage material. This will include specific heat, density, volumetric thermal coefficient of expansion, heat of fusion, and supercooling effects if applicable. For the containment material, the contractor shall provide cost and compatibility data to JPL.

Task 2. Thermophysical Property Verification--If the thermophysical properties of the buffer storage material are unavailable from open literature or considered unreliable, the contractor shall conduct a limited number of bench scale tests to either obtain or verify the required data.

Task 3. Engineering Concept Drawings--The contractor shall prepare one engineering concept drawing for each of the buffer TES designs at the three temperature levels presented in Task 1. The drawing shall provide overall dimensions, weight, type and cost of materials used, ad identify the overall integration techniques of the buffer TES in the receiver. The purpose of the concept drawing is to provide rough engineering information, and not the fabrication or assembly information.

Technical Progress

Effort is underway to award a contract to Hanford Engineering Development Laboratory, Hanford, WA. A contract start date in August, 1980 is planned.

Technical Problems

None

Publications

None

6.5 Latent Heat Storage In-House Studies - Jet Propulsion Laboratory

Objectives

The objective of this project is to support and complement the contracted efforts on the development of dish mounted latent heat buffer storage systems. Power conversion cycles under consideration include Rankine, Brayton, and Stirling. The effort includes in-house research and developing the appropriate background, data base, and the technical capability for writing and managing industrial contracts for the development of thermal energy storage for parabolic dish applications in small community experiments.

Tasks

The project is divided into four tasks (note that contract management tasks are not included here):

Task 1. Latent Heat Buffer Storage System Definition--This task provides for a preliminary system definition of dish mounted latent heat buffer storage concepts. The task includes: (a) identification of several candidate salts for system applications such as the Small Community Solar Experiment (SCSE) and Isolated Load Experiment Series (ILES); (b) assembly of the salt thermophysical property data and heat engine thermal performance data; (c) identification of various integrated receiver-storage containment designs for including the latent heat system at the dish focal point.

Task 2. Materials Evaluation--This task provides for laboratory testing of candidate salt and containment materials. Tests to assist and complement the contracted effort described under 6.2 will be conducted. They include (a) differential thermal analysis; (b) differential scanning calorimetry; (c) molten salt thermal conductivity; (d) Cr-Mo alloy steel and stainless steel containment and cycling; (e) Cr-Mo alloy steel and stainless steel thermal convection loop tests.

Task 3. Latent Heat Buffer Storage System Modeling--A computer code, which will evaluate the thermal performance of each of the concepts developed in Task 1, will be developed for the transient analysis of receiver integrated latent heat storage. The computer code shall perform a dynamic analysis for a given insolation-profile and will generate the unsteady response of the dish receiver-integrated latent heat storage and heat engine assembly. Based on the results of the dynamic analysis, the optimum size of the energy storage will be determined and checked against the contracted effort.

Task 4. Preliminary Concept Design--Designs of the Point Focusing Distributed Receiver (PFDR) integrated latent heat buffer storage will be developed. Thermal performance and cost estimates based on in-house analyses for possible applications at various temperatures from 427 to 816°C (800 to 1500°F) will be generated. These designs will complement the contracted efforts on the SRE definitions.

Technical Progress

Task 1. Latent Heat Buffer Storage System Defintion--(a) The following salt candidates - containment combinations have been tentatively selected for more detailed investigations into their applicability as storage media for dish mounted receivers:

Applications Temperature	Salt Composition (By Weight)	Melting Point	Containment Material
427-454°C (800-850°F) (Rankine)	61 KCl-39MgCl$_2$	436°C (816°F)	316 & 321 SS, Cr-Mo alloy steel
538-566°C (1000-1050°F) (Steam Rankine)	25.9 Na$_2$CO$_3$-38.8 NaCl-35.3 NaF	557°C (1035°F)	316 & 321 SS, Cr-Mo alloy steel
802-829°C (1475-1525°F) (Brayton, Stirling)	66.9 NaF-33.1MgF$_2$	813°C (1495°F)	316 & 321 SS
788-829°C (1450-1525°F) (Brayton, Stirling)	75 NaCl-25 Na	795°C (1463°F)	321 SS
802-829°C (1475-1525°F) (Brayton, Stirling)	100 NaCl	802°C (1475°F)	9 Cr/1 Mo alloy steel

(b) Assembly of available thermophysical property data on fluorides and carbonates has been completed. Data on thermal conductivity, viscosity, and thermal expansion are generally incomplete. Efforts to locate the missing data are continuing.

Task 2. Materials Evaluation--Existing data on several containment materials were studied to (a) provide a preliminary screening of candidates materials for futher study; (b) identify areas where further materials work is needed.

(a) The screening tests investigated Cr-Mo alloy steels, stainless steels, and superalloys such as Haynes 150, Haynes 188, Inconel 617, and Hastalloy N. In addition, gettering materials, such as aluminum, hafnium, titanium, and zirconium, were examined to control the activity of free halogen gases with constituent elements of the stainless steels. Based on cost, availability and corrosion resistance the Cr-Mo alloys, 316 SS and 321 SS, along with a zirconium getter, were selected for further study.

(b) Experiments have been identified to provide additional materials data. Materials experiments in support of the first two application temperatures described under Task 1 will be contracted and are described in 6.2. Experiments to be conducted at JPL are as follows:

(1) Capsule Tests--The salts listed below will be heated and thermally cycled above and below their melting temperature in alloy or stainless steel capsules for test periods of 500, 2000, and 8000 hours. Both commercial and high purity salt material will be tested with and without a zirconium getter. A total of 36 capsules will be tested.

66.9 NaF-33.1MgF_2 in 321 SS

75 NaCl-25 Na in 321 SS

NaCl in 9 Cr/1Mo alloy steel

(2) Rapid Cycling Tests--One commercial purity + getter capsule will be tested in a tube furnace with N_2 flowing as cover gas to obtain rapid temperature cycling.

(3) Thermal Convection Loop Tests--Three loops, each with commercial purity salt + getter, will be tested up to 8000 hours.

Equipment and material purchases have been initiated for each of the above experiments.

Task 3. Latent Heat Buffer Storage System Modeling--A computer program called High Temperature Energy Storage (HTES) has been developed and assembled to simulate a parabolic dish receiver which has latent heat buffer storage. The model predicts the performance of the dish mounted receiver under varying solar flux, ambient temperatures, varying amounts of latent heat buffer storage, and different thermal control techniques. The program handles the receiver-TES system on a nodal basis, and hence is capable of yielding local receiver, and receiver coolant temperature variations for the transient simulation. Models for energy conversion systems (Rankine, Brayton, and Stirling) will be added to the computer program to obtain their response as a function of the buffer storage size. Various designs of the receiver-TES combinations can be easily modeled to identify attractive concepts.

Technical Problems

There may be short delays in obtaining pure phase change materials and some stainless steel 321 tubing, but no serious problem is anticipated. The computer program (HTES) now takes too much computer time to converge to an acceptable solution. Effort is underway to minimize the running time.

Publications

None

6.6 Heat Pipe Receiver Module Design, Fabrication, and Testing* - General Electric Company

Objectives

The objective of this project is to design, fabricate and acceptance test a heat pipe receiver with thermal energy storage (TES) for use with a parabolic dish-Stirling solar power system in the 15-20 kWe power range. It involves a solar heat receiver, latent heat thermal energy storage, and alkali metal heat pipe thermal transport. The latter supplies heat to a Stirling engine-generator to form an integrated power conversion system. This integrated system is located at the focus of a paraboloidal solar concentrator.

A prototype Heat Pipe Solar Receiver with Thermal Energy Storage (HPSR/TES) is being developed by the General Electric Co., Advanced Energy Programs, in Evendale, OH, under contract to JPL. The objective is to demonstrate one to two hours of low-cost latent heat TES, focus mounted on a dish-Stirling system experiment. Applications studies have previously shown that heat transport is required with the TES, and that the heat pipe receiver provides the highest efficiency for the point focus subsystem. The subsystem is also being designed with a fueled combustor for hybrid operation during periods of cloud cover, thus assuring a maximum capacity rating for the electric generation system for a minimum TES. The HPSR/TES prototype demonstration is scheduled for late FY 1981. Tasks to be accomplished are the conceptual, preliminary and detailed design, modular experiment test, and combustor development.

Tasks

The major storage related tasks which constitute the total program effort are outlined below.

Task 1. Preliminary Design--A preliminary design of the receiver TES subsystem will be performed. Included will be design analysis, mechanical design, materials and process selection, and a preliminary manufacturing plan. Concurrently, a modular experiment, consisting of one heat pipe, one or more TES salt-filled cans, and necessary heaters and heat rejection devices, will be designed, built, tested, and analyzed. Also, the conceptual and preliminary design of a fossil burner for integration with the receiver will be performed. Small-scale experiments will be made to provide basic test experience upon which to base the combustor design.

In August, 1979 an additional subtask was added to cover additional conceptual design effort on advanced concepts which would be potentially amenable to very low cost in mass production.

Task 2. Detailed Design--The detailed design of the receiver-TES subsystem will be completed. The end result will be a complete set of manufacturing drawings and a manufacturing plan including tooling requirements and special procedures. In addition, a limited study of the estimated mass production cost of the unit will be made (more than 100,000 units per year). An objective will be to identify factors which could lead to lower production costs.

Task 3. Fabrication, Assembly, and Testing--The contractor will procure materials, fabricate subassemblies, and finally assemble the entire subsystem with a JPL furnished Stirling engine or heat extraction device. The subsystem will be instrumented and charged with sodium. Finally, the complete focus mounted system will be shipped to Edwards Test Station for acceptance testing.

Task 4. Interface Definition--This task covers a group of related additional studies including: definition of the interfaces between the heat receiver and the Stirling engine and between the heat receiver and the concentrator; definition of potential mounting limitations of orientation effects; and a short study of safety concepts.

Technical Progress

Task 1B. Modular Experiment--Testing of the GE Modular Test Experiment for the Heat Pipe Solar Receiver (HPSR) has been completed for high elevation angles. Low angle tests will be completed during March, 1980 after addition of sodium to assure optimum heat pipe operation. Test equipment includes a single primary (solar receiver) heat pipe, a subscale secondary (thermal storage) heat pipe that contains three full-diameter TES capsules, and a cooling air heat extractor. Purpose of the experiment has been to establish overall thermal heat transport parameters that will allow accurate analytical modeling of the complex, full scale design for HPSR.

Tests have been very successful, and computer analyses have been fully qualified. Test data show 17°C (30°F) TES capsule surface temperature variations from full latent heat charge to complete latent heat discharge. This is a great improvement over the initially estimated ΔT of 42°C (75°F). Capsules, with 0.15 cm (0.060 in) wall thickness have been cycled several hundred times without problem. Temperature rise of the primary heat pipe (maximum thermal rating of 7 kWt) above the heat extraction temperature depends upon the area of the heat pipe condenser section extending into the secondary heat pipe. Data are being evaluated.

Task 1G. Alternate Design Concepts--The mechanical and thermal design analysis of the TES has been reviewed and expanded. The thermal analysis includes the phase change process associated with the moving boundary between liquid and solid phase with time. It is now possible to calculate the time taken for the wave front to travel from the outside surface to the center of the capsule for a given ΔT applied on the outer surface. Extensive mechanical design of various components has been included using plate, shell, and beam theory. Preliminary results indicate that larger can diameters and fewer cans may be used which may lead to further cost reductions.

Technical Problems

The program has been replanned to recognize the slippage in the overall schedule caused by the addition of Task 1G and to permit resumption of the preliminary design of the Heat Pipe Solar Receiver.

Publications

1. "A Conceptual Design Study on the Application of Liquid Metal Heat Transfer Technology to the Solar Thermal Power Plant, Final Report," JPL Contract No. 955018, General Electric Report No. GEAEP-54, September 25, 1979.

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