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Comparative Ranking of Thermal Storage Systems, Volume I

For Water/Steam, Organic Fluid, and Air/Brayton Solar Thermal Collector-Receivers

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PREFACE

The Thermal Energy Storage for Solar Thermal Applications program was initiated by the U.S. Department of Energy (DOE) to develop thermal storage technologies for solar thermal collector/receiver systems. The program plan was developed as a joint effort of the Office of Advanced Conservation Technologies, Division of Physical and Chemical Energy Storage (PACES) and the Office of Solar Applications for Industry, Division of Solar Thermal Energy Systems (STES). PACES is responsible for the implementation of thermal energy storage research and development. The objective of the program is to propose thermal energy storage technologies that incorporate cost/performance improvements over currently available storage technologies. The Solar Energy Research Institute (SERI) supports the program with research and systems analyses. The systems analysis activity consists of both value analyses and comparative rankings of thermal storage concepts. This report documents the results of a comparative-ranking study of thermal energy storage technologies for selected solar thermal applications.

SERI was assisted in the analyses by Stearns-Roger Services, Inc. (S-R). S-R provided the cost and performance data. SERI conducted the sensitivity studies, value analyses, and comparisons, and drew the conclusions and recommendations. The study had many contributors, however. Data from developers of thermal energy storage was an essential ingredient. The first of two reviews of the material was held in September 1980; 32 people representing 14 organizations were involved. The purpose of that meeting was to provide mid-study guidance on the study method, on the cost data base, on the descriptions of the thermal storage concepts, and on the order in which the concepts should be studied. The workshop results are separately documented in Copeland, Robert J., and Larson, Ronal W., _A Review of Thermal Storage Subsystems Integrated into Solar Thermal Systems, A Workshop Summary_, SERI/TR-631-439, January 1982.

The second, final review was held in January 1981, and 26 people representing 14 organizations attended. Action items were generated during the final review; those tasks have been accomplished, and the results are included in this report.

The S-R effort provided consistently calculated cost and performance data. Volume II of this report documents that data.

The authors wish to thank the many contributors to this work, especially Charles Wyman, Ronal Larson, Mike Karpuk of SERI, and Scott Faas, Cliff Schafer, and Lee Radosevich of Sandia-Livermore. The support of Doug Madison is also greatly appreciated.

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SUMMARY

The DOE Department of Advanced Conservation, Technologies Division of Physical and Chemical Energy Storage and the Office of Solar Applications for Industry, Division of Solar Thermal Energy Systems have developed a joint program plan to accelerate the development of thermal storage for solar thermal applications. The plan focuses on the development of thermal energy storage for six solar thermal collector/receiver systems and the specific applications of each system. This report documents the SERI systems analysis of thermal storage concepts for water/steam receivers, organic fluid receiver systems, and an air/Brayton receiver system. The objectives of the study are to conduct a comparative ranking of thermal storage technologies and to make recommendations on the future development of those technologies. These objectives were met by providing

- consistently calculated cost data for several thermal storage concepts associated with both central receiver and distributed collector solar thermal systems;
- consistent and realistic performance data for thermal storage concepts integrated into solar thermal systems;
- the same kinds of data projected for a mature technology based on the state of the art and anticipated improvements in storage technologies; and
- the sensitivity of the data to costing uncertainties.

This study is limited in scope to the evaluation of thermal storage concepts in the following solar thermal system applications:

- a 100-MW_e advanced water/steam central receiver solar electric power system;
- an organic fluid receiver for a 400-kW_e total energy system (Shenandoah Technology);
- a 150-MW_e closed Brayton-cycle solar electric power system; and
- process heat applications using the water/steam and organic fluid receivers specified above, less power-conversion and other related equipment.

Two methods are used to compare thermal storage concepts. One method is a present worth of revenue requirements (PWRR) economic method; it considers energy-related equipment (tanks, insulation, etc.); power-related equipment (pumps, compressors, fans, etc.); storage media, installation, and indirect costs; and first-year variable costs, such as O&M, electrical energy, and chemical usage. The second method determines the impact of storage systems on the delivered energy cost of solar thermal systems and includes the effects of storage inefficiencies.

Water/Steam Receiver (Power)

The relationship between present worth revenue requirements and hours of storage for the water/steam receiver (power) application with the storage concepts studied is shown in Figure S-1. As indicated, the caloria/granite-draw salt two-stage storage concept is the most economical at below approximately six hours' storage. For more than six hours of storage, underground pressurized water (in a steel-lined cavern) is the best first-stage choice. Of the latent heat storage systems, a direct-contact heat exchange system with a sensible heat second stage using phase-change media appears attractive. A modified tube-intensive heat exchange concept utilizing an enhanced heat exchange surface also appears to be very cost-effective.

Water/Steam Receiver (Process Heat)

For water/steam receiver process heat cases, supplying 288°C (550°F) saturated steam, the cost summary is shown in Figure S-2. For this specific application, underground pressurized water in a steel-lined cavern is clearly the most economical for high storage capacities. A modified tube-intensive heat exchange concept, utilizing an enhanced heat exchanger surface, also appears to be very cost-effective.

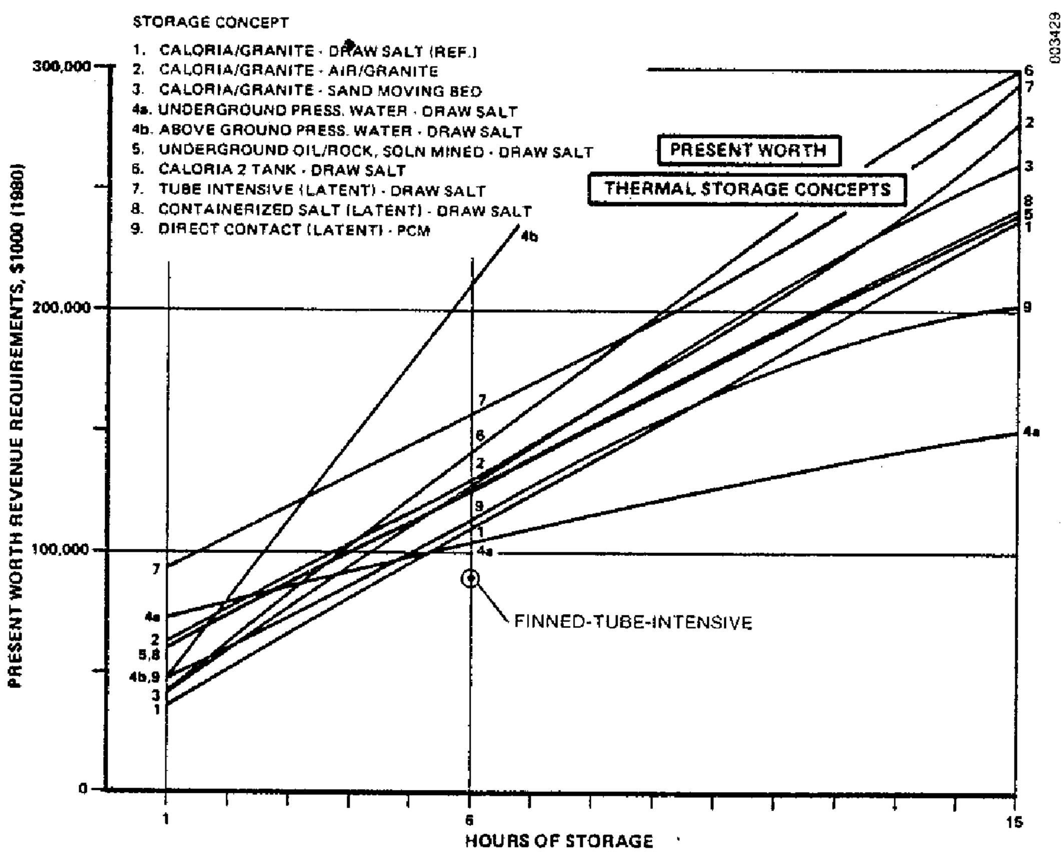

Figure S-1. Present Worth Revenue Requirements for Water/Steam Receiver (Power)

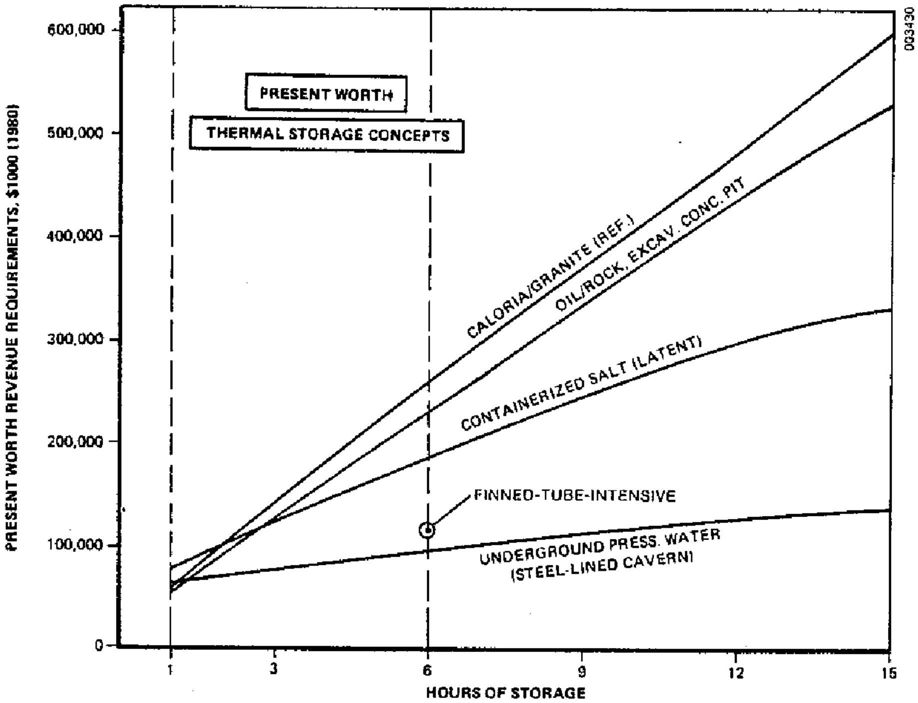

Figure S-2. Present Worth Revenue Requirements for Water/Steam Receiver (Process heat)

Organic Fluid Receiver

The PWRRs for the organic fluid receiver (total energy application) thermal storage concepts are shown in Figure S-3. At less than approximately seven hours, the reference Syltherm/taconite, trickle charge, storage concept is the best choice. Above seven hours, the Hitec salt (sensible) and direct-contact (latent) systems become cost-effective, owing primarily to high Syltherm 800 fluid cost and degradation.

For the organic fluid receiver process heat application, nothing was identified with more promise than Caloria/granite or Caloria only (two-tank).

Closed Air/Brayton Receiver (Power)

The PWRR for the thermal storage concepts for the closed air/Brayton cycle operating at 816°C (1500°F) is shown in Figure S-4. Nothing was identified with significantly more promise than the reference air/alumina brick sensible heat storage system. A tube-intensive latent heat system (not shown) was investigated and reported; however, its performance was poor.

Sensitivity Results

The data will be affected by the uncertainties inherent in any development program. However, the conclusions and recommendations should not change in the ranges expected for the following items:

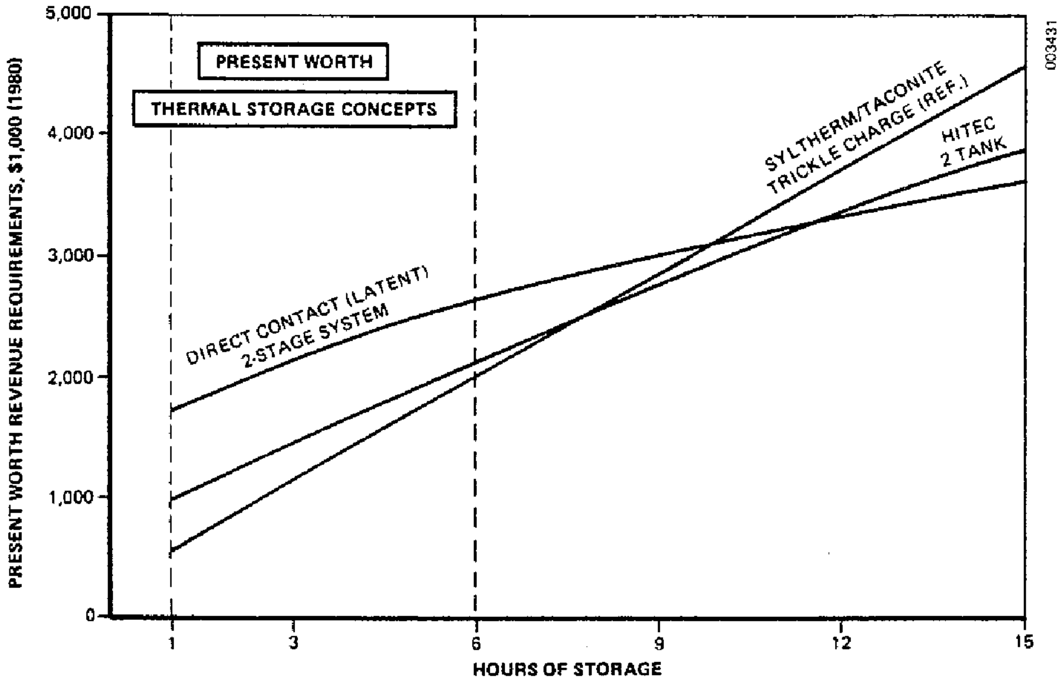

Figure S-3. Present Worth Revenue Requirements for Organic Fluid Receiver (Power)

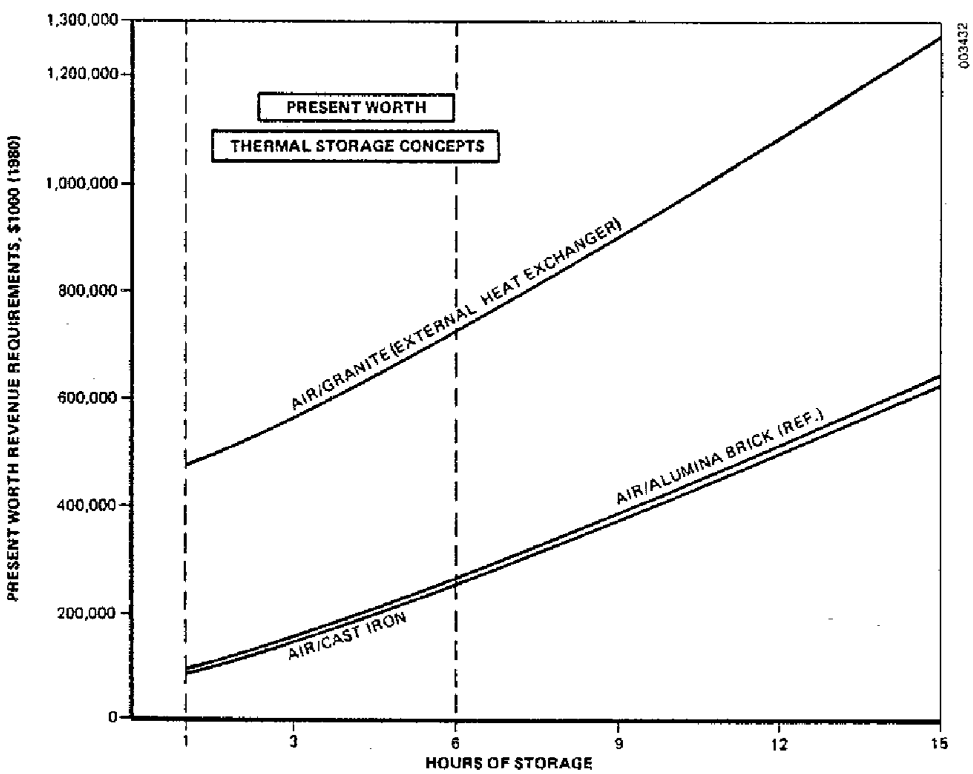

Figure S-4. Present Worth Revenue Requirements for Closed Air/Brayton Receiver (Power)

- the economic data base assumption (i.e., the cost of money);
- the costing methodology (i.e., the magnitude and distribution of indirect factors);
- operations and maintenance (O&M) cost data;
- dispatch of storage; and
- uncertainty in cost estimates.

The largest effect is caused by the uncertainty in the cost estimates. For concepts that can probably meet the program goals, the data are definitive.

Comparison to Value

Value is a measure of what a user will pay for thermal storage. Value is determined by calculating the fossil fuel savings and the capital credit gained in using storage. Obtainable cost estimates are compared with value for both electric power and process heat applications. Conclusions are summarized below.

Electric Power

- Water/steam receivers: Thermal storage costs are less than value at approximately six hours of thermal storage or less;
- Organic fluid receiver (Syltherm): No concept was identified with costs less than value; and
- Air/Brayton: Thermal storage costs are less than value at approximately one hour or less.

Process Heat

- Water/steam receivers: Thermal storage costs are less than value for approximately six hours or more.
- Organic fluid receiver:
  - Caloria receiver: Storage costs are less than value at approximately six hours or more of thermal storage; and
  - Syltherm receiver: No concept was identified that costs less than its value.

Recommendations

The first-generation thermal storage concepts are sound; completion of development efforts is recommended. These concepts include (1) dual-media, Caloria/granite thermocline; (2) molten salt; and (3) ceramic brick for air receiver systems. However, no thermal storage concept that is coupled to a Syltherm receiver meets the value criteria. Redirection of some program elements to an advanced technology status is recommended, especially for the trickle-charge, dual-media, Syltherm taconite concept.

Second-generation thermal storage concepts have been identified that represent substantial improvements over the first-generation systems, and development of a finned-tube-intensive, latent-heat storage for water/steam receivers is recommended. Underground, pressurized water storage is one of the lowest cost concepts for water/steam receivers. However, the concept is site-specific, entails substantial technical risks, and involves a costly development program. Additional studies on underground pressurized water are recommended before the development effort continues. Cost improvements over first-generation technologies can be obtained with direct-contact, latent-heat storage, but less than that obtained with finned-tube-intensive latent heat and underground pressurized water. Continued research and low-priority development is recommended on alternative direct-contact, latent-heat storage concepts.

Other concepts that offer minor improvements over first-generation technologies were identified but are not specifically recommended for development.

The following concepts are not recommended for development because they are either more costly than the first-generation technologies or significantly less attractive than other thermal storage concepts:

- Containerized salt
- Above-ground pressurized water
- Tube-intensive latent heat with an oil intermediate loop.

The sand moving bed and air/rock thermal storage concepts did not represent an improvement over molten draw salt storage. Two concepts are deemed to be more appropriate for liquid metal receivers. An evaluation of these two concepts with liquid metal receivers is recommended before any development is conducted on sand moving bed and air/rock thermal storage.

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SECTION 1.0

INTRODUCTION

Solar thermal power systems* developed for commercial use must operate continuously during periods of variable insolation, operate even during nonsolar hours, buffer potentially harmful system transients caused by abrupt insolation changes, and ensure that productive capacity is available during emergency periods. Two options exist to meet these requirements: conventional backup systems and thermal storage.** Backup systems are a viable near-term solution; however, as conventional fuel supplies become critically limited because of cost or availability problems, thermal storage will become increasingly important.

A comprehensive program has been drafted to accelerate the development of thermal energy storage technologies by matching them to solar thermal system requirements and scheduled milestones. The plan for this program [1] was prepared at the joint request of the DOE Divisions of Solar Thermal Energy Systems (STES) and Physical and Chemical Energy Storage (PACES). The strategy of the program reflects the current direction of the solar thermal power systems program. Thermal storage for repowering/industrial retrofits, total energy, and small community system applications will be stressed in the early years.

1.1 THERMAL STORAGE TECHNOLOGY DEVELOPMENT PLAN

1.1.1 Objective of the Program Plan

The goals of the development program are to provide

- Second-generation storage subsystems that represent cost and performance improvements over first-generation storage subsystems for solar thermal power applications (the most promising concepts must offer at least a 25% improvement over first-generation concepts);
- First-generation storage subsystems for solar thermal applications that presently have no associated storage subsystems; and
- A technology base to support storage subsystem development for future solar thermal power applications (third generation).

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*Solar thermal power systems collect and concentrate the sun's radiant energy to heat a working fluid; i.e., they convert the radiant energy to thermal energy. That thermal energy can be used directly for heat applications (process heat, heating, cooling, etc.) or to drive a heat engine, producing mechanical and/or electrical energy. Applications for the latter include, but are not limited to, electric utility power plants, irrigation pumping systems, and total energy systems (cogeneration).

**Backup systems include utility grids, fossil-fueled systems, batteries, pumped hydro, etc. Thermal storage includes sensible heat, latent heat, and thermochemical concepts.

1.1.2 Program Elements

Seven elements make up the storage development program. Six of them are keyed to storage development for specific collector/receiver technologies. The elements include storage for

- Water/steam-cooled collector/receivers
- Molten salt-cooled sensible heat collector/receivers
- Liquid metal-cooled sensible heat collector/receivers
- Gas-cooled sensible heat collector/receivers
- Organic fluid-cooled sensible heat collector/receivers
- Liquid metal/salt-cooled latent heat collector/receivers
- Advanced storage technologies (third generation).

Project applications for the first six elements have been identified, which provides a focus for the storage technology development.

1.1.3 The Role of SERI Systems Analysis

SERI is supporting the joint program plan with systems analysis, including both value analysis and comparisons of thermal storage technologies. The value of thermal storage in a solar thermal system/application is a measure of its worth, or benefit, to the user. This benefit is measured by the costs saved in conventional fuel and equipment by using thermal storage. If the cost of a thermal storage system exceeds its value, the user would certainly favor a fossil-fueled system. Program cost goals are set equal to or less than value, ensuring that only technologies that have the potential to meet or surpass cost goals will be developed and will be marketable.

Several thermal storage technologies are expected to meet value-derived cost goals. Program resources are limited, so only a few thermal storage concepts can be developed. These should be the most promising, technically and economically. SERI supports the selection process by reviewing data being generated by the developers of each technology and comparing the technologies on an equal basis. To support the program, thermal energy storage technologies are identified that are appropriate to each of the solar thermal systems specified.

1.2 OBJECTIVES OF THE STUDY

The objectives of the SERI study are to identify and make recommendations on promising thermal storage concepts based on a comparative ranking. So that the study will be conducted fairly, the analyses provide

- consistently calculated cost data for several thermal storage concepts in different solar thermal systems;
- consistent and realistic performance data for thermal storage concepts integrated into solar thermal systems;

- these cost and performance data projected for a mature technology based on the state of the art and anticipated improvements in storage technologies;
- sensitivity to costing uncertainties; and
- data for a range of storage capacities.

Cost data are also compared with the value of thermal storage to provide information on the future market potential of the concepts being considered for development.

1.3 SCOPE

The scope of this study is limited to the evaluation of thermal storage concepts in the following solar thermal system applications:

- a water/steam central receiver for an electric power plant and a process heat plant;
- an organic fluid receiver for a dish receiver total energy application and a process-heat-only application; and
- a gas receiver for a closed-cycle Brayton electric power plant.

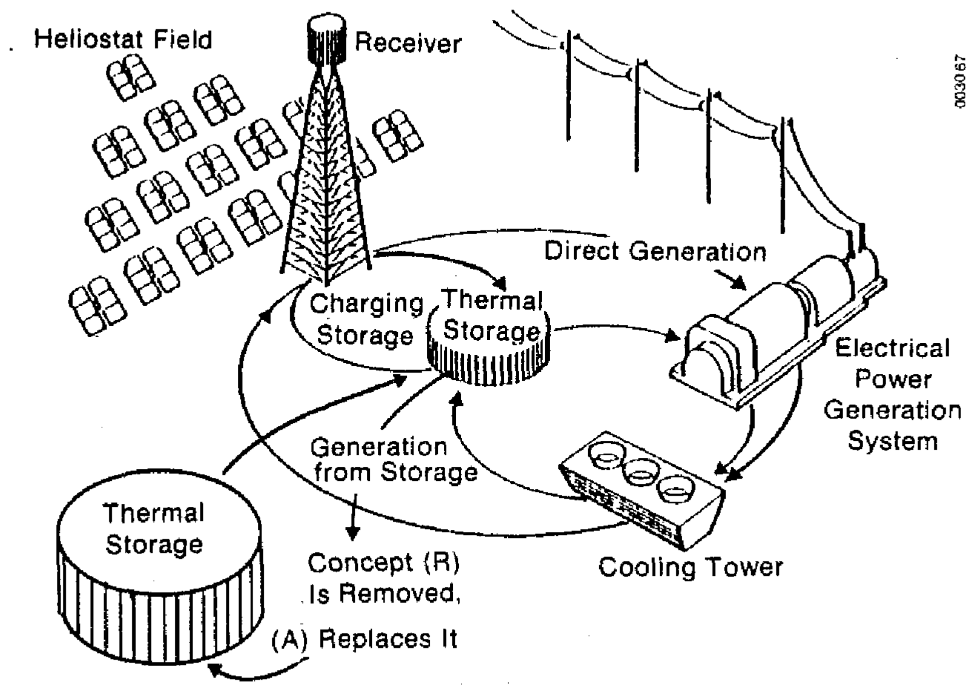
These systems represent three of the seven program elements. Analyses of thermal storage for the remaining elements are also planned, but at later dates consistent with the schedule of each element.

1.4 APPROACH

1.4.1 Comparative Rankings

Thermal storage is not an energy source, but a means of modulating the energy supply to meet a demand. The cost of thermal storage includes both the cost of the storage hardware and the costs associated with the performance of the storage subsystem. To determine the latter, a solar thermal system must be defined. To isolate the differences among the thermal storage concepts, all those concepts have been examined in reference to the same solar thermal collector/receiver system and compared with a reference thermal storage concept, designated R.

Figure 1-1 illustrates the approach. A complete solar thermal system is first selected for the analysis, including the collector, power generation subsystem (if applicable), thermal storage subsystem, etc. Without changing the remainder of the subsystems, we remove the reference thermal storage concept, R, and replace it with an alternative concept, A. All necessary changes are included, and the cost differentials (either up or down) are considered to be part of the cost of the alternative concept. This process is repeated, systematically varying the size of the collector field (with a proportional change in the tower/receiver system), dispatch strategy, location, and quantity of



All other elements are unchanged (except as may be associated with the new storage, e.g., a dual admission turbine may be replaced with a single admission turbine if the storage allows it).

Figure 1-1. Comparison of Thermal Storage Concepts

storage. The impact on total energy system cost is determined for each combination. This approach identifies which conditions, if any, must influence the selection of appropriate thermal storage concepts.

1.4.2 Caveats

SERI's systems analysis method attempts to identify promising thermal storage concepts for future development. Since the concepts are in an early stage of development, there is a risk that the concept will not function as described. No explicit judgment is, therefore, made on technical feasibility. Rather, the approach is to determine if the concept is sufficiently promising to merit resolving the technical risks.

The specific solar thermal storage concepts examined in this study are either currently being developed or are slight modifications of current concepts. Whenever possible, data from the concept's developer have been included. Many modifications were made to either improve the concept or add technical features. For example, the phase-change concepts were modified to include a capability to superheat steam (during discharge). Different phase-change media than those specified in the original plans may be used, as appropriate. Modifications to concepts generally involve relatively minor technical changes; similar technologies are either currently being developed or have already been demonstrated. Some modifications and other similar improvements could be developed simultaneously with second-generation concepts. In all cases, modifications help to achieve the best system configuration for each concept.

SECTION 2.0

STUDY GUIDELINES

2.1 REFERENCE SYSTEMS

This study provides cost and performance data for alternative thermal energy storage concepts in each of the following reference solar thermal systems:

(1) A 100-MW_e advanced water/steam central receiver [1] (Fig. 2-1).

(2) An organic fluid receiver for a 400-kW_e total energy system--Shenandoah Technology [2] (Fig. 2-2).

(3) A 150-MW_e closed-cycle air/Brayton central receiver system [3] (Fig. 2-3).

(4) For process heat, the reference systems are (1) and (2) above, less power conversion and related equipment. Both process heat solar thermal systems will deliver dry, saturated steam in all operating modes. For the advanced water/steam technology (Fig. 2-4), the steam temperature will be 288°C (550°F); for the organic fluid receiver (Fig. 2-5), the steam temperature will be 172°C (341°F). Only process heat is provided.

Tables 2-1 and 2-2 present the operating conditions for all the reference systems.

2.2 THERMAL STORAGE COST BASE

The cost and performance data were determined under the following conditions:

- The rate of charging the thermal storage is the same as the reference system.
- The rate of discharging the thermal storage is the same as the reference system.
- The capacity to store the thermal energy is the same as the reference system. Note: because the work conversion efficiencies may differ, the electrical storage ratings may also differ, even though the amounts of thermal energy discharged are identical.
- One hour of thermal energy storage is defined as the ability to store the thermal energy from the receiver that would have operted the plant for one hour at its thermal discharge rating if that energy had not been stored.
- The nameplate rating is the same as it is for the reference system.
- The collector area is the same as it is for the reference system.
- All items not affected by thermal storage are the same as in the reference system.

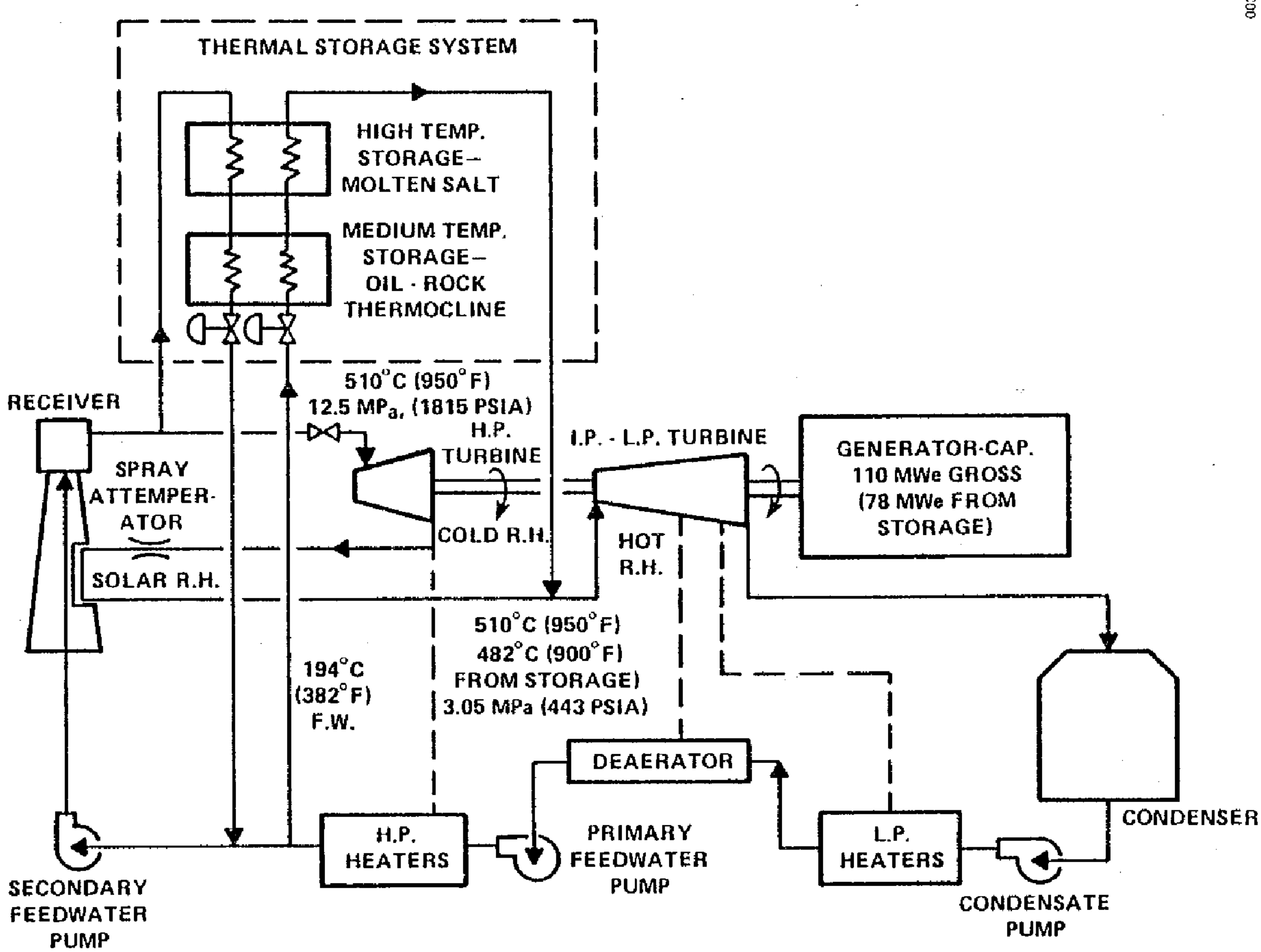


Figure 2-1. Reference System for Water/Steam Power Cycle

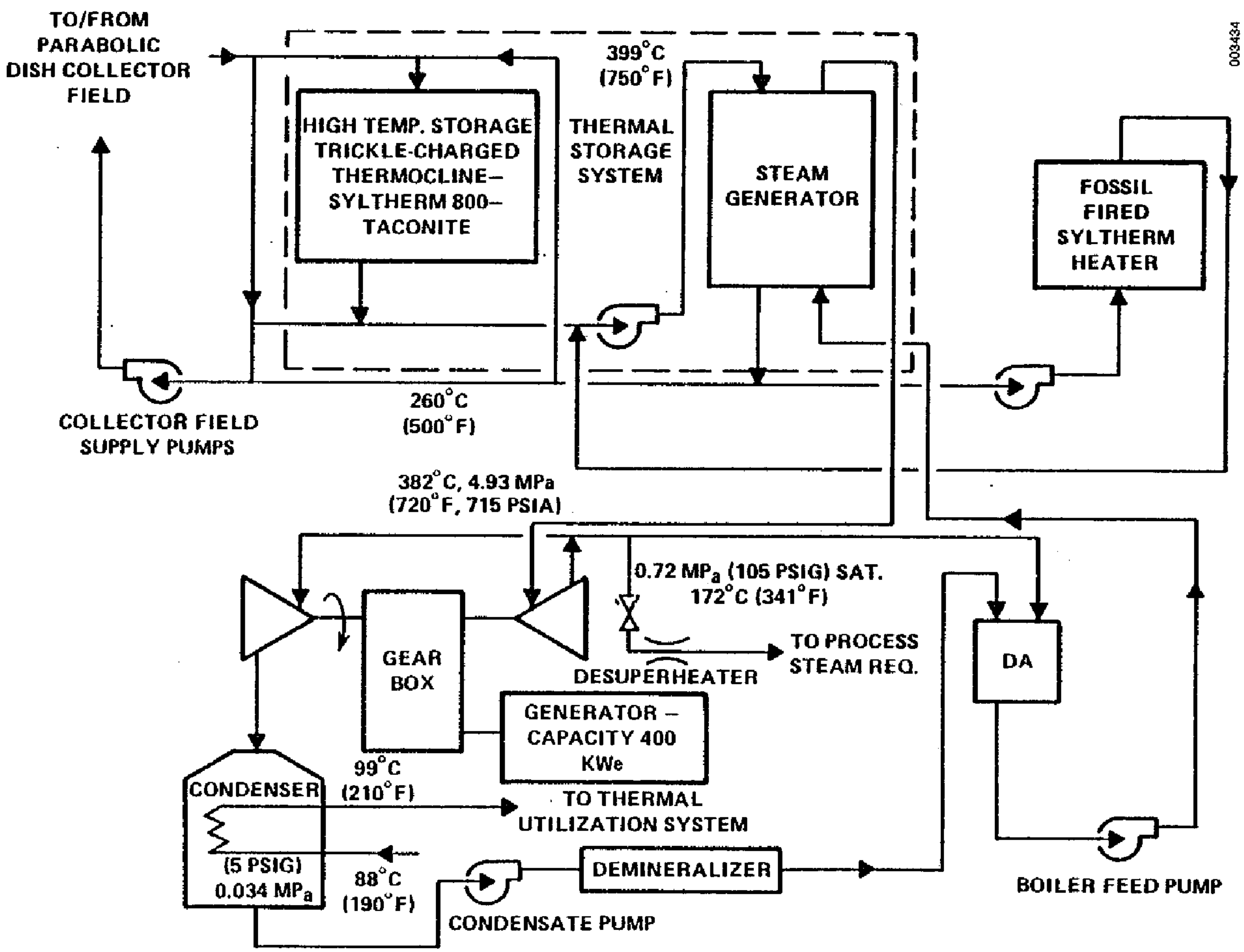


Figure 2-2. Reference System for Organic Fluid Power Cycle

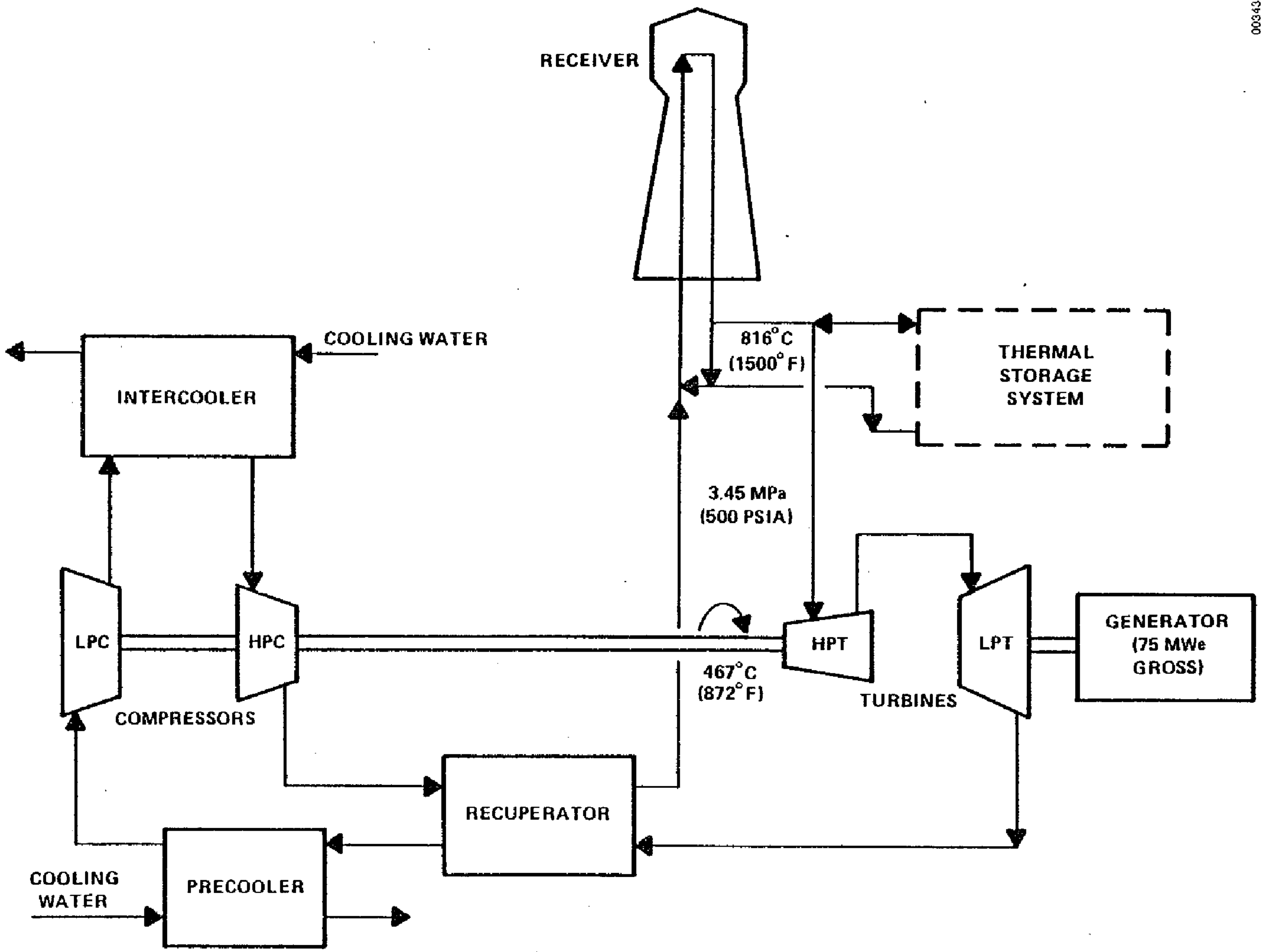


Figure 2-3. Reference System for Closed Air/Brayton Cycle
(Two 75-MWe gross modules)

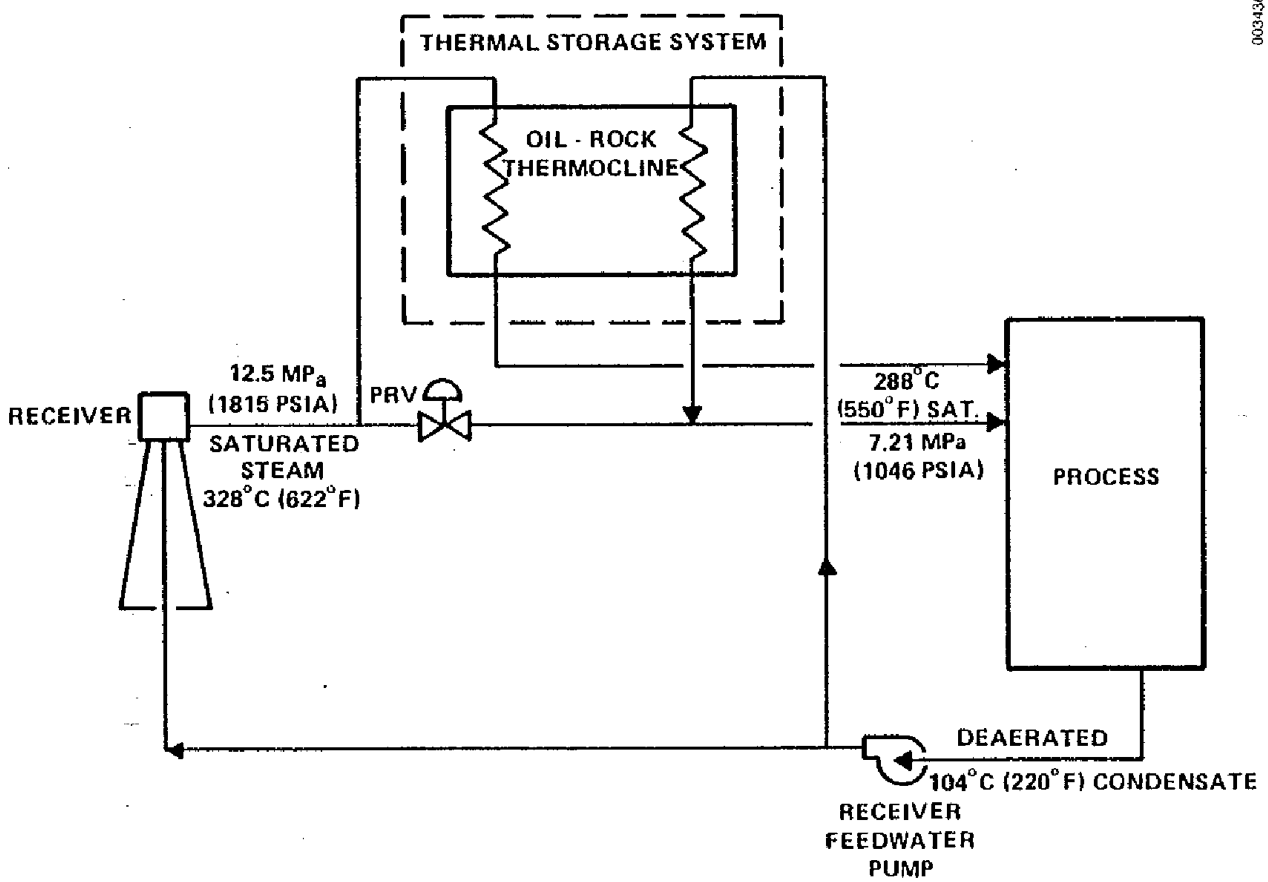


Figure 2-4. Reference System for Water/Steam Process Heat Cycle

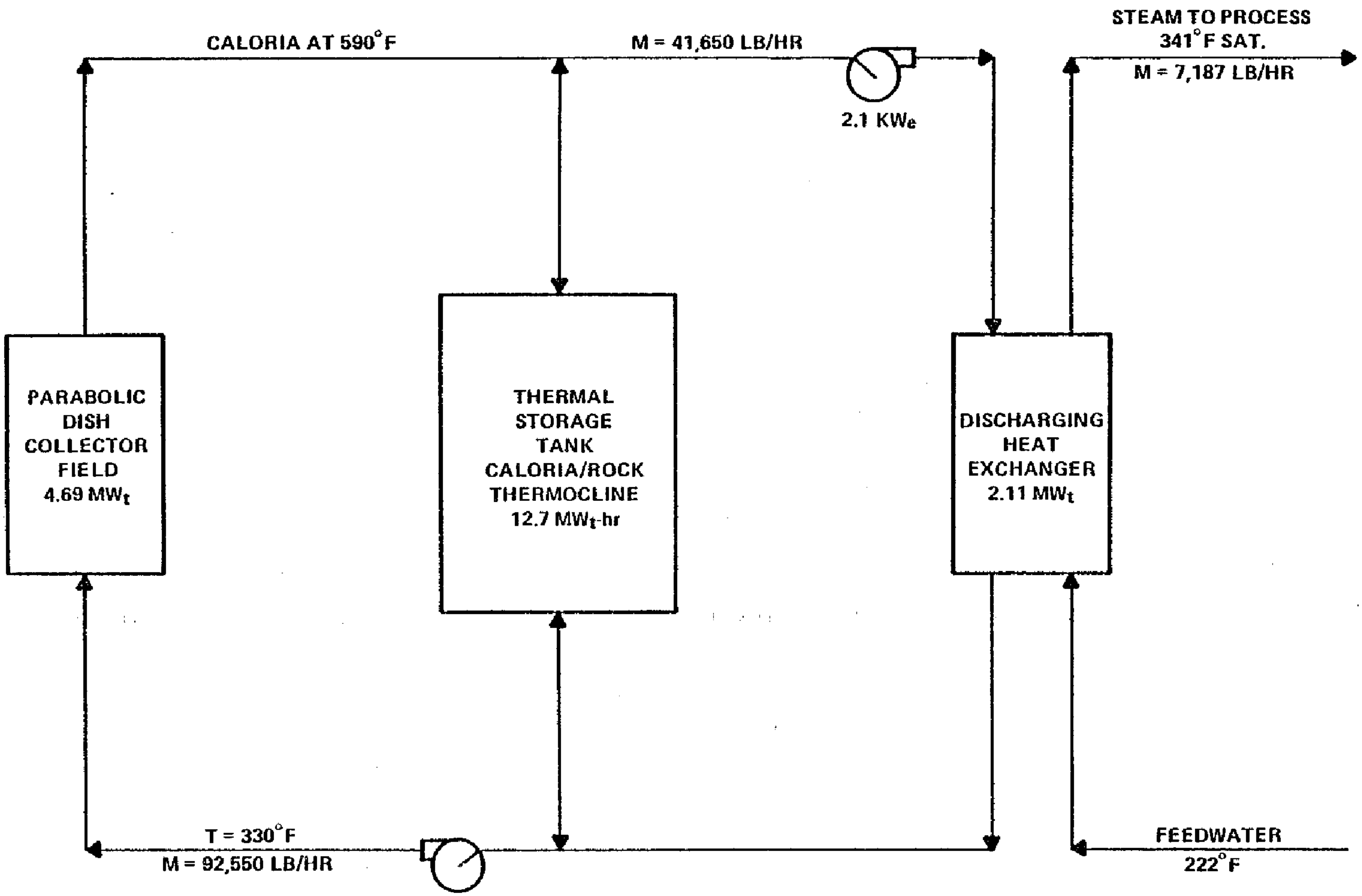


Figure 2-5. Reference System for Organic Fluid (Process) Storage System, Caloria/Rock Thermocline

Table 2-1. Reference Cycle Data

	Type of Receiver				
	Water/Steam		Organic Fluid		Air/Brayton
	Power	Process	Total Energy	Process	Power
1. Generator rating	110,000 kW_e (78,000 kW_e from storage)	N/A	400 kW_e	N/A	2-75,000 kW_e
2. Receiver temperature	510°C (950°F)	328°C (622°F) (saturated steam)	399°C (750°F)	310°C (590°F)	816°C (1500°F)
3. Turbine inlet pressure	12.5 MPa (1815 psia)	N/A	379 MPa (750 psia)	N/A	260 MPa (500 psia)
4. Turbine inlet temperature	510°C (950°F)	N/A	382°C (720°F)	N/A	816°C (1500°F)
5. Turbine reheat temperature	510°C (950°F)	N/A	N/A	N/A	N/A
6. Process steam temperature	N/A	288°C (saturated steam)	172°C (341°F)	172°C (341°F)	N/A
7. Process steam pressure	N/A	7.21 MPa (1046 psia)	0.72 MPa (120 psia)	0.72 MPa (120 psia)	N/A

Table 2-2. Design Criteria for Thermal Storage Concepts

Thermal Storage Concept	Units	Storage Time (hours)		
		1	6	15
Water/steam receiver (electric power or process heat)				
Solar multiple	-	1.16	1.96	2.80
Charge rate	MW_t	42.5	255.0	475.2
Discharge rate	MW_t	224.0	224.0	224.0
Storage capacity	MW_th	224.0	1344.0	3360.0
Organic fluid receiver (total energy or process heat)				
Solar multiple	-	1.20	2.22	3.20
Charge rate	MW_t	0.43	2.58	4.64
Discharge rate	MW_t	2.11	2.11	2.11
Storage capacity	MW_th	2.11	12.66	31.05
Closed air/Brayton receiver				
Solar multiple	-	1.17	2.00	2.80
Charge rate	MW_t	60.0	360.0	648.0
Discharge rate	MW_t	360.0	360.0	360.0
Storage capacity	MW_th	360.0	2160.0	5400.0

2.3 ALLOWABLE CHANGES IN THE REFERENCE SYSTEMS

Integrating alternative storage systems requires that changes be made to the reference systems. Any change that does not affect the primary nonstorage equipment is allowable. The following is a partial list of allowable changes:

- Conversion-cycle temperatures and pressures
- Receiver temperatures and pressures
- Dual admission turbine changes to single admission or changes in design point admission conditions
- Changes in any item associated with the thermal storage subsystem.

2.4 NONALLOWABLE CHANGES IN THE REFERENCE SYSTEMS

Any change that modifies the receiver or power conversion cycle is not allowed. The following is a partial list of nonallowable changes:

- Change in the power conversion cycle (e.g., from a reheat steam cycle to a nonreheat cycle)
- Changes in the receiver transport fluid, except for the organic fluid receiver, in which at least two organic transport fluids are investigated

- Changes in the receiver design (e.g., from an external surface to a cavity)
- Changes in the plant nameplate rating, including process heat delivery rate and quality.

2.5 THE SITE

The site for this study is assumed to be Albuquerque, N. Mex. Environmental design conditions are assumed as follows:

- A maximum design wind speed (including gusts) of 45 m/s (100 mph)
- Seismic UBC Zone 2
- A soil bearing of 192 kPa (4000 psf).

Certain underground storage concepts--i.e., solution-mined caverns for oil/rock storage that require natural salt deposits and underground caverns for pressurized water storage that must be established in solid rock formations--may not specifically apply to Albuquerque, but they represent viable storage concepts.

2.6 STANDARD COSTING DATA

Standard procedures were established to determine the cost of thermal storage subsystems. Materials and equipment prices are all given in 1980 dollars. A standard pricing list was prepared and reviewed by developers of the concepts; changes recommended by the developers were included in the final costing of each concept.

2.7 METHODS OF ECONOMIC ANALYSIS

Two economic analysis methods are employed in this study. One method is the present worth revenue requirement (PWRR). Stearns-Roger Services, Inc., (S-R) estimated the parameters for the PWRR method based on an investor-owned electric utility (see Sec. 4.0). The PWRR is calculated for the thermal storage subsystem only; the method accounts only for the cost parameters (power-related, energy-related, media, parasitic power, operation and maintenance, and replacements). The efficiency of thermal storage impacts on the solar thermal system are not induced in PWRR calculations.

The second method is the unit delivered energy cost of the storage-coupled solar thermal system that includes efficiency impacts on the system. The economic parameters employed by SERI in this method are those specified by the Solar Thermal Interlab Committee on Goals. The investor-owned utility assumptions are only slightly different from those of S-R, but the two economic methods differ significantly for process heat and total energy applications. In this study, SERI evaluated the sensitivity of the study's conclusions to the economic parameters. These data are presented in Sec. 5.0.

SERI

SECTION 3.0

THE THERMAL ENERGY STORAGE CONCEPTS

The study initially considered over 130 thermal energy storage concepts integrated into solar thermal systems. A rough screening reduced the number of concepts to 40. (The screening rationale are presented in Volume II, the S-R report.) Preliminary cost data were prepared for the concepts on the reduced list, from which 20 were selected for more detailed evaluation. Conceptual designs and cost data for these concepts were prepared. These data were reviewed at a workshop in September 1980 that included most of the developers of the concepts that were to be evaluated. The data from the workshop are documented [3] including the preliminary cost data on the original 40 concepts. After the workshop, the list of concepts was revised, conceptual descriptions were modified, and some special cases were evaluated. Section 3.1 presents the concepts that were analyzed in detail, and Sec. 3.2 describes some examples.

3.1 CONCEPTS FOR FINAL EVALUATION

The thermal storage concepts for the water/steam receiver (power) system are shown in Table 3-1. Water can be preheated and boiled at moderate temperatures, but superheating water requires high temperatures. Two-stage thermal

Table 3-1. Thermal Storage Concepts for a Water/Steam Receiver (Power)

	First Stage[a]	Second Stage[b]	Rationale
1.	Caloria/granite	Draw salt (two-tank)	
2.	Caloria/granite	Air/rock	Experiment on second-stage concepts
3.	Caloria/granite	Sand, moving bed	
4.	Pressurized water - Underground - Above ground	Draw salt (two-tank)	
5.	Underground oil/rock	Draw salt (two-tank)	Experiment on first-stage concepts
6.	Caloria (two tank)	Draw salt (two-tank)	
7.	Tube-intensive HX	Draw salt (two-tank)	
8.	Containerized salt	Draw salt (two-tank)	
9.	Direct-contact HX, phase change	Phase-change media	Unique capability
10.	Finned-tube-intensive	Draw salt	New concept--6 hours only

[a]The first stage provides the capability to boil water at 3.2 MPa (468 psia) producing a saturated vapor at 238°C (486°F).

[b]The second stage superheats the steam to approximately 510°C (900°F) for delivery to the IP/LP turbine.

energy storage concepts provide the energy needed to preheat and boil water in the first stage and superheat in the second stage. An analytical comparison of latent-heat storage heat exchange (HX) methods was made for water/steam (power) first-stage latent heat storage concepts. The same phase-change media, NaOH, $NaNO_3$, MnO_2 ("Thermkeep"), were used for the four latent-heat storage concepts--i.e., tube-intensive, direct-contact, rotating drum scrapper, and containerized salt. A preliminary cost evaluation indicated that the tube-intensive concept had the highest evaluated system cost, followed by the rotating drum scrapper HX, the direct-contact HX, and containerized salt. Because there were insufficient test data on the rotating drum scrapper HX, that concept was discountinued in the final screening process. Work continued on the tube-intensive HX, the direct-contact HX, and the containerized salt concepts through conceptual design and cost analysis phases.

Table 3-2 shows the thermal storage concepts selected for the water/steam receiver process heat application. For latent-heat concepts, the containerized salt storage concept was selected as representing all phase-change systems in this specific application. A finned-tube-intensive phase-change concept was added late in the study.

The thermal storage concepts selected for the reference total energy system are shown in Table 3-3. As indicated in the table, for the Caloria receiver total energy and process heat system cases, no concept showed more promise than Caloria/granite or Caloria (two-tank).

Table 3-2. Thermal Storage Concepts for a Water/Steam Receiver (Process Heat)

Concept	Comments
1. Caloria/granite	Reference system
2. Underground pressurized water	Low-cost media
3. Oil/rock--excavated concrete pit	Test of alternate containment of oil/rock system (most favorable condition for alternative containment, i.e., largest quantity of oil and rock and thus largest tank)
4. Containerized salt	Representative of phase-change system[a]
5. Finned-tube-intensive, latent	New concept--6 hours only[b]

[a]Initially, containerized salt was the only phase-change thermal storage concept to be evaluated for process heat. The comparative ranking on latent heat systems is conducted in the water/steam receiver electric power case (see Table 3-1).

[b]Finned-tube-intensive latent heat thermal storage was added late in the study, so only a limited evaluation was performed. This data point also provides a means of validating the latent-heat rankings conducted in the water/steam electric power case.

Table 3-3. Thermal Storage Concepts for an Organic Fluid Receiver

Concept	Rationale
Syltherm receiver	Total energy system
1. Syltherm 800/taconite	Reference system
2. Molten salt	Does not require oil-to-rock contact
3. Direct-contact phase change as two-stage system	Representative of phase-change[a] systems (sensible heat stored in melted phase-change media)
Caloria receiver[b]	
Total energy system None	Nothing identified with more promise than Caloria/granite or Caloria only (two-tank)
Process heat only	
None	Nothing identified with more promise than Caloria/granite or Caloria only (two-tank)

[a]Only one latent-heat system was evaluated in this application. The comparative ranking of latent thermal storage concepts is conducted in the water/steam receiver electric power case (see Table 3-1).

[b]Several concepts were investigated and preliminary cost data were generated (see Ref. 3).

The storage concepts selected for the closed air/Brayton cycle solar thermal system are shown in Table 3-4, including two sensible heat, internal heat transfer concepts, air/alumina brick, the reference concept, and an air/cast iron OPT (Meehanite). The air/granite storage concept was evaluated to test external heat exchange systems, and a latent-heat concept was evaluated that represented a test of phase-change storage concepts.

Table 3-4. Thermal Storage Concepts for a Closed Air/Brayton Receiver (Power)

Concept	Rationale
1. Air/Al_2O_3 brick (internal heat transfer)	Reference system
2. Air/cast iron (Meehanite) internal heat transfer)	More effective media
3. Air/granite (external heat exchanger)	Test of external heat exchange storage systems
4. Latent heat	Test of latent-heat storage--6 hours only

Special studies were also conducted to evaluate the influence of alternative organic fluids. Caloria was selected for all oil/rock and oil (two-tank) storage. Alternative 316°C (600°F) fluids were considered for the following applications:

- Water/steam receivers
  - -electric power
  - -process heat
- Organic fluid receiver
  - -process heat

Since the decomposition of Syltherm at 399°C (750°F) was identified as a potential problem, alternative fluids were evaluated.

3.2 A DESCRIPTION OF THE CONCEPTS

Detailed descriptions of all the concepts are contained in the S-R final report (Vol. II of this document). System schematics, equipment sizes, and material usage for 1, 6, and 15 hours of storage are included. The following paragraphs describe one example concept for each of the applications that were evaluated in detail.

3.2.1 Water/Steam Receiver, Power Concept

For the water/steam receiver (power) application, the TES system schematic is shown in Fig. 3-1. A modified tube-intensive latent-heat storage concept, currently in the conceptual design stage at Comstock & Wescott and Combustion Engineering (C&W/CE) [4], was evaluated for six hours of storage. The second-stage sensible heat draw salt (two-tank) storage system is identical to that for the reference system.

The C&W/CE design (see Fig. 3-2) consists of rectangular steel tanks filled with salt and rectangular modular tube bundles; each tube bundle, in turn, consists of a number of parallel, small-diameter, seamless carbon steel tubes. The tubes are fabricated into a serpentine configuration and are separated and supported by closely spaced channel shapes formed from light-gauge sheet aluminum and carbon steel. These channel shapes are known as "heat transfer enhancement sheets" because they also promote heat transfer by acting as extended surfaces from the tubing to the salt mass. C&W/CE computer simulations of the concept design selected indicate that the overall heat transfer coefficient (calculated using external tube area only) is over 480 J/s-m^2-°C (80 Btu/h-ft^2-°F).

C&W/CE's current concept design work has been based upon the use of the NaOH-$NaNO_3$ eutectic (81.5 mol % NaOH) which does not have a high enough melting temperature for best application to the water/steam receiver (power) cycle. Accordingly, "Thermkeep" (91.8 wt % NaOH, 8% $NaNO_3$, 0.2% MnO_2), with a melting point of 292° C (558°F), was selected for the SERI study. The tube diameter, 0.15-m (0.5-ft) spacing, horizontally and vertically, and the 1.91-cm

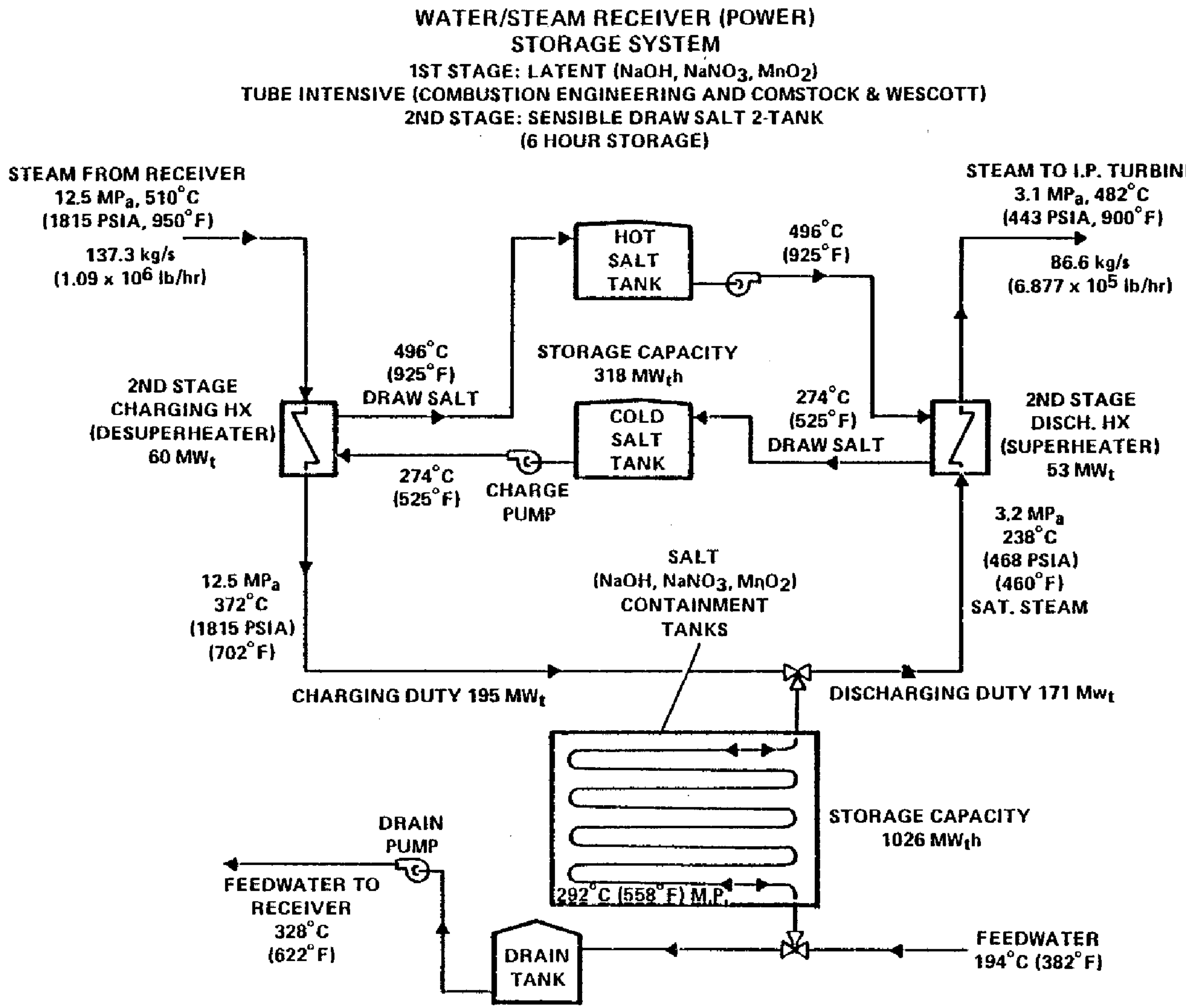


Figure 3-1. Thermal Storage Subsystem--Finned-Tube-Intensive (Latent)

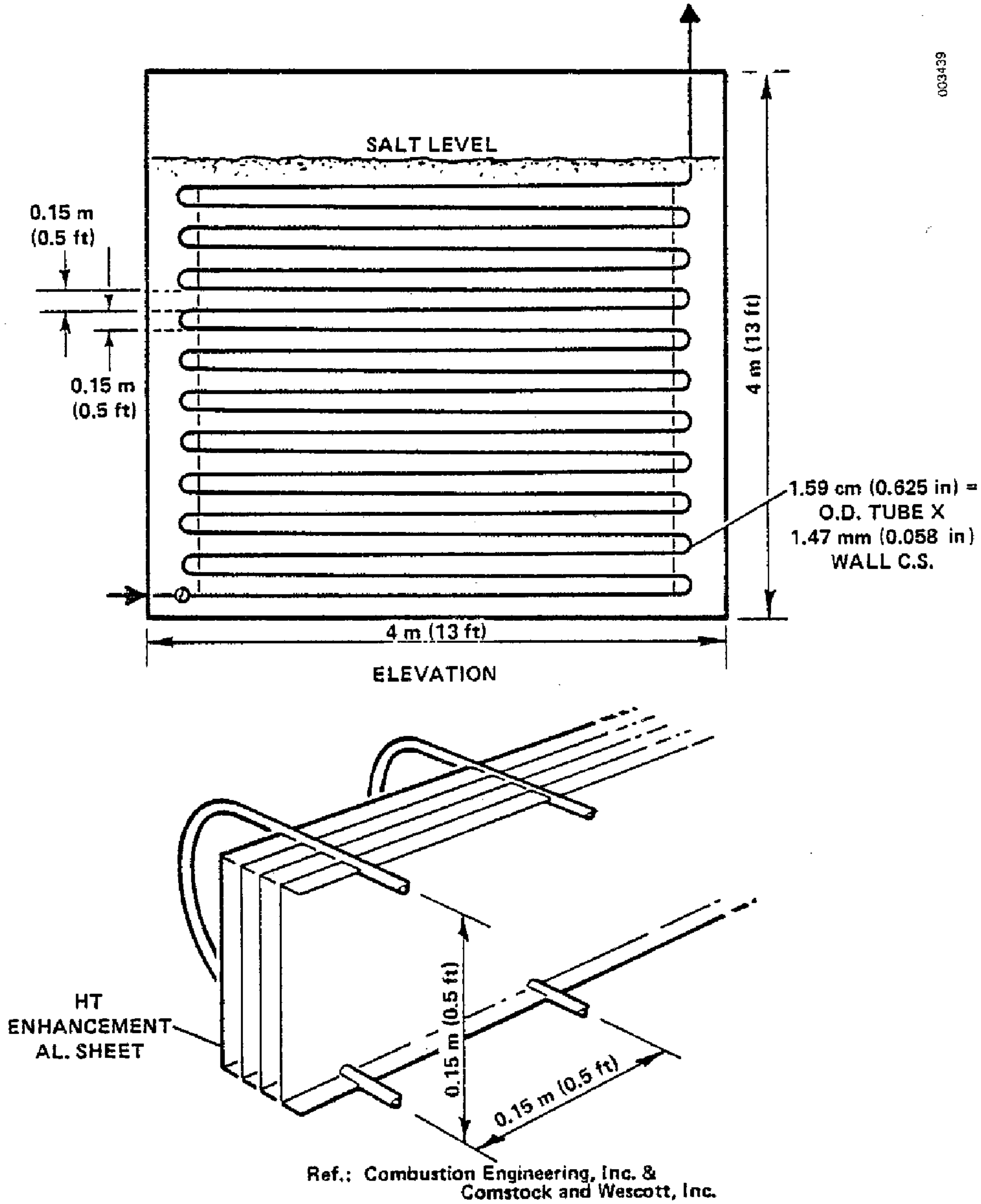


Figure 3-2. Finned-Tube-Intensive Concept

(0.75-in.) heat transfer enhancement sheet spacing of the C&W/CE concept have been retained. SERI's calculated (discharging) overall heat transfer coefficient is lower (by about 15%) than the one used by C&W/CE, so the design should be conservative if C&W/CE computer simulations are accurate.

The modified tube-intensive HX latent-heat thermal storage concept currently under study by C&W/CE appears to offer cost advantages. However, some technical questions need to be addressed in the development of this type of system:

- Will serpentine coils (with long, horizontal segments) be subject to sluggish flow when operating in the charging (condensing) mode and in the discharging (evaporating) mode?
- Can effective contact be maintained between the tubes and the heat transfer enhancement sheets?
- Considering the large number of tube welds required, can tube leaks be avoided and, if not, can the leaks be detected, located, and repaired easily?
- If carbon steel tubes are used and a leak does occur, will the resulting evolution of hydrogen constitute a safety hazard?

3.2.2 Water/Steam Receiver, Process Heat Concept

Figure 3-3 presents a TES for a water/steam receiver in a process heat application. The underground pressurized water storage concept proposed for this application utilizes an underground steel-lined cavity, as shown in Fig. 3-3. The cavity would be located approximately 549 m (1800 ft) below grade in a solid rock or solid salt formation. Demineralized water is used as the storage medium.

As indicated in Fig. 3-3, the receiver steam is supplied during charging directly into the underground water containment where it is condensed, which increases the pressure and temperature of the water. During discharging, steam is admitted through a pressure control valve which maintains 7.2 MPa (1000 psia) of pressure. As steam is removed from storage, the pressure in the cavity decreases and more water is flashed to steam. The pressure in the cavity ranges from 11.9 MPa (1725 psia) fully discharged with a corresponding temperature range of 324°C (615°F) to 7.2 MPa (1050 psia), 288°C (550°F). Although this is not shown on the diagram, it is necessary to add a small amount of feedwater to storage during charging in order to achieve a mass and enthalpy balance between charging and discharging.

The underground pressurized water requires a suitable subterranean structure, so it is site-specific. Probable sites have been identified in 47 states, but not in all areas of each state. Risks are involved, however, because of the unknown behavior of the large steel-lined cavities when they are subjected to thermal and pressure cycling. Underground construction involves uncertainties in methods and costs that are not reflected in this study.

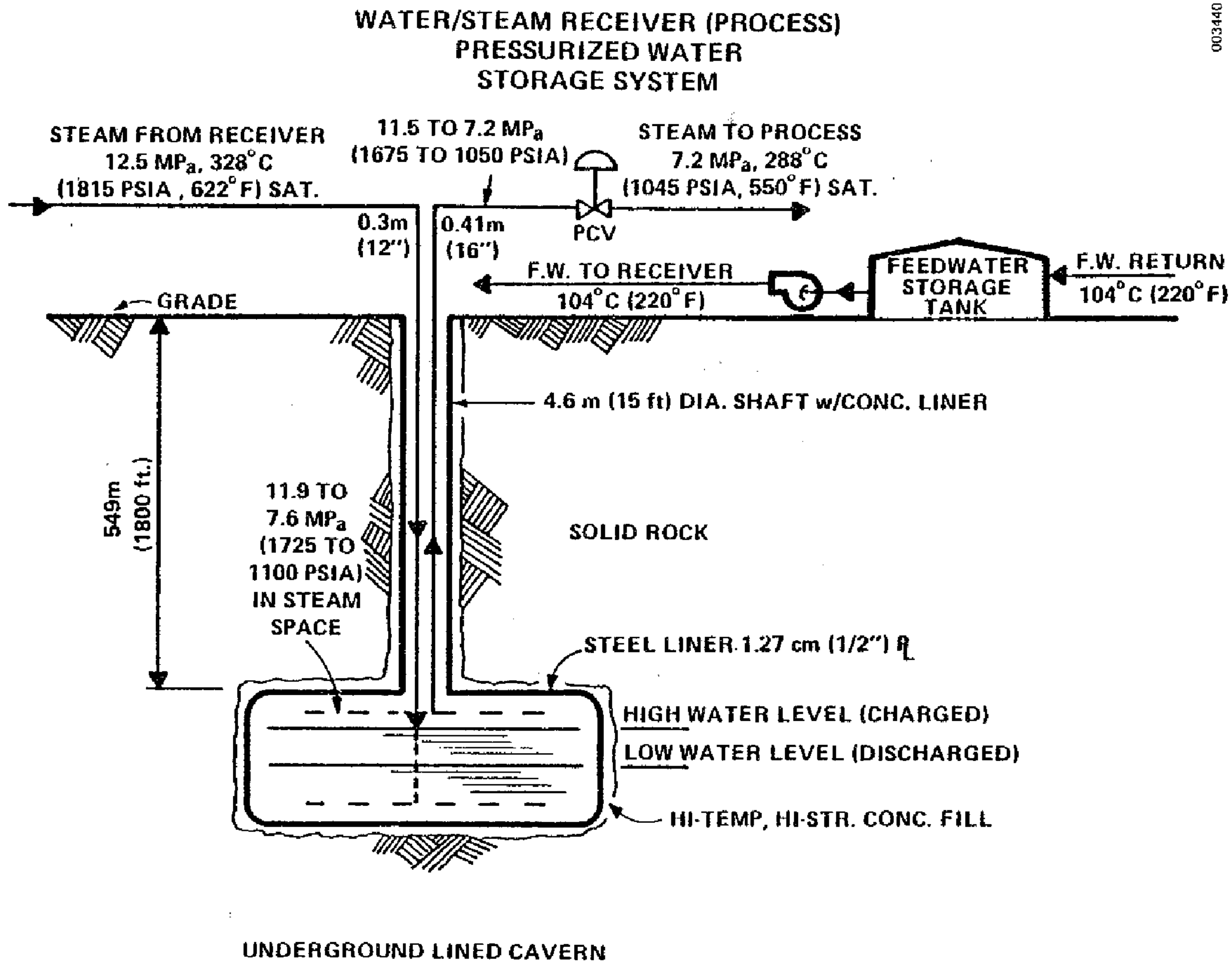


Figure 3-3. Thermal Storage Concept for Underground Pressurized Water

3.2.3 Organic Fluid Receiver (Total Energy) Concept

A flow diagram showing thermal energy storage for the organic fluid receiver system is shown in Fig. 3-4. The direct-contact concept utilizes the latent-heat as well as the sensible-heat properties of a salt mixture in a two-stage combined system. The first stage incorporates a solid-liquid salt phase change with a unique spray chamber system, which is being developed by Grumman Aerospace Corporation [5]; the second stage incorporates a sensible two-tank system using only a hot salt tank, since the cold tank was part of the first stage.

During the discharging mode, the first-stage discharge pump takes molten salt at 310°C (590°F) from the first-stage liquid salt storage tank and pumps it to the main spray chamber where it is mixed with liquid lead-bismuth (Pb/Bi) at 279°C (534°F). The hotter molten salt gives up its latent heat as it freezes into salt granules to the cooler Pb/Bi fluid. Then, primarily because of the large difference in specific gravities of the two substances, the salt granules float to the top of the chamber and carry over the sides to be deposited in the bottom of the tank as granules of solid salt. In the process, the liquid Pb/Bi mixture is heated by the freezing salt to 299°C (570°F) and, after sinking to the bottom of the spray chamber, is pumped away to the liquid metal storage tank and then on to the first stage of the discharging heat exchanger (evaporator/preheater). There, it is cooled back to 279°C (534°F) to complete the cycle. At the same time, the second-stage discharge pump takes molten salt at 385°C (725°F) from the second-stage hot tank and pumps it through the second stage of the discharging heat exchanger (superheater) where it is cooled to 310°C (590°F) while generating steam at 4.92 MPa (715 psia), 371°C (700°F). The discharge steam flow rate, because of the lower throttle temperature, had to be increased approximately 1% over the reference storage system to maintain a constant thermal discharge rate of 2.11 MW_t. The cooled molten salt then continues back to the liquid salt storage tank. Note that the direct-contact phase-change concept has been sized to handle the full receiver output of 4.69 MW_t. As it is presently conceived, this direct-contact storage concept does not allow steam generation directly from the receivers except when it passes through the storage system. In this respect, the system is always operating from storage when generating steam.

Because the second stage is a molten salt two-tank thermal storage system, its technical feasibility is reasonably certain. However, the technology proposed in the first stage has not been demonstrated. For example, the Pb/Bi and the salt mixture are supposed to be immiscible fluids, but some carryover should be expected. The following issues are a few of many that must be resolved:

- How much carryover will there be of salt to Pb/Bi or Pb/Bi to salt, or both?
- How will carryover affect the properties of the Pb/Bi and the salt?
- How will carryover affect the makeup requirements of the Pb/Bi and the salt?
- How effective will the direct-contact heat transfer be?

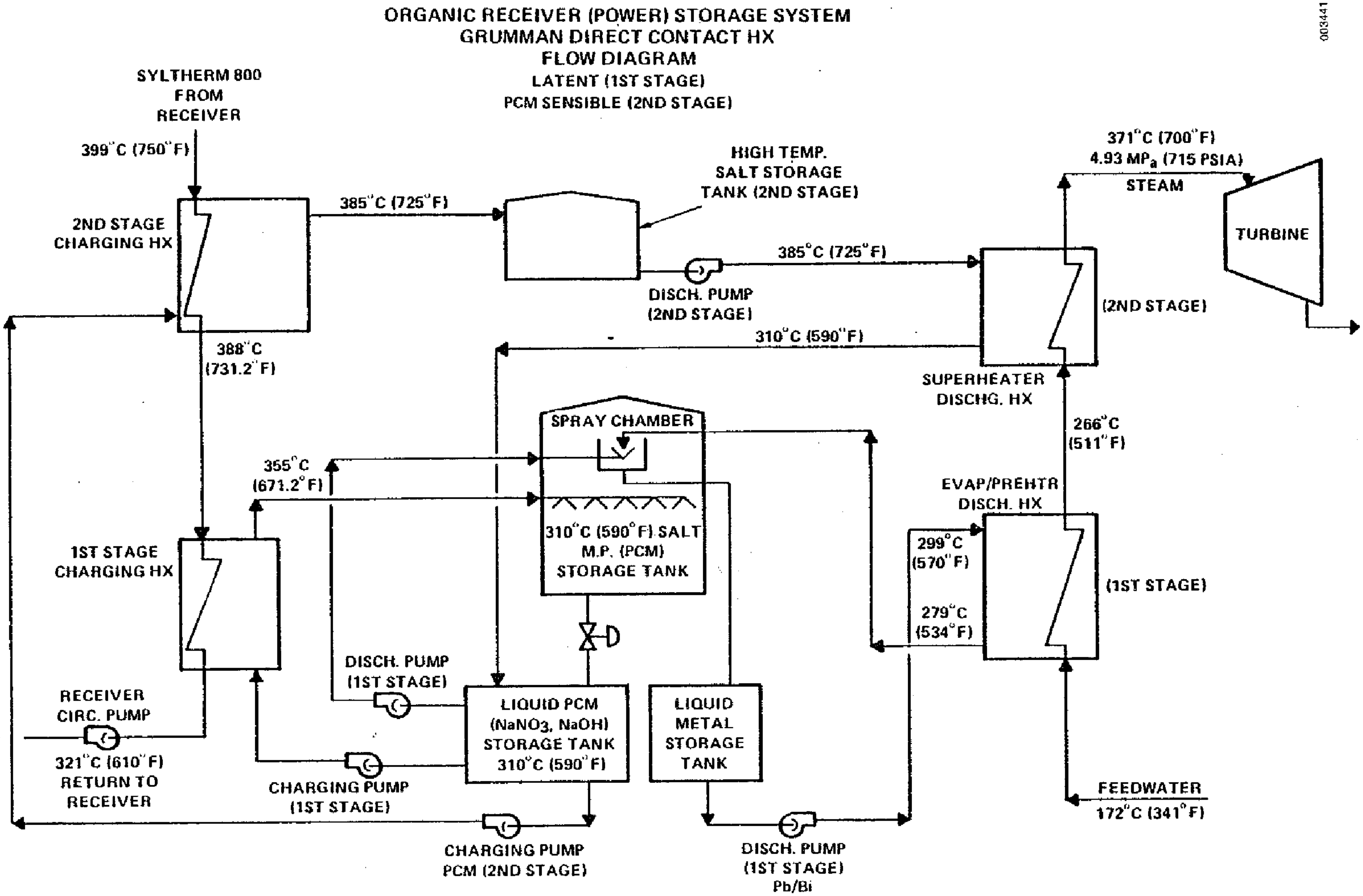


Figure 3-4. Thermal Storage Concept for a Latent, Direct-Contact PCM (Two-Stage)

Because of the many uncertainties surrounding the first stage of this concept, a 4% O&M has been assigned to the first stage, as opposed to 2% on the second stage.

3.2.4 Closed Brayton Cycle Concept

Figure 3-5 presents the TES for the closed Brayton cycle system. The latent-heat, tube-intensive HX six-hour thermal storage system is a scale-up of an earlier Boeing Engineering and Construction concept [6]. The Boeing design was for six hours of thermal storage for a 50-MW_e turbine. The present storage concept consists of a large buried rectangular concrete thermal storage tank with internal insulation (refractory brick) and a superalloy liner. The thermal storage medium contained in the tank is the eutectic salt 7 wt % CaF_2-54% KF-39% NaF; this salt has a melting temperature of 682°C (1260°F). A large number of parallel, vertical Inconel 617 tubes contain the working fluid that transfers heat to or from the thermal storage medium. The tubes are arranged in a rectangular array with centerline spacings of 8.54 cm (3.362 in.); the outside diameter of the tubes is 1.049 cm (0.413 in.) and they are constructed of 22 BWG tubing. The tubes are connected to large inlet/outlet piping at the top and bottom by "capillary network" manifolding. (See flow diagram, Fig. 3-5.) This manifolding is complex with many levels of branching but the alternative, high-pressure plenums--such as the heads in a single-pass shell-and-tube heat exchanger--would not be practical for such a large, high-pressure vessel.

The piping is arranged so that hot working fluid enters or leaves the vessel at the top and cold working fluid enters or leaves from the bottom; i.e., during charging, hot working fluid enters the top and during discharging, cold working fluid enters the bottom. As a result, the melt pool is always on top of the solid salt, eliminating the possiblity of void formation, and consequent heat transfer impairment, during salt solidification. A circulation compressor, consisting of a large electric motor-driven centrifugal compressor, is provided to make up the pressure drop (4% of the compressor outlet pressure) through the storage unit (and through the receiver during standalone operation).

Boeing's configuration for the phase-change thermal energy storage system is based on the use of helium as a working fluid--a popular working fluid in 1976. Boeing has since reported work on thermal energy storage systems for closed Brayton cycles using air as a working fluid [3], but these were sensible heat storage systems. Since the physical properties of helium are so much different from those of air--i.e., helium has almost five times the heat capacity, over seven times the specific volume, and has a much higher thermal conductivity than air--Boeing's latent-heat thermal storage system is likely to have been different, and more expensive, had it been optimized for air as the working fluid. Since it was outside the scope of S-R's effort to redesign and optimize the thermal storage system using a different working fluid, S-R has scaled up the Boeing system for 2-6 hours × 75-MW_e modules, retained the helium working fluid, and assumed the same average turbine cycle efficiency that Boeing estimated for the two 50-MW_e helium turbines of their concept.

If the thermal storage system is fully charged, the initial helium outlet temperature will be essentially the same as the receiver temperature, 816°C

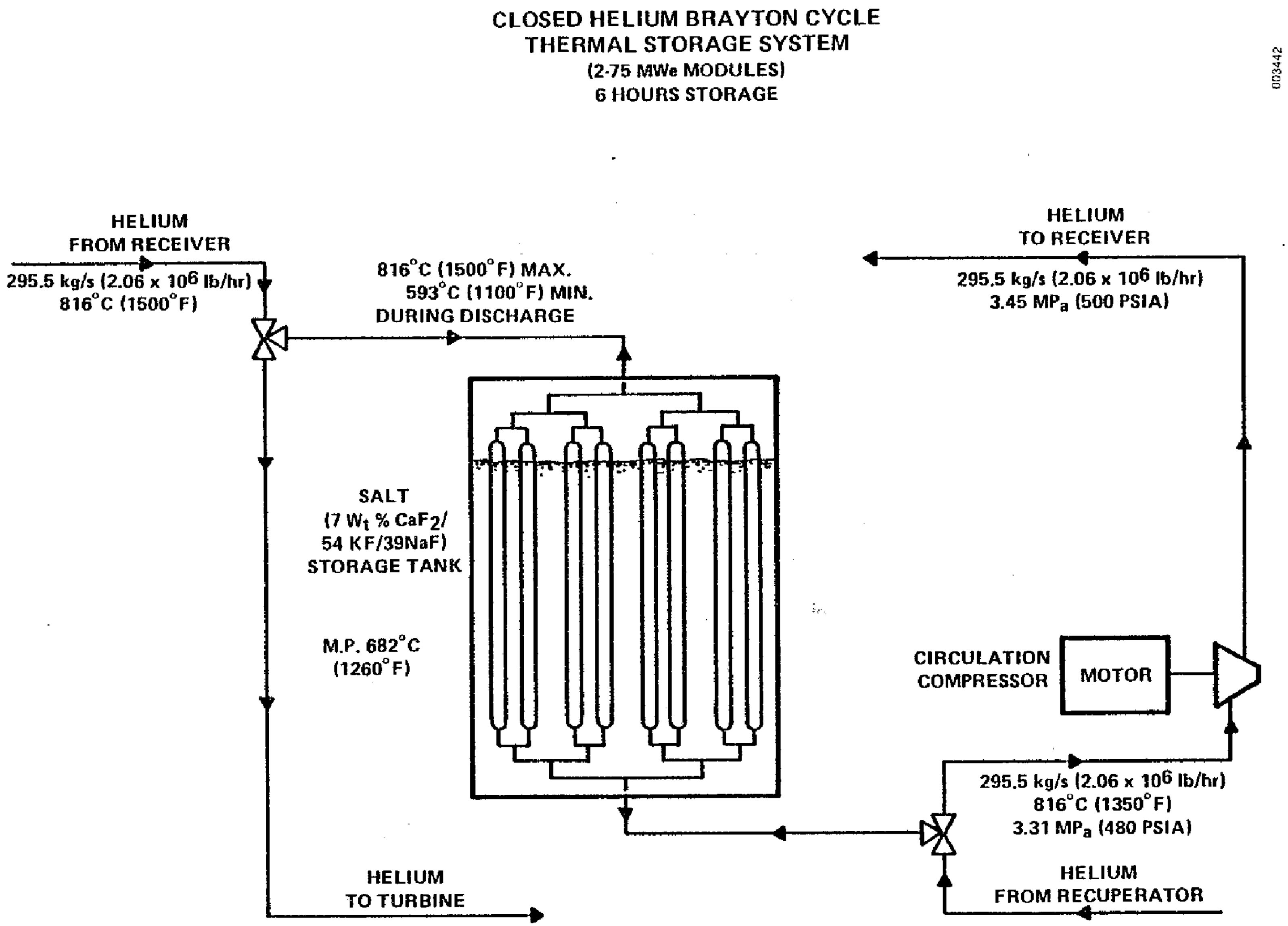


Figure 3-5. Thermal Storage Concept for a Latent-Heat Tube-Intensive Heat Exchanger, Air/Brayton

(1500°F), but that temperature will drop rapidly to essentially the salt freezing temperature and remain there for some time. As most of the tube's surface becomes surrounded by fused salt, temperature gradients appear and the outlet temperature will drop below the salt freezing temperature. When the helium outlet temperature drops as low as the minimum turbine inlet temperature (593°C or 1100°F), the system is fully discharged and operation from storage terminates. By employing variable-pressure operation, rated turbine output can be maintained during the entire discharge cycle. Average turbine gross cycle efficiency is only 34.1%, however; consequently, a larger thermal storage system and a larger solar multiplier are required than would be the case if a higher turbine inlet temperature and resulting higher efficiency could be maintained.

Boeing reported in Ref. [6] that the principal obstacle to the development of phase-change tube-intensive thermal energy storage systems suitable for high-temperature Brayton cycles is that salts that are thermally and chemically stable at such high temperatures tend to be corrosive to superalloy metals used to contain the salts. Oak Ridge National Laboratories has done some research on salt corrosivity for the molten salt reactor program and is developing protective liners such as Hastelloy N. Phillips Laboratories of Germany has proposed the use of gettering agents such as powdered aluminum to react with the corrosive impurities in the salt to protect the low chromium superalloys used for heat exchanger tubing. Boeing reports that

> Considerable experimental testing of this approach will be required to verify the suitability of the heat exchanger tubing for a 30-year life... . It appears that with adequate testing, appropriate materials and corrosion control agents can be obtained for the phase-change concept.

Another question that must be answered regarding the Boeing phase-change tube-intensive HX thermal storage concept is how much of its cost advantage can be maintained if its design is changed to accommodate an air working fluid. It is likely that the tubing cross-sectional area, and hence, costs, will increase if system frictional losses are held to economical levels.

SERI

SECTION 4.0

COST ANALYSIS

4.1 SCOPE

This section presents the methodology that was used to cost and evaluate various thermal storage concepts in solar thermal systems. The capital cost and present worth summaries are also presented for each thermal storage concept costed for 1, 6, and 15 hours of storage.

4.2 METHODOLOGY

Capital cost estimates were prepared for each thermal storage concept using current materials prices, equipment cost estimates, budget quotations, and construction cost factors based primarily on S-R's past experience in electric utility plant cost estimating and construction. Cost estimates were prepared for these major items:

- Energy-related equipment
  - tanks
  - tank insulation and lagging
  - tank foundations
  - piping
- Power related equipment
  - pumps/compressors/fans
  - heat exchangers
- Storage media
- First-year variable costs
  - O&M
  - energy (parasitic power)
  - chemical usage
- Major replacement costs.

Costs are presented in 1980 dollars and include material and equipment, field installation, indirect field costs, and engineering.

4.2.1 Construction Cost Factors

The methodology used to arrive at a total capital investment cost incorporated a number of cost factors, or multipliers, to convert fabricated material and factory equipment costs to direct field costs and total capital investment. These construction cost factors are based on S-R's experience with similar construction and previous studies. The cost equation used is as follows:

$$CI = 1.95\ [1.8\ (CE + CP) + MEDIA]\ ,$$

where

CI = capital investment

CE = energy-related equipment cost

CP = power-related equipment cost

MEDIA = media cost

1.8 = multiplier on equipment cost to arrive at direct field cost (accounts for field labor)

1.95 = multiplier on direct field cost and media to arrive at total capital investment.

The 1.95 capital investment factor includes

- engineering
- interest during construction
- fees, permits, state and local taxes
- indirect field costs, including
  - field expense
  - temporary facilities
  - construction equipment
  - payroll taxes, insurance
  - performance bonds
- contingency allowance.

For purposes of this study, it was assumed that the construction cost burdens apply equally to all capital expenditures.

4.2.2 The Economic Method

The economic method S-R used to evaluate various thermal storage concepts is present worth revenue requirement (PWRR). The PWRR method has become the standard for the electric utility industry and other industries as well. The economic model used in this study is based on the methods of analysis outlined in a July 1979 EPRI report [7].

The economic model gives the PWRR for each thermal storage concept. The ones with the lowest PWRR values are the most desirable economically. Based on the various economic tables and assumed economic factors, the PWRR equation is

$$PWRR = PWFC + PWVC + PWRC$$

where, for typical economic factors for an investor-owned utility,

PWFC = present worth of fixed costs = 1.6 × (CI)

PWVC = present worth of variable costs (operations and maintenance and fluid or chemicals replacement) = 20.1 × (FYVC)

PWRC = present worth of replacement costs = (replacement cost in Xth year) × (P/F)

where (P/F) = series present worth factor for replacement year X.

The third term, PWRC, was not used in the study because no major replacement costs were identified for any thermal storage concept.

4.3 PWRR DATA

4.3.1 Water/Steam (Power)

Figure 4-1 presents the PWRR of the concepts evaluated for a water/steam receiver in an electric power application. Only three concepts represent cost improvements over the reference system: (1) finned-tube-intensive (latent heat), (2) underground pressurized water, and (3) direct-contact (latent heat). Data for the finned-tube-intensive concept are for only six hours of storage. This concept had not been described when the S-R study began. Combustion Engineering [4] provided data late in the S-R study; consequently, only a limited analysis was possible. Costs of the finned-tube-intensive concept at 1 and 15 hours are uncertain. The slope of the PWRR vs. storage capacity line should be similar to that of concept 7 (another tube-intensive concept). At one hour's storage capacity, the costs are probably less than concept 1 (oil/rock); at 15 hours, the costs are probably equivalent to concept 9 (direct-contact, latent). At high storage capacities (15 hours), substantial cost reductions are possible with underground pressurized water.

4.3.2 Water/Steam (Process Heat)

Figure 4-2 presents the PWRR of concepts evaluated for a water/steam receiver in a process heat application. Underground pressurized water is the lowest-cost storage concept for all storage capacities greater than about one hour. The finned-tube-intensive concept is evaluated only at six hours' capacity. Assuming the slope of the PWRR line is similar to that of containerized salt, the finned-tube-intensive concept is less than oil/rock at one hour, and between underground pressurized water and containerized salt at 15 hours. The excavated concrete pit is lower in cost than the oil/rock reference concept. In process heat applications, there are large variations in plant ratings. In fact, many applications are much smaller than those evaluated in this study. Except for underground pressurized water, our results are not particularly sensitive to scale. The underground system, however, is not applicable to sizes less than 100 MW_t.

4.3.3 Organic Fluid, Total Energy

Figure 4-3 presents the PWRR for an organic fluid receiver (Syltherm) in a total energy application. Caloria receivers for both process heat and total energy applications were considered as part of this study; however, data obtained early in the study demonstrated that no second-generation thermal

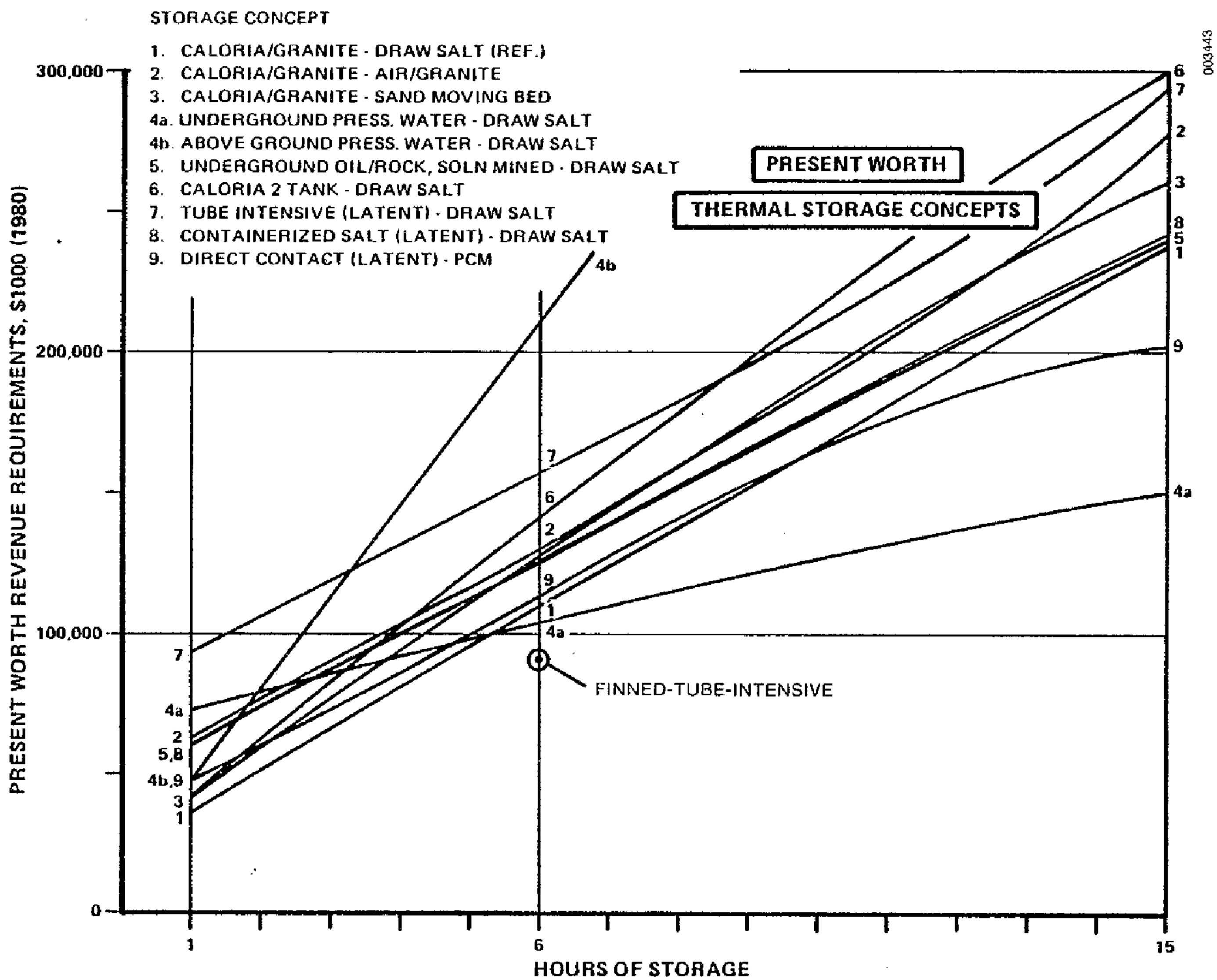


Figure 4-1. Present Worth Revenue Requirements for a Water/Steam Receiver (Power)

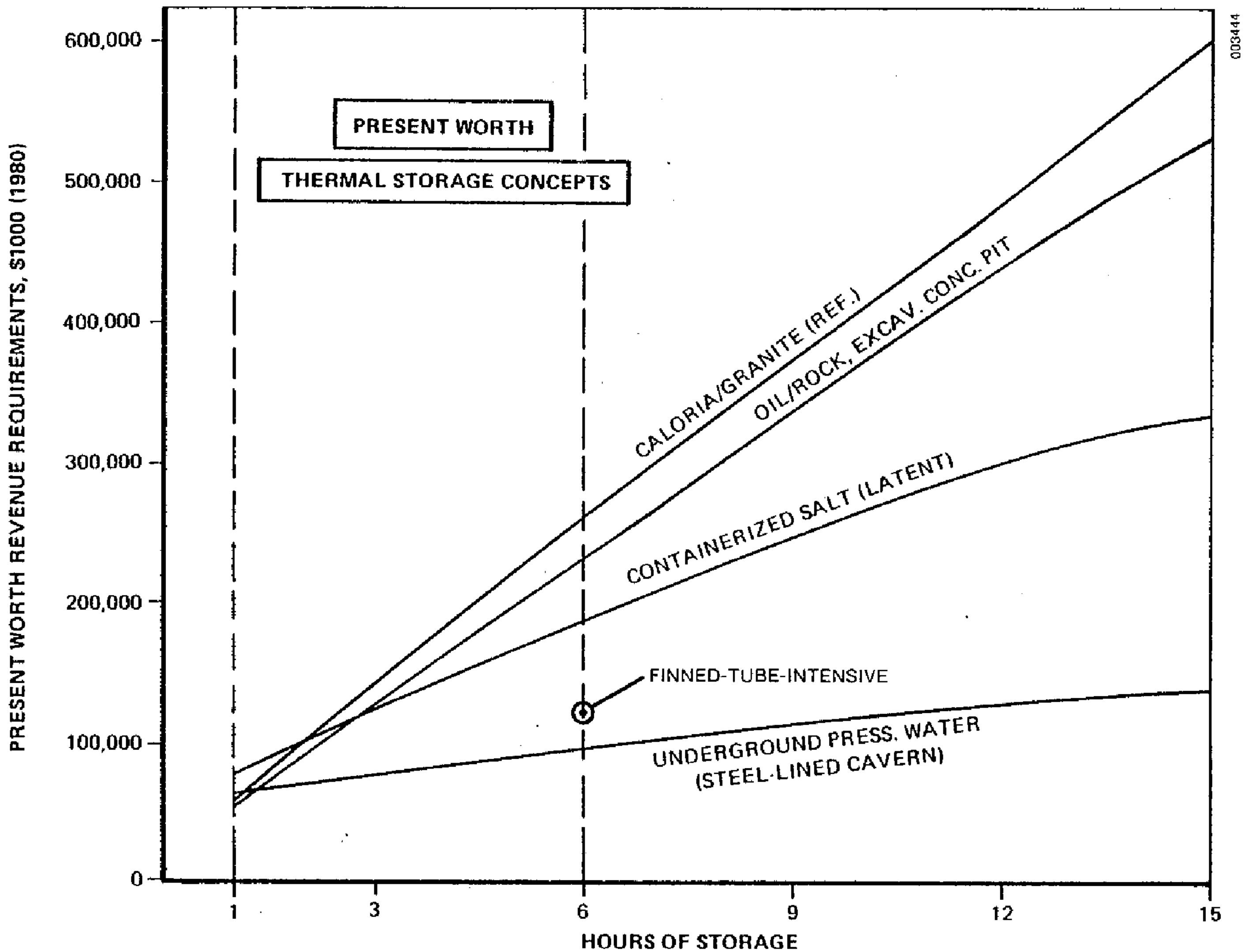


Figure 4-2. Present Worth Revenue Requirements for a Water/Steam Receiver (Process Heat)

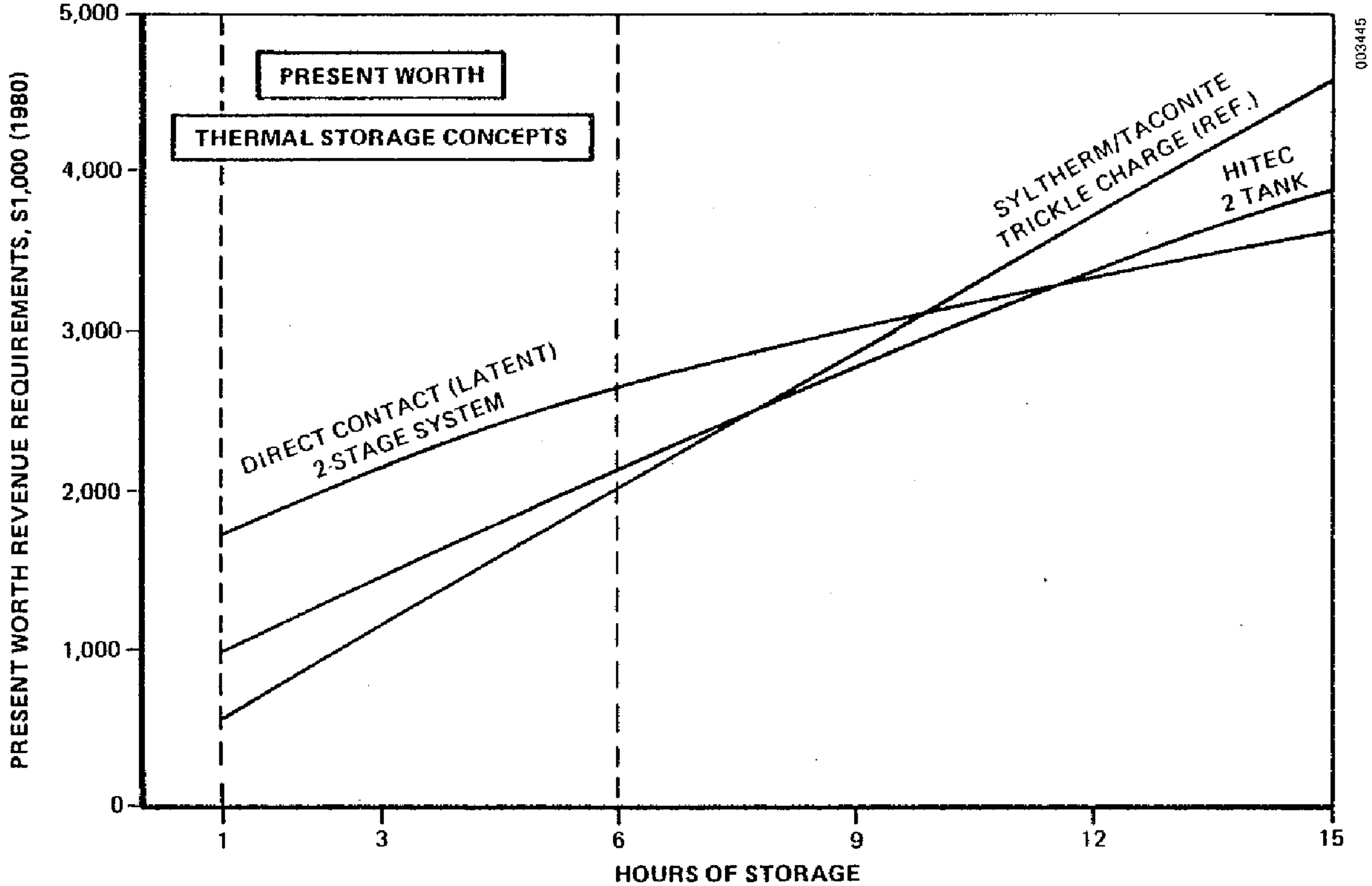


Figure 4-3. Present Worth Revenue Requirements for an Organic Fluid Receiver (Total Energy)

storage concept identified had a potential for lower cost than the first-generation concepts (oil/rock or oil, two-tank). More effort was then applied to the water/steam receiver cases, because the results of the Caloria receiver case made it obvious that that system was not appropriate.

4.3.4 Closed-Cycle Air/Brayton

Figure 4-4 presents the PWRR of thermal storage concepts with an air-cooled receiver in a Brayton-cycle electric power application. The external heat exchanger with oil/rock storage is very high in cost, primarily because it employs a large, high-temperature, air-to-air heat exchanger. Since the charging heat rate increases to provide a larger amount of heat during the collection period, the charging heat exchange increases with size. No advantage occurs with this concept at any storage capacity. Other external heat transfer concepts (e.g., moving sand beds and fluidized beds with sand storage media) may be lower in cost than the air/rock concept; however, due to the similarities (all require a pressurized air heat exchanger on at least one side and all have a low cost storage medium) and the large cost differences from the air/alumina system, no external heat transfer system is anticipated to have lower costs for this application than the reference concept. In addition, the efficiency of the air/rock concept is significantly lower because of both lower temperatures in the conversion cycle and parasitic power requirements.

The latent-heat concept is lower in cost than the reference concept, air/alumina. However, its overall efficiency is much lower. Because it has such a high return temperature when charging storage, the receiver's efficiency is greatly reduced. Since the air-flow rate must increase because of the reduced temperature difference in the receiver, the parasitic power is increased, which reduces the net power delivered. Also, the air temperature delivered to the turbine when discharging storage is lower than the reference concept, and the cycle efficiency is reduced so less power is generated. The net effect is a low storage efficiency; i.e., only 31.2% can be delivered of the net electric energy that could have been generated if the air/alumina concept had been employed. The impact of such efficiency is presented in Fig. 4-5. The data represent the ratio of the system's busbar energy cost (BBEC) of a solar thermal air/Brayton system to the BBEC of the reference air/alumina concept. The data are presented as a function of the cost of the phase-change (PC) thermal storage subsystem to the cost of the reference system. The estimated cost of the phase-change concept is also presented. At the calculated 31.2% efficiency, delivered energy is more expensive here than with the reference concepts. Because design improvements are possible (i.e., a more efficient receiver design, larger designs for transport piping which would reduce parasitic power, and other phase-change materials), the efficiency was arbitrarily doubled, assuming the same cost. Even with those optimistic assumptions, however, the phase-change concept would increase the system's delivered energy costs.

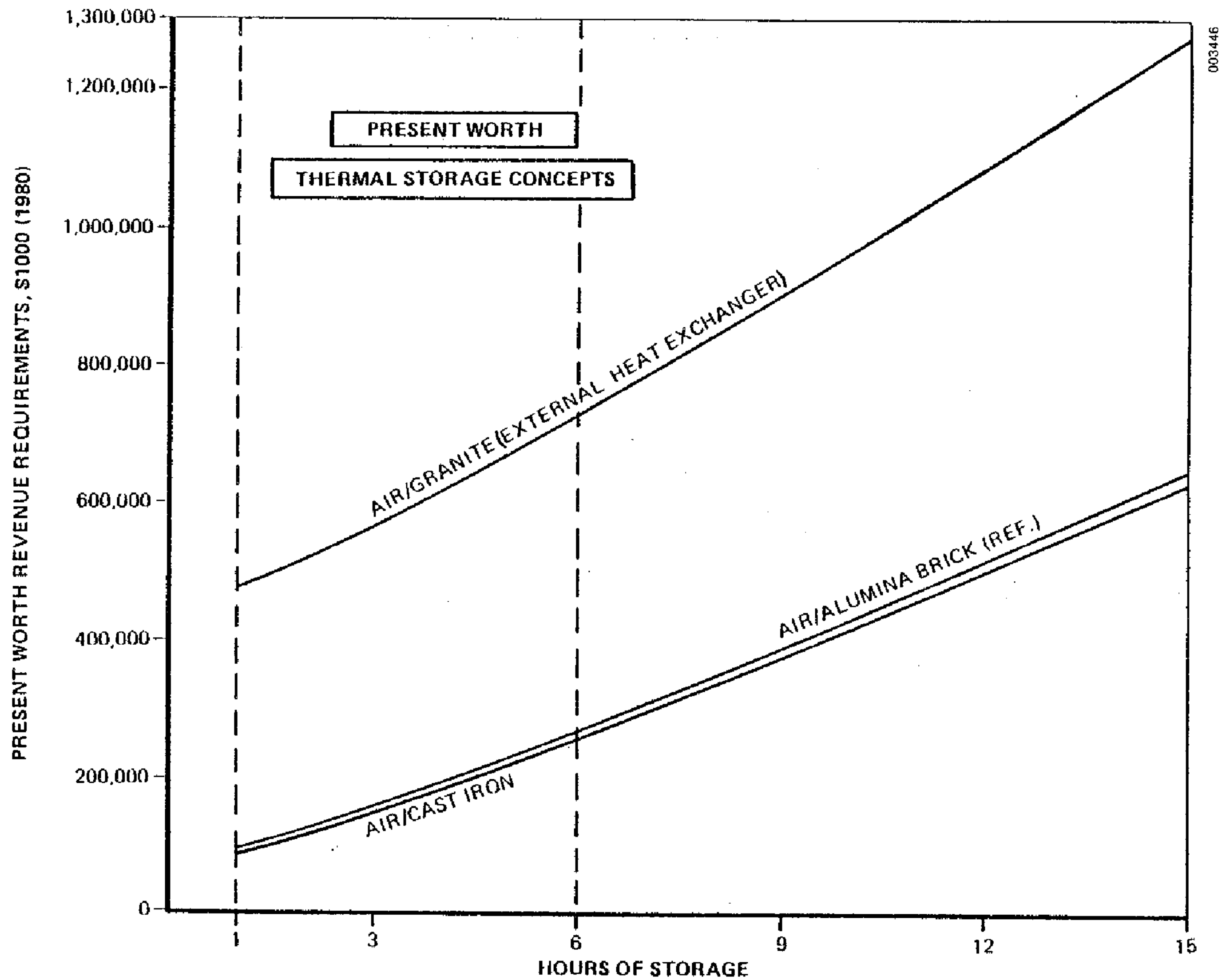


Figure 4-4. Present Worth Revenue Requirements for a Closed Air/Brayton Receiver (Power)

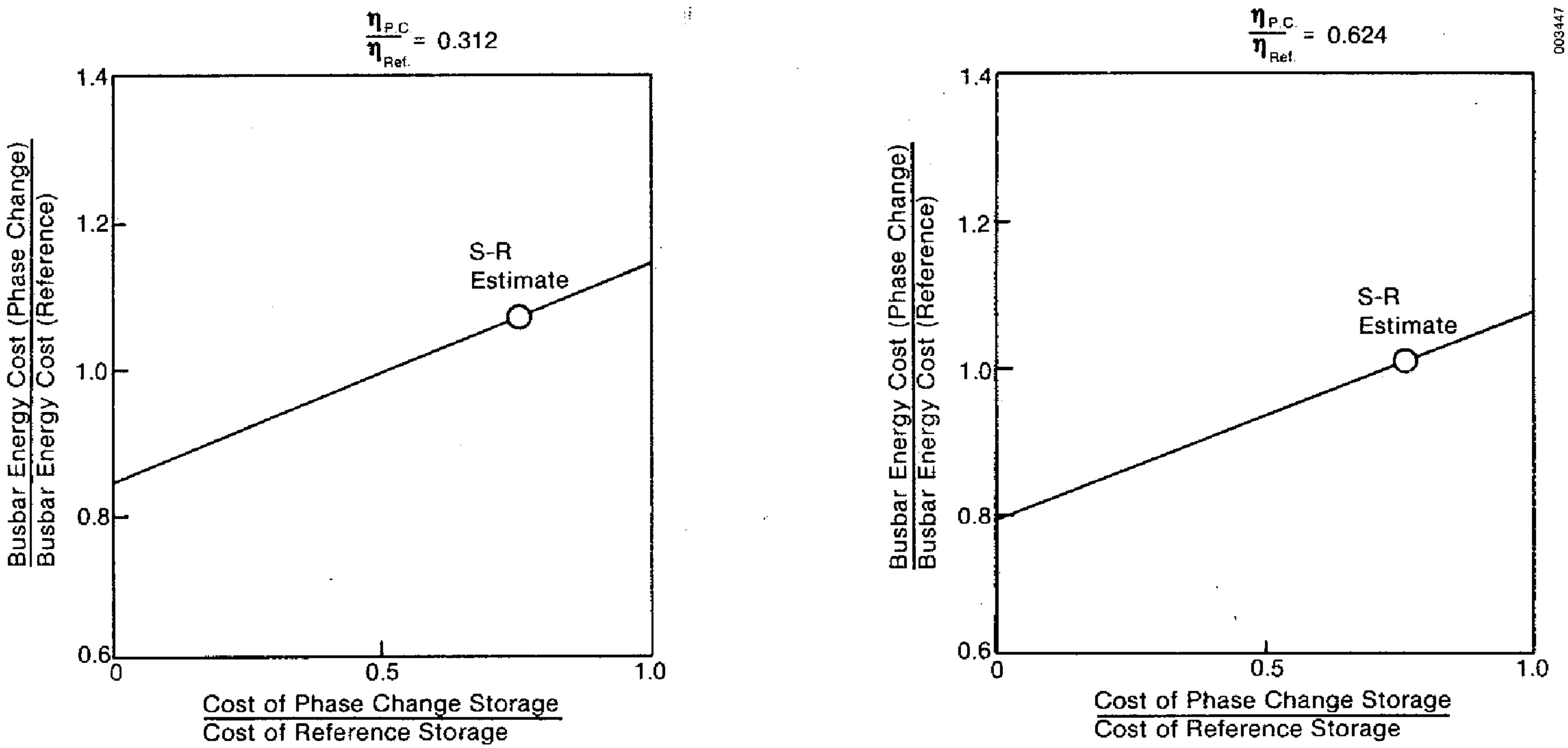


Figure 4-5. Storage Performance Impacts on System Energy Cost for Six Hours, Phase-Change, Air/Brayton

4.3.5 Special Fluid Studies

4.3.5.1 The New 399°C (750°F) Oil/Organic Fluid Receiver System

Scope of the Study. Because Syltherm is high in cost and there is concern over its fluid stability, an alternative 399°C (750°F) receiver fluid was evaluated. The reference thermal energy storage system used with the new receiver fluid was the Shenandoah total energy system, employed in the study with six hours of Hitec two-tank molten salt storage. The system cost of the Hitec two-tank concept, as well as the performance of the system with the new fluid, was to be determined.

Approach. First, an acceptable alternate receiver fluid had to be chosen. The only fluid identified suitable for 399°C (750°F) service was MCS 1980, manufactured by the Monsanto Company. MCS (Monsanto Chemical Sample) 1980 is a proprietary organic heat transfer fluid. It has a higher density, higher specific heat, and lower apparent loss rate than Dow Corning's Syltherm 800, but costs about 10% more, initially. Fluid loss rates, in percent per 2500 hours, for Syltherm 800 and MCS 1980, were taken from test results documented by Burolla [9], with loss rates adjusted to reflect fluid temperatures used in the study. All other characteristics of the fluids were provided by Dow Corning and Monsanto.

In this analysis, all of the receiver loop equipment (i.e., collectors, piping, charging heat exchanger) was unchanged for each different receiver fluid. The only changes involved the size of the circulating pump, because of the different densities of the fluids, and the addition of heat tracing to the MCS 1980 system. This allowed us to use the capital costs obtained in the study and provided a good basis for comparison. With the same size [0.15 m (0.5 ft)] line, pump costs, pumping heads, and pumping power do change. This change was determined using viscosity and velocity ratios to specific powers, using the fluid hydraulic data in Cameron [10].

Results of the alternative receiver fluid evaluation are shown in Table 4-1. The total present worth cost of the system using MCS 1980 is 10.9% less than the system using Syltherm 800, primarily because of the lower fluid loss rate demonstrated by MCS 1980. In addition, for Syltherm 800 to be competitive at the fluid loss rate shown for MCS 1980, the fluid loss rate for Syltherm 800 would have to be 5.8%/yr or less. Obviously, MCS 1980 would be more suitable economically than Syltherm 800 for a 399°C (750°F) receiver fluid application.

In addition to the cost savings caused by its low fluid loss rate, MCS 1980 could provide other cost advantages as well. Because of the higher storage density of MCS 1980 (53% higher), the size of the line in the receiver loop could be reduced to the next smallest pipe size, therefore making a lower inventory of MCS 1980 necessary as well as a lower capital cost for pipe. Insignificant increases in system costs, however, will be caused by increased pumping power requirements. The cost savings resulting from such changes are expected to show that MCS 1980 is more attractive than is evident in Table 4-1.

Table 4-1. Cost Comparison Using Syltherm 800 and MCS 1980 Receiver Fluids with an Organic Fluid Receiver--Total Energy (Six hours' storage)

Receiver Fluid	CE	EP	Media Cost[a]	CI	FYVC	PWRR
	Cost[b] (thousand dollars)					
Syltherm 800	78	125	217	1135	34	2502
MCS 1980	83	124	223	1163	18	2229

[a]Media cost includes receiver fluid and storage media (HITEC).

[b]1980 dollars.

Receiver Loop Heat Loss Evaluation. A heat loss analysis on the receiver loop was performed for the system concept using the MCS 1980 receiver fluid to determine overnight (12-hour) temperature losses in the receiver loop. The fluid temperature after 12 hours of cooling was calculated to be about 204°C (400°F). Overnight heat loss was therefore not considered to be a concern with MCS 1980, because the temperature remained well above the pour point. For 35 days each year, the plant would be down for maintenance or cloudy days. This downtime amounted to a 20-kW_e heat tracing load on the system for 840 h/yr to maintain temperature above the pour point [93°C (200°F)] in the receiver loop when MCS 1980 is used. The cost of this power is included in the FYVC term of Table 4-1.

4.3.5.2 Fluids Cost Sensitivity Analysis

This study was conducted employing Caloria HT-43 as the organic fluid in all oil/rock or oil, two-tank concepts for 316°C (600°F) or less service.

Scope of the Study. During the course of the study, we discovered that fluid costs and loss rates both had significant impacts on the cost of the total thermal storage system. To evaluate the effect for fluids other than Caloria, a 600°F fluid cost sensitivity analysis was adopted as part of the scope of work for the following storage concepts:

- Water/steam (power)
  - first stage: oil/rock; second stage: draw salt (two-tank)
  - first stage: oil (two-tank); second stage: draw salt (two-tank)
- Water/steam (process heat)
  - oil/rock (above-ground tanks).

Approach. To maximize the usefulness of the data, the study was conducted very generally; fluid cost, fluid loss rates, and hours of storage were the parameters considered. Fluid costs used were $1, $7.50, and $15/gal; fluid loss rates were assumed at 0%, 15%, and 30%/2500 h; and hours of storage were 1, 6, and 15 hours. All of the fluids considered in the study fell within the bounds of these cost and loss rates.

Cost and design data from work already performed for 1, 6, and 15 hours of storage were used as a base, and fluid cost and loss rates were varied. These variations were reflected in the present worth costs of the systems.

Results and Discussion. Results of the cost sensitivity analysis are shown in Figs. 4-6, 4-7, and 4-8. Although fluid cost, fluid loss rate, and hours of storage all have significant impacts on the total present worth cost of the system, using a low-cost fluid provides the greatest cost savings because it affects not only the initial cost of the fluid inventory but replacement costs as well, regardless of the fluid loss rate. For example, for the water/steam (power) reference case, a fluid costing approximately $5/gal would have to have a zero fluid loss rate to be competitive with Caloria HT-43 at about $1.50/gal, even though Caloria has an estimated 27%/2500 h fluid loss rate at 316°C (600°F). More specifically, for Therminol 66 (at $10.85/gal, and with a 5.7%/2500 h fluid loss rate) to be competitive with Caloria HT-43 at six hours of storage, the Caloria fluid loss rate would have to exceed 125%/2500 h, which appears highly unlikely. This analysis shows the obvious importance of using a low-cost fluid in designing a thermal storage system.

This study has not attempted to evaluate all the candidate fluids. For example, Therminol 55 has a cost of $2.53/gal. However, good fluid loss rate data are not readily available for this fluid. If the loss rates are similar to those of Therminol 66, then Therminol 55 has a potentially lower life-cycle cost than Caloria HT-43. Several fluids are characterized by low losses and low costs; the data presented in Figs. 4-6, 4-7, and 4-8 provide some criteria for evaluating them.

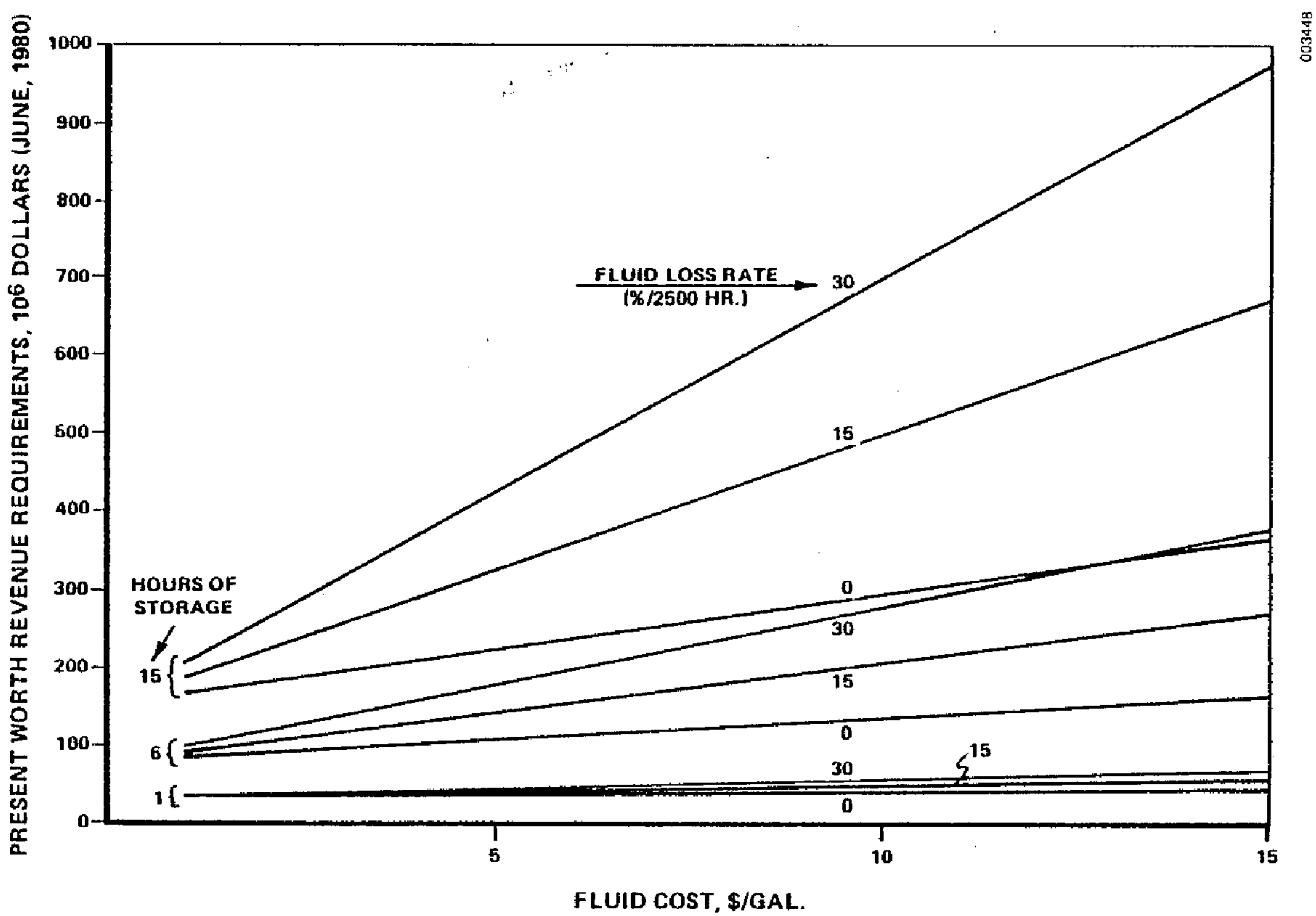


Figure 4-6. Fluid Sensitivity Cost Curves for a Water/Steam Receiver (Power)
First Stage: Oil/Rock; Second Stage: Draw Salt (Two-Tank)

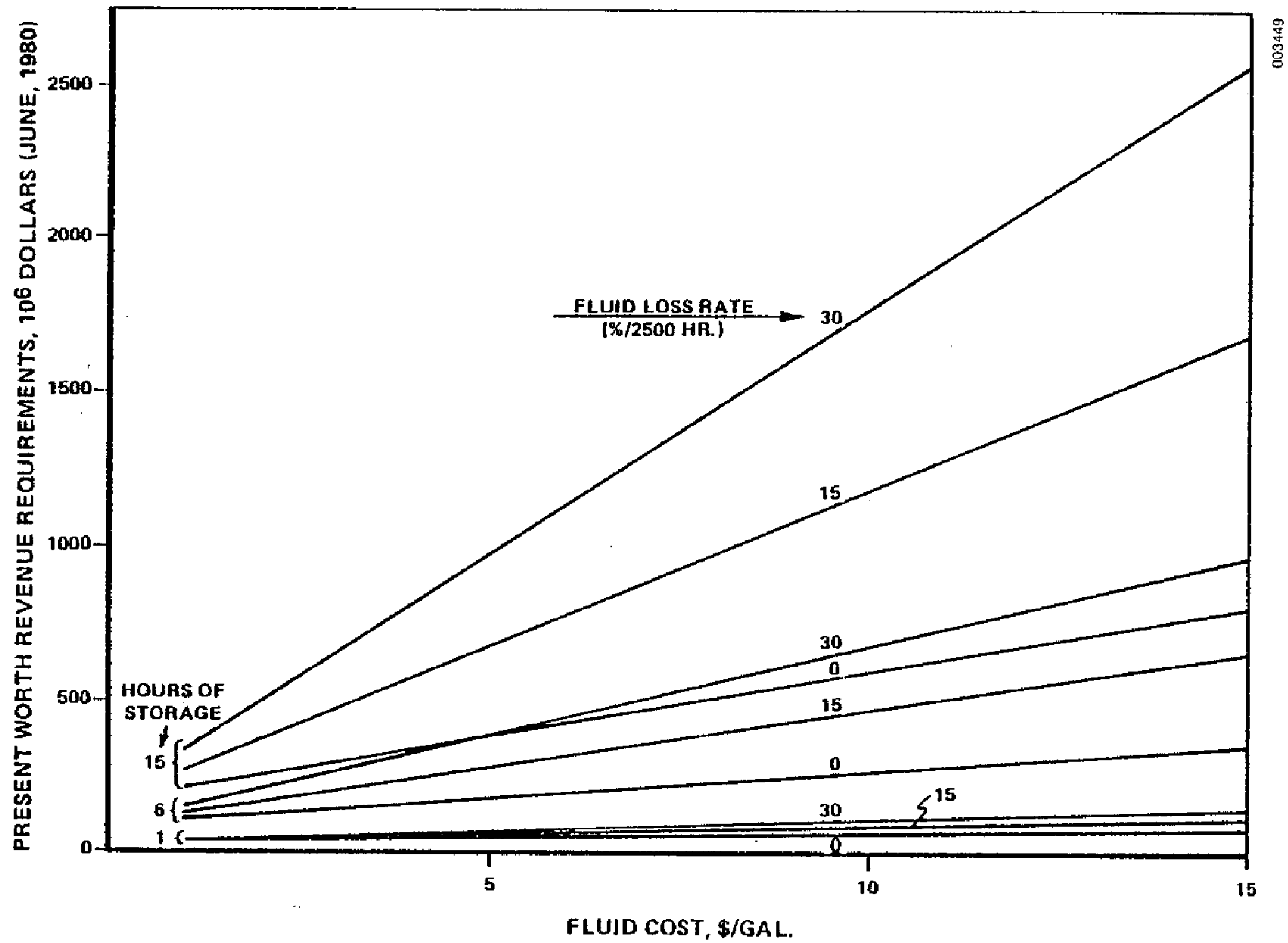


Figure 4-7. Fluid Sensitivity Cost Curves for a Water/Steam Receiver (Power)
First Stage: Oil (Two-Tank); **Second Stage: Draw Salt** (Two-Tank)

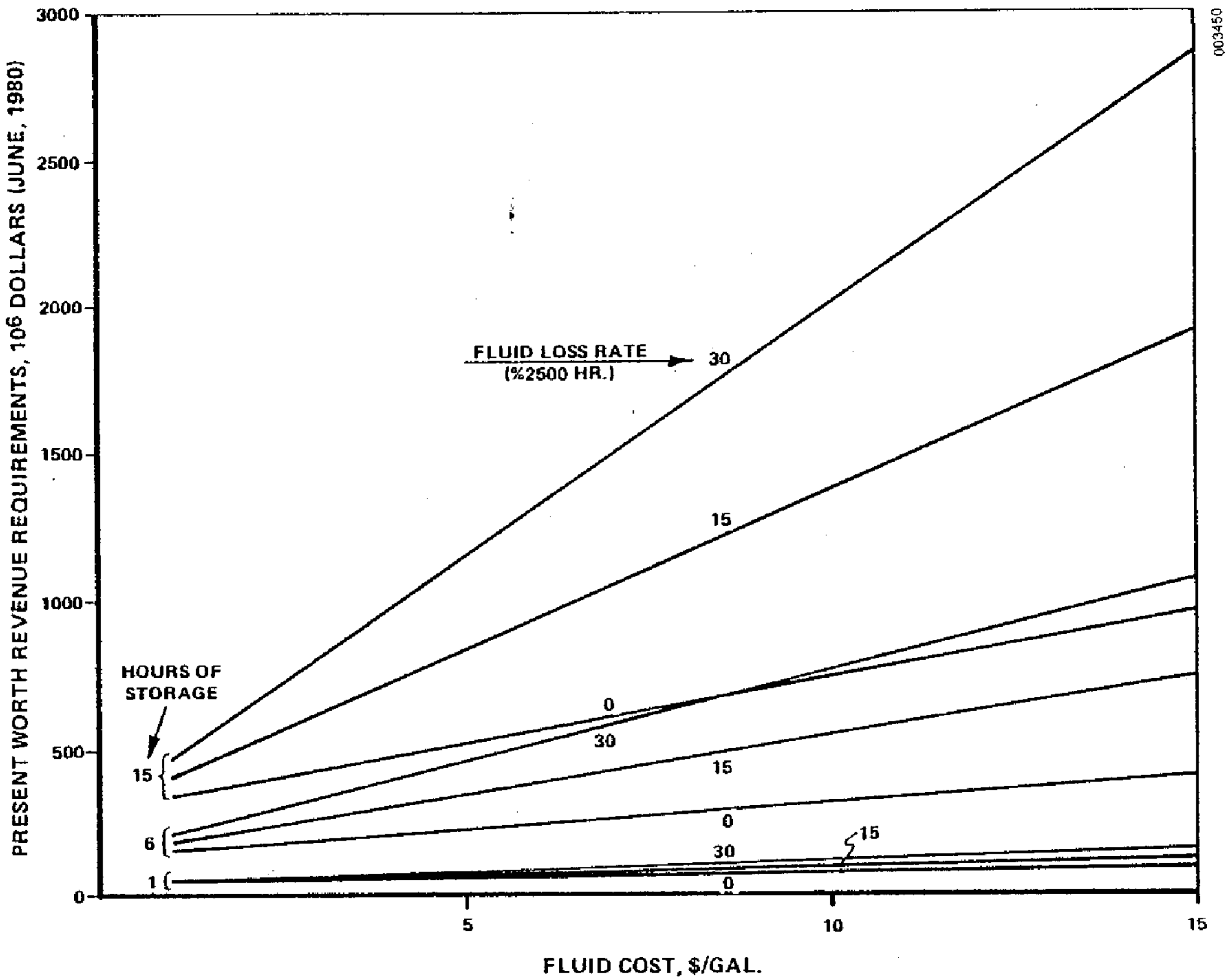


Figure 4-8. Fluid Sensitivity Cost Curves for a Water/Steam Receiver (Process Heat) Oil/Rock Storage

SECTION 5.0

SENSITIVITY STUDY

We evaluated the sensitivity of the study results to a number of different parameters, based on cost and performance data provided by S-R. An important part of the sensitivity study was the consideration of both the cost of the thermal storage and its efficiency (i.e., performance). The data are all calculated on a unit-of-delivered-energy cost basis for a storage-coupled solar thermal system. Parasitic power requirements are included in the net cycle efficiency in power-generation applications. Receiver efficiency impacts and thermal losses from storage are also included in these calculations. The cost of the solar collector, storage, and balance of plant are included in calculating the unit energy cost. By comparison, the S-R PWRR data represent only thermal storage subsystem costs (i.e., efficiency is not included). The economic data employed in the sensitivity calculations are those recommended by the Solar Thermal Interlab Committee on Goals. These data are different from those employed in the PWRR calculations, and the impacts of two different economic assumptions are thus determined. Detailed data for the sensitivity study are presented in the Appendix. Significant results are discussed in this section.

Three economic parameters were varied during the sensitivity study: (1) the factor for indirect costs associated with storage equipment; (2) the factor accounting for installation and indirect costs of the storage media; and (3) the factor accounting for storage operations and maintenance. The total indirect cost for the storage equipment was assumed to be 95% of the storage subsystem's capital cost. To determine the sensitivity of our results to this assumption, the storage ranking was done with a 95% factor and then with a 44% factor for indirect costs. No significant change in results occurred; the storage concepts that appeared to be most promising at an indirect-cost level of 95% of capital cost also appeared to be most promising at the 44% indirect-cost level. The same variation was used for the storage media installation and indirect costs. Initially, this cost was set at 95% of the direct media cost, then the ranking was done a second time with the factor set at 44% of the direct cost. Again, no significant change in results was observed. After these two factors were varied individually, the ranking was done again with both factors set at 44%; still, no significant change in the ranking was observed.

The third economic factor examined in the sensitivity study, storage O&M cost, was initially set at 2% of the storage equipment direct cost for a given storage subsystem. Recognizing that the O&M costs would not uniformly be 2% for all concepts, a schedule was developed to reflect the variance in O&M costs among the concepts. (The schedule is provided in the Appendix.) Although the variable rate schedule is a more accurate estimate of the O&M costs for a system, once again, the results show no significant difference from those obtained with the 2% O&M charge.

Another parameter that was varied during the sensitivity study is the level of storage use. This parameter incorporates the performance effects of collector area, location, and dispatch strategy. A complete description of the variable is provided in Ref. [11], but it is sufficient to note here that variations in the level of storage use did not yield significant changes in results from nominal conditions.*

Fluid degradation rates for storage concepts that use oil as a medium were determined from the small amount of empirical data available. The accuracy of the assumed rates is unknown, so a brief check was made to examine the sensitivity of the results to the assumptions. While no strong conclusions can be drawn from the results, it should be noted that inaccuracies in the assumed rates would change the relative rankings of the storage concepts.

The final consideration in the sensitivity analysis was the overall uncertainty of the storage subsystem cost. The cost estimates developed for the storage concepts are as accurate as possible, but there is no precedent for these estimates since many of the storage technologies are in the conceptual, experimental, or developmental stages. Given this low level of experience with actual systems construction, it is clear that there is a significant uncertainty associated with these cost estimates. Using the nominal conditions and assuming a cost uncertainty of 20%, the ranking was repeated; example results are shown in Figs. 5-1 through 5-4. In the charts, the position of the heavy line at the center of each bar represents the percent difference in BBEC for a storage concept compared with that of the reference concept, both at nominal conditions. The top of a bar indicates the BBEC percentage change if the storage subsystem costs were to be 20% greater than the cost estimate. The bottom of a bar indicates the percentage change if the storage costs were 20% less than the cost estimate.

For the water/steam receiver electricity production application shown in Fig. 5-1, at nominal conditions, only the finned-tube-intensive and the underground pressurized water, draw-salt concepts show potential improvement in BBEC with respect to the oil/rock, draw-salt reference system. If, however, the cost estimates are incorrect, the results could be very different. For example, if the cost of the reference concept has been significantly underestimated, i.e., if the top of Bar 1 more accurately represents the energy cost, then Systems 2, 3, 4, 6, 9, and 10 all show potential cost improvements at their nominal values. Conversely, if the reference concept costs have been overestimated, then none of the alternatives are attractive. Because of the magnitude of the uncertainties involved, the results for 6 hours of storage are not definitive; i.e., the lowest-cost system cannot be identified. For 15 hours of storage (see Fig A-4 in the Appendix), the results are definitive, and two concepts--underground pressurized water and direct-contact phase-change salt--are more attractive than the reference oil/rock concept. But the finned-tube-intensive, phase-change concept is also expected to be more attractive than the reference concept.

For the water/steam receiver process heat application (Fig. 5-2), all three alternate storage concepts show potential improvement over the reference system for 6 hours of storage, particularly the underground pressurized-water

*Nominal conditions are (1) midrange storage use, (2) 95% fee for indirect storage equipment costs, (3) 95% fee for installation, (4) the indirect costs of storage media, and (5) the variable O&M schedule.

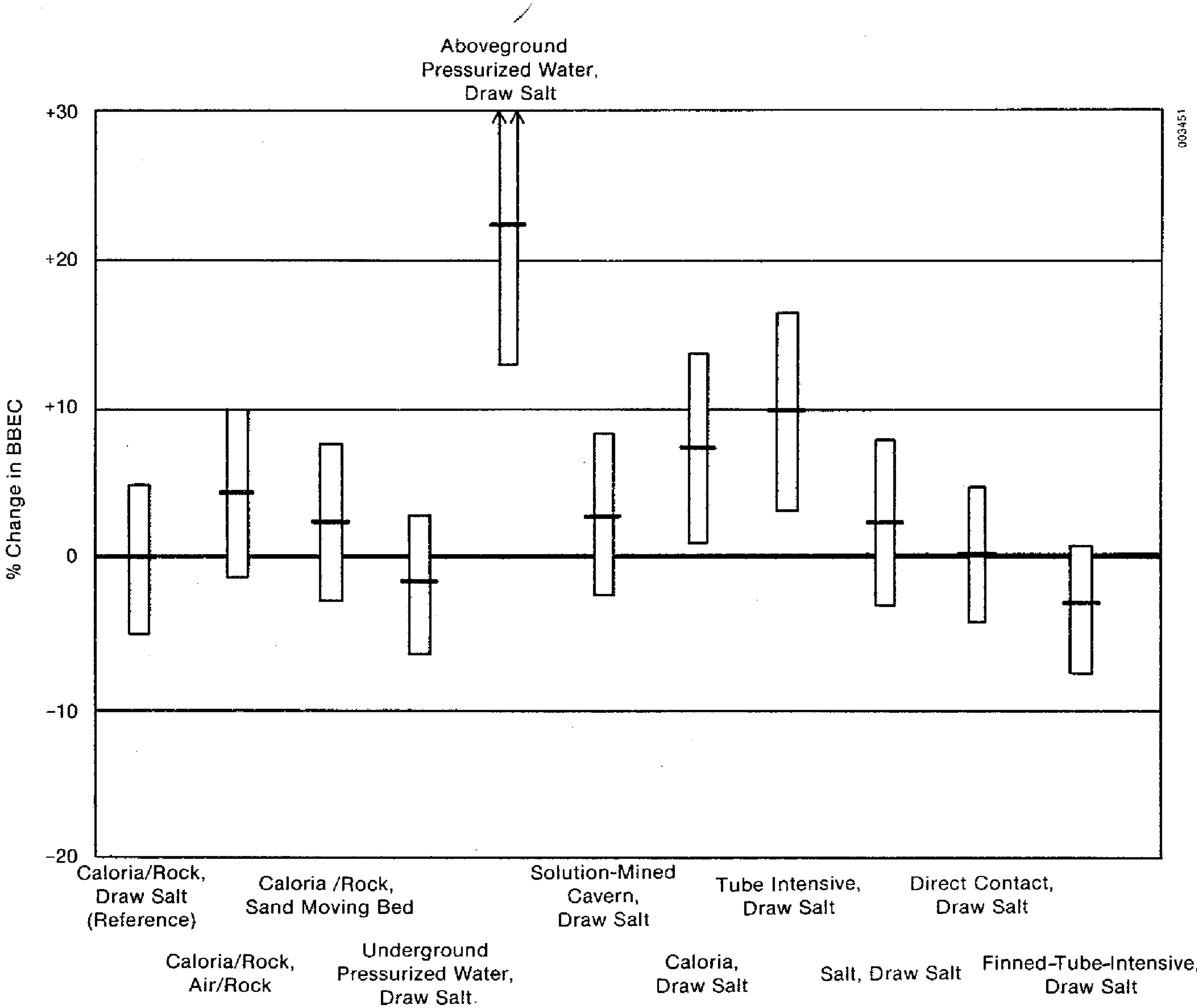


Figure 5-1. Effects of ±20% Cost Uncertainty for Water/Steam Power Concept
(6-hour storage capacity)

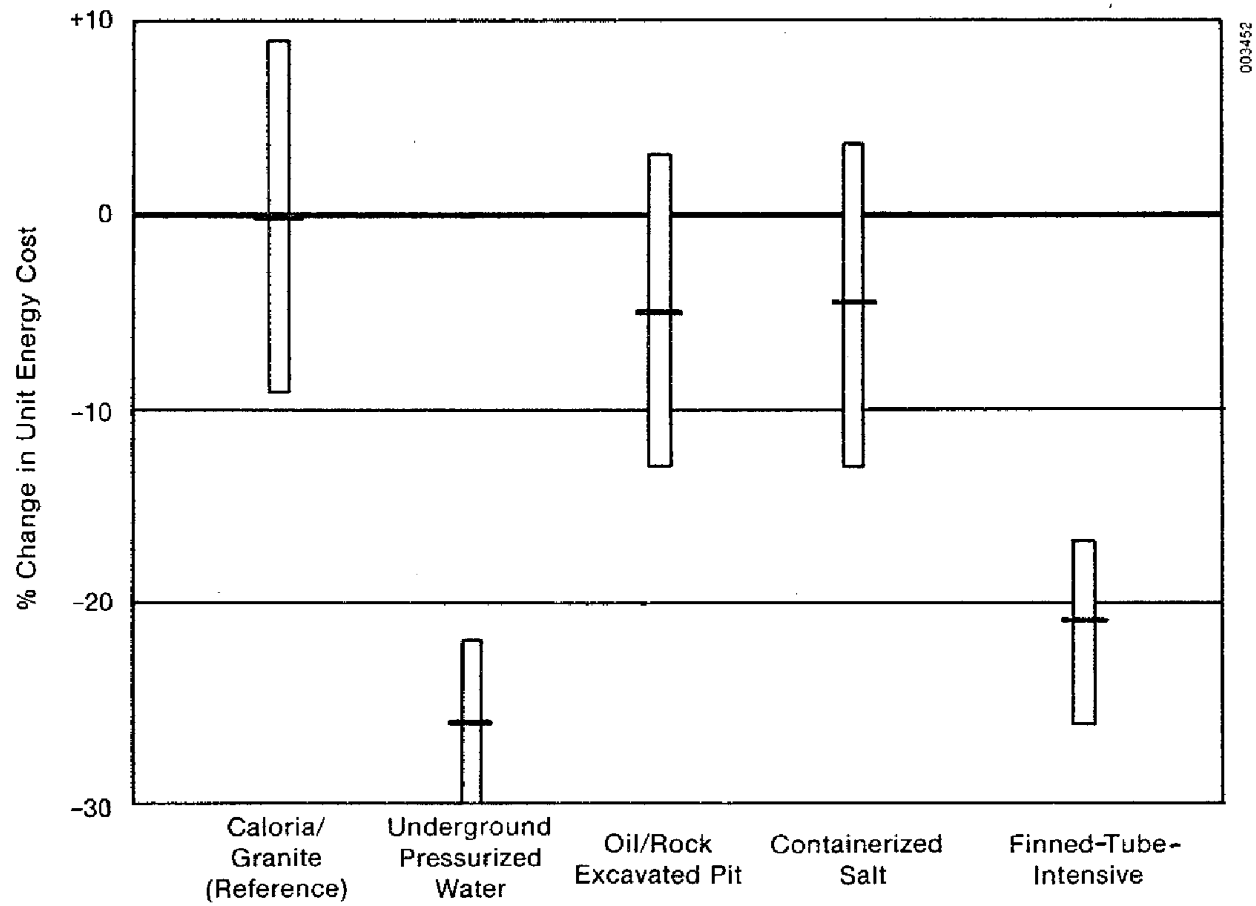


Figure 5-2. Effects of ±20% Cost Uncertainty for Water/Steam Process Heat Concept (6-hour storage capacity)

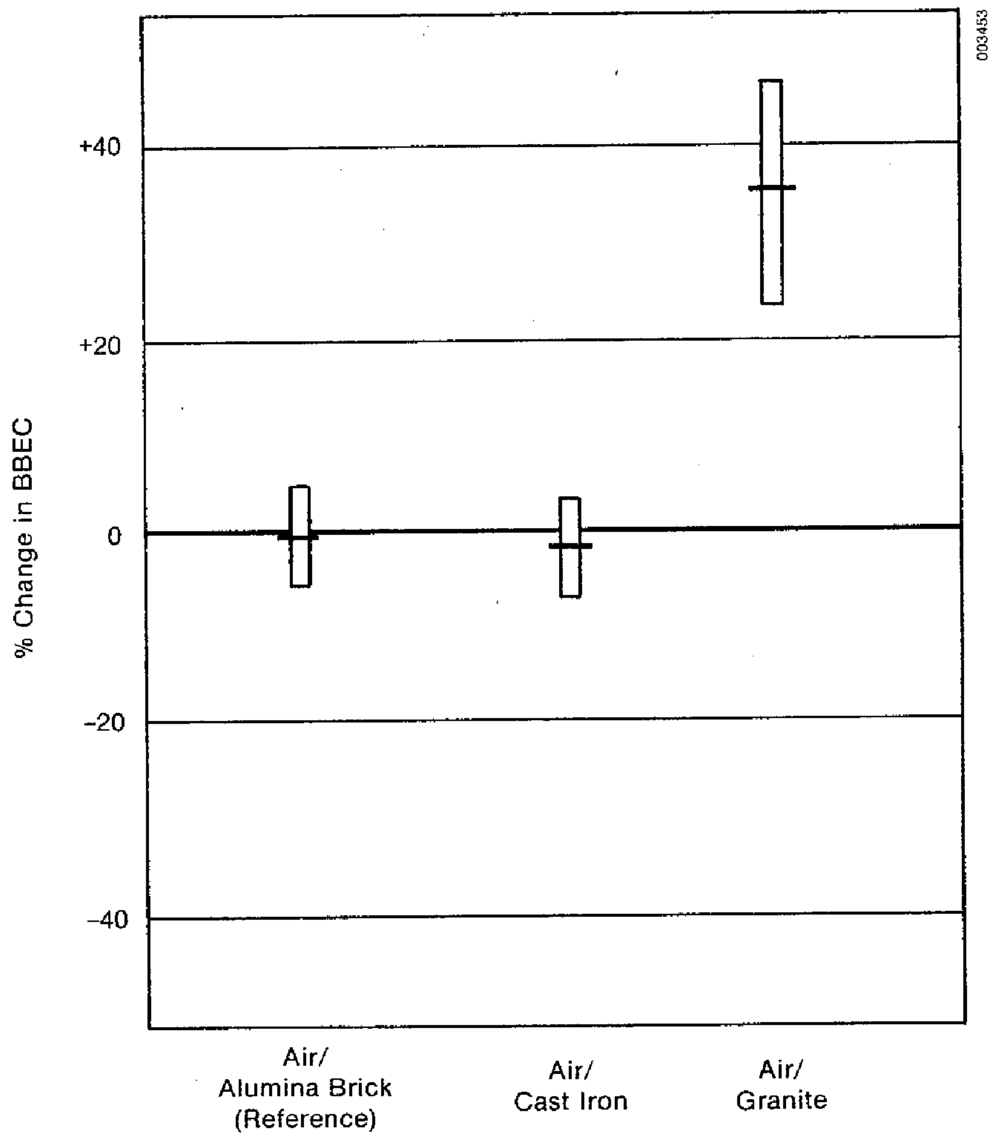


Figure 5-3. Effects of ±20% Cost Uncertainty for Air/Brayton System Concept
(6-hour storage capacity)

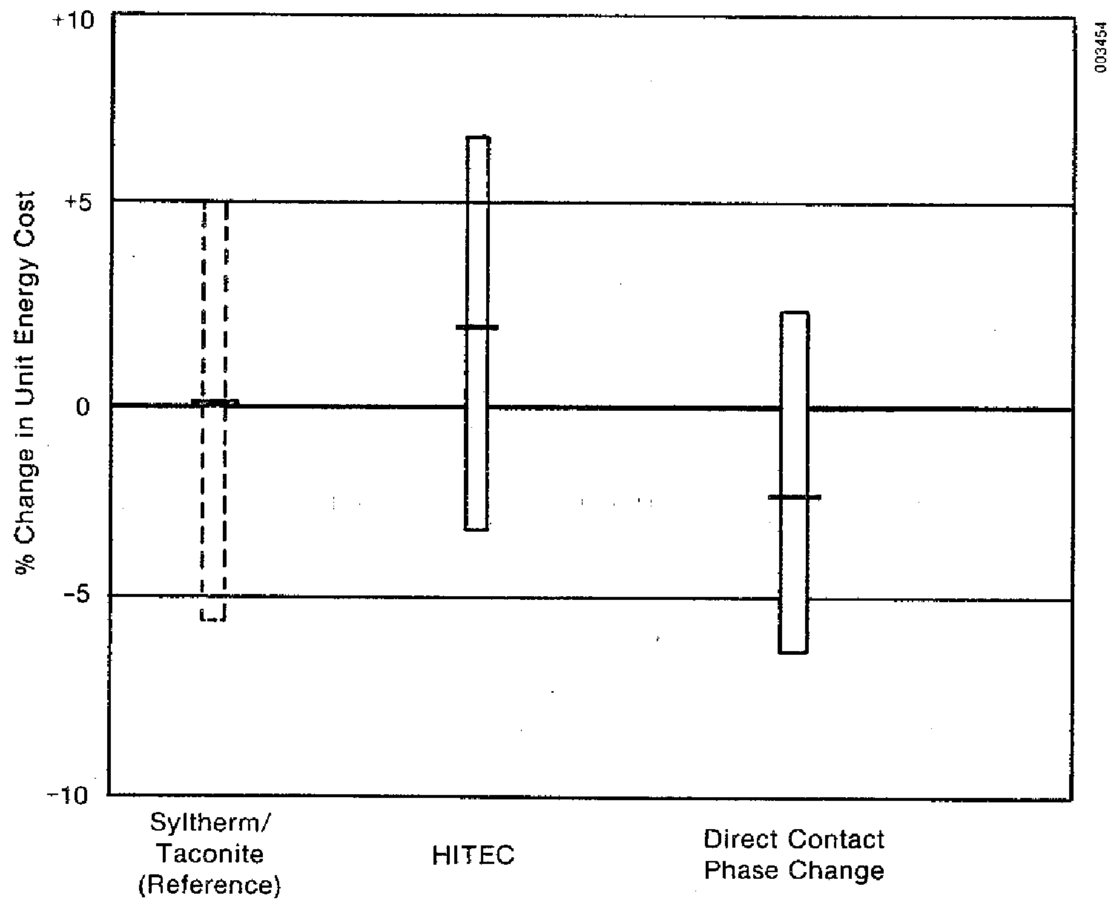


Figure 5-4. Effects of ±20% Cost Uncertainty for Organic Fluid Receiver, Total Energy Concept (15-hour storage capacity)

concept. If the cost of the reference system has been underestimated, the alternative concepts are even more attractive by comparison; if the reference cost has been overestimated, both the underground pressurized water and the finned tube-intensive concepts would still represent cost improvements. For 15 hours of storage, the results are the same with an even stronger preference for the underground pressurized-water concept.

The air/alumina brick and air/cast iron concepts for the Brayton cycle power-generation application are close enough in estimated BBEC (Fig. 5-3) to make it unreasonable to choose one over the other on the basis of anticipated cost. This is true for both nominal conditions and for large-cost-uncertainty conditions. Under no conditions does the air/granite concept show any potential for BBEC improvements.

The organic-fluid, total energy application illustrates the importance of considering the effect of cost uncertainty. In Fig. 5-4, it is clear that the three storage concepts examined for this application are so close in estimated energy cost that it is again unreasonable to choose one system or another on this basis. Any of the concepts could be significantly better or significantly worse than the others if cost inaccuracies are as great as the 20% considered here.

In summary, the reasons for considering the uncertainties of the storage cost estimates are twofold: first, to highlight concepts that show potential for unit-energy-cost improvements regardless of cost estimate inaccuracies, such as the underground pressurized-water system for the water/steam receiver process heat application. Second, conducting this portion of the analysis points out (as in the water/steam receiver electricity generation application) the results' sensitivity to cost estimating accuracy--if cost estimates are inaccurate, storage concepts may rank significantly higher or lower than in the nominal ranking.

In considering the cost of storage in a solar thermal system, the system unit-energy cost, shown in Figs. 5-1 through 5-4, is an important measure. For storage program purposes, however, it is also important to determine the percentage change in the storage subsystem cost relative to the reference concepts. The program's goal was to identify storage concepts that have the potential to decrease storage subsystem costs by 25% or more, compared with the reference concept. In this study, only storage concepts associated with the water/steam receiver demonstrated the potential to meet this goal (Table 5-1). The results suggest that the underground pressurized-water and latent-heat salt storage concepts are attractive for both power and process heat applications at middle and high storage capacities.

The sensitivity analysis was conducted to determine the effects of various factors and assumptions on study results. The lack of sensitivity shown to many of the parameters described here lends credence to the results. The analysis has also shown, however, that it is important to recognize the cost uncertainties inherent in the results and not to base decisions on nominal costs alone.

Table 5-1. Storage Concepts with the Potential of Meeting Program Goals[a]

Water/steam receiver, electric power and process heat
Finned-tube-intensive, latent heat
Underground pressurized water
Direct-contact, latent heat
Containerized salt, latent heat (process heat only)[b]
Organic fluid receiver
None identified
Air/Brayton receiver
None identified

[a]A 25% or more improvement in the thermal storage equipment cost, including efficiency impacts.

[b]The study was structured to evaluate the various types of latent-heat thermal storage in the water/steam electric power case. In that comparative ranking, containerized salt was a poor third, with significantly less promise than the finned-tube-intensive concept and direct-contact latent heat at all storage capacities. The limited data available for water/steam process heat point to the same ranking.

SECTION 6.0

COMPARISON OF COST TO VALUE

Value is a measure of the worth of the thermal storage subsystems in a solar thermal system. Value is determined by calculating the avoided costs of the alternative fossil fuel system (fuel, fossil-fired equipment, other equipment, and operations and maintenance). Thus, if obtainable cost exceeds value, users will tend to select the fossil-fueled system over a solar thermal system with thermal storage. Conversely, thermal storage is preferred when its costs are less than its value. The goal of DOE's program is to develop technologies that can contribute substantially to the nation's energy supply; clearly, that goal requires technologies whose obtainable (mature technology) costs are less than or near their value.

The value of thermal storage subsystems has been calculated in other reports. Copeland [11] presents the thermal storage value of solar thermal electric power applications. Hock and Karpuk's work [12] presents thermal storage value for solar thermal process heat applications; to date, thermal storage value had not yet been determined for total energy applications. However, thermal storage for the total energy system evaluated here may be used for other applications. Omitting appropriate parts of the system enables a user to determine the cost of thermal storage as an electric-power-only or process-heat-only storage system.

In a solar thermal system, a total energy application has, in general, a value equal to the sum of the price of the displaced fossil fuel and purchased electricity. Total energy (cogeneration) applications are not unique to solar thermal systems. Any fossil fuel (oil, gas, coal) can be employed to operate the power conversion cycle, extraction steam, and low-temperature reject heat collection systems at precisely the same conditions as the solar thermal system. Consequently, the solar thermal energy may be regarded as saving fossil fuel. The solar thermal energy simply provides high-grade heat to a system. In this study, superheated steam is supplied to a turbine, but if the turbine is considered to be another type of heat user, the application can be considered a process heat application. Total energy applications are, in general, industrial; the same economic parameters as process heat exist in the two applications. Thus, if superheated steam is considered a process heat application, the value of the thermal storage in a cogeneration application becomes the same as that value in a process heat application.

The same logic allows us to assess the value of the thermal storage in an electric power application. In that case, the extraction steam and low-temperature heat subsystems are eliminated, conversion cycle efficiencies are appropriately accounted for, and utility financing is employed. The storage subsystem cost, with an organic fluid receiver in either electric power or process heat, is the same in both cases; however, the rating in terms of kW_t or kW_e is different. The appropriate cost per unit rating is compared with an appropriate value.

6.1 ELECTRIC POWER APPLICATIONS

Table 6-1 presents the obtainable cost and value for the referenced thermal storage systems in a solar thermal electric power application. The value of thermal storage is presented for a high-insolation site (e.g., Albuquerque, New Mex.). Data for other locations have been calculated but are always lower for lower-insolation sites. The value is for an investor-owned electric utility with a relatively small solar thermal penetration into the utilities' generation capacity. All data are in 1980 dollars, except that plant startup time is assumed to be around 1990. The value data are based on future projections of fuel and capital equipment prices. Obviously, the data are not precise; considerable uncertainty still exists. The authors have examined fuel price projections from several sources. The value data have an estimated accuracy of ±30% (even this level may be an overestimation of the precision involved). The value data should not be considered absolute criteria for thermal storage, because of nonquantitative benefit factors (e.g., reduced dependence on uncertain supplies of oil, uncertainty about future environmental restrictions and fuel prices, risks associated with employing new technologies, etc.).

There is, in fact, a distribution for end-users' predicted value of thermal storage. Even when cost is equal to or less than value, not all users will select thermal storage; conversely, when cost is greater than value, some users will still select a thermal storage subsystem. The value data are not precise measures but serve as an indicator of how future decisions will be

Table 6-1. Value Comparison for Electric Power Applications

Storage Concept	Capital Investment for Storage Capacity ($\$/kW_e$)[a]		
	1 hour	6 hours	15 hours
Thermal storage value (High-insolation site)	320	440	560
Water/steam			
Oil/rock: draw salt	134	387	780
	145	387	667[b]
Organic fluid			
Trickle charge			
Syltherm/taconite	417	1067	2140
Gas/Brayton			
Ceramic brick	116	627	1545

[a]1980 dollars.

[b]Underground pressurized water at 15 hours with draw salt second stage.

made. The authors adopt the point of view that whenever cost is less than or slightly greater than value, a reasonably large market for thermal storage will exist.

The cost data in Table 6-1 are based on S-R estimates. S-R employed a multiplying factor of 1.95 times the direct cost to calculate the capital investment required for the thermal storage. This factor takes into account several indirect factors and is based on S-R's experience with electric power plants (fossil-fueled and nuclear). A solar thermal plant is capital-intensive; it requires a great deal of standardized equipment (primarily the modular collector field). This results in a larger capital base over which to distribute indirect costs. Because of this, the Solar Thermal Interlab Committee on Goals recommends multiplying the direct cost by a factor of 1.44. The obtainable cost data in Table 6-1 are based upon that lower factor; to obtain S-R's cost data, the values in Table 6-1 may be factored up by the ratio of 1.95 to 1.44.

The obtainable costs of thermal storage with a water/steam receiver could potentially be less than their value. At both 1 and 6 hours of storage capacity, costs are substantially less than value. At 15 hours of capacity, the costs of both oil/rock and underground pressurized water storage are greater than value. However, these differences are not great (about 30%) and are within the range of uncertainty for these data. Second-generation concepts were identified with cost improvements in the 6- through 15-hour range. Data for underground pressurized water storage are included in Table 6-1 and offer the greatest potential for meeting value; the differences are less than the uncertainty in cost and value data.

The organic fluid receiver case includes Syltherm/taconite thermal storage. At all storage capacities, the costs are substantially greater than value. None of the second-generation concepts offer sufficient improvement to date to alter this conclusion.

The gas/Brayton case employs ceramic bricks in an internally insulated, welded-steel pressure vessel. At 1 hour's storage capacity, the cost is much less than value. However, at 6 and 15 hours of storage capacity, costs are substantially greater. None of the second-generation concepts offer sufficient improvement to alter these conclusions at this time.

6.2 PROCESS HEAT APPLICATIONS

Table 6-2 presents cost and value data for thermal storage in solar thermal process heat applications. These value data were calculated for a hybrid solar thermal plant. The thermal storage value was determined to be the difference between the price of the fuel saved and the cost of the added solar thermal collector field. Due to the uncertainties in projected fuel prices and in the cost of solar collectors, the value of thermal storage is obviously uncertain. The expected range of thermal storage value is presented for each storage capacity. The cost of the storage is similarly uncertain, as noted in Sec. 6.1.

Table 6-2. Comparison to Value for Process Heat Applications

Concept	Capital Investment ($/kW$_t$)[a]		
	1 Hour	6 Hours	15 Hours
Value of thermal storage (High insolation site)	10-20	60-120	150-300
Water/steam			
238°C (460°F) saturated steam			
Oil/rock	41	119	247
288°C (550°F) saturated steam			
Oil/rock	75	266 (147)[b]	576 (211)[b]
Organic fluid			
171°C (341°F) saturated steam (Caloria receiver)			
Oil/rock	(33)[c]	93	(200)[c]
700 psi, superheated steam (Syltherm receiver)			
Trickle charge			
Syltherm/taconite	78	202	405

[a]1980 dollars

[b]Underground pressurized water

[c]Extrapolated data

Data for two process heat (saturated steam) cases are presented for water/steam receivers. One case is saturated steam at 238°C (460°F). This quality of steam is generated in the first stage of the electric-power case. (Note that the storage is also charged with saturated steam.) The costs were determined from electric power data by subtracting the cost of the second stage (draw salt). Data for the 288°C (550°F) saturated steam case are those previously calculated by S-R. In both cases, costs are substantially greater than value at 1 hour of storage. At 6 hours' capacity, costs are slightly greater than value. At 15 hours' capacity, costs are potentially less than value with oil/rock storage and a 238°C (460°F) saturated steam application and with underground pressurized water storage in a 288°C (550°F) saturated steam application. These data illustrate that the most favorable economic conditons exist at high storage capacities. This is true because the cost per unit capacity of thermal storage decreases as storage capacity increases, but the value per unit storage capacity in a process heat application is relatively constant.

Data for two process heat applications were generated for organic fluid receivers. In one case, saturated steam is delivered at 171°C (341°F) with a Caloria receiver and Caloria/granite thermal storage. In the other, 4.93 MPa (700 psi) of superheated steam at 382°C (720°F) is delivered, with a Syltherm receiver and Syltherm/taconite thermal storage. For all storage capacities, the Syltherm/taconite storage is significantly greater in cost than its value. Even the second-generation improvements are not sufficient to alter this conclusion for a Syltherm receiver. With the Caloria receiver, oil/rock storage is attractive at both 6 and 15 hours. The Caloria/granite data estimated by S-R are preliminary cost data calculated only for 6 hours; SERI extrapolated the S-R data to both 1- and 15-hour capacities.

SERI

SECTION 7.0

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

7.1.1 Conclusions Based on Cost and Value Comparisons

7.1.1.1 Water/Steam Receiver Applications

Thermal storage concepts with water/steam receivers could potentially cost less than their value in an electric power and process steam application. The most favorable conditions exist at relatively small diurnal storage capacities (1-6 hours). For process heat, the most favorable conditions occur at larger diurnal storage capacities (6-15 hours).

Three second-generation thermal storage concepts represent significant improvements over the reference system. These are as follows:

- Finned-tube-intensive (latent heat)
- Underground pressurized water
- Direct-contact (latent heat).

The research and development (R&D) effort for the finned-tube-intensive concept has been estimated by Combustion Engineering to be a minimum of $1.5 million; that effort includes materials testing and the design, construction, and testing of a subscale research experiment (SRE). The research and development cost of the underground pressurized-water concept is on the order of $15 million. Direct-contact, latent heat concept development has not yet been estimated. The finned-tube-intensive, latent heat concept data indicate, however, that the R&D effort necessary is on the order of $2 million. None of the other concepts investigated show sufficient promise to warrant further study at this time. Many actually impose cost penalties, in fact.

7.1.1.2 Organic Fluid Receivers

Thermal storage cost-versus-value results for organic fluid receivers depend strongly on the particular system, specifically, on the type of receiver and on the storage applications involved. For relatively low-temperature storage (e.g., low-pressure steam), an inexpensive organic fluid (e.g., Caloria) may be employed. The thermal storage cost is low because the receiver's working fluid can be used in the storage, eliminating one set of heat exchangers. The value of this concept is higher than the estimated cost of Caloria/granite storage and the economics are very favorable. The most favorable conditions occur at high storage capacities (6-15 hours).

For storage at relatively higher temperatures, expensive organic fluids (e.g., Syltherm) must be employed because inexpensive organics will rapidly decompose. Using the receiver working fluid in the storage avoids the expense associated with heat exchangers. However, the cost of the storage is significantly greater than the value for all storage capacities and all applications investigated at this time.

Second-generation concepts represent at least minor improvements over first-generation Syltherm/taconite thermal storage subsystems. The capital investment for Syltherm/taconite is lower than that for direct-contact, latent-heat, or Hitec two-tank concepts. However, due to the high replacement cost of Syltherm, the other concepts shows some advantages in PWRR at high storage capacities.

Because of the relatively high rate of decomposition of Syltherm at high temperatures, an alternative organic receiver fluid was evaluated--MCS 1980. The lower replacement cost of MCS 1980 provided some reduction in PWRR, but this fluid also requires heat tracing in all field piping. If operational problems occur with Syltherm, however, MCS 1980 is a viable alternative.

Caloria HT-43 was the oil employed in all storage applications at 316°C (600°F) or less. This oil also has a relatively high decomposition rate, so alternative 316°C (600°F) oils were evaluated. Even with a high decomposition rate, Caloria HT-43 is the preferred oil unless the alternative is significantly lower in cost. Therminol 55, however, is the only alternative fluid identified to date with a sufficiently low cost to warrant further evaluation as an alternative to Caloria.

7.1.1.3 Air/Brayton Systems

For air receiver/Brayton-cycle power generation, thermal storage has limited potential. At relatively small diurnal storage capacities (approximately 1 hour), the economics are favorable. At higher storage capacities (6-15 hours), the storage cost is significantly greater than value.

None of the concepts evaluated in this study represented a significant improvement over the referenced storage concept, alumina/brick. Magnesia and cast-iron storage media provide relatively small improvements, less than the goal of the thermal storage program. Prestressed cast iron vessels represent the greatest improvement (~10%), still less than the goal of 25% or more.

A latent-heat thermal storage concept was also evaluated. Its cost was significantly less than the alumina/brick concept. However, it was much less efficient; the loss in performance associated with latent heat more than offsets the cost advantage. In fact, the latent heat concept would actually increase the cost of delivered solar thermal energy.

7.1.2 Sensitivity Study Conclusions

In the sensitivity study, several parameters were investigated that could affect the data.. Changes did occur in the data, but none of them were sufficiently large to affect our conclusions and recommendations. The largest effect was the result of the basic uncertainties that exist in the estimated cost of thermal storage (see the Appendix).

7.2 RECOMMENDATIONS

7.2.1 First-Generation Concepts

The reference concepts in the study are all first-generation thermal storage concepts. These concepts are generally very good; continued development is recommended. The following specific recommendations, however, are made:

- Oil/Rock Storage
  Reduce the uncertainties and technical risks (tank ratcheting, heat exchanger foiling, and oil decomposition rate). Evaluate oil (Caloria) stability with other, potentially more available, low-cost solid media (glass and slag).
- Trickle Charge Syltherm/Taconite Storage
  The economic viability of diurnal thermal storage with this concept is questionable. Based on an analysis of obtainable cost versus thermal storage value, little market penetration is expected. Continued development, therefore, is not recommended. Rather, additional research is needed to identify technologies that can meet program goals; redirection of this program element to third-generation (advanced technology) status is recommended.

7.2.2 Second-Generation Concepts

Three concepts were identified as having significant potential and are recommended for continued research and development. Those recommended, in order of priority, are as follows:

(1) Finned-tube-intensive, latent heat concept

(2) Underground pressurized-water concept

(3) Direct-contact, latent heat concept.

The finned-tube-intensive concept appears to be the most cost-effective for electric power and second best for the process heat application. If the latent-heat salt is changed, it can be used at a wide range of temperature conditions; the development cost should be moderate. This concept may have applications to liquid metal and organic fluid receivers in addition to water/steam receivers in both large and small systems.

The underground pressurized-water concept appears to be the most cost-effective for process heat and second best for water/steam electric power. However, this concept is site-specific and suitable only for large solar thermal water/steam receiver systems. In addition, development costs are high, about 10 times greater than the finned-tube-intensive, latent-heat concept. Research is recommended only at low levels to resolve technical uncertainties. If technical risks are shown to be minimal, then large scale developmental testing on SRE should be considered.

The direct-contact concept was the lowest in cost in the total energy application at high storage capacities; it was third best in the electric power application with a water/steam receiver. The concept is applicable to large and small systems and may be more advantageous with a liquid metal receiver. R&D costs are anticipated to be moderate. Continued research is recommended to resolve technical risks and to improve the performance and costs of the concept. A development effort is not recommended at this time.

7.2.3 Potential Third-Generation Improvements

From the data generated in this study, the following suggestions can be made concerning potential improvements to the concepts studied. Because no evaluations have yet been performed--economic or technical--some of the items may prove to be impractical:

- Using taconite, granite, slag, and glass as low-cost media in a molten-salt thermocline
- Employing multistage latent heat in a gas/Brayton system to improve performance
- Using alternative transfer fluids for discharge in direct-contact, latent heat storage; reducing the cost of lead/bismuth inventory and parasitic pumping power [suggested fluids are the organic oils (both as sensible heat transfer and as a boiling liquid) and other inorganic media]
- Alternating phase-change concepts for organic fluid receivers (e.g., finned-tube-intensive with an integral oil and steam heat exchanger in the phase-change tank)
- Using alternative low-melting-point transport fluids for dishes and troughs [these fluids should be low in cost and high in temperature capabilities (400°C, 750°F)]; molten salts (Hitec and $AlCl_3$ eutectics) are suggested for both transport and storage media]
- Employing high-temperature concretes in storage tanks with high-temperature storage media (e.g., molten salt)
- Incorporating new ideas in direct-contact storage using low-cost storage fluids.

7.2.4 Other Recommendations

7.2.4.1 Evaluations Using Liquid Metal Receivers

The specific operating conditions of a given application affect the choice of an appropriate thermal storage system. Some of the concepts were originally proposed for liquid metal (sodium) solar thermal receivers, but modified to match the conditions in this study, specifically the air/rock and direct-contact, latent heat concepts. Evaluation of these two concepts and the moving sand bed in combination with a liquid metal solar thermal receiver is recommended.

7.2.4.2 Low-Priority Development

Several items provided some cost improvements, but these were less than those required by the program goals. Development of the following is recommended, on a low-priority basis:

- Prestressed cast iron vessels
- Concrete pits
- Alternative media for air/Brayton
  - cast iron
  - MgO.

No relative ranking on these is assigned at this time.

7.2.4.3 Unpromising Concepts

Development of unpromising concepts is not recommended. In general, major improvements in these concepts are needed. If such needed improvements can be identified, then these essentially become new concepts and as such should be considered for third-generation research rather than as second-generation development items.

SERI

SECTION 8.0

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APPENDIX

THE SENSITIVITY STUDY

A.1 INTRODUCTION

SERI used thermal storage subsystem cost estimates from Stearns-Roger (S-R), in conjunction with performance data to compare the delivered energy costs of the storage concepts under study. The accuracy of the conclusions drawn from such a study obviously depends on the accuracy of the cost and performance data used and, in turn, on the accuracy of the assumptions made in generating the cost and performance data. Therefore, a sensitivity analysis of various parameters was performed to determine the effect of variations in cost estimating assumptions on the final conclusions of the study.

From discussions with Storage Program personnel and with the proponents of specific concepts, the parameters that would be subjected to the sensitivity analysis were determined. As described in more detail below, the parameters examined were those associated with indirect costs, O&M costs, and installation costs. Also investigated were the effects of uncertainty in the overall storage subsystem costs and the effects of assumptions as to the level of use of storage.

The analysis was conducted for all of the solar thermal applications considered: a water/steam receiver for both power generation and process heat generation; an air receiver for Brayton cycle power generation; and organic fluid receivers for a total energy system. The detailed results of the sensitivity analyses for each application are given below, following an explanation of the data base and the approach used to conduct the study.

A.2 DATA BASE, ECONOMICS, AND RANKING INDEX

The storage subsystem cost data base for this study was developed by S-R; information about a particular concept's cost is provided in the cost breakdown tables in Volume II of this report. The economic data base used is shown in Table A-1. The values for the parameters listed were taken from those of the Solar Thermal Cost Goals Committee (August 1980). The analysis was done using 1980 dollars and assuming the solar thermal plant would be operational beginning in 1995.

The cost algorithm for the complete solar thermal plant was simply the sum of the costs of the storage subsystem and the nonstorage plant cost:

$$CC = PC + [SC * SF] \tag{A-1}$$

$$\text{Total Capital Cost of Solar Thermal Plant} = \text{Nonstorage Plant Cost} + \text{Storage Subsystems Cost} * \text{Storage Factor}$$

Table A-1. Data Base--1995 Plant On-Line (1980 dollars)

	Utility	Industry
Fixed charge rate	15.2%	28.2%
Plant service life	30 years	20 years
Levelizing factor for fuel	2.44	1.68
Levelizing factor for O&M	1.90	1.68
Discount rate	9.84%	19.0%
Escalation rate:	2.6%	1980 - 1990
	2.2%	1991 - 2000
	1.1%	2001 - 2014
Electricity cost	$9.40/MBtu	
Oil cost	$8.53/MBtu	

The plant cost, PC, was defined as:

$$C = RC + HC + BOP$$

$$\text{Nonstorage Plant Cost} = \text{Receiver Subsystem Cost} + \text{Heliostat/Dish Cost} + \text{Balance of Plant Cost} \qquad \text{(A-2)}$$

The algorithm used to compute the cost of the storage subsystems--the area of primary concern in this study--is given in the left column with a brief description of the term provided in the right column.

SC = [FI * FN * (CP + CE)]	Storage Cost = Power & Energy Equipment Costs
+ [FI * FOM_1 * (CP_1 + CE_1)]	+ O&M Cost for First Stage
+ [FI * FOM_2 * (CP_2 + CE_2)]	+ O&M Cost for Second Stage
+ [FM * MED]	+ Media Cost
+ [LFOM * FLUID/FCR]	+ Media Replacement Cost
+ [LFF * FUEL/FCR]	+ Purchased Fuel Cost (A-3)

A definition of the variable is given at the end of this appendix. Values for the power-related and energy-related equipment costs, media costs, fluid replacement rates and costs, and amount of purchased fuel required were all generated by S-R. The factor FI (labor for installation of equipment) was set at 1.8 throughout the study.

The sensitivity study investigated variations in several parameters: FM, the factor applied for installation and direct costs associated with the storage media; FN, the factor accounting for indirect costs of storage equipment; and FOM_x, the factors accounting for operations and maintenance (O&M) costs of storage. In their cost estimates, S-R used 1.95 as the value for both FM and FN. During the sensitivity study, we applied 1.95 to both factors, then changed each one independently and then simultaneously to 1.44 to determine the impact of such variations in assumptions on our conclusions.

Other parameters that were varied were the FOM terms. S-R compiled a schedule (Table A-2) of O&M rates for various storage concepts. This schedule was used in their cost estimating and in our study. Additionally, we ran a permutation in which the O&M charge for all stages and all concepts was set at 2% rather than at the variable schedule.

The final parameter varied in this portion of the study was the factor FS, which was applied to the overall storage subsystem cost. Nominally, FS was set at 1.0. A general cost uncertainty of 20% was assumed, and the factor FS was raised to 1.2 and then dropped to 0.8 to determine the effects of such uncertainties. This parametric variation was investigated only for the nominal case; for the other cases, FS was set at 1.0.

In Table A-3, the combinations of parameter values used in the sensitivity study are summarized. Note that Case 1 is considered to be the nominal case, and it includes the values used by S-R in their study. Nominal values for collector areas for the three storage times considered are given in Table A-4.

Table A-2. O&M Schedule*

Concept	O&M Rate
Caloria/granite	2%
Underground pressurized water	2%
Solution-mined cavern (oil/rock)	3%
Caloria, two tank	3%
Tube-intensive HX	3%
Containerized salt	3%
Direct contact HX, first stage	4%
Direct contact HX, second stage	2%
Draw salt, second stage	2%
Air/rock, second stage	3%
Sand moving bed, second stage	4%
Oil/rock excavated pit	3%
Air/alumina brick	2%
Air/cast iron	2%
Air/granite, external HX	4%

*Excludes fluid replacement charges. This rate is the first-year charge for O&M as a percentage of the capital investment.

Table A-3. Magnitudes of the Items in the Sensitivity Study

Case Number	FN	FM	O&M[a]	FS
1[b]	1.95	1.95	Variable	1.2
				1.0
				0.8
2	1.44	1.95	Variable	1.0
3	1.44	1.44	Variable	1.0
4	1.95	1.95	2%	1.0

[a]see Table A-2.

[b]Case 1 is the nominal case when FS = 1.0.

Table A-4. Nominal Collector Areas (m^2)

Receiver	1 Hour	6 Hours
Water/steam	534,000	902,000
Air	766,000	1,310,000
Organic	6,400	11,800
	15 Hours	
Water/steam	1,288,000	
Air	1,838,000	
Organic	17,000	

A.3 THE RANKING INDEX

The method used to compare the storage concepts within each solar thermal application was to compute and compare the "Ranking Index" of each concept. The ranking index method, developed by R. J. Copeland, is explained and documented in Ref. [11]. Basically, the method allows us to calculate the busbar energy cost (BBEC) (or unit energy cost) of a solar thermal plant that will be using a particular storage concept. The ranking index (RI) is defined as

$$RI = \frac{BBEC_A}{BBEC_R} . \qquad \text{(A-4)}$$

The equation represents the ratio of the busbar energy cost of a solar thermal plant using an alternative storage subsystem (A) to the busbar energy cost of the same plant using the reference storage subsystem (R). As can be seen from later equations, calculation of the ranking index accounts for both cost and performance variations that result from alternative storage concepts. The solar thermal plant remains the same for a given application, except as it would be altered by the particular storage subsystem employed. For example, the same water/steam receiver solar thermal plant for a process heat application would be used with various storage concepts except as the concepts would affect system temperatures and power requirements, and as a result, overall system efficiencies. Such differences in plant efficiencies are accounted for in computing the ranking index.

From the definition of the ranking index, an alternative storage concept for which RI < 1.0 indicates that the concept is more promising than the reference storage concept for that particular set of conditions and applications. For RI > 1.0, the alternative concept is less promising than the reference system. Certainly, this method of comparison has its limitations; it is important that qualitative information be combined with results from the ranking index approach in drawing final conclusions about the storage concepts.

For electric power generation applications,

$$RI = \frac{\frac{CC_A}{CC_R} * \left[\frac{ESR}{EDR} + 1\right]}{\left[\frac{A}{R_{RT}} * \frac{A}{R_{CYC}} * \frac{ESR}{EDR}\right] + \left[\frac{AD}{RD_{CVC}} * \frac{AD}{RD_{COL}}\right]}, \quad \text{(A-5)}$$

where

$\frac{CC_A}{CC_R}$ = the ratio of capitalized cost of total solar thermal plant with alternative storage subsystem to capitalized cost of total solar thermal plant with reference storage subsystem [see Eq. (A-1)]

$\frac{ESR}{EDR}$ = the ratio of usable energy delivered from storage to usable energy delivered direct for the reference system

$\frac{A}{R_{RT}}$ = the ratio of first-law (round-trip) efficiencies of the alternative and reference storage concepts

$\frac{A}{R_{CYC}}$ = the ratio of conversion cycle efficiencies for the alternative and reference storage concepts when operating through storage

$\frac{A}{A_{COL}}$ = the ratio of solar collector (receiver) efficiencies for the alternative and reference storage concepts when charging storage

$\frac{AD}{RD_{CYC}}$ = the ratio of conversion cycle efficiencies for the alternative and reference storage concepts when operating direct

$\frac{A}{RD_{COL}}$ = the ratio of solar collector (receiver) efficiencies for the alternative and reference storage concepts when charging storage.

Values for CC_A and CC_R were calculated as described in Sec. A2. ESR/EDR values were calculated at SERI to support this and similar studies. A/R_{RT} was determined from S-R calculations of storage heat losses and purchased energy requirements; higher heat loss or greater amount of energy purchased resulted in a lower efficiency and a lower A/R_{RT} value for a concept. S-R, in an earlier study, supplied SERI with values of conversion efficiencies of solar thermal power systems [Ref. 11], and, therefore, values for A/R_{CYC}. A/R_{COL} was taken from Ref. 11, Fig. 4-8, with extrapolation of the curves and assuming the sodium receiver curve to be accurate for a steam receiver. AD/RD_{CYC} and AD/RD_{COL} were set at 1.0 throughout the study with the exception of the total energy system application, in which AD/RC_{CYC} was assumed to be equal to A/R_{CYC}.

For process heat applications, the ranking index equation becomes

$$RI = \frac{\left[\frac{CC_A}{CC_R} * \frac{ESR}{EDR} + 1\right]}{\left[\frac{A}{R_{RT}} * \frac{A}{R_{COL}} * \frac{ESR}{EDR}\right] + \left[\frac{AD}{RD_{COL}}\right]}. \quad \text{(A-6)}$$

This is the same as Eq. (A-5), with the cycle efficiency terms equal to 1.0.

Calculating the ranking index for a total energy system is somewhat more complex.

$$RI = \frac{[CC_A - CC_R] + [STWER * DPE * FA]}{TCR}$$

$$FA = 1 - \frac{\left[\left(\frac{A}{R_{CYC}} * \frac{A}{R_{COL}} * \frac{A}{R_{RT}} * \frac{ESR}{EDR}\right) + \left(\frac{AD}{RD_{CYC}} * \frac{AD}{RD_{COL}}\right)\right]}{1 + \frac{ESR}{EDR}}$$

$$TCR = CC_R + [WET - STWER] * DPE + [QT - STQ] * DPQ ,$$

where

WET = total annual electricity demand of the reference system

STWER = annual solar thermal electricity delivered by the reference system

DPE = annualized, levelized purchased electricity cost

QT = total annual heat demand of the reference system

STQ = annual solar thermal heat delivered by the reference system

DPQ = annualized, levelized purchased heat cost.

Values for STWER, WET, QT, AND STQ were derived from data developed for the Shenandoah, Georgia, solar thermal plant design [4]. DPE and DPQ were calculated using energy costs from the Solar Thermal Cost Goals Committee and economic methods suggested by EPRI [5].

A.4 WATER/STEAM RECEIVERS

A.4.1 Electric Power Generation Application

The nonstorage solar thermal plant cost was calculated using cost estimates from Sandia Livermore Laboratories [6] and equations of the form given in SERI's work on the cost and performance of solar thermal systems. The results, referring to the terms in Eq. (A-2), were as follows:

$$RC = 21.5A + 197 \cdot (A)^{0.8}$$
$$HC = 80A$$
$$BOP = 480 * RP$$

where A is the collector area in m^2 and RP is the rated power of the solar thermal plant in kW. The constants were arrived at assuming a 10% increase in equipment costs from 1978 to 1979 and from 1979 to 1980; this assumption was held throughout the sensitivity study.

Performance data of the storage concepts considered for the water/steam receiver electric power application are given in Table A-5. The table is

Table A-5. Water/Steam Power Application Performance Data

Concept	Hours of Storage	Fluid Replacement Cost ($/Yr)	O&M[a] ($)	Efficiency Ratios: First-Law A/R_{RT}	Efficiency Ratios: Cycle A/R_{CYC}	Efficiency Ratios: Collector A/R_{COL}
Oil/rock, draw salt (reference)	1	136,000				
	6	1,169,000	.03/.02	1.0	1.0	1.0
	15	3,315,000			(0.284)[b]	
Oil/rock, sand moving bed	1	127,000		0.91		
	6	1,095,000	.03/.03	0.94	0.98	1.00
	15	3,129,000		0.92		
Underground pressure (water, draw salt)	1	12,000		1.06		
	6	74,000	.02/.02	1.01	1.00	1.01
	15	186,000			1.01	
Aboveground pressure (water, draw salt)	1	12,000		0.98		
	6	74,000	.02/.02	0.99	1.00	1.01
Solution-mined cavern, draw salt	1	116,000		1.00		
	6	990,000	.03/.02	1.01	1.00	1.00
	15	2,800,000		1.00		
Caloria, draw salt	1	116,000		1.00		
	6	994,000	.03/.02	0.99	1.00	1.00
	15	2,817,000		0.99		
Tube-intensive, draw salt	1	17,000		0.95		
	6	80,000	.03/.02	0.96	1.00	0.99
	15	199,000		0.97		
Containerized salt, draw salt	1	14,000		1.00		
	6	82,000	.03/.02	1.03	1.00	0.99
	15	205,000		1.01		
Direct-contact HX, salt	1	41,000		0.90		
	6	244,000	.04/.02	0.88	1.00	0.99
	15	606,000		0.83		

[a]First stage/second stage.

[b]Absolute efficiency--actual.

self-explanatory, and the information is provided so that comparisons can be made between the performance characteristics of the various storage concepts. Note that the efficiencies are given as ratios with respect to the reference system's efficiencies and are not actual or absolute values.

The primary results of the water/steam power application study are shown in Fig. A-1. As suggested by RI values of less than one, both the direct-contact heat exchanger concept (#9) and the underground pressurized-water concept (#3) may yield significant improvements in BBEC over the oil/rock, draw salt reference system at high storage capacities. Concepts 1, 2, 4, 5, 6, and 7, with RI values near or above 1.0, show little or no potential improvement in delivered energy cost, compared with the reference concept at all storage capacities. All lines represent nominal-condition results. The dashed line (#10) was included to show the sensitivity of the results to assumptions of the oil-replacement rate for the reference system. The condition considered was that of no oil replacement; this was designated an unrealistic case, but was employed to define the lower limit of oil-replacement rates. Line 10 on the graph is significant because it shows that the conclusions drawn from the graph might be altered if the assumed oil-replacement rates are inaccurate. That is, if the oil-replacement rates used in this study are significant overestimates of the rates determined from actual testing and use, the two alternative storage concepts that showed promise will be closer in BBEC to the reference system, and the concepts showing little or no improvement in BBEC in Fig. A-1 will look somewhat worse.

The results of the sensitivity study are given in Table A-6 for the water/steam receiver power application. All values are expressed in terms of percent change in BBEC with respect to the reference system operating at the same conditions and using the same economic parameters. In the nominal column, the data from Fig. A-1 are presented numerically. The next two columns show the results of applying the 1.44 factor to the media term alone and to both the media and equipment terms, respectively. We can see from this data that variations in these parameters, while they alter the results by a few percentage points, have no effect on our conclusions. Results from applying the 2% O&M to all concepts rather than the variable rate schedule are shown next. Again, the percent change in BBEC values vary by a few points from the nominal case, but the conclusions remain unchanged. The last two columns in the table contain the results of varying the ESR/EDR parameter--varying the level of storage use. The percentages again change only slightly, and conclusions drawn from the nominal case are still valid.

The effects of uncertainties about overall storage subsystem costs are shown in Figs. A-2 and A-3 for 6 and 15 hours of storage, respectively. These charts illustrate the most significant finding of the sensitivity study. In both figures, the underground pressurized-water and direct-contact heat exchange concepts show the most promise of decreasing energy costs, yet it is also apparent that the validity of other conclusions depends on the accuracy of the cost estimates. For example, at 6 hours of storage, if the nominal reference system cost has been underestimated by 20%, the top of Bar #1 in Fig. A-2 would represent the actual reference BBEC value, and Concepts 2, 3, 4, 6, 9, and 10 would all show potential improvement with respect to the reference system. This condition further supports the caveat that final conclusions should not be drawn from only one estimate of costs.

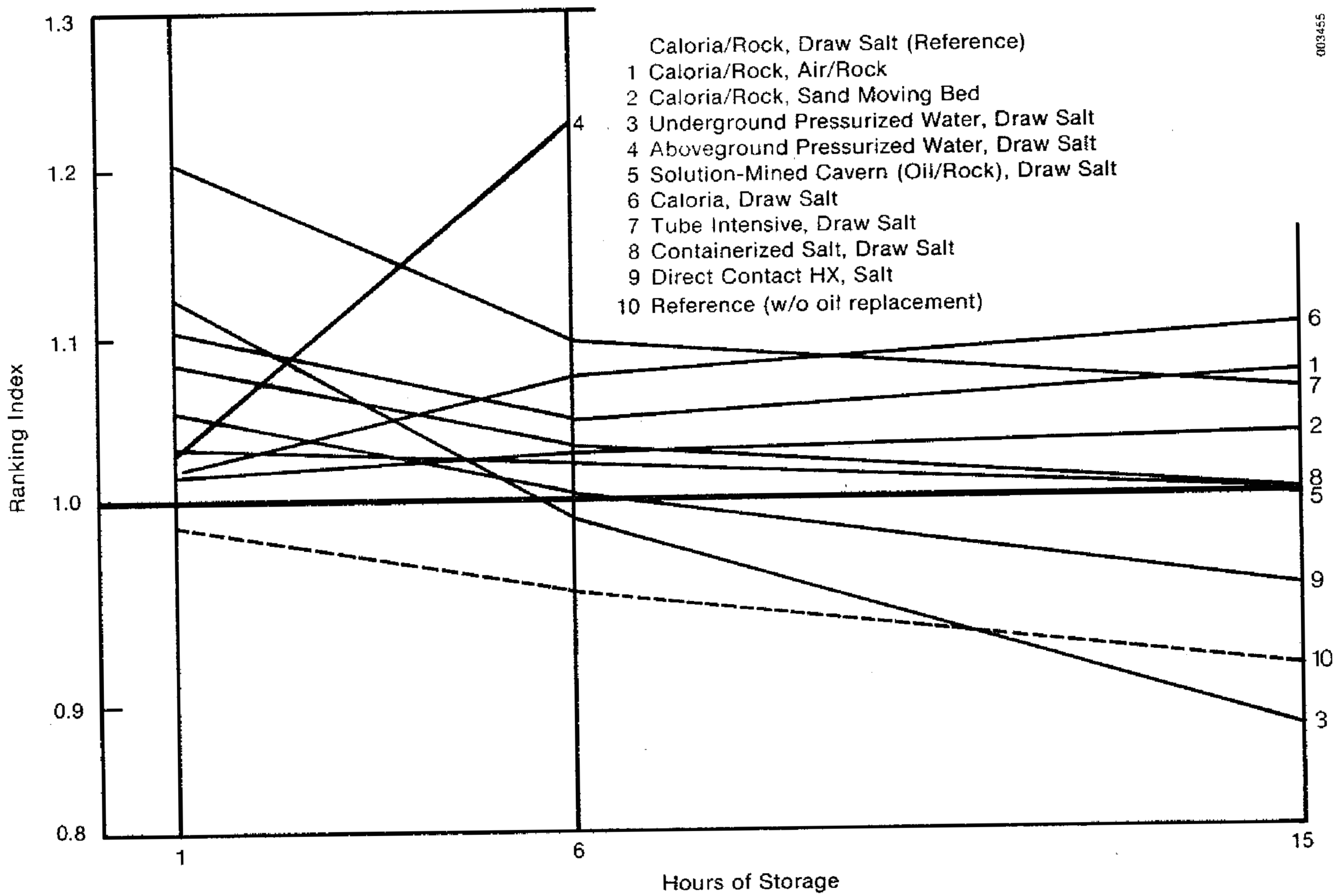

Figure A-1. Water/Steam Power Application

Table A-6. Water/Steam Power Application BBEC

Concept	Hours of Storage	Percent Change in BBEC: Nominal	On Media (1.44)	On All Equipment (1.44)	O&M (2%)	Low Storage Use	High Storage Use
Oil/rock, air/rock	1	+11	+11	+ 9	+10	+10	+12
	6	+ 4	+ 5	+ 4	+ 4	+ 4	+ 7
	15	+ 7	+ 7	+ 6	+ 6	+ 6	+11
Oil/rock, sand moving bed	1	+ 2	+ 2	+ 1	+ 1	+ 1	+ 2
	6	+ 2	+ 3	+ 2	+ 2	+ 2	+ 3
	15	+ 3	+ 4	+ 3	+ 2	+ 3	+ 4
Underground pressure (water, draw salt)	1	+13	+13	+10	+13	+14	+12
	6	− 2	− 1	− 3	− 1	− 1	− 2
	15	−15	−14	−15	−14	−15	−15
Aboveground pressure (water, draw salt)	1	+ 3	+ 3	+ 2	+ 3	+ 3	+ 3
	6	+23	+24	+17	+23	+23	+23
Solution-mined cavern, draw salt	1	+ 9	+ 9	+ 7	+ 8	+ 9	+ 9
	6	+ 3	+ 3	+ 2	+ 3	+ 3	+ 3
	15	0	0	− 1	0	0	0
Caloria, draw salt	1	+ 2	+ 2	+ 2	+ 2	+ 2	+ 2
	6	+ 8	+ 6	+ 6	+ 7	+ 8	+ 8
	15	+10	+ 8	+ 8	+10	+10	+10
Tube-intensive, draw salt	1	+21	+20	+17	+20	+20	+22
	6	+10	+10	+ 7	+ 9	+ 9	+12
	15	+ 7	+ 6	+ 3	+ 6	+ 6	+ 7
Containerized salt, draw salt	1	+ 3	+ 3	+ 2	+ 3	+ 3	+ 3
	6	+ 3	+ 2	+ 1	+ 2	+ 3	+ 2
	15	0	− 1	− 2	0	0	0
Direct-contact HX, salt	1	+ 5	+ 4	+ 4	+ 5	+ 4	+ 6
	6	0	− 1	− 1	0	− 1	+ 5
	15	− 6	− 7	− 6	− 6	− 8	+ 1

Reference: oil/rock, draw salt.

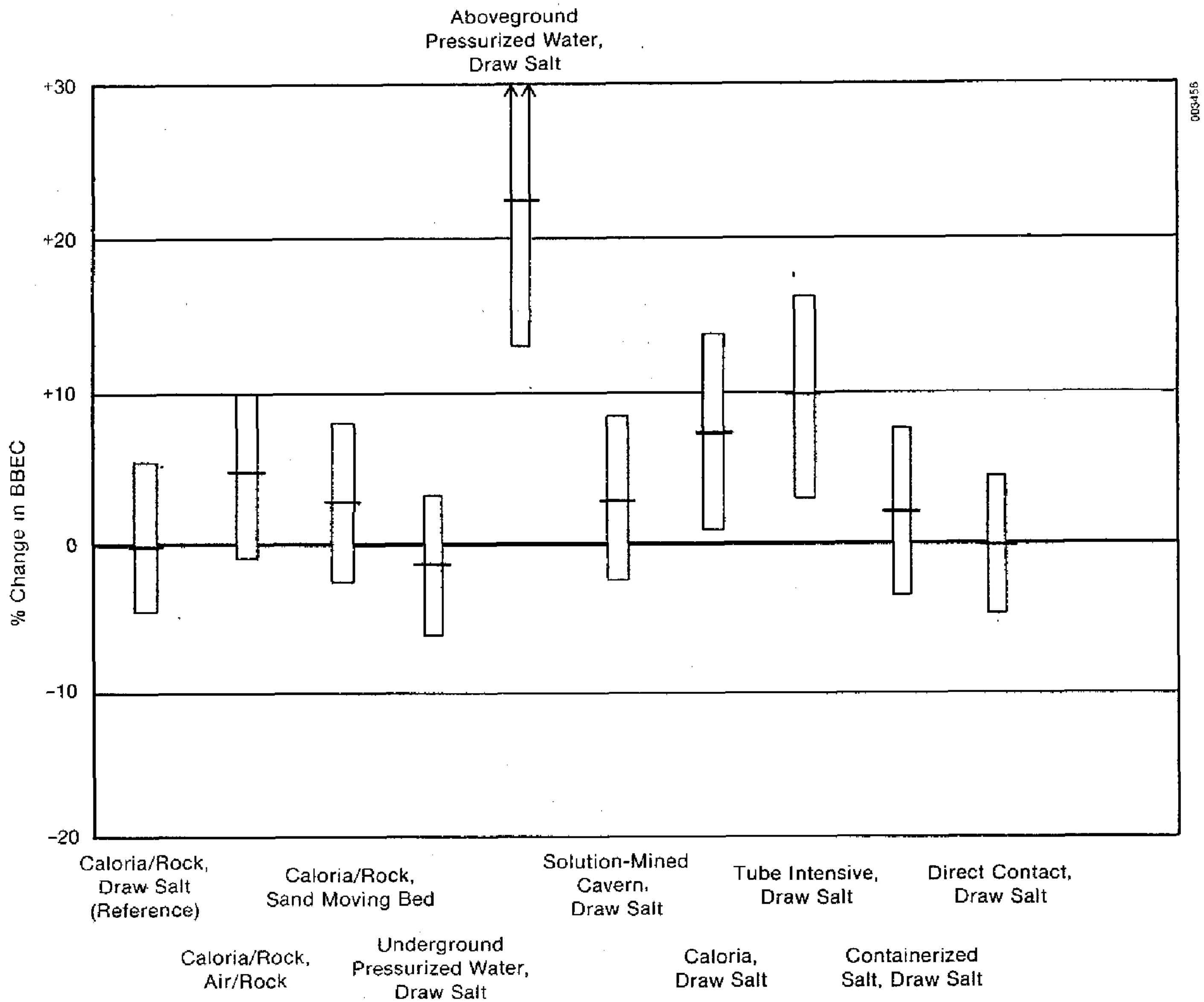

Figure A-2. Effects of ±20% Cost Uncertainty for Water/Steam Power Concept
(6-hour storage capacity)

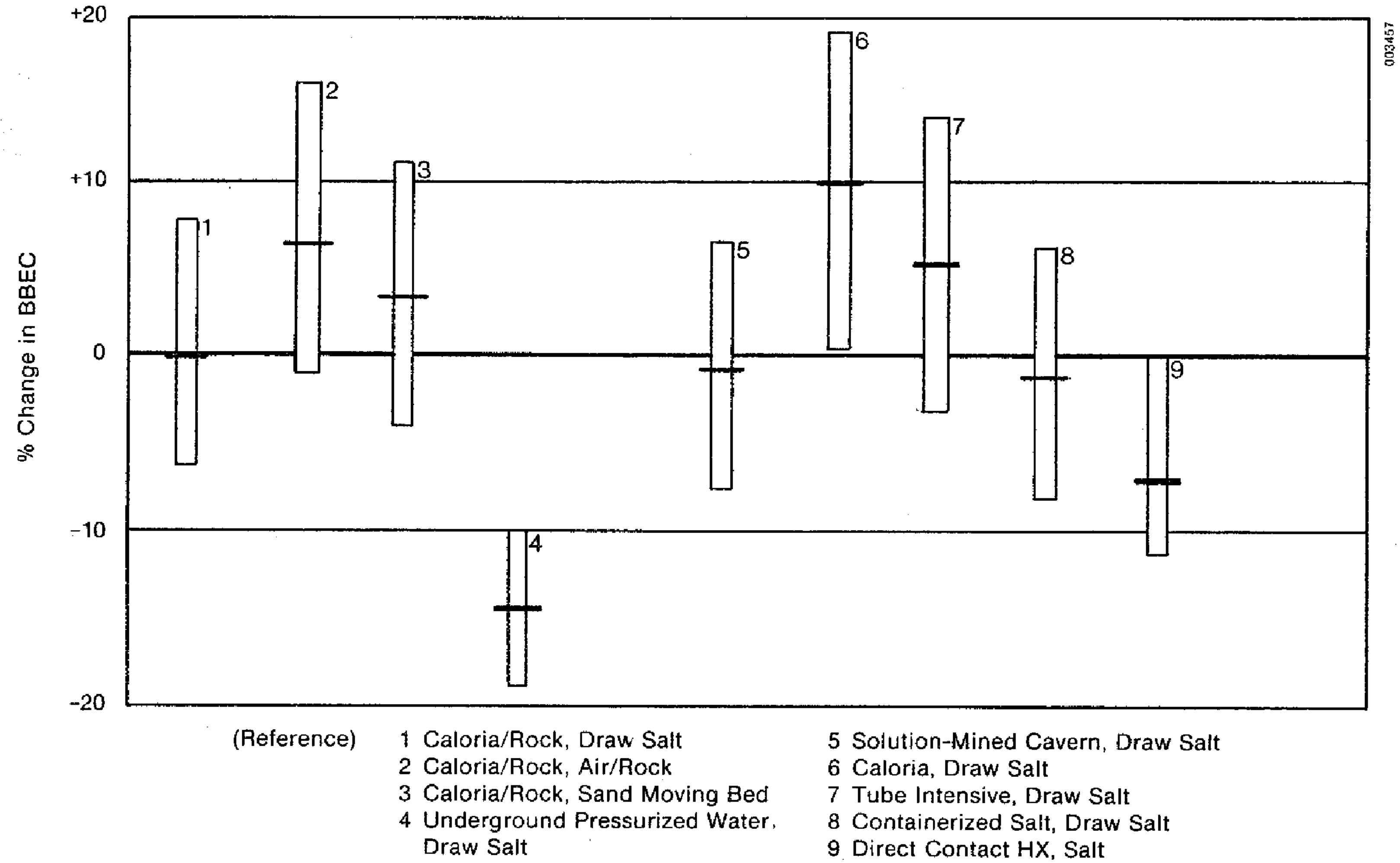

Figure A-3. Effects of ±20% Cost Uncertainty for Water/Steam Power Concepts (15-hour storage capacity)

An objective of the storage program is to decrease storage subsystem costs by 25%; Table A-7 presents BBEC increases or decreases and associated storage cost increases or decreases. For the water/steam receiver power application, only the underground pressurized-water and the direct-contact heat exchange concepts show promise of achieving the program goal; at high storage capacities, these concepts are expected to decrease actual storage subsystem costs by approximately 30% to 40%. The other concepts are hardly significant improvements over the storage costs of the reference system.

Table A-7. Percent Change in Storage Subsystem Cost
(Water/steam power application)

Concept	Hours of Storage	Change in BBEC (%)	Change in Storage Cost (%)
Oil/rock, air/rock	1	+11	+ 75
	6	+ 4	+ 12
	15	+ 7	+ 11
Oil/rock, sand moving bed	1	+ 2	+ 10
	6	+ 2	+ 8
	15	+ 3	+ 7
Underground pressure (water, draw salt)	1	+13	+110
	6	- 2	- 5
	15	-15	- 40
Aboveground pressure (water, draw salt)	1	+ 3	+ 23
	6	+23	+ 92
Solution-mined cavern, draw salt	1	+ 9	+ 70
	6	+ 8	+ 12
	15	0	0
Caloria, draw salt	1	+ 2	+ 15
	6	+ 8	+ 30
	15	+10	+ 28
Tube-intensive, draw salt	1	+21	+161
	6	+10	+ 36
	15	+ 7	+ 16
Containerized salt, draw salt	1	+ 3	+ 25
	6	+ 3	+ 12
	15	0	0
Direct-contact HX, draw salt	1	+ 5	+ 33
	6	0	+ 12
	15	- 6	- 30

Reference: nominal and used.

The percentage of the total solar thermal plant cost that makes up the storage subsystem cost increases with increasing storage capacity. In Table A-8, the total capitalized cost of the complete solar thermal plant is given, as well as its breakdown into storage and nonstorage (plant) costs (see Eq. A-1). Note that the storage costs presented are calculated for the reference oil/rock draw salt system under nominal conditions.

Table A-8. Plant Cost Breakdown (Water/steam power application)

Hours of Storage	Capitalized Cost ($M)	Storage Cost[a] ($M)	Plant Cost ($M)
1	155	19	136
6	248	61	187
15	374	134	240

[a]Reference storage system, nominal conditions.

A.4.2 Process Heat Application

The second application considered for a water/steam receiver was the production of process heat. Appropriate modifications were made to nonstorage equipment designs; the algorithms used to determine the cost of this equipment reflect those changes. The receiver (RC), heliostat (HC), and balance-of-plant (BOP) cost algorithms are, respectively,

$$RC = 26.3A + 77.5(A)^{0.8}$$
$$HC = 80A$$
$$BOP = 149 * RP.$$

The differences in cost algorithms for the power application and the process heat application are the result of differences in materials requirements in the receiver subsystems and the absence of the turbine/generator and related equipment in the process heat system. Subsystem costs were derived from values, obtained by Sandia National Laboratories, as were the materials distributions for the receiver [6].

The performance data for the storage concepts are given in Table A-9. Again, the efficiencies have been normalized to the reference system's efficiencies and so, with the exception of the cycle efficiencies, they are not absolute values. While the other alternative concepts are very close to the oil/rock reference system performance, the underground pressurized-water system is consistently higher in efficiency and lower in recurring costs than the reference system.

Table A-9. Water/Steam Process Heat Application Performance Data

Concept	Hours of Storage	Fluid Replacement Cost ($/yr)	O&M (%)	Other Recurring Costs[a]	Efficiency Ratios: First-Law	Efficiency Ratios: Cycle	Efficiency Ratios: Collector
Oil/rock (reference)	1	386,000		77,000			
	6	3,406,000	3	514,000	1.00	1.0	1.00
	15	9,715,000		1,317,000			
Underground pressure (water)	1			46,000	1.02		
	6	0	2	288,000	1.03	1.0	1.01
	15			729,000	1.04		
Oil/rock excavated pit	1	386,000		77,000	1.00		
	6	3,406,000	3	514,000	1.00	1.0	0.99
	15	9,715,000		1,317,000	1.01		
Containerized salt	1	6,000		35,000	1.00		
	6	23,000	3	226,000	1.00	1.0	0.99
	15	49,000		596,000	1.00		

[a]Purchased electricity.

Unlike the power application results, results for the water/steam receiver process heat application suggest that all of the alternative storage concepts have potentially lower energy costs than the reference concept at some storage capacities (see Fig. A-4); the underground pressurized-water concept is particularly attractive if a high storage capacity is required. The containerized salt concept might also be preferable at capacities above five hours, and the oil/rock excavated pit concept shows a moderate energy cost improvement at all capacities. Line 4 has been included to illustrate the effects of oil replacement rate assumptions. Again, the conclusions drawn from the data may be sensitive to this assumption; a lower replacement rate would make the salt and the excavated pit concepts appear little better than the reference concept.

In Table A-10 the percent change in unit energy cost with respect to the reference system is shown for variations in several parameters. Again, the results of the sensitivity study are easily summarized by noting that the trends shown in the ranking index plot for nominal conditions (Fig. A-4) are maintained throughout the parametric changes listed in Table A-10. Altering the O&M, installation, and indirect factors applied to the storage subsystems did not significantly alter the results.

The effects of up to a 20% storage cost uncertainty in the process heat application are shown in Figs. A-5 and A-6. The underground pressurized-water concept consistently stands out as being the concept most likely to provide the lowest-cost energy, even if major cost-estimate uncertainties still exist. For the other concepts, however, cost uncertainties make it questionable to assume that the unit energy cost from one system would be significantly different from that of another system; given a 20% uncertainty, the ranges of energy costs for these systems are very close.

In light of the 25% cost improvement program goal, the values in Table A-11 suggest that the goal could be achieved with an underground pressurized-water system at capacities greater than buffer storage. Also, the containerized salt concept could adequately reduce storage cost at high capacities, but the oil/rock excavated pit concept is not expected to do so.

The solar thermal plant cost breakdown is presented in Table A-12 for the process heat application. Again, the percentage of total plant cost that is allocated to the storage subsystem increases with increasing storage capacity, and, in fact, dominates the cost at high storage capacities.

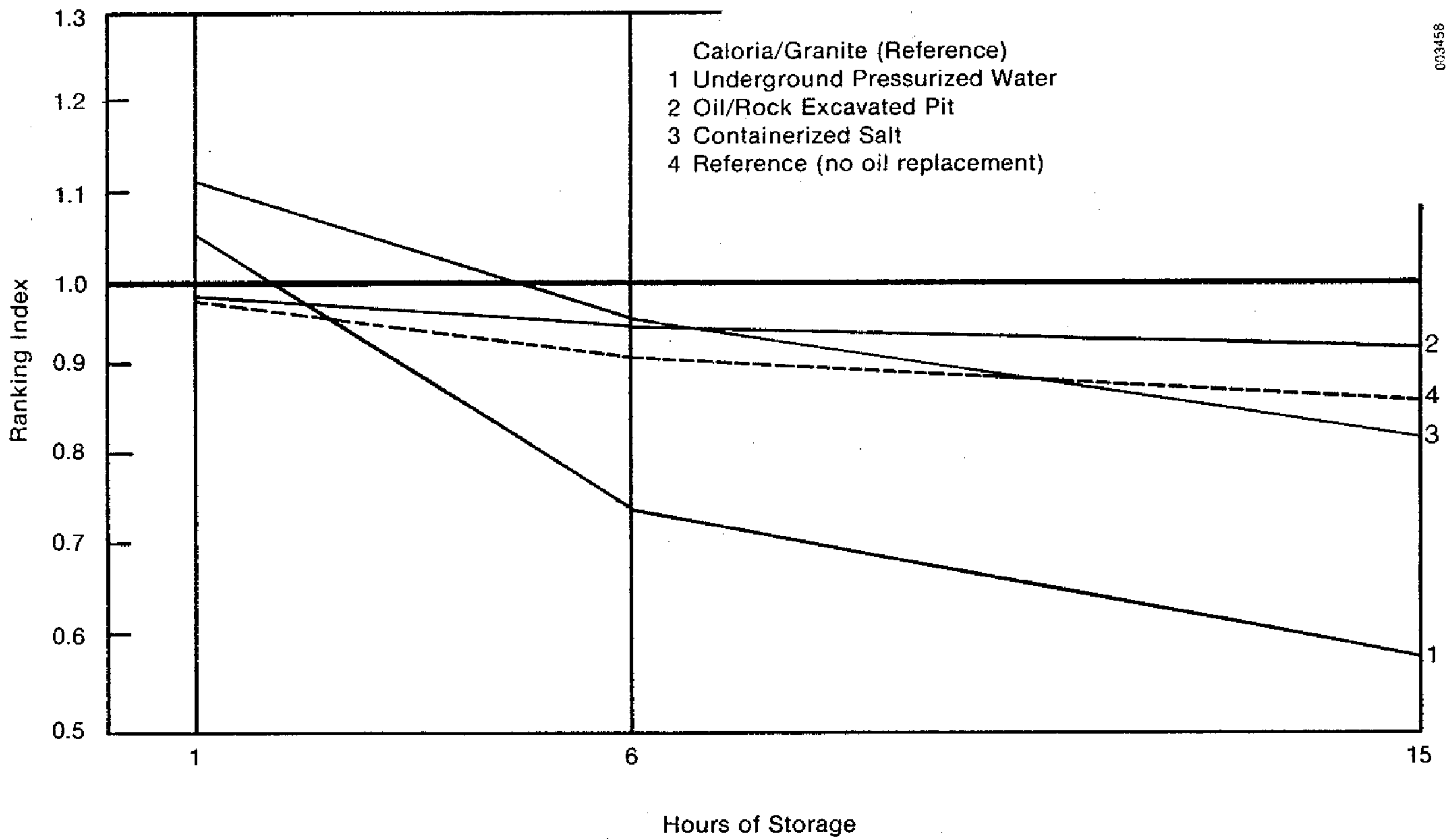

Figure A-4. Water/Steam Process Application

Table A-10. Water/Steam Process

Concept	Hours of Storage	Percent Change in Unit Energy Cost: Nominal	On Media (1.44)	On All Equipment (1.44)	O&M (2%)	Low Storage Use	High Storage Use
Underground pressure, water	1	+ 6	+ 7	+ 4	+ 6	+ 6	+ 6
	6	-26	-24	-24	-25	-25	-27
	15	-42	-43	-40	-42	-42	-43
Oil/rock, excavated pit	1	- 2	- 2	- 1	- 2	- 2	- 2
	6	- 4	- 4	- 5	- 4	- 4	- 4
	15	- 7	- 7	- 6	- 7	- 7	- 7
Containerized salt	1	+12	+11	+ 9	+12	+12	+12
	6	- 4	- 5	- 6	- 4	- 4	- 4
	15	-17	-18	-18	-17	-17	-17

Reference: oil/rock system.

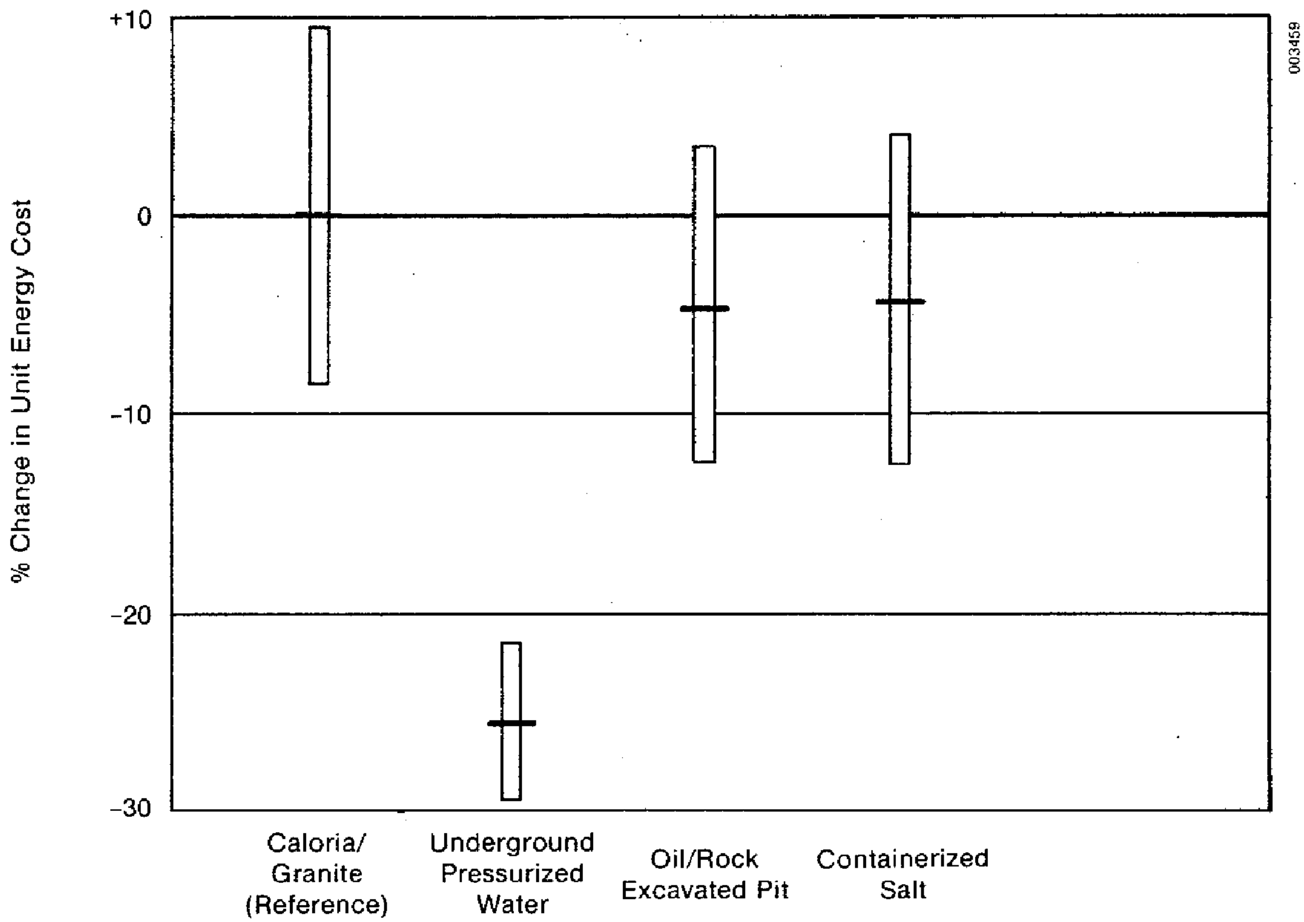

Figure A-5. **Effects of ±20% Cost Uncertainty for Water/Steam Process Heat Concept** (6-hour storage capacity)

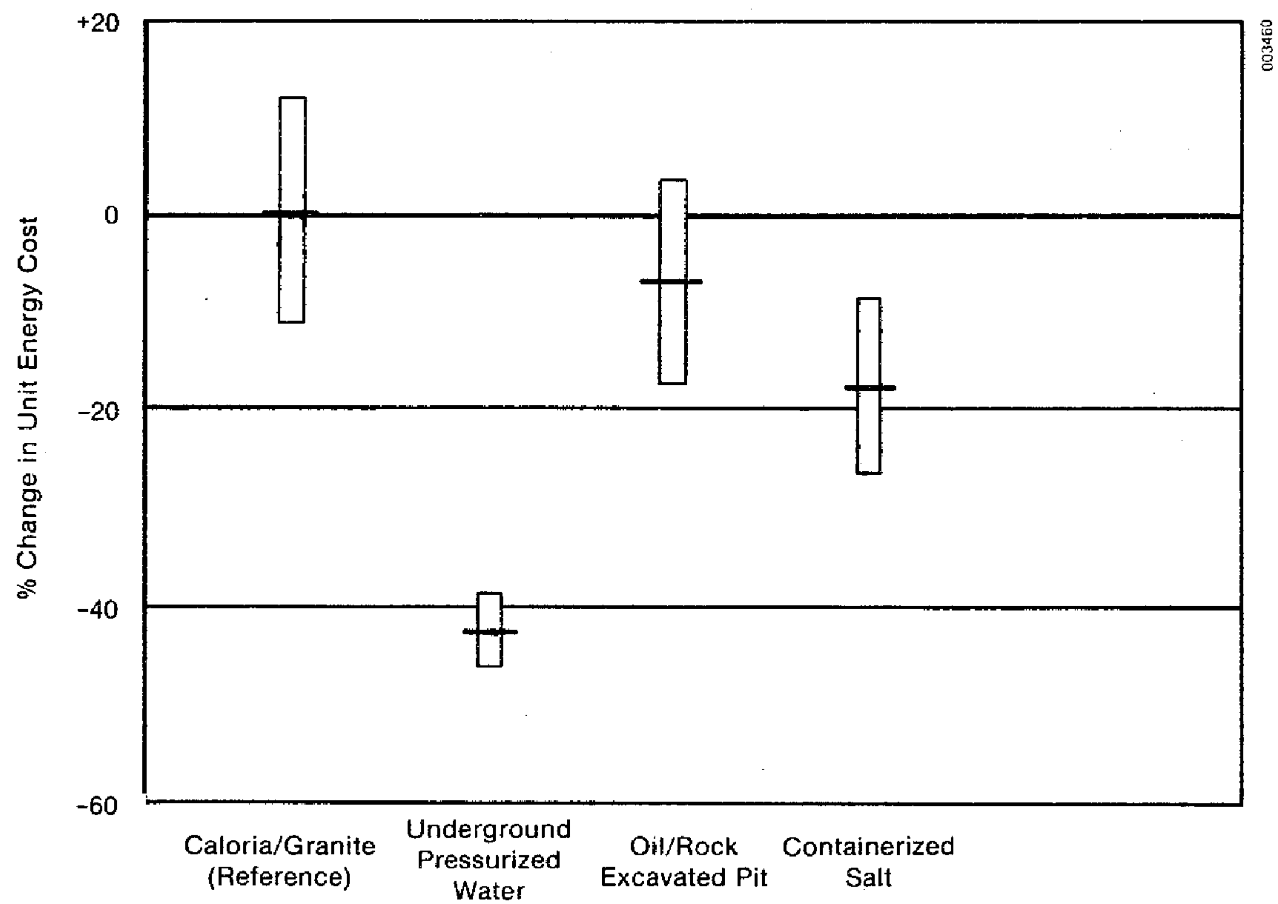

Figure A-6. Effects of ±20% Cost Uncertainty for Water/Steam Process Heat Concept
(15-hour storage capacity)

Table A-11. Percent Change in Storage Subsystem Cost
(Water/Steam Process Heat)

Concept	Hours of Storage	Change in BBEC (%)	Change in Storage Cost (%)
Underground pressure, water	1	+ 6	+25
	6	-26	-55
	15	-42	-71
Oil/rock, excavated pit	1	- 2	- 7
	6	- 4	-10
	15	-17	-12
Containerized salt	1	+12	+48
	6	- 4	- 9
	15	-17	-30

Reference: oil/rock system.

Table A-12. Plant Cost Breakdown
(Water/steam power application)

Hours of Storage	Capitalized Cost ($M)	Storage Cost[a] ($M)	Plant Cost ($M)
1	110	27	83
6	237	108	129
15	424	248	176

[a]Reference storage system, nominal conditions.

A.5 AIR RECEIVER-BRAYTON CYCLE POWER GENERATION

The third application considered in this study was a closed Brayton cycle power-generation application using an air-cooled central receiver solar thermal plant. A schematic and description of the plant are given in Volume II, along with schematics for the reference and alternative storage subsystems.

The cost algorithms for nonstorage plant equipment were developed from SERI data. For the closed Brayton cycle system we have

$$RC = 6.14A + 323(A)^{0.8}$$
$$HC = 80A$$
$$BOP = 662 * RP.$$

Table A-13. Brayton Power Application

Concept	Hours of Storage	Percent Change in BBEC					
		Nominal	On Media (1.44)	On All Equipment (1.44)	O&M (2%)	Low Storage Use	High Storage Use
Air/cast iron	1	0	0	0	0	0	− 1
	6	0	− 3	− 1	− 1	− 1	− 1
	15	+ 1	+ 3	− 1	− 1	− 1	− 2
Air/rock	1	+71	+72	+58	+71	+66	+76
	6	+36	+41	+33	+36	+33	+58
	15	+43	+35	+28	+43	+33	+70

Reference: air/alumina brick system.

Performance data for the three storage concepts are given in Table A-13. While the air/cast iron system demonstrates higher first-law efficiency than the reference system, the air/granite concept exhibits a decrease in efficiency, caused by higher pumping power requirements. The cycle efficiency for the air/granite system is also lower because the temperature of the air entering the turbine is lower.

The results of the ranking, presented in Fig. A-7, indicate that the air/granite concept is most likely to increase the BBEC, while air/cast iron storage would have very little effect on energy cost.

As with the applications previously discussed, variations in the level of storage use and in the O&M, installation, and indirect factors applied to the systems yield conclusions the same as those drawn from nominal condition results. The results of these parametric variations are given in Table A-14. Although the numerical values of the percent change in BBEC vary somewhat, they do not vary enough to affect the conclusions.

Cost-uncertainty effects for 6-hour and 15-hour capacities (Figs. A-8 and A-9) do not alter the conclusions in this case; the air/granite system still appears to be undesirable, and the air/cast iron system remains almost identical to the air/alumina reference. These conclusions are borne out by the data in Table A-15, in which the air/cast iron concept appears to have as little effect on storage subsystem cost as on energy cost, and the air/rock concept is even less attractive when the storage costs are compared. The plant cost breakdowns for each storage capacity of the reference concept at nominal conditions are shown in Table A-15.

Table A-14. Percent Change in Storage Subsystem Cost
(Brayton electric power application)

Concept	Hours of Storage	Change in BBEC (%)	Change in Storage Cost (%)
Air/cast iron	1	+ 0	- 4
	6	0	- 2
	15	+ 1	- 2
Oil/rock, excavated pit	1	+71	+400
	6	+36	+107
	15	+43	+ 54

Reference: air/alumina brick system.

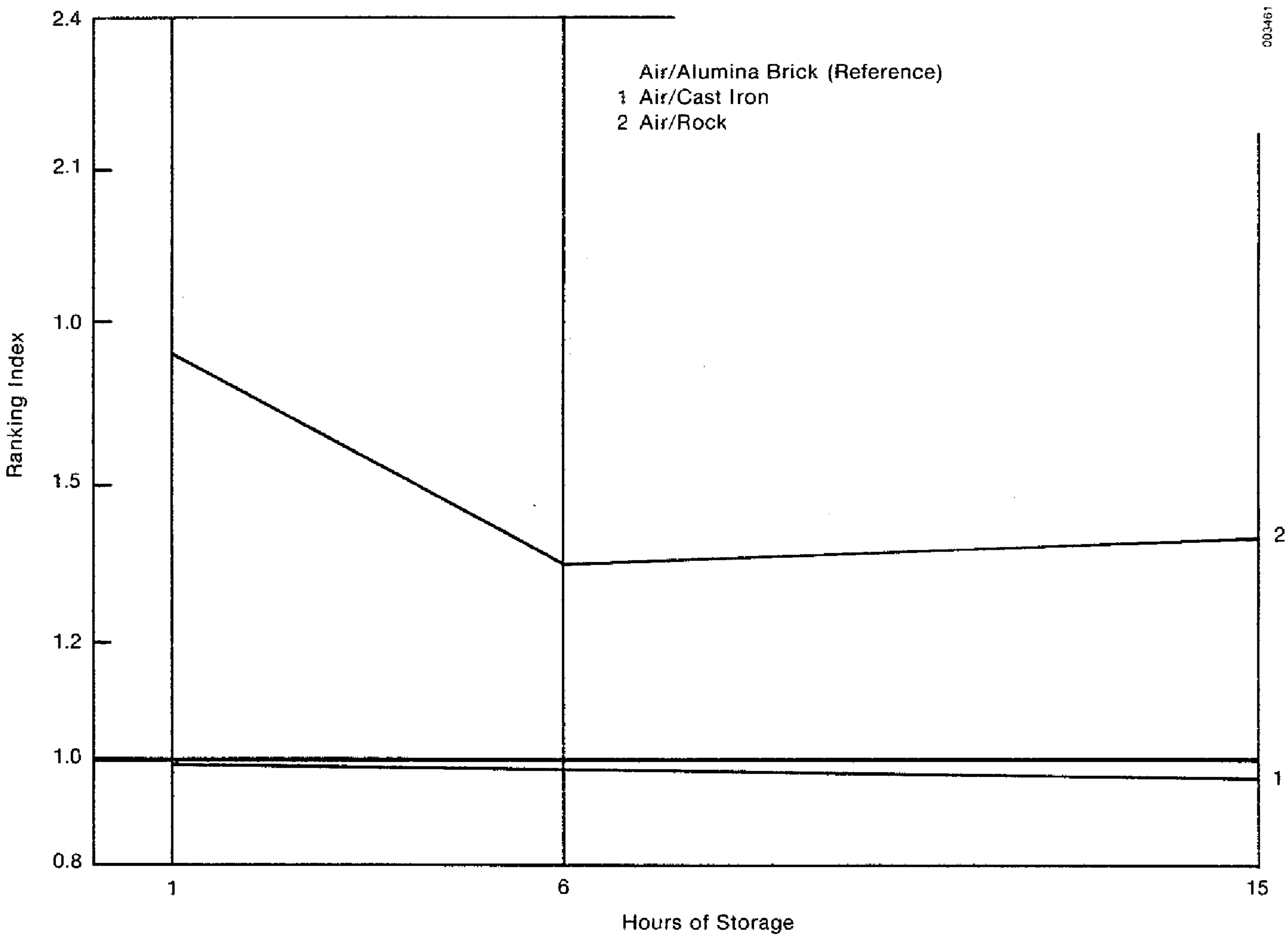

Figure A-7. Brayton Power

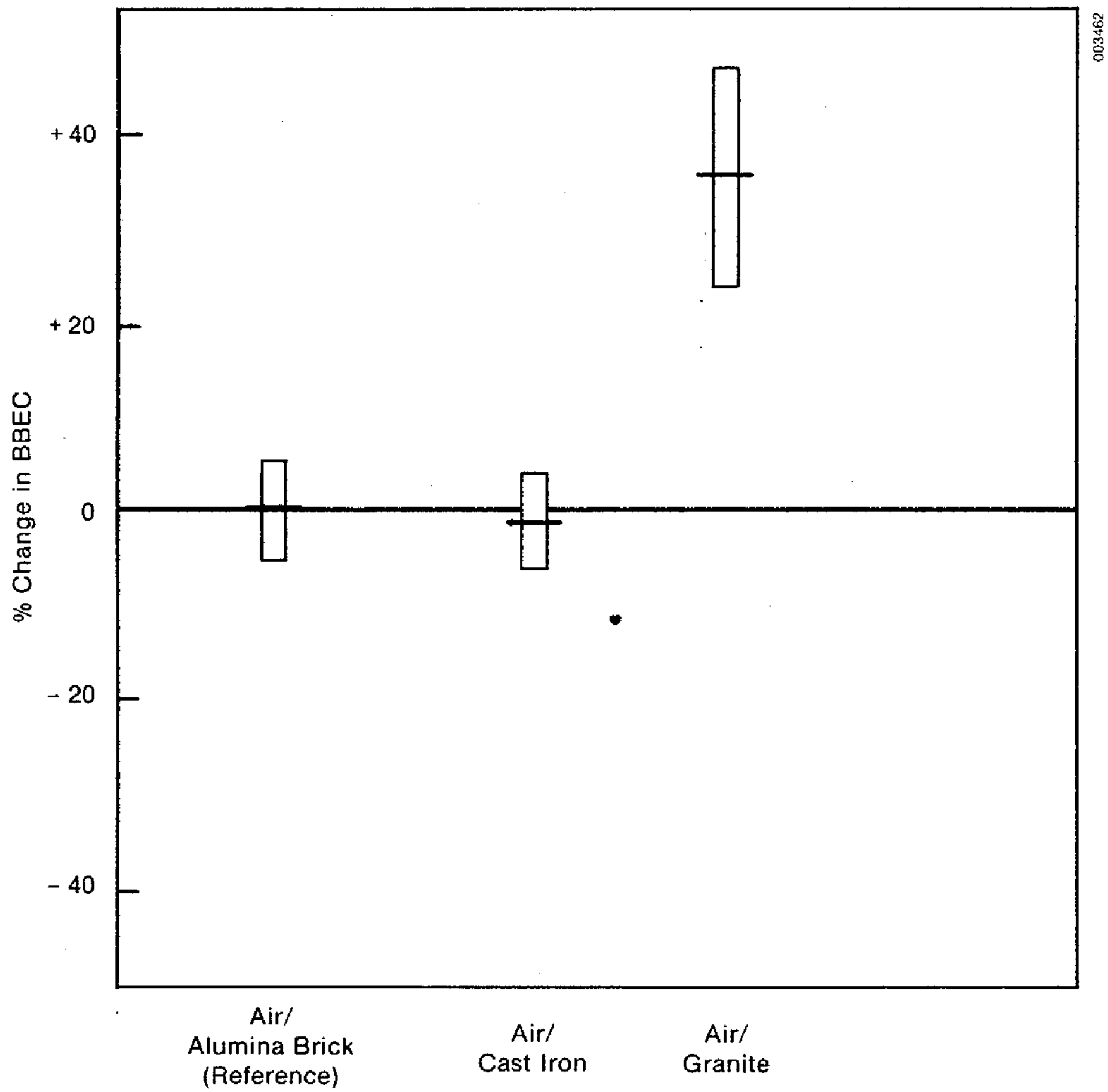

Figure A-8. Effects of ±20% Cost Uncertainty for Brayton Power
(6-hour storage capacity)

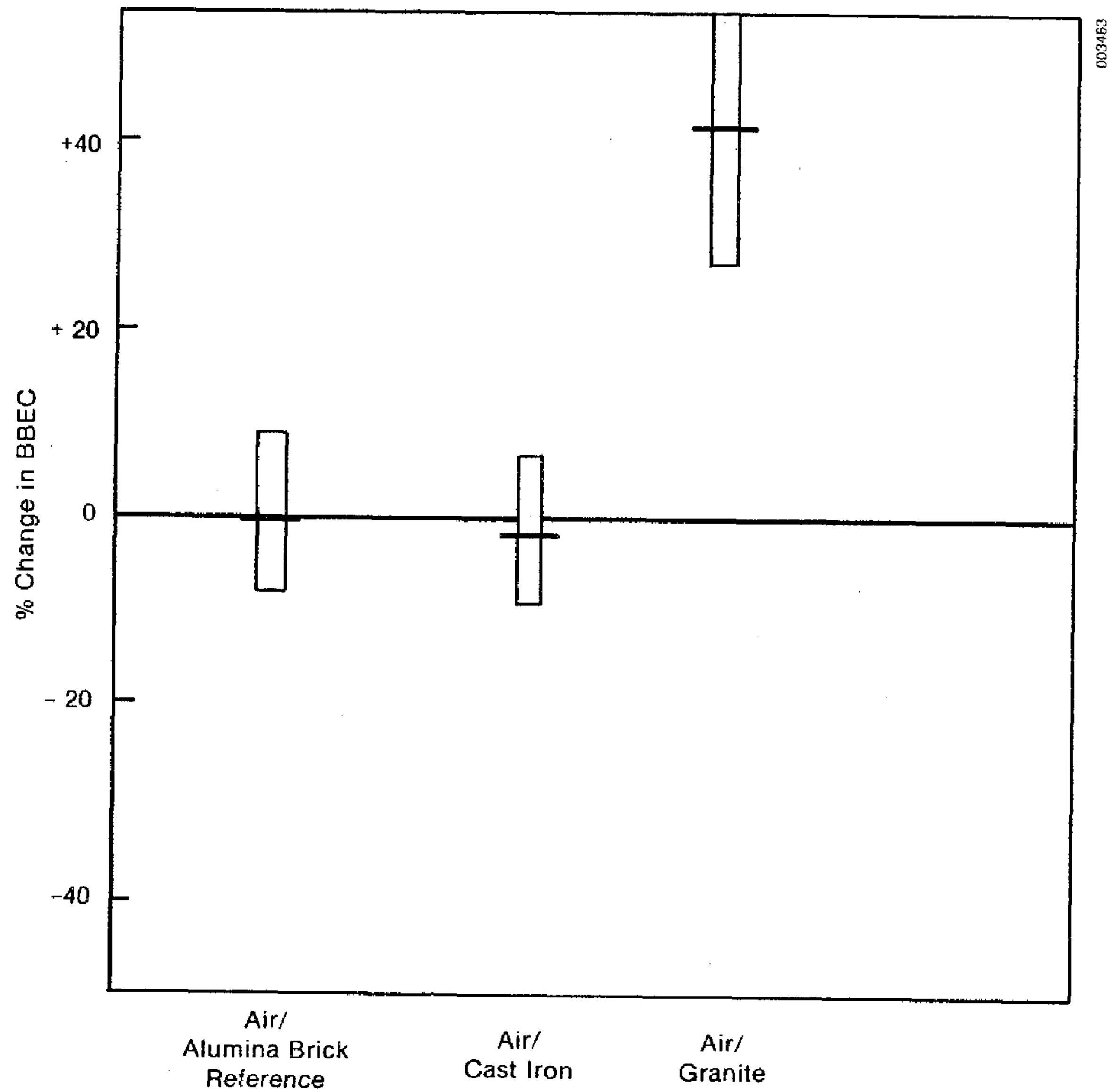

Figure A-9. Effects of ±20% Cost Uncertainty for Brayton Power
(15-hour storage capacity)

Table A-15. Plant Cost Breakdown (Brayton power cycle application)

Hours of Storage	Capitalized Cost ($M)	Storage Cost[a] ($M)	Plant Cost ($M)
1	332	25	307
6	537	135	402
15	824	332	402

[a]Reference storage system, nominal conditions.

A.6 ORGANIC FLUID RECEIVER--TOTAL ENERGY SYSTEM

The final application investigated in this study was an organic fluid, parabolic dish solar thermal plant used as a total energy system; i.e., the design for the Shenandoah, Georgia, system. The plant schematic and the storage subsystem schematics and conditions are given in Volume II.

Nonstorage costs for this application were broken down into only two categories, because collector and receiver costs are combined into one subsystem. The costs were calculated as

$$RC + HC = 203A$$
$$BOP = 7100 * RP.$$

These algorithms were also developed using SERI data.

The performance of the associated storage concepts (Table A-16) appears to be very similar. The lower temperatures delivered by the two alternative systems (see the table) account for their slightly lower cycle efficiencies. The actual reference cycle efficiency was approximately 15%.

Calculating the ranking index for the concepts yields the curves shown in Fig. A-10. Neither alternative concept represents a significant improvement in unit energy cost, compared with the Syltherm/taconite reference concept. The direct-contact heat exchange concept may yield an improvement at high capacities, but, as seen in Table A-17, it is a very slight improvement. As with the other applications already discussed, varying the O&M percentage, the various economic factors, and the level of storage use does not significantly affect our conclusions.

Figures A-11 and A-12 illustrate the similar busbar energy costs provided by these concepts. The direct-contact concept does not appear to be attractive at six hours of storage, even if cost uncertainties are taken into consideration.

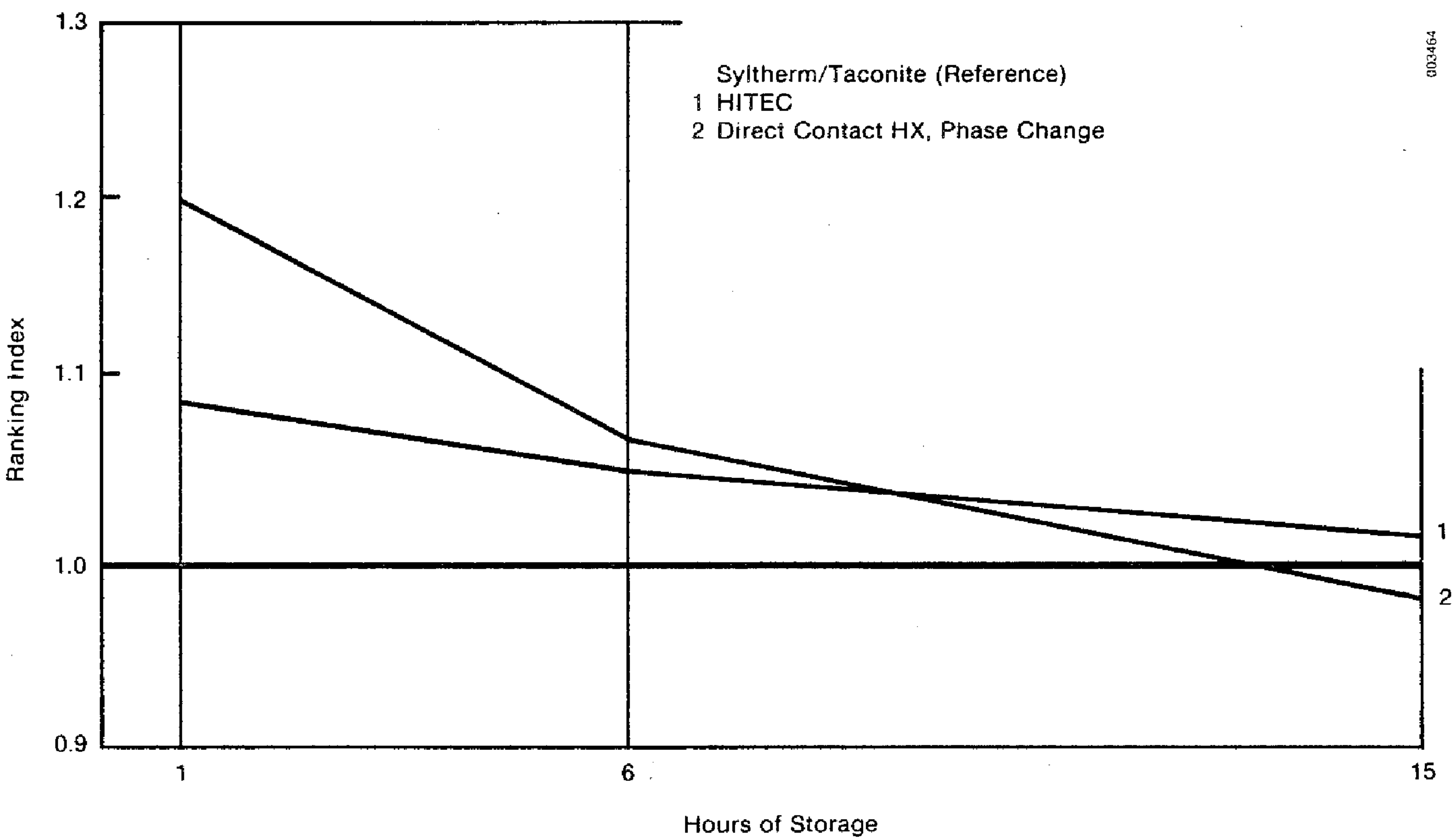

Figure A-10. Organic Total Energy

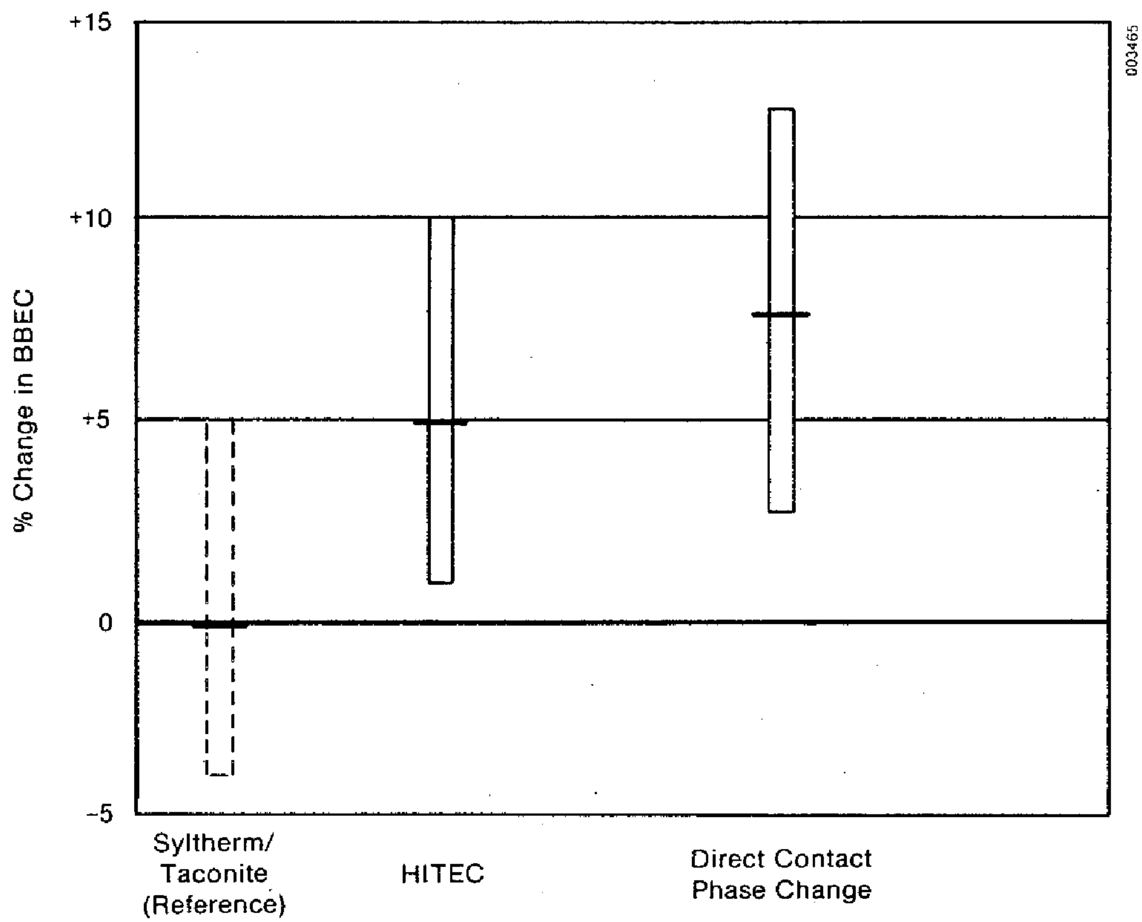

Figure A-11. Effects of ±20% Cost Uncertainty for Organic Total Energy
(6-hour storage capacity)

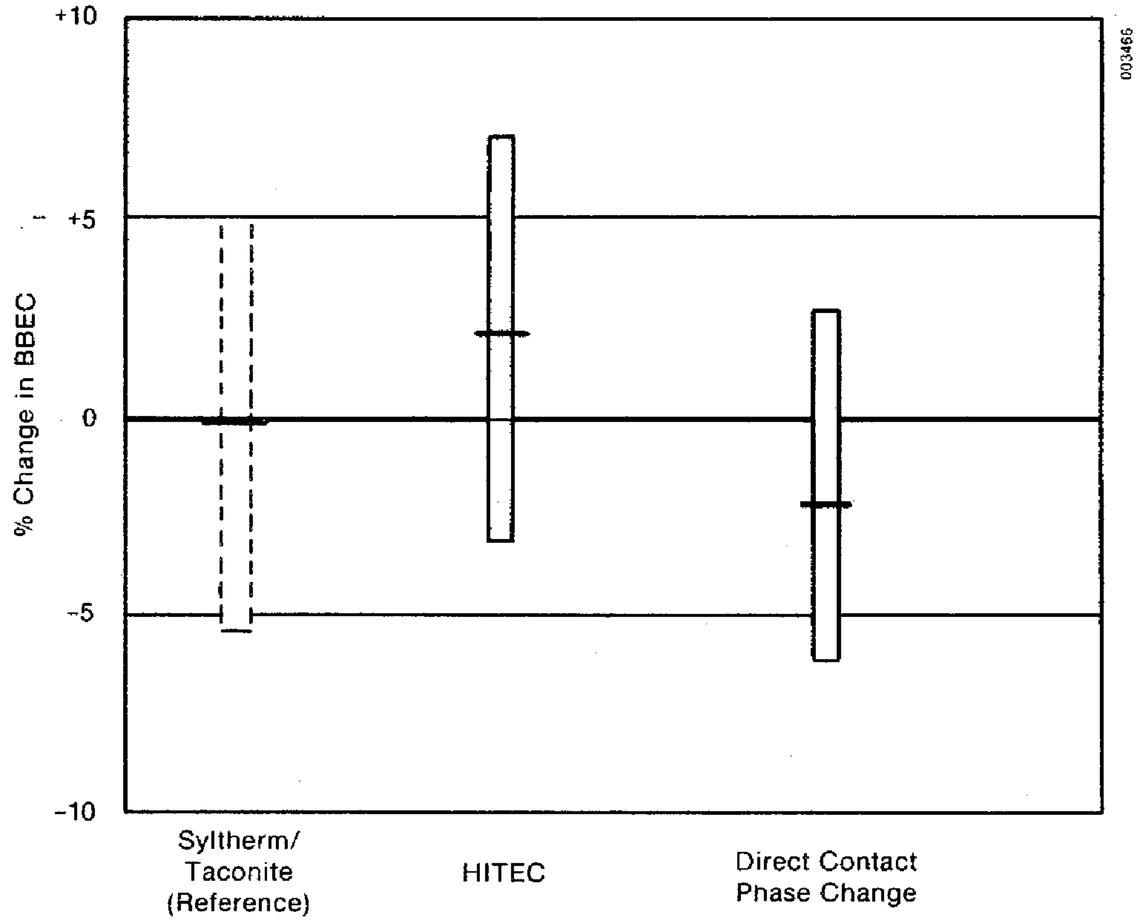

Figure A-12. Effects of ±20% Cost Uncertainty for Organic Total Energy
(15-hour storage capacity)

Table A-16. Organic Total Energy System: Performance Data

Concept	Hours of Storage	Fluid Replacement Cost ($/yr)	O&M (%)	Efficiency Ratios		
				First-Law	Cycle	Collector
Syltherm/taconite (reference system)	1	5,000				
	6	43,000	3	1.0	1.0	1.0
	15	119,000			(0.15)	
Hitec, two-tank	1	1,000				
	6	8,000	2	1.0	0.99	1.0
	15	20,000				
Direct-contact, phase change	1	400				
	6	2,000	4/2	1.0	0.99	1.0
	15	6,000				

With that exception, based on anticipated BBEC, the bar graphs suggest that one concept is no more attractive than the others at middle and high storage capacities.

The expected changes in storage subsystem costs are given in Table A-18. Neither of the alternative systems has the potential to meet the program goal of a 25% decrease in cost. The plant breakdown is presented in Table A-19, and it indicates that the percentage of the total solar thermal plant cost that would have to be allocated to storage is much lower for this system and application than for the others we examined.

Table A-18. Percent Change in Storage Subsystem Cost
(Organic total energy application)

Concept	Hours of Storage	Change in BBEC (%)	Change in Storage Cost (%)
Hitec	1	+ 9	− 95
	6	+ 5	+ 32
	15	+ 2	+ 8
Direct-contact, phase change	1	+20	+200
	6	+ 8	+ 50
	15	− 2	− 8

Reference: Syltherm/taconite system.

Table A-17. Organic Total Energy System

Concept	Hours of Storage	Percent Change in BBEC					
		Nominal	On Media (1.44)	On All Equipment (1.44)	O&M (2%)	Low Storage Use	High Storage Use
Hitec	1	+ 9	+ 9	+ 7	+ 9	+ 9	+ 9
	6	+ 5	+ 5	+ 3	+ 6	+ 5	+ 5
	15	+ 2	+ 2	+ 2	+ 2	+ 2	+ 2
Air/rock	1	+20	+19	+16	+19	+20	+20
	6	+ 8	+ 9	+ 6	+ 8	+ 8	+ 8
	15	- 2	- 1	- 3	+ 6	- 2	- 2

Reference: Syltherm/taconite system.

Table A-19. Plant Cost Breakdown (Organic total energy application)

Hours of Storage	Capitalized Cost ($M)	Storage Cost[a] ($M)	Plant Cost ($M)
1	2282	267	2015
6	4575	857	3718
15	7252	1897	5355

[a]Reference storage system, nominal conditions.

A.7 CONCLUSIONS

Results of the sensitivity studies conducted for each of the solar thermal system applications have now been presented. Several general conclusions can be drawn that appear to be true for all the applications.

Referring to the storage cost calculation [Eq. (A-3)], we found that variations in the factors FM, FN, and FOM did not produce different conclusions than the ones that were drawn from the nominal case. That is, varying the factor applied for installation and direct costs associated with the storage media (FM) between 44% and 95% of the media cost did not produce a significant variation in results. The concepts that appeared promising--in terms of decreasing unit energy costs--with FM = 1.44 remained promising with FM = 1.95. The same effect was observed when FN, the factor accounting for indirect costs of storage equipment, varied between 1.44 and 1.95 or 44% and 95% of the initial capital investment. Also, as the FOM terms were varied, thereby varying the O&M percentage applied to each storage concept, the conclusions again remained unchanged.

Although varying the economic factors did not yield significant variations in results, two other conditions may indeed have some effect on the conclusions of this study. The study's results are sensitive to the accuracy of the assumed Caloria replacement rate for water/steam receiver applications. If the rates assumed are overestimates of the actual amounts required, the ranking index would be higher for each of the water/steam receiver storage concepts. If this should be the case, the alternative concepts that appeared marginally promising would then apppear to be less promising than the reference concept. The degree to which the results would be affected depends on the degree of inaccuracy in the replacement-rate assumption.

The overall uncertainty about storage subsystem costs can also affect these conclusions. An uncertainty of 20% means we are defining a range of possible costs rather than a single value. Although the nominal unit energy cost of a concept may be higher than that of its reference concept, if the range of uncertainty is considered, the two systems' predicted energy costs may overlap. This condition prompts the caveat that, for concepts in which this overlap exists, our conclusions about which concept is most promising are not definitive.

Conclusions were also drawn about the specific storage concepts considered for each application. For the water/steam receiver power-generation application, the busbar energy cost of the underground pressurized-water, draw salt concept is a significant improvement above about six hours of storage. The direct-contact heat exchange, draw salt concept exhibits less dramatic but still significant BBEC improvments above eight hours of storage.

In the water/steam receiver, process heat generation application with underground pressurized-water appeared to be very promising for both midrange and high-capacity storage. Containerized-salt and oil/rock excavated-pit storage appeared to have lower unit energy costs at all storage capacities, but not as significantly lower as the pressurized-water concept.

For both the air receiver Brayton cycle power generation application and the organic fluid total energy system application, none of the alternative storage concepts considered promise to significantly reduce the busbar energy cost, compared with the reference storage concepts.

It is important to note that the conclusions given here are based solely on the results generated in this sensitivity study. The conclusions and results of the overall study are presented in the body of the report.

LIST OF VARIABLES

A	Gross collector area (m^2)
CE_X	Cost of energy-related equipment; e.g., storage tanks, piping, insulation. Subscript indicates storage stage--first or second--if applicable
CP_X	Cost of power-related equipment; e.g., pumps, heat exchangers. Subscript indicates storage stage--first or second--if applicable
FCR	Fixed charge rate (see Table A-1)
FI	Factor accounting for installation and other direct costs of storage equipment
FM	Factor accounting for installation and indirect costs of storage media
FN	Factor accounting for indirect costs of storage equipment
FOM_X	Factor accounting for operations and maintenance costs for storage stage
FLUID	Cost of annual storage media replacement
FUEL	Cost of purchased electricity of thermal energy required by storage subsystem
LFF	Levelizing factor for fuel
LFOM	Levelizing factor for O&M
RP	Rated power of solar thermal plant (kW)

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