SERI/STR-250-3516
DE89009426

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Final Subcontract Report On the Symposium Held October 19-20, 1988 Helendale, California

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Solar Energy Research Institute
CBY Associates, Inc.

Prepared under Subcontract No. HH-9-18108-1

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UC Category: 202
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Russell Hewett and Bimleshwar Gupta

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Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401-3393

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A08

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications which are generally available in most libraries: *Energy Research Abstracts (ERA)*; *Government Reports Announcements* and Index (*GRA* and I); *Scientific and Technical Abstract Reports (STAR)*; and publication NTIS-PR-360 available from NTIS at the above address.

PREFACE

The research and development described in this document was conducted within the U.S. Department of Energy's Solar Thermal Technology Program. The goal of this program is to advance the engineering and scientific understanding of solar thermal technology and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates the solar flux using tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two-axes tracking mirrors) to focus the sun's radiant energy onto a single, tower-mounted receiver. Point focus concentrators up to 17 meters in diameter track the sun in two axes and use parabolic dish mirrors or Fresnel lenses to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multimodule system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from 100°C in low-temperature troughs to over 1500°C in dish and central receiver systems.

The Solar Thermal Technology Program is directing efforts to advance and improve each system concept through solar thermal materials, components, and subsystems research and development and by testing and evaluation. These efforts are carried out with the technical direction of DOE and its network of field laboratories that works with private industry. Together they have established a comprehensive, goal-directed program to improve performance and provide technically proven options for eventual incorporation into the Nation's energy supply.

To successfully contribute to an adequate energy supply at reasonable cost, solar thermal energy must be economically competitive with a variety of other energy sources. The Solar Thermal Technology Program has developed components and system-level performance targets as quantitative program goals. These targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and developing optimal components. These targets will be pursued vigorously to ensure a successful program.

Thermal energy storage offers important operating advantages to solar electric power plants. The work described in this report was conducted under a subcontract to assess storage options. Although the primary focus of the work was on phase-change storage materials, other reasonable alternatives were considered.

The symposium was jointly organized by Luz International Ltd. and SERI with the valuable assistance and planning capabilities of CBY Associates. Moreover, the assistance of other organizations that provided time and the travel expenses of the participants is both acknowledged and appreciated. These organizations were Oak Ridge National Laboratories, Pacific Northwest Laboratories, the University of Houston, Platforma Solar de Almeria/DFVLR, Argonne National Laboratories, and Luz International Ltd.

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INTRODUCTION

Thermal energy storage (TES) offers important operating advantages to solar electric power plants. Luz International Ltd. has successfully commercialized solar electric plants at the 30-80 MWe level as evidenced by the operation of SEGS I–V (Solar Electric Generating Systems) in the Mohave desert region of California, and the ongoing construction and design activities of SEGS VI–VIII. By the end of 1988, 194 MWe will be on-line. Heretofore, the use of thermal energy storage for these plants at the current operating temperature of the solar field, 735°F (397°C), has not been possible because cost-effective, reliable TES systems have not been available.

In seeking a solution to this need, Luz developed two conceptual designs of TES systems utilizing phase change materials in the temperature range of interest for a SEGS plant. [These conceptual designs are described in the pre-assessment background paper by Luz included in this report.] Further, Luz proposed that the Department of Energy and Luz join in a cost-shared program to develop such a TES system. As a first step, it was decided that experts in phase change storage technology or related approaches should be assembled to provide advice and input into the feasibility, content and structure of a program designed to provide cost-effective energy storage, with emphasis on phase change materials, for SEGS-type facilities. The Symposium described in this report is the result.

While phase change storage was the primary focus of the Symposium, it was recognized that reasonable alternatives to this approach would be appropriate for discussion. Consequently, the experts assembled for the meeting represented a fairly broad spectrum of knowledge and expertise in thermal energy storage issues. The Symposium was organized to evoke discussion and seek tentative recommendations on key economic and technical issues related to the topic. More specifically, the primary subtopics of the Symposium were:

- The value of thermal energy storage for large intermediate temperature solar electric plants,

- The materials, engineering and economic issues relevant to phase change TES systems,

- Candidate TES systems for this application other than phase change materials, including the materials, engineering and economic issues for each,

- Expected key research and development needs for favored candidate TES systems, and the programmatic avenues to further development of the selected technologies.

BACKGROUND INFORMATION

Background Paper

A paper was prepared by Luz Industries–Israel to provide both a background on the operation of the SEGS plants and the analysis of the thermal energy storage options already performed by Luz. The full paper is included in this report (Appendix A) and an abstract appears below.

Thermal Energy Storage for Medium Temperature Solar Electric Power Plants Using PCM's: A Preliminary Assessment

Luz Industries Israel

The basic characteristics of five operating Luz solar power plants and two plants under construction are described and their performance is discussed. The first plant, which operated at a temperature below 315°C (600°F) had short-term thermal energy storage in oil, but the high operating temperatures of subsequent plants have made oil storage economically infeasible. Although the current plants operate economically using auxiliary natural gas firing without storage, there are technical and economic benefits to including either long-term or short-term storage capacity in plants built in the future. A quantitative estimate of the value of long-term storage is about $14/kWh$_t$ while the short-term storage, because of operational benefits, has an estimated value of $25/kWh$_t$. Two concepts employing the liquid-solid heat of fusion of salts are presented as candidates for achieving the desired cost goal of less than $25/kWh$_t$. One concept employs a cascade of PCM material between the solar loop and the steam loop with a single heat exchanger for charging and discharging each stage of the storage to the heat transfer fluid. Steam is generated and superheated in a separate heat exchanger. The second concept also involves multiple PCM materials, but the steam generator and superheater are integrated in the storage. The selection criteria for the PCM's are discussed and a preliminary identification of candidate salts is presented. The technical and economic considerations related to the selection and design of a thermal energy storage subsystem for the Luz power plants are presented in sufficient detail to serve as a basis for discussion in the Symposium.

Abstracts of Presentations

Several of the participating experts were invited to present brief descriptions of their work in solar energy storage or other research that was considered to be directly applicable to the goals of the symposium. Brief abstracts of those presentations are contained in this section. The visual aids that were used in the symposium presentations are contained in Appendix B.

An Overview of ORNL TES Work and its Applicability to LUZ Solar Electric Needs

M. Olszewski
J. J. Tomlinson

Thermal energy storage is being developed in three programs being conducted at Oak Ridge National Laboratory (ORNL). The DOE TES program has developed technology in the area of shell-and-tube and encapsulated PCM concepts. In addition, form-stable composites and chemical systems (using complex compounds) are being examined. Other storage activities are in support of SDI and NASA needs. Encapsulated LiH is being developed for use in SDI burst power applications. Metallic PCM's are being used in support of advanced power supplies for the Space Station. In addition, a 3-D time-dependent thermal performance code has been developed to predict the thermal behavior of the PCM in earth (1-g) and space (0-g) environment. Based on the existing TES work at ORNL several concepts were proposed for the LUZ SEGS application. They included: evaporating water and storing the vapor in zeolite, a slurry heat transport and storage system using microencapsulated PCM, a conventional shell-and-tube concept, open composites in a packed bed, sensible heat storage using a one-tank thermocline system, and a chemical storage concept using hydrated complex compounds or hydroxide/oxide reactions. A preliminary economic analysis of these concepts indicates that the chemical and sensible systems offer promise to meet the LUZ goal of $25/kWh$_t$.

A Review of Solar-Related Thermal Energy Storage Research

Mark S. Bohn

Several solar projects have been funded by the Department of Energy in which energy storage for solar thermal applications were investigated. For the most part, the projects have involved sensible heat storage (single-tank thermocline, two-tank molten salt) applied to parabolic trough or dish systems in the temperature range 200 to 600°C at pilot- or full-scale sizes. Operational experiences and performance of these systems was, in general, good although the storage systems are not necessarily applicable to solar thermal plants which utilize costly heat transfer fluids. One system study compared three storage methods applicable to the temperature range of interest: trickle-charge thermocline, two-tank nitrate salt, and direct-contact phase change. Trickle-charge thermocline was the most cost-effective for storage durations of less than 7 hours. The direct-contact phase change system was primarily intended to eliminate the heat transfer penalty generally associated with the solid phase of the phase change material and proved to be the most cost-effective of the three systems for storage durations greater than 7 hours.

Latent Heat Storage for Solar Thermal Power

N. Shamsundar

Existing tools for design and performance calculations for passive latent heat storage heat exchangers are summarized. The tools are adequate to treat the more critical stage, namely, the heat recovery stage, for shell-and-tube heat exchangers. Additional development work is necessary to address the storage stage, viscous heat transfer fluids, finned tubes and system optimization.

DFVLR/CIEMAT Study on Thermal Energy Storage for Commercial Applications

Michael Geyer

Within the Spanish-German cooperative program on solar thermal research at the Platforma Solar, a feasibility study of developing thermal energy storage for commercial applications (TESCA 200) was initiated and partly funded by DFVLR and CIEMAT, sharing costs with the companies INITEC, Siempelkamp, GERTEC and Flachglas and Luz. The study – started in June 1988 – has a time span of one year. Technical and economic feasibility of three concepts is being analyzed:

- TES in solid media
- TES in molten salt sensible heat media
- TES in cascaded phase change media

Preliminary results of the first 3-month study period are:

- According to Siempelkamp's initial design and cost calculations, only concrete has the potential of meeting the \$25/kWh$_t$ cost goal. Although piping costs are twice as expensive for the concrete as for the salt, media costs are much cheaper in the concrete case resulting in \$27.50/kWh$_t$ for the concrete system and \$60/kWh$_t$ for the solid salt. Basic cost reduction potential lies in increasing the temperature difference and reducing the discharge rate. Major problems to be solved include thermal expansion and thermal cycling.

- The storage costs of the two-tank molten salt system, including the tank and Hitec salt (with a salt price of \$0.78/kg), amounts to \$22/kWh$_t$ to which \$25/kWh$_t$ have to be added for the 200 MW$_t$ heat exchanger. A 10 - 15% cost reduction is possible if the charging is extended to 3 hours and discharge is performed directly with steam. Specific costs decrease with higher capacities and higher temperature differences. With HITEC, such a system can be built without further research and development.

- The results for the PCM concepts still contain some uncertainties and are only preliminary. According to INITEC, between 26000 and 46000 m^2 of heat exchanger area are required for the cascaded PCM system depending on the selection of the melting points. This is 30% more than the 20000 m^2 required for the 200 MW active oil/salt heat exchanger, the assumed heat transfer coefficient of approximately 400 W/m^2•K needs further experimental verification. Due to the heat exchanger costs, the total system cost rises to \$50/kWh$_t$.

Encapsulated PCM Concepts for Heat Storage

Robert A. Rapp

The encapsulation of PCM eutectics in a strong, corrosion-resistant coating with a sufficient central void to accommodate the volume increase upon melting, offers the opportunity for direct contact with the heat transfer fluid (HTF) and savings in the fabrication of the heat exchanger. Metallic eutectics based on the Al-Si, Al-Si-Mg, etc. are attractive at temperatures greater than 560°C, but offer no promise for storage below 400°C as required for the Luz application.

In general, if encapsulation of a PCM is possible, then a hypereutectic composition rich in the component of highest latent heat of fusion can be used to increase the heat storage capacity and widen its range of application to between the liquidus and the eutectic temperatures.

If an encapsulated PCM eutectic or hypereutectic composition is arranged in a fixed bed, then the cocurrent flow of the HTF through the bed (for the charging and utilization cycle) can yield a nearly constant outlet temperature if the bed exit is maintained at the eutectic temperature.

Calculations were made for the introduction of encapsulated Al-Si-Mg ternary eutectic spheres into the hot salt storage tank of a solar central receiver facility. Per unit volume, the PCM latent heat offers at least a 35% increase in storage capacity compared to the sensible heat change for the HTF (fused salt). With a minor change in the operational procedures the increased heat storage could be used to extend the duration of power output by the plant.

An Overview of ANL
Advanced Energy Transmission Fluids Work

K. E. Kasza

Argonne National Laboratory (ANL), under sponsorship of the U.S. Department of Energy, Office of Buildings and Community Systems, has been conducting a comprehensive, long-range program to develop high-performance advanced energy transmission fluids.

ANL has identified two concepts that hold considerable promise for improving the performance of thermal system working fluids. These two concepts are (1) utilization of very low concentration of non-Newtonian additives to the carrier liquid to reduce flow frictional losses, and (2) utilization of a pumpable phase change slurry, comprising particles of material with a high heat of fusion conveyed by a liquid, to enhance both bulk convective energy transport and heat transfer coefficients at the heat exchanger surfaces. The two concepts can be used separately or combined to achieve maximum benefits. When the concepts are combined, the energy transmission fluid is composed of the phase change particles, friction-reducing additive, and carrier liquid.

The current study focuses on the development of phase change slurries as advanced energy transmission fluids operating in the temperature range of 32 - 290°F. The objectives are (1) to establish proof-of-concept of enhanced heat transfer in a pure carrier liquid; (2) to investigate the effect of particle volumetric loading, size, and flow rate on the slurry pressure drop and heat transfer behavior with and without friction-reducing additives; and (3)to generate pressure drop and heat transfer data needed for the development and design of improved thermal systems. Two types of phase change materials were used in the experiments: ice slush for cooling, and cross-linked, high density polyethylene (X-HDPE) particles with diameters of 1/8 and 1/20" (3.2 and 1.3 mm) for heating. The friction-reducing additive used in the preliminary tests was Separan AP-273 at 65 wppm.

The frictional loss associated with phase change-type slurry flows was found to be significantly less than that typically associated with heavy particle slurries (i.e., $\rho_p >> \rho_l$). Under some conditions, X-HDPE slurries with 1/20" diameter particles at loadings up to 30% and ice slush slurries exhibited significant friction reduction compared to pure water. No satisfactory correlations have been identified to accurately predict the slurry pressure drop and viscosity measured in the laboratory. The slurry tests also showed that the flow behavior is strongly influenced by the particle size, which is either neglected or considered to be a weak function in existing correlations.

The heat transfer measurements for X-HDPE slurries with 1/8" diameter particles under non-melting conditions showed a modest enhancement of heat transfer over that of water, but the data with 1/20" diameter particles showed a modest degradation. The results also show a significant effect of particle size on slurry heat transfer, which requires further study.

The results for combined-concept fluids have demonstrated that a friction-reducing additive can substantially reduce pressure drop for a slurry of water and X-HDPE particles. This effect should also exist for other types of particulate slurries. The use of phase change slurries holds promise for improving the thermal-hydraulic performance of SEGS including facilitating incorporation of thermal storage into the systems. In future work, slurry pressure drop and heat transfer with different PCM materials, particle sizes and carrier liquids should be examined and experiments performed under SEGS operating conditions to explore suitability for SEGS.

SUMMARY OF DISCUSSIONS

Cost Goals for SEGS Plants

The Luz background paper on thermal energy storage for medium temperature solar electric plants (Appendix A) reviews the rationale, utilization and acceptable costs of thermal storage systems in SEGS applications. The paper served as background for the discussions at the symposium. Two types of storage systems were considered in an attempt to set realistic cost goals based on SEGS economics:

- Large storage systems [2500 MWh_t] for use in base-load applications of solar power plants, and

- Small storage systems [200 MWh_t] for improving solar plant system performance in peaking applications by:

    - Dampening solar field fluctuations
    - Shifting electrical production to later times
    - Utilizing peak excess solar field output
    - Improving field and heat exchanger response
    - Providing quicker morning startups, and freeze protection when needed.

The Luz analysis was carried out using an hour-by-hour plant performance model, with the objective of comparing the incremental benefits (revenues) of a plant with storage to a base-case plant without storage. An important assumption in the analysis is that the average price of electricity was 6.5 cents/kWh_e. While this is an optimistic assumption for base-load plants given the low avoided cost rates used by Southern California Edison (SCE) today it may be reasonable under future pricing scenarios. However, the 6.5 cents/kWh_e price level is not at all unrealistic for the electricity revenue during peak periods under current pricing arrangements in the SEGS plants (which are, in essence, peaking plants). The analysis for the small storage systems was carried out for (a) consideration of the electrical production shifting only, and (b) the added value of the other benefits listed above. The results of the analysis, discussed more fully in the background paper, show the following acceptable costs for thermal energy storage:

	Storage Size MWh_t	Cost Goal $\$/kWh_t$
Base-load plants:	2500	25
Peaking plants:		
Saving peak excess	200	14
All benefits	200	25

Phase Change Storage

A number of technical issues were identified by those attending the symposium which must be addressed before commercial implementation of phase change storage systems can be achieved.

The arrangement or configuration of the PCM's with respect to the HTF is an obvious concern and perhaps the first issue which must be resolved. It was noted that the Luz proposal of a cascaded system of PCM storage modules in series when compared to a single medium PCM system, makes more effective use of the latent heat capacity of the PCM in each module and minimizes the pinch-point problem (discussed in more detail below). A second storage system, applicable where steam was generated directly in the collector, also was presented by Luz (see Appendix A). Phase change storage is particularly applicable for the case of direct steam generation, which illustrates the importance of the system configuration and the method by which the storage system is integrated with the rest of the plant.

As a result of the symposium discussions, three generic configurations for PCM systems were identified:

- shell-and-tube heat exchangers (in which the PCM would be contained in the tubes and the HTF would be circulated on the shell side or vice versa),

- a packed bed configuration of encapsulated PCM spheres contained in a pressure vessel, and

- a direct contact configuration (in which heat transfer between the PCM and the HTF is brought about by bringing the two into intimate contact).

From the standpoint of cost and required phase change temperature, it appeared that salts were the most practical candidates for the PCM in this application. A number of salts and salt eutectics are available at reasonable cost and with ranges of phase change temperatures satisfactory for the application to SEGS plants.

Unfortunately, phase change salts have less favorable heat transfer characteristics than media such as sensible heat liquids. In either a shell-and-tube or packed bed configuration, heat transfer characteristics are very important, with the shell-and-tube arrangement clearly being more sensitive to these considerations. Heat transfer limitations result in more costly storage modules because their surface area must be increased to provide the desired charge and discharge rates.

The first heat transfer limitation is primarily a result of the relatively poor thermal conductance across regions of solid PCM compared to convective heat transfer in the HTF. As the solid layer of PCM builds up during the discharge cycle, increased heat transfer surface area is required to accomplish the heat transfer in a specified discharge time. Thus, the system would need to be designed with the maximum heat transfer surface anticipated and this would likely have a negative impact on the cost effectiveness of the storage unit.

A second heat transfer limitation is the pinch-point problem which would apply equally to either packed-bed or shell-and-tube. Pinch-point refers to the relatively small temperature differences between the PCM and the charging or discharging HTF which occur at the points in the heat exchanger where the PCM is just dropping below or rising above the phase change temperature. At these points, with relatively small temperature differences available for driving the heat transfer, large heat transfer surface area is needed. (The pinch-point effect noted here is analogous to that occurring in standard boilers where the feedwater enters below the saturation temperature.) Again, a potential exists for increasing the cost of the storage module due to a requirement for large heat transfer surface area. However, the pinch-point characteristic is either eliminated or greatly reduced for the configuration with direct steam generation. Likewise the pinch-point problem would be minimized if the cascade arrangement were replaced by a hypereutectic multicomponent salt for which the liquidus temperature equaled the maximum HTF temperature and the eutectic temperature equaled the turbine inlet temperature. Such operation would require concurrent flow of the HTF during the storage and utilization cycles.

For the packed bed arrangement of PCM's, encapsulation and pressurized design are the critical issues. Encapsulation refers to provision of a protective outer layer for the PCM which isolates the PCM from the HTF and reduces their relative incompatibilities. Encapsulation for the packed bed arrangement plays the role of the tubes in the shell-and-tube arrangement, but with the very important advantage of providing a high surface area for heat transfer and reducing the resistance for heat conduction within the encapsulated sphere. Although encapsulation has been investigated for metal alloy PCM's by ORNL and Lanxide/DuPont, only recently has consideration been given to encapsulation for salt-based PCM's. Commercial interest in this area may result in a commercially available salt-based PCM in the future. However, because encapsulation is in an early stage of development, the cost of such a process is not clear at this time. Therefore, perceived benefits of PCM systems due to the relatively low cost of the salts may be lost after encapsulation is considered, though clearly this is a promising area for research.

A major issue related to encapsulation is the design of the storage vessel. Since the vessel must contain the working fluid, potentially at a pressure level of 10-15 bars, a pressure vessel will almost certainly be required, adding to the cost of the system. One advantage of the shell-and-tube configuration over the packed bed configuration is that if the HTF is contained in the tubes (the most likely arrangement), containment of the HTF vapor pressure is simpler and less expensive.

Rapp suggested consideration of the containment of a hypereutectic salt in pipes of either steel or glass to minimize costs. These pipes would be positioned vertically and surrounded by the pressurized HTC which would flow from bottom to top for both cycles. However, glass tubes could suffer creep deformation.

Microencapsulation of PCM was also discussed as a means for creating a HTF slurry in which the storage media would be directly incorporated in the collector loop. By introducing these small PCM particles in the collector loop, the effective specific heat of the HTF could be increased sufficiently to serve for short-term buffer storage. For longer term storage, the particles might be separated from the HTF and stored in a vessel until needed for discharging at which point they would be reintroduced into the HTF stream. The major unknowns are the potential for erosion of pumps, valves and other collector loop components, difficulties of encapsulation (as discussed in the previous paragraph) amplified by the problems associated with the small scale, and the complexities of the separation and storage phases.

From a technical viewpoint, packed bed configuration has the potential to outperform the shell-and-tube configuration because the packed bed provides such large surface areas at potentially lower cost, subject to the cost of a pressurized containment vessel. Detailed system feasibility studies are required to size the system and to properly treat issues such as pressurization and encapsulation of the PCM.

Sensible Heat Storage

Several concepts were discussed in which heat storage is accomplished by a sensible temperature change in a single phase (without phase change). These systems include a single tank thermocline (in which hot and cold HTF is stored in the same stratified tank), a single tank trickle-charge thermocline (in which a the tank contains a large volume fraction of low-cost sensible heat storage media and the HTF is trickled over the media), two-tank molten salt system (in which heat is transferred from the HTF to a salt loop and two tanks are used to separate hot and cold salt), and dual media systems (in which the HTF is pumped through pipes imbedded in a massive sensible heat storage medium such as cast salt plates or concrete plates).

Generally, these systems were viewed as being more nearly ready for implementation than the phase change systems, though not necessarily more attractive, and a comparison on the basis of a complete system study would reveal the best sensible TES candidates. However, certain technical issues must be considered. For the dual-media systems, sufficient heat transfer surface area may be a limitation due to the relatively poor conductive heat transfer through the solid heat storage media. In a thermocline system, storage of large quantities of HTF probably is not economical and reduction of this inventory of HTF in the trickle charge system may be attractive. The two-tank system requires heat exchangers, and the cost of these components may offset the cost advantage of using a low-cost heat storage medium in place of the HTF. Especially in the dual media systems, careful design is needed to assure that the HTF outlet temperature during discharge is sufficiently high.

On the basis of preliminary work performed to date in the German-Spanish cooperative agreement, it appears that among the dual media concrete plate, dual media salt plate, and the two-tank salt systems, the dual media iron plate system is best positioned to meet the storage system cost goal of $25/kWh$_t$. The remaining sensible heat storage options should be retained in this ongoing study so that a better comparison of all options can be made.

Chemical Storage

Storage of energy via reversible chemical reactions was discussed briefly. It appears that at least one class of reactions may hold promise for the SEGS and has received some attention in the past for transport of energy. The hydroxide/oxide reaction between CaO and H_2O was mentioned as a possibility and, based on a preliminary cost assessment, such a system could have a lower installed capital cost than the sensible storage options. Although generally viewed as higher risk and possibly longer range than some of the other storage options, chemical storage appears to offer sufficient potential to warrant consideration for future developments.

Ranking of Technologies and Approaches

After the presentations and discussions of the critical issues associated with the phase change thermal energy storage, as well as some consideration of selected thermal storage alternatives, the experts at the symposium were polled to get opinions on the most promising approaches and alternatives. The basis for judging the alternatives was the ability to meet the cost goal of $\$25/kWh_t$ within five to seven years. The rankings were not quantified but were based on interpretation of the individual statements of the experts when asked to evaluate the probability of each of the options meeting the cost goals within the time stated and given a reasonable budget for development. These opinions are based on expertise in different, sometimes narrow, fields and are derived from general beliefs rather than from the results of a thorough comparative analysis.

Phase Change Storage Approaches

The experts were asked to evaluate the probability of success of the following options:

- Continuous PCM media with embedded heat exchanger,
- Continuous PCM media with direct contact heat exchange,
- Dispersed PCM media in some form of packed bed.

Most participants either explicitly or implicitly expressed the view that a dispersed encapsulated PCM in a fixed packed bed is the most likely to meet near-term cost goals. There was, however, considerable conservatism regarding the probability of near-term technical success. It was generally agreed that simple encapsulation techniques could be developed using suitable mixtures of salts and glass or iron containers, but there was considerable skepticism about the ability of these simple approaches to meet the cost and performance goals. Spherical capsules suitable for packed beds were considered more difficult to develop, but more likely to be cost competitive. The major barrier to cost effectiveness of the packed bed approach, assuming a successful coating, was the possible cost of the pressure vessel to contain the packed bed and heat transfer fluid at pressures of 15 bars or higher. Specific design feasibility studies are needed to provide a solid basis for comparison.

Although there were some questions regarding the available cost estimates of tube in shell PCM storage designs, the general consensus was that shell-and-tube systems were almost certainly too expensive because of the large area of tubes and fins required to compensate for the poor thermal conductivity of the salts. Further and more detailed analytical results are needed to quantify the heat transfer area question.

Direct contact heat exchange was considered the most promising approach to reduce the cost of the system, but most of the participants were dubious about the possibility of finding a compatible salt and heat transfer fluid that would also meet the system requirement.

Alternative Thermal Energy Storage Options

Several alternatives to the phase change storage concept were considered:

- Chemical storage based on reactions such as hydrated complex compounds and calcium oxide – calcium hydroxide,
- Slurries of particles in the heat transfer fluid – either PCM or other high heat capacity materials,
- Sensible heat storage in a single tank (thermocline), two-tank system, or solid system.

The majority of participants expressed the opinion that one or more of the sensible storage options could be successfully developed to meet the cost goals using current engineering knowledge. The development would require thorough and careful engineering development and small scale testing, but should not require new research. The choice between the three sensible heat storage options was not clear. Preliminary results from the German-Spanish study indicate that concrete castings with embedded steel tubes are already in the cost-effective range. The massive structures would still require careful design and installation to deal with problems of thermal expansion and leakage. Single tank thermocline molten salt storage has not been shown to meet the cost goal, but there was some confidence among the participants that it could be accomplished. Some of the problems that have received attention for higher temperature levels, such as high radiant heat transfer through the optically transparent molten salts, appear to be less troublesome in the temperature range of interest for parabolic trough solar plants. Two-tank active storage using molten Hitec-type salts also was considered likely to be cost competitive since up to 420°C inexpensive steels can be used for piping and tanks.

At least half the participants felt that chemical storage might have the potential to be the most cost-effective of the options considered. The promise of chemical reactions involving metal oxides and metal hydroxides would be further enhanced if the solar collector field working fluid were steam rather than oil. Clearly, additional research is required to identify the best reactions, establish chemical compatibilities, prove the process, and integrate the process into the complete system. Currently, work is in progress on hydrated and ammoniated complex compounds for high – and low – temperature applications. Success in this work gives confidence that the chemical energy storage concepts using complex compounds or oxide/hydroxide reactions could be developed within a few years. Engineering and development of a commercial system might be accomplished within five to seven years.

Many of the participants found the concept of adding energy storage to the circulating working fluid, i.e., slurries, to be quite interesting and potentially effective. Considerable research is required to develop particles with the necessary thermochemical, thermophysical, fluid dynamic, and mechanical properties. Most of the participants considered slurry-based storage systems a higher risk development than chemical storage.

Required Analysis and Cost Studies

Although the symposium discussions produced opinions regarding the most promising near- and long-term options for thermal energy storage in SEGS plants, it was generally believed that more definitive feasibility studies are required to quantify the issues discussed in the symposium, probably at a relatively modest effort in analysis and cost estimation. Some of the work required already is planned as a part of the German-Spanish project and the results should be available in six to eight months. Other preliminary analyses are within the capabilities of the participants or their associates and might be performed on an informal *ad hoc* basis. The table below shows the tasks to be performed by storage option and possible organizations to accomplish the work.

Storage Option	Required Analysis or Study	Means
Sensible Storage	Complete and verify results from German/Spanish study of concrete and molten salt sensible storage.	DFVLR
	Extend study of trickle charge sensible storage to the temperature range of interest for SEGS plants.	SERI
Phase Change	Determine the least lower bound on cost of phase change storage using spherically encapsulated PCM's in a fixed packed bed by optimizing the size of spheres and ignoring the cost of encapsulation.	ORNL/DFVLR
	Carry out more detailed analysis to better quantify the heat transfer area requirement. The model developed by the University of Houston could greatly simplify this analysis.	LUZ/DFVLR/UH
	Determine the least lower bound on cost of direct heat exchange phase storage by calculating the volume required for a salt with infinite thermal conductivity.	ORNL/DFVLR
	Determine the maximum benefits available from adding salt PCM's to heat transfer fluids in slurries.	ANL
Chemical	Identify one or more promising reactions and perform preliminary cost analyses for SEGS plants.	ORNL/SERI/DFVLR

Research Needs

One of the original objectives of the symposium was to identify and define research and development tasks that would be required in a program to develop successful phase change storage components for SEGS power plants. Given the previous work carried out in the technical areas under discussion, the consensus of the participating experts was that the most probable routes to cost effective storage in the near-term require engineering development rather than research. However, recommendations on detailed development tasks could best be made after further exploratory analyses and prototype testing are completed.

It was clear from the discussions that much could be learned from careful and complete evaluations of the most promising options. With respect to PCM's, such evaluations are made more difficult by the lack of crucial thermophysical property data. Consequently, determination of such data will be a requirement early in the development phase.

The encapsulation of PCM's and the development of chemical storage are areas that will require further research. Since additional analysis is required to determine if it is necessary or desirable to initiate development of these options, the definition of research tasks was deferred until that determination has been made.

Program Issues

Some thermal energy storage research is currently funded by at least two offices of the U.S. Department of Energy and the German DFVLR. At present, none of the work supported by the DOE is specifically targeted for solar power plants operating at temperatures in the range of the SEGS plants. The work supported by the Solar Thermal Technologies Division of the Office of Solar Heat Technologies is tailored for solar power plants operating at considerably higher temperatures characteristic of central receiver or parabolic dish solar collectors. The Thermal Storage Office of the Office of Residential and Industrial Conservation supports storage research for a broad range of temperatures, but does not focus on solar applications. At present the Thermal Storage Office is not supporting any research that is directly applicable to the SEGS plant applications. The German and Spanish governments are currently funding a study that is directly related to the storage of heat in a temperature range suitable for parabolic trough plants.

Commercial SEGS plants make substantial contributions to the displacement of fossil fuels by clean, renewable sources of energy. The recognition that these plants could be even more effective and more broadly applicable if cost-effective thermal storage were available presents a strong argument in favor of increasing resources devoted to thermal energy storage research and devoting a significant part of that research to tasks that could benefit the SEGS applications.

CONCLUSIONS

The conclusions reached by the participants in the Symposium can be described in terms that apply to the present status of thermal energy storage for plants of the SEGS type, and those that apply to the potential for future development. These conclusions are based on opinions, and suffer from lack of detailed system-scale comparisons to provide clarity to the technical and cost issues.

For the present and the immediate future, phase change energy storage systems probably will not meet the cost goals for the SEGS plants. Sensible heat storage, however, using either solid media or molten salts does appear to offer a near-term possibility that may be achieved through careful engineering and development.

The long-term potential for phase change storage systems using molten salt depends on providing the necessary heat transfer surface at low cost as well as upon solving various technological problems of materials compatibility and stability. Two questions related to heat exchange need to be answered: 1) do phase change salts offer enough benefits to offset any increase in heat exchanger cost, and 2) are there technically feasible and economically attractive options for improving heat exchanger effectiveness in salt based systems? The first question can be answered by a relatively straightforward engineering cost analysis of idealistic (most optimistic) systems. The second question requires the identification and evaluation of both conventional and innovative system configurations in a careful engineering feasibility study.

Two potentially effective, but riskier, alternatives to the present storage options emerged which require further research efforts. Encapsulation, or microencapsulation, of phase change salts might provide a solution for the problems resulting from the poor thermal conductivity of salts by increasing the possible surface-to-volume ratio of the PCM. However, the cost issues of pressurized vessels and the encapsulation process itself were identified as critical, as well as the potential for reliability problems. Chemical energy storage using hydroxide/oxide reactions seems attractive in the longer term, and may offer low costs if suitable reactions can be found and if the process can be efficiently integrated into the power plant.

RECOMMENDATIONS

The symposium participants recommended that near-term detailed comparative system studies be conducted to evaluate the most-promising options, following the conclusions and discussions noted in this report. These studies should define the technical and cost issues, and establish a time-schedule for applications by 1992 or beyond. The most promising alternatives should be explored in addition to phase change materials.

These evaluations will enable Luz to make well-informed decisions about designing and building thermal energy storage for its current series of SEGS plants and will provide guidance for Luz, DOE, and others about the most promising avenues for future research to facilitate the development of thermal storage for the next generation of SEGS plants.

The results of these evaluations will provide the technical and economic bases for further efforts, including the design and installation of prototype field systems and detailed engineering design studies with supporting R&D activities.

APPENDIX A

Background Paper

THERMAL ENERGY STORAGE
for
MEDIUM TEMPERATURE SOLAR ELECTRIC POWER PLANTS USING PCM's:
A Preliminary Assessment

1 October 1988

Luz Industries Israel

A. SYSTEM CONSIDERATIONS

1. Solar Electric Generating System (SEGS) Power Plants

The basic concept of the SEGS plants is to supply thermal energy via the solar field to produce steam to drive a Rankine cycle steam turbine, which in turn drives an electric generator to produce power. A Rankine cycle, which is a particular type of thermodynamic power cycle, is used in all conventional coal, oil-fired or gas-fired steam plants. Because the Rankine cycle conversion efficiency increases significantly with an increase in the temperature and pressure of the steam supplied to the steam turbine, it is advantageous to supply steam to the power cycle at the highest pressure and temperature possible given the energy source, piping systems, and other plant equipment and support systems.

Luz International Limited has been developing line-focus parabolic-mirror technology for solar industrial process heat systems and commercial solar electric power plants since 1979. During the past four years, Luz has built five solar power plants with a combined generating capacity of 134 MWe and will bring two more 30 MWe plants on line in 1988. The seven power plants will produce 194 MWe of solar generating capacity, making Luz the single largest solar power generator in the world. The first five plants have demonstrated that power can be produced via the Luz technology on a commercial scale.

Since the inception of SEGS I, advancements in the mechanical structure of the Luz solar collector technology have permitted a steady increase in the outlet temperature of the solar field, from 585°F in the LS-1 design to 660°F in the LS-2 design used in SEGS III-V. Further advances, notably the introduction of a sputtered cermet selective coating on the heat collection element (HCE), have allowed solar field outlet temperatures of about 735°F in SEGS VI/VII and future plants.

Five plants were in operation in the Mojave desert of Southern California during 1988 - the first plant 13.8 MWe net capacity and the succeeding four plants 30 MWe net. All facilities are privately owned and sell the electricity produced to the Southern California Edison utility under individual power purchase agreements. Two additional 30 MWe plants are under construction for placement in service in late 1988.

To optimize plant revenues, it is very important that maximum electrical output is delivered during the utility on-peak hours when electricity revenues are highest. This is partially accomplished with the aid of a natural gas boiler which can either supplement the solar field or operate independently. The energy supplied by natural gas is limited to 25% of the total effective annual plant energy input by regulations of the U.S. Federal Energy Regulatory Commission.

The basic characteristics of the five operating plants (SEGS I-V), the two plants in construction (SEGS VI-VII), and the next plant (SEGS VIII) are given in Table 1. The first two plants are located at Daggett, California, about 110 miles northeast of Los Angeles. The next five plants are located at Kramer Junction, California, about 40 miles west of the Daggett site. SEGS VIII will be located at Harper Lake, between the previous sites and about 30 miles west of Daggett. Luz International Limited, a U.S. corporation with subsidiaries in Los Angeles and Jerusalem, has led the development of the SEGS plants since its inception in 1979. The ensuing period has seen continuous advancements in both the plant system design and the solar collector technology.

SEGS I through SEGS V are presently in daily operation and producing electricity with excellent reliability. SEGS VI and VII will be operational in December, 1988. The design levels of annual electrical output are given in Table 1. Plant performance projections are derived from an hour-by-hour performance model that was developed by Luz and has been in use since SEGS III. The model utilizes published insolation data and takes into account all of the significant factors influencing the solar field and turbine performance.

Table 1. Basic Characteristics of SEGS I-VII

Plant	First Full Operating Year	Status	Turbine Capacity (MWe net)	Solar Field Temp (°F)	Solar Field Size (m^2)	Turbine Cycle Efficiency Solar	Turbine Cycle Efficiency Nat Gas	Annual Output (MWh net)
I	1985	Operational	13.8	585	82960	31.5*	---	30100
II	1986	Operational	30	600	165376	29.4	37.3	80500
III	1987	Operational	30	660	230300	30.6	37.4	92780
IV	1987	Operational	30	660	230300	30.6	37.4	92780
V	1988	Operational	30	660	233120	30.6	37.4	91820
VI	1989	Construction	30	735	188000	37.5	39.5	90850
VII	1989	Construction	30	735	194280	37.5	39.5	92646
VIII	1990	Design	80	735	464340	38.1	38.1	245890

* includes natural gas superheating

SEGS III-V, the most recently operating plants, have achieved excellent performance during 1987 and 1988 to date. These plants have benefited from the lessons learned in SEGS I and II in both the solar field and power block systems. After the initial two months of solar field checkout and acceptance procedures, the availability of the solar fields (fraction of the solar collector assemblies able to track the sun) has been consistently above 90-95% for SEGS III and IV, with an even better start in SEGS V. For reference, the mature solar field availability (percent capable of tracking) assumed in the performance projections is 97%.

As a result of the rapid progress in start-up, the electrical output of SEGS III and SEGS IV has been excellent with similar performance levels of both plants. The 1988 performance of SEGS III-V compared to warranty projections is given in Figure 1 for the period January through August. SEGS V shows excellent results for its start-up year performance in 1988. The 1988 performances of SEGS III-IV are perhaps most significant, however, in that these plants are operating at expected design levels in their first normal operating year. These results demonstrate the success of the plant design and operation, as well as the validity of the performance modeling used to project plant outputs.

A process schematic of the latest system design is shown in Figure 2. In this system, thermal energy collected by the solar field is added to the Heat Transfer Fluid loop which circulates through the solar heat exchangers to generate steam. Thermal storage is contemplated for the HTF side of the system, though it is conceivable that thermal storage be utilized on the steam side. In fact, a development objective for future SEGS plants is to eliminate the intermediate HTF loop and generate steam directly in the solar field.

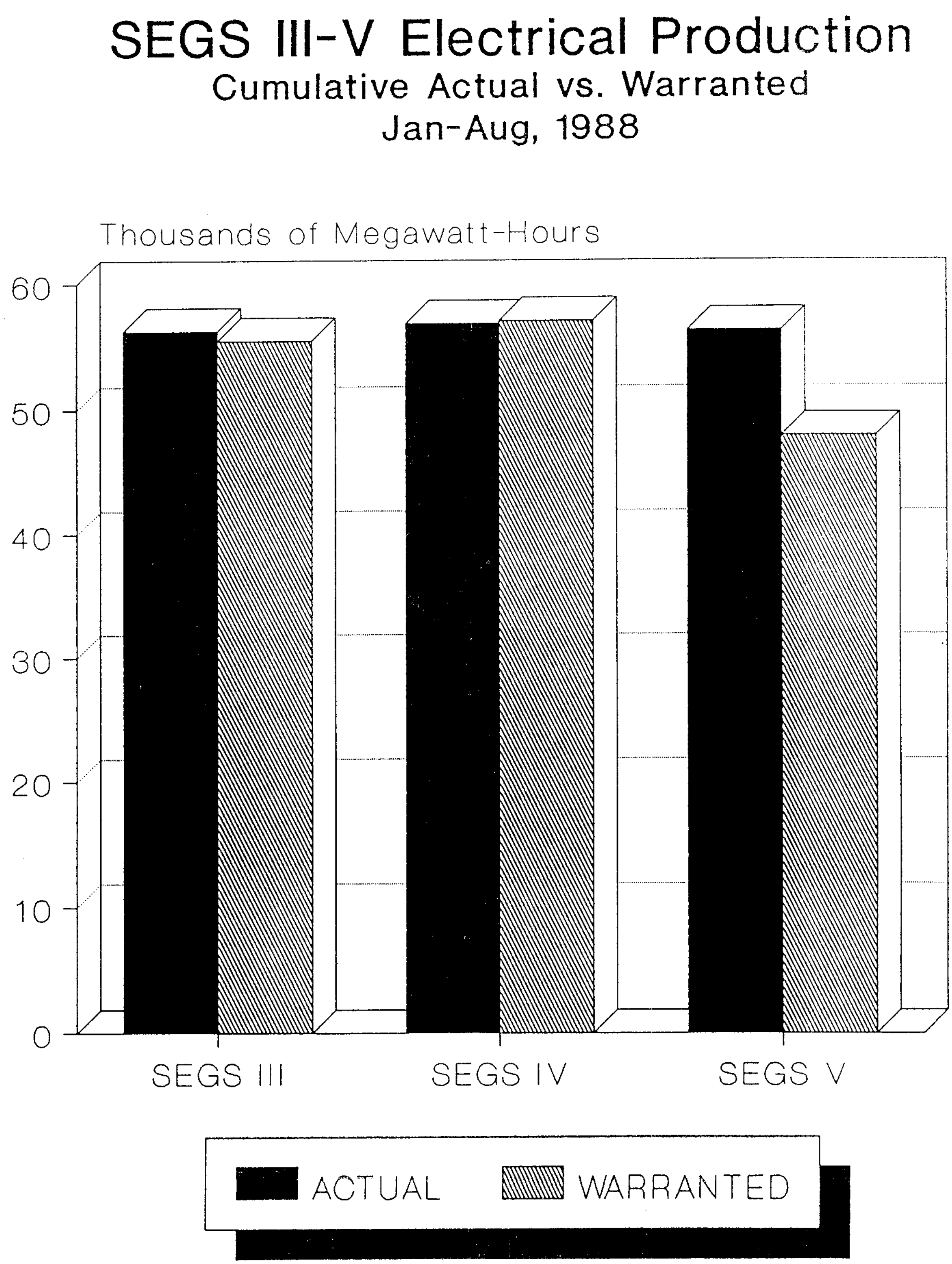


Fig. 1. 1988 Cumulative Electrical Performance of SEGS III-V

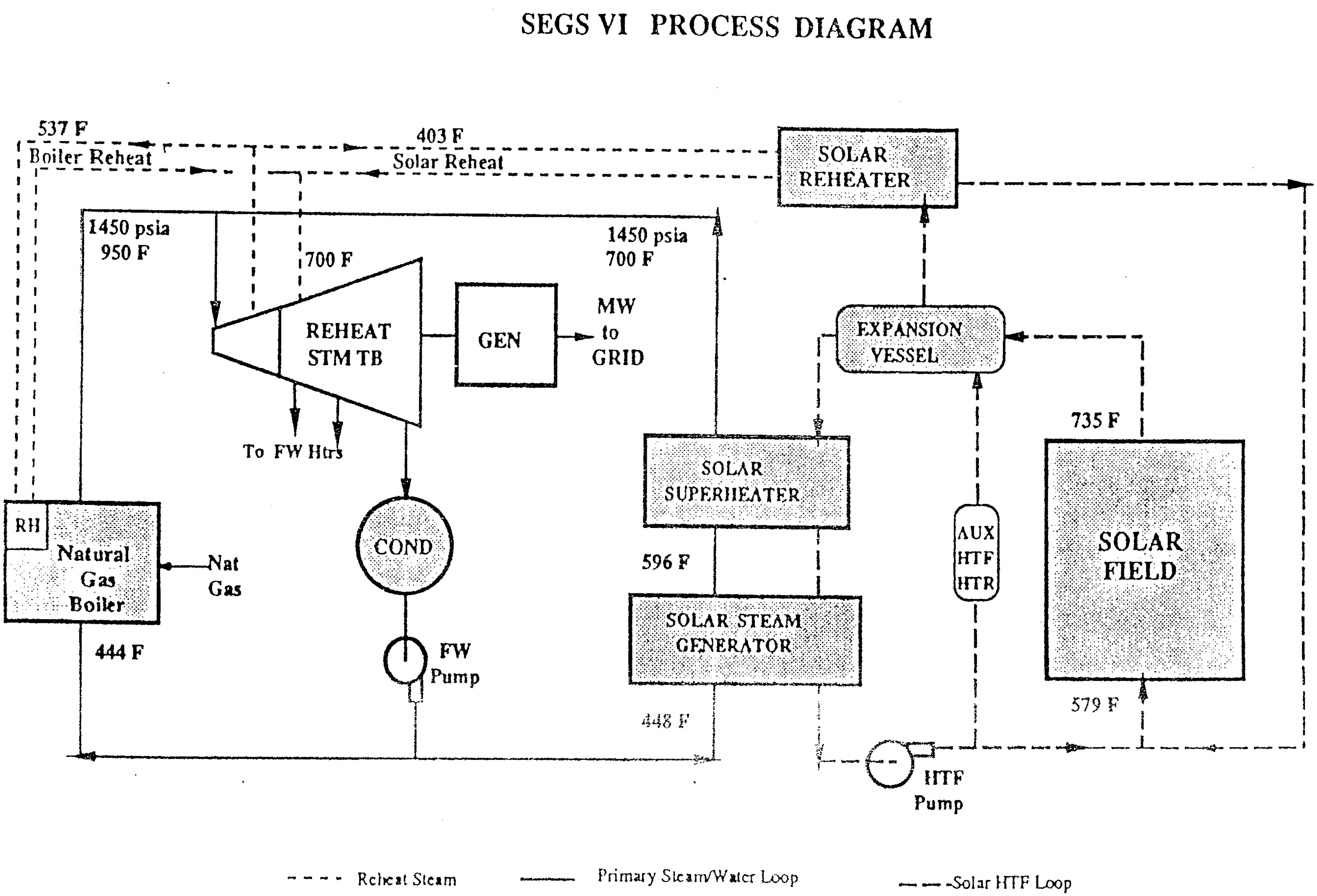


Fig. 2. Process Schematic of SEGS VI-VII Plants

2. Thermal Energy Storage

Solar thermal applications are particularly enhanced by the capability to store energy. Unlike traditional electric power plant fuel sources, such as petroleum, natural gas, and coal, solar "fuel" can not be directly stored, and solar energy supply is independent of electric demand. Thermal energy storage primarily enhances the solar eléctric power system by adding the capability to store energy during peak insolation periods for later use during afternoon and evening hours, though there are a number of secondary benefits as discussed below. In general, the economics, operational effectiveness and operating strategy of the SEGS plants can all benefit significantly from the use of thermal energy storage.

a. TES – General

A schematic representation of a solar power plant with a thermal energy storage system is shown in Figure 3. Different system designs are discussed in section 2 of this assessment. The power plant energy storage system can be operated in four modes.

- *Storage charging only.* This mode applies when there is solar field output, but the solar output can be more effectively used at a different time of the day. In this case, the HTF flows from the solar field through the thermal storage heat exchangers and back to the pumping station.

- *Steam generation and storage charging.* In this case, thermal energy that is not used to generate steam is stored. The HTF flows from the solar field through both sets of heat exchangers in parallel and then back to the pumping station.

- *Steam generation from storage discharge only.* This situation applies when there is no solar field output and steam is required. The HTF runs in a loop between the two sets of heat exchangers -- that is, from the storage heat exchangers to the preheater, steam generator, superheater, and reheater, and then back to the storage heat exchangers.

- *Steam generation from solar field and storage discharge.* This applies when there is solar field output, but it is desirable to supplement that output (e.g., to reach peak output) with energy from storage. The HTF flows from the solar field and thermal storage heat exchangers (the solar field and heat exchangers act in parallel) to the process steam heat exchangers. From there, HTF returns to both the pumping and the storage heat exchangers.

b. TES – Phase Change Materials

A number of thermal energy storage schemes have been proposed and investigated to date. These schemes differ in energy storage density, operational characteristics during storage and retrieval, and the state of development of the storage technology. Comparison of these schemes indicate that thermal energy storage based on latent heat of phase change materials (PCM's) provides the highest energy storage densities. PCM storage based on reversible solid-liquid transition requires relatively small volumes, with the additional advantage that energy is stored and retrieved at a constant operating temperature.

It is envisaged that the PCM heat exchanger will consist of a large number of small diameter tubes immersed in an insulated PCM holding tank. The tubes would incorporate an enhanced external heat transfer surface using spines or fins. Further PCM conductivity enhancement may be obtained with the addition of aluminum or stainless steel honeycomb or wool. Individual tube length and the total number of tubes will be specified according to the design rate of heat transfer and the required total energy storage capacity. Tube geometry may be either strait or coiled, depending on the heat transfer fluid type and rate of flow. Modular construction would be used where possible to simplify inspection, maintenance, and repair.

c. TES–SEGS Example

The specific requirements for a thermal energy storage system will, naturally, be plant-specific. The general requirements for a thermal energy storage system compatible with an actual 80 MWe SEGS plant–and compatible with the SEGS plants that are planned for the next several years–are as follows:

- Nominal Operating Characteristics of the Solar Field

- Solar field nominal output temperature	390	°C
- Solar field nominal input temperature	293	°C
- Full load operation	240	MWt
- Flow at full load	3.63×10^6	kg/hr

- Storage Charging

- Storage capacity	200	MWh
- HTF inlet temperature	390	°C
- Maximum HTF outlet temperature	315	°C
- Maximum flow through storage		
a) Storage mode (80% full flow)	3×10^6	kg/hr
b) Hybrid mode (25% over flow)	0.91×10^6	kg/hr

- Storage Discharge

- Minimum HTF outlet temperature	350	°C
- Maximum load (80% turbine load)	198	MWt
- HTF inlet temperature	265	°C
- Maximum flow	3×10^6	kg/hr
- Period between charge and discharge	12	hr

As specified, such a system would provide approximately one hour of thermal storage–a very small system. The use of thermal energy storage with the current configuration of the SEGS plants is still developmental, though use of storage has been quite successful in SEGS I. Near-term SEGS plants, therefore, are designed to be economic without energy storage.

d. TES – Economics

The addition of thermal energy storage to a solar power plant provides significant operating advantages. Perhaps the most significant, albeit long-range, advantage of thermal energy storage with solar power plants is the potential to meet the crucial need for solar-only systems for base load electrical generation without fossil fuels.

A base load solar/storage plant would require 10 to 12 hours of thermal storage capacity. The economics of incorporating a thermal energy storage system into a solar power plant, naturally depends on the specific contract, system and component design, and field condition.

A comparative economic analysis was performed between two 80 MWe SEGS plants – a base load solar/storage plant and a SEGS plant without storage. Using a cost of $135 per square meter of installed solar field (a value consistent with actual Luz LS-3 solar collector experience) and $25 per kWh_t of storage (the current target), a large-size thermal energy storage system is justified at approximately 6.5 cents per kWh_e. Other important differences between the two plants include:

	Solar Only	Solar with Storage	Difference
Solar field size (m^2)	464,000	1,000,000	536,000
Annual Output (MWh_e)	245,000	455,000	210,000
Annual Output (MWh_t)	565,000	1,165,000	600,000
Storage (MWh_t)	0	2,500	2,500
(Hours)	0	10	10
Solar field multiplier			2.5

Base load electric payments of 6.5 cents per kWh_e are much greater than realized today. However, an average price of 6.5 cents per kWh_e – that is, the average price of off-, mid, and on-peak – is realistic. For example, the mid-peak period of Southern California Edison ends at 11pm during the summer and 9pm during the winter. The average rate during this period is approximately 6 cents per kWh_e. According to the Pacific Gas and Electric (PG&E) energy storage study, at 6 cents per kWh_e a 6-hour storage system is optimal, based on PG&E's system demand characteristics.

Using the prior SEGS plant example, except reducing the storage capacity to 1,500 MWh_t (approximately 6 hours), 6.5 cents per kWh_e can be achieved with a solar field of 800,000 square meters. Such a system is well sized to generate electricity during high-value on-peak and mid-peak evening hours.

Utility time-of-use peak period definitions vary considerably between utilities, and are subject to change depending on changing utility needs. Whereas most U.S. Southwest utilities have summer peak periods in the afternoon from noon until 5 or 6 pm, at least one utility (in Las Vegas) has its peak in the late afternoon and early evening. Energy shifting is clearly desirable in this case: this is but one example of unique conditions that exist in specific utilities where a thermal storage option would allow better matching of a solar electric plant to the electricity demand curve.

Several external factors further improve the economics of large-size solar/storage systems. For example, U.S. Federal Energy Regulatory Commission (FERC) policy limits the quantity of back-up natural gas to approximately 25 percent of a SEGS plant's electric output. Because of this restriction, the plant can not operate during approximately half of the winter mid-peak period. Energy storage could be used to fill this gap.

In addition, regulations tightening emissions standards may further limit the allowable quantity of natural gas and fossil fuels burned for power production back-up, thereby improving the relative economics of energy storage.

As previously stated, energy storage is still developmental, and, therefore, near-term SEGS plants are designed to be economic without storage. A comparative economic analysis was performed between an 80 MWe SEGS plant and one with a very small storage system – 200 MWh_t, corresponding to approximately 45 minutes. Such a system would be used to smooth fluctuations during intermittent cloud cover and to extend operating time.

A large-size storage system is justified if built for approximately \$14 per kWh_t – much less than the current target of \$25 per kWh_t. A small-size system, however, has other daily operating benefits which increases its value to \$25 per kWh_t. These operating advantages include:

- Dampens solar field fluctuations. The storage system can provide a thermal buffer to dampen solar field output fluctuations due to intermittent clouds, thus providing for smoother turbine and power system operation.

- Matches supply and load characteristics. Heat energy can be shifted to more closely match electric load characteristics. For example, energy absorbed during the day can be stored and then used later for peak demands in the evening.

- Absorbs excess solar field output. The size of the solar field is generally optimized for total annual production without storage. The result of such a design is that on peak summer days the solar field can actually produce thermal energy in excess of the power block design capacity. This excess energy can be stored and used to generate steam in the evening, thus extending the power block operating hours. This energy would otherwise be rejected by the system.

- Responds quickly. Because the storage operates at the same temperature and can use the same heat exchangers as the solar field to generate steam, it can be brought on-line much more quickly than auxiliary boilers. Fossil-fuel boilers operate with many more cycling restrictions due to the need to balance flame and metal temperatures.

- Provides options for quicker morning startup. The power block is designed to work under constant temperature conditions. It, therefore, takes time each morning for the HTF to reach working conditions and run the turbine.

- Anti-freeze protection. Storage energy could be used as HTF anti-freeze protection.

B. PROPOSED CONCEPT

The Luz storage concept uses a series of separately contained phase-change materials (PCM's), each having a different liquid-solid phase-change temperature and each storage bath having its own individual heat exchanger. The cascading of several PCM's achieves the same energy transfer at flow rates lower than a single PCM system; or, greater energy transfer at lower flow rates. Three general configurations are possible.

- HTF/HTF – Hot HTF is pumped through the heat exchange tanks in one direction to melt the salts, and "charge" the storage, while cold HTF will be pumped through the same heat exchangers in the opposite direction to freeze the salts and "discharge" the storage.

  Figure 3 is a schematic representation of such a system with five heat exchange tanks. Each tank is filled with a PCM of different T_{pc} (temperature of phase change) and arranged from top to bottom, in a sequence of diminishing T_{pc}'s.

- HTF/steam – Figure 4 presents the concept of charging the storage with HTF and discharging with water/steam. The thermal storage system acts as the steam-generating equipment, thus eliminating the need for two sets of heat exchangers (steam-generating heat exchangers and thermal-storage heat exchangers). The basic system operation would, however, be essentially the same as an HTF/HTF system. The T_{pc} sequence is this system is $T_{pc2} \geq T_{pc3} > T_{pc1}$.

- Steam/steam – Steam is used to charge and to discharge the PCM storage, thus eliminating the need for HTF and heat exchangers. Because of the shape of the water/steam phase diagram, only a cascading PCM storage system would likely be economic with this system.

PASSIVE MOLTEN SALT LATENT HEAT STORAGE
HTF / HTF

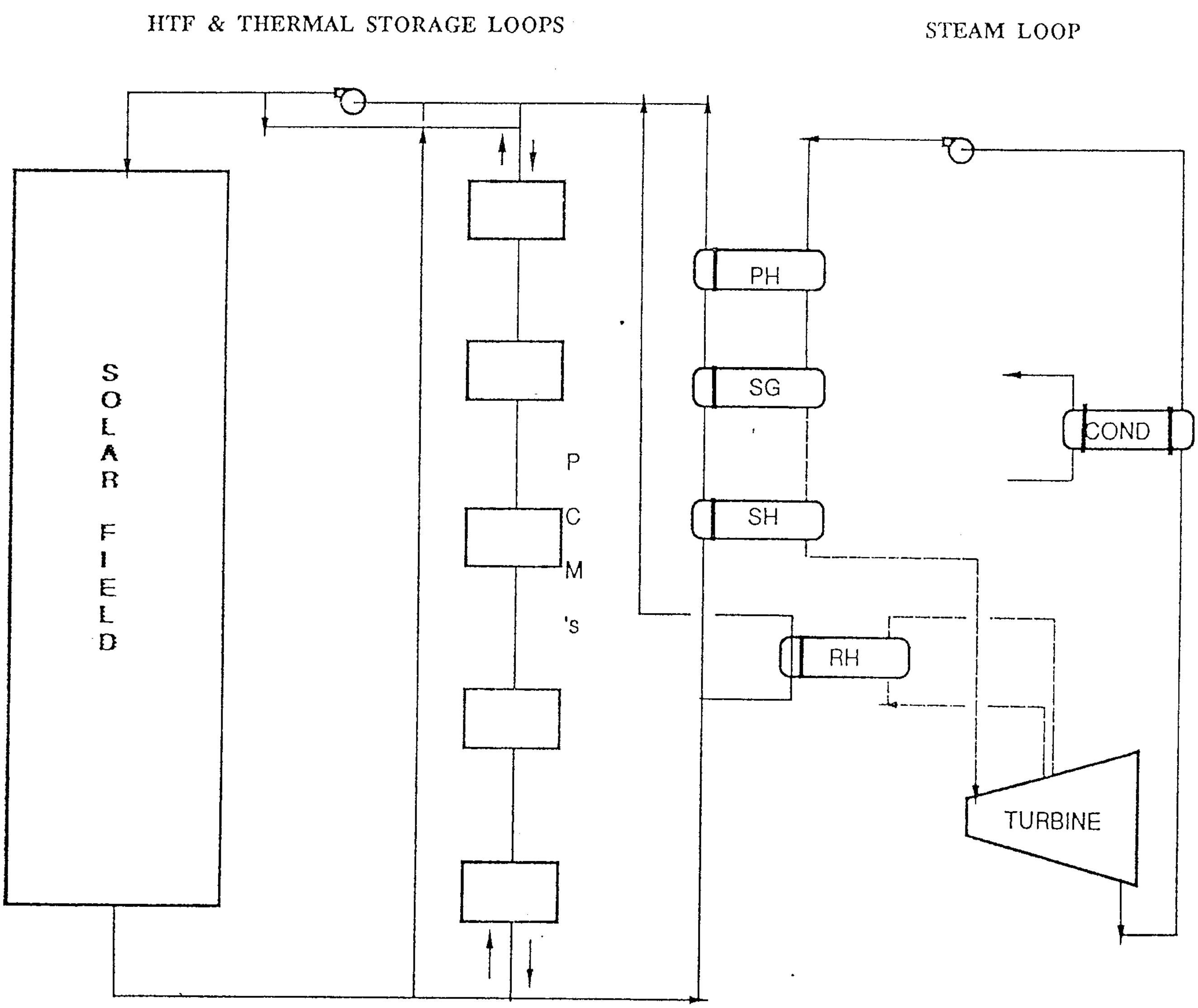


Fig. 3. Process Schematic of Cascading HTF-to-HTF PCM TES System

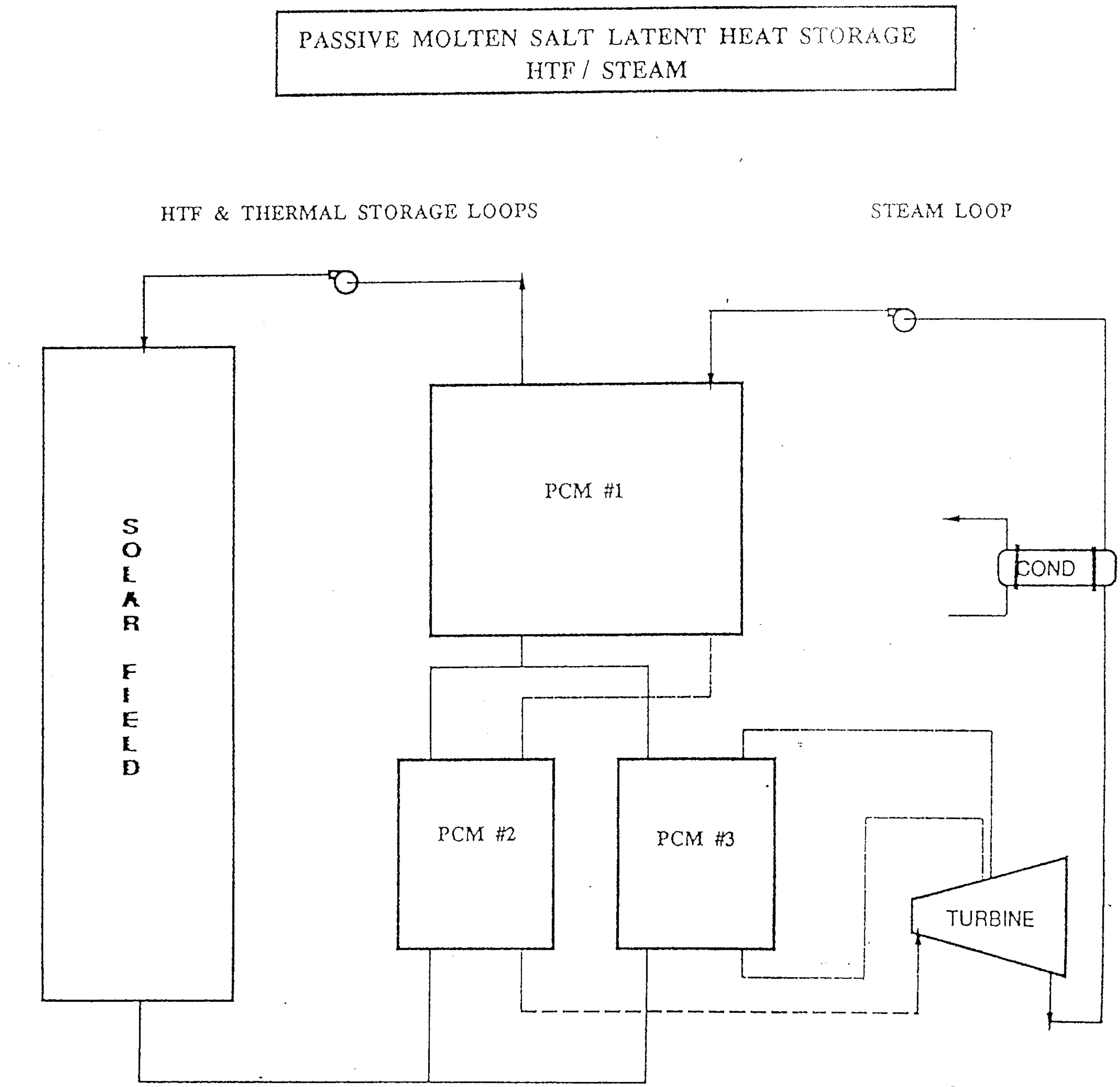


Fig. 4. Process Schematic of HTF-to-Steam PCM TES System

C. APPLICABLE PCM's

1. PCM's – SelectionCriteria

The selection of applicable salts for a molten salt storage system was based on three groups of criteria – thermodynamic properties, safety, and economics.

- Thermodynamic properties. The initial screening of salts included the evaluation of phase change temperature and heat of fusion. Salts that melt outside of the appropriate temperature range or with an energy density too low were excluded. Also reviewed in this step was the phase diagram, volume change characteristics and thermal conductivity of each salt mixture.

- Safety. Materials were examined for stability, volatility, corrosiveness, and toxicity. Of course, most industrial chemicals have some associated hazard, and some of the materials which passed the screen have potential problems with regard to corrosion, fire and explosion hazards. Most of the selected candidates, however, are well-known chemicals which can be safely handled using existing engineering practices.

- Economics. In addition to the cost per unit weight of salt, many other factors effect the system economics of using a particular salt. Some of these other economic factors include heat of fusion and storage volume, corrosiveness and containment costs, heat transfer costs, and overall system costs.

2. PCM's – Candidates

Based on these criteria a preliminary list of PCM candidates for a five cascade molten salt storage system has been prepared. These candidates, with their important properties are listed in Table 2.

Table 2. Candidate PCM's

Temperature (C)	Composition (mole%)	T_f (C)	Ht.Fusion (kJ/kg)	Relative Cost
367	NaOH, NaCl(20)	370	370	1.00 [1]
	KOH	360	167	4.39
347	KNO_3, KBr(10), KCl(10)	342	140	4.04
	NaCl, KCl(24), LiCl(43)	346	281	5.44
328	KNO_3	337	116	3.80
	KNO_3, KCl(6)	320	150	3.33
	NaOH	318	158	2.78
		286-299	316 [2]	1.20
308	NaCl, NaOH(93.7)	314	?	?
	$NaNO_3$	310	174	1.35
	NaF, $NaNO_3$(96.5)	304	?	?
	LiOH, KOH(60)	314	341	3.57
289	Na_2SO_4, NaCl(8.4), $NaNO_3$(86.3)	287	176	1.30
	$NaNO_3$, NaCl(6.4)	284	171	1.20
	KNO_3,$Ba(NO_3)2$(87)	290	124	2.85
	$NaNO_2$	282	212	3.33
	$NaNO_2$, KNO_3(45.2)	285	152	3.61
	NaOH, NaCl(7.8), Na_2CO_3(6.4)	282	316	2.90

[1] Based on NaCl at 0.05 \$/kg and NaOH and 0.35 \$/kg, the resulting storage capacity cost is 2.7 \$/kWh. This is given only as an indication for comparison.

[2] NaOH is reported to have an additional solid state transition. The higher heat of fusion is the sum of both transitions. The cost is based on this combined value.

D. TECHNICAL ISSUES

One important objective of the TES Symposium is to discuss the technical problems and operational experience with phase-change materials, with emphasis on heat exchanger configuration, heat transfer phenomena, long-term chemical stability, material compatibility and safety. The experts participating in the meeting will address these issues from the perspective of their own knowledge and experience. From these discussions, the development steps necessary to evaluate and test the most promising candidates will be tentatively developed.

APPENDIX B

Visual Aids

INTRODUCTORY REMARKS BY

THE CHAIRMAN

Phase Change Thermal Energy Storage Symposium

October 19-20
Inn at Silver Lakes
Helendale, California

by

Charles A. Bankston
CBY Associates, Inc.
Washington, DC

October 19, 1988

ISSUES FOR DISCUSSION

ECONOMICS

ENGINEERING ISSUES

RESEARCH NEEDS

RESEARCH TASK DEFINITIONS

PROGRAM ISSUES

ECONOMICS

1. DEFINITION OF TERMS

2. VALUE OF STORAGE

   a) Operational Benefits

   b) Rate Shifting

   c) Base Load Plants

3. COST OF STORAGE

   a) Storage Media

   b) Containment and Insulation

   c) Heat Exchangers

   d) Transport Media

4. OPTIMIZATION

   a) Least Capital Cost

   b) Greatest ROR

   c) Least Cost Power

ENGINEERING ISSUES

1. THERMODYNAMIC CONSIDERATIONS

    a) Latent or Latent/Sensible Storage & Fluids

    b) Single or Multiple Stage

2. STORAGE MEDIA

    a) Heat Capacity

    b) Media Form (bulk or discrete particles)

    c) Surface to Volume Ratio

    d) Insulation Optimization (Cyclic)

    e) Material Compatibility

    f) Safety, Maintenance, and Life

3. HEAT TRANSFER

    a) Delta T and Surface Area

    b) Heat Exchange Fluids

    c) Safety, Maintenance, and Life

ENGINEERING ISSUES (cont.)

4. COLLECTOR FIELD

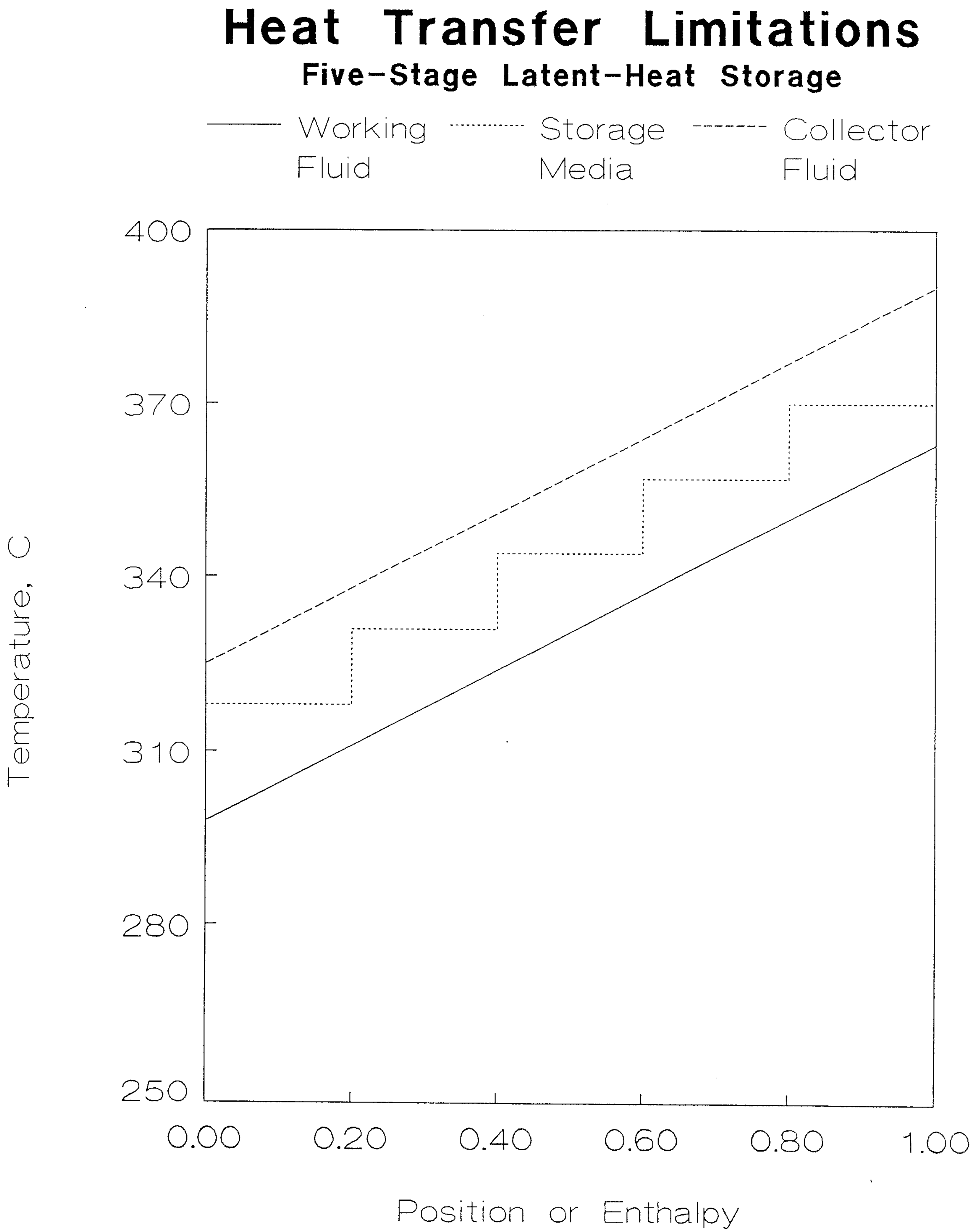
    a) Heat Transfer Fluid

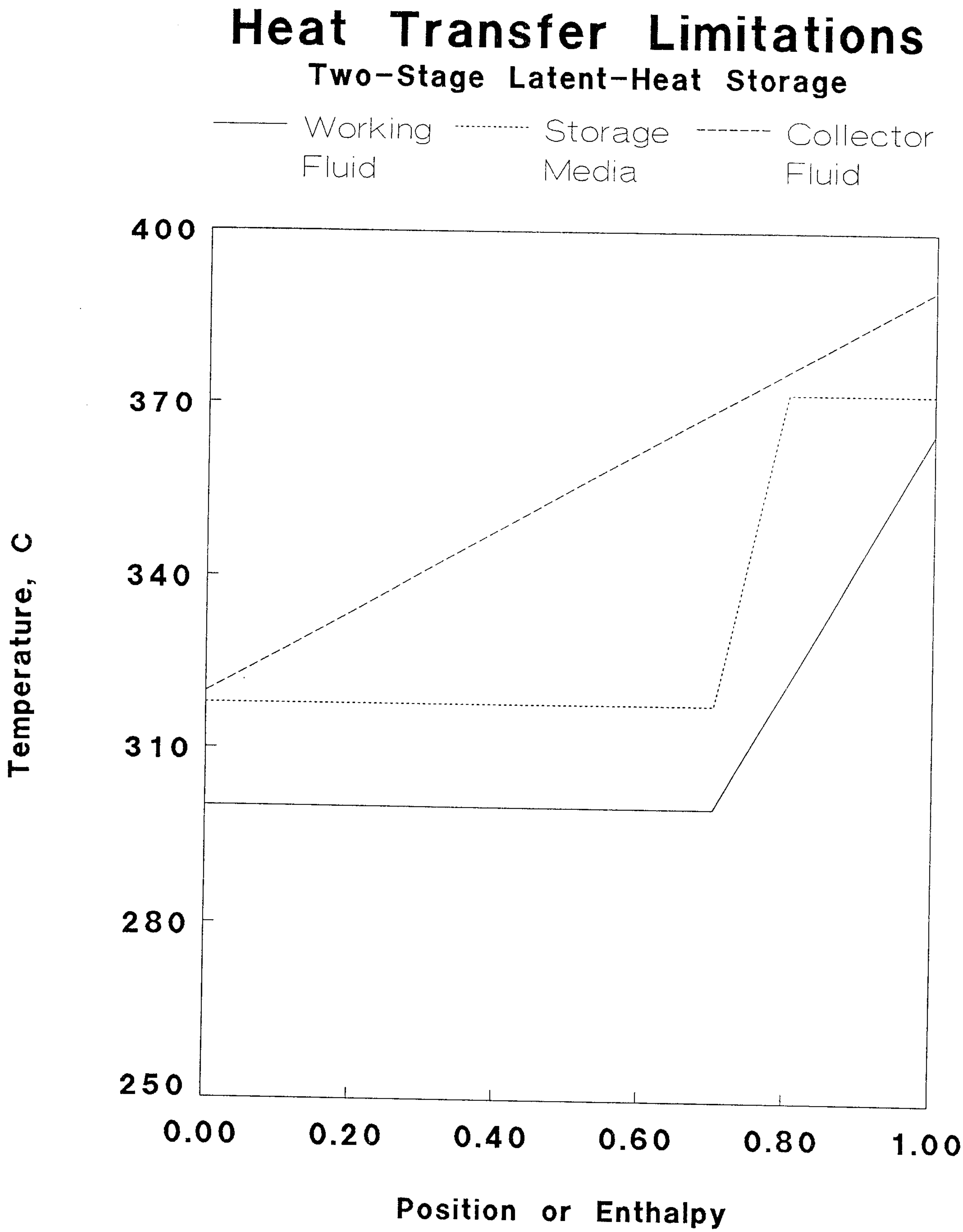
    b) Operating Temperature

5. CONTROL SYSTEMS AND STRATEGIES

    a) Short Term/Long Term

    b) High Loss/Low Loss Storage


Heat Transfer Limitations
Five-Stage Latent-Heat Storage
Working Fluid
Storage Media
Collector Fluid
400
370
340
310
280
250
Temperature, C
0.00
0.20
0.40
0.60
0.80
1.00
Position or Enthalpy



Heat Transfer Limitations
Two-Stage Latent-Heat Storage
Working Fluid
Storage Media
Collector Fluid
400
370
340
310
280
250
0.00
0.20
0.40
0.60
0.80
1.00
Temperature, C
Position or Enthalpy

RESEARCH NEEDS

1. ANALYTICAL TASKS

    a) Heat Exchange Design/Optimization

    b) Control Strategies

    c) Economic Optimization

2. LABORATORY RESEARCH

    a) Materials Characteristics

    b) Heat Transfer Studies

3. PLANT SCALE EXPERIMENTS

    a) Heat Exchanger Performance

    b) Control Systems and Strategies

    c) Safety, Operations, Maintenance, and Life

RESEARCH TASK DEFINITIONS

1. NEED

2. GOAL

3. DESCRIPTION

4. PROMISING APPROACHES

5. MAJOR OBSTACLES

6. PROBABLE TIME AND COST

PROGRAM ISSUES

1. Who (has the expertise to do the research)?

2. When (can the results be expected)?

3. How (can the research results be integrated)?

4. Why (should DOE participate in research)?

A Review of Solar-Related Thermal Energy Storage Research

Symposium on Phase-Change Thermal Energy Storage

October 19-20, 1988

Mark S. Bohn

Contents

- Background on Phase Change Storage Research
- Coolidge Irrigation Project
- Shenandoah Total Energy Project
- CRTF Molten Salt Two-Tank Test
- Comparison of three storage concepts

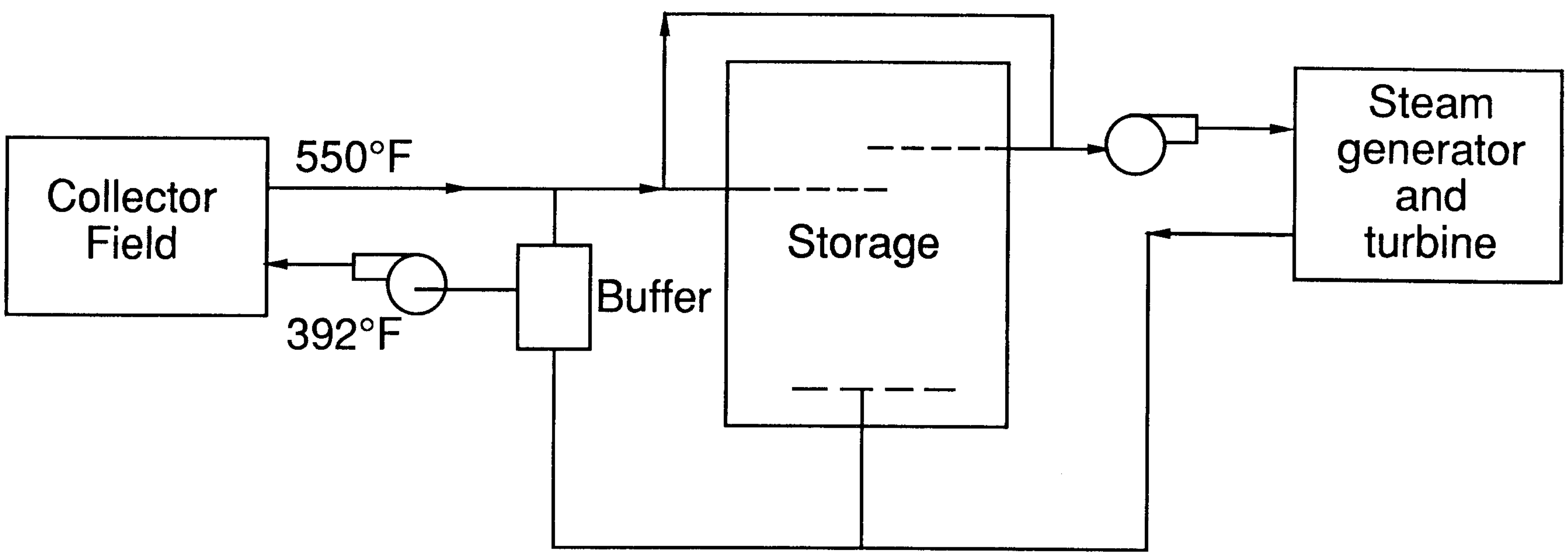
Phase Change Storage Research

- In the temperature range of interest only 1 system study and 1 experimental study appear applicable
- Probable reasons for lack of interest
  - heat transfer across solidified pcm generally poor
  - expansion/contraction of pcm
  - containment is difficult
  - most sensible methods appear simpler
- Potential for phase change has been recognized but not exploited in DOE solar-related storage research

Coolidge Irrigation Project
1979-1982

- 23,000 ft^2 parabolic trough system
- Caloria heat transfer fluid
- 392°F → 500°F
- Toluene organic Rankine cycle
- 30,000 gallon thermocline storage tank ~5 hours
  - efficiency measured
  - thermocline stability determined
  - no problems specifically mentioned
  - no economic analysis provided
- Thermocline probably not applicable due to
  - high cost of Syltherm in Luz system
- Technical feasibility demonstrated in event a lower-cost high-temperature HTF is developed
- SAND83-7125

Coolidge System



M4-CD-G0351703

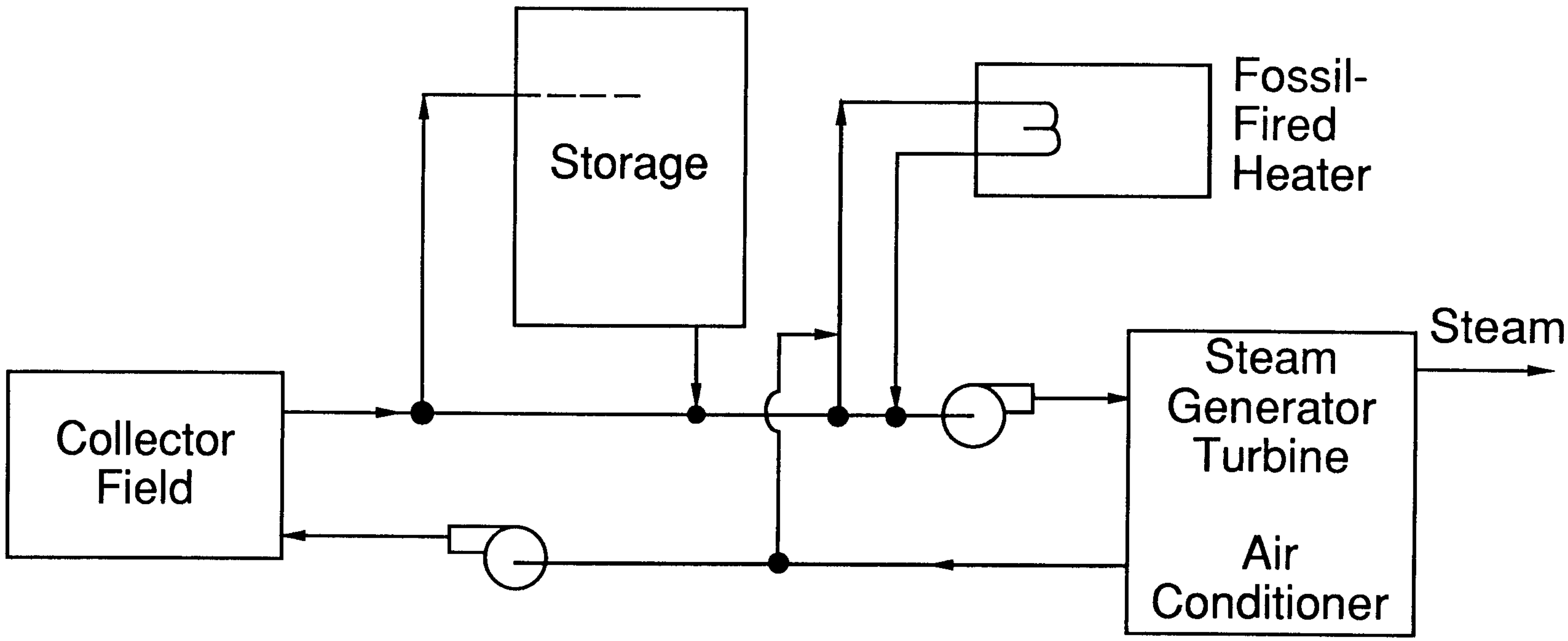
Collector Field	Size:	48 Acurex collector groups with N-S axis orientation - 23 040 ft^2
	Fluid:	Caloria® HT-43
	Temperature:	Inlet, 392°F; outlet, 550°F
Thermal Storage	Type:	Stratified liquid (thermocline)
	Tank size:	50,000 gal - 13.67 ft dia by 49-ft length (30,000-gal usable storage)
	Storage temperature:	392° to 550°F
	Storage medium:	Caloria® HT-43
	Insulation:	12-in-thick fiberglass
Cooling System	Type:	Vapor condenser
	Water (make-up):	10 gal/min
	Condensing temperature:	105°F
Power Generation	Type:	Organic Rankine cycle
	Working fluid:	Toluene
	Gross efficiency:	20%

Shenandoah Solar Total Energy Project

1982-1984

- 47,000 ft^2 parabolic dishes
- Syltherm 800 heat transfer fluid
- 500°F → 750°F
- Steam Rankine cycle
- 11,000 gallon thermocline storage tank ~1 hour
  - heat loss measured
  - thermocline stability determined
  - storage capacity measured
  - need for more storage was identified for improved load matching
- SAND87-7108

Shenandoah System



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Molten Salt Storage Tests at CRTF

1987

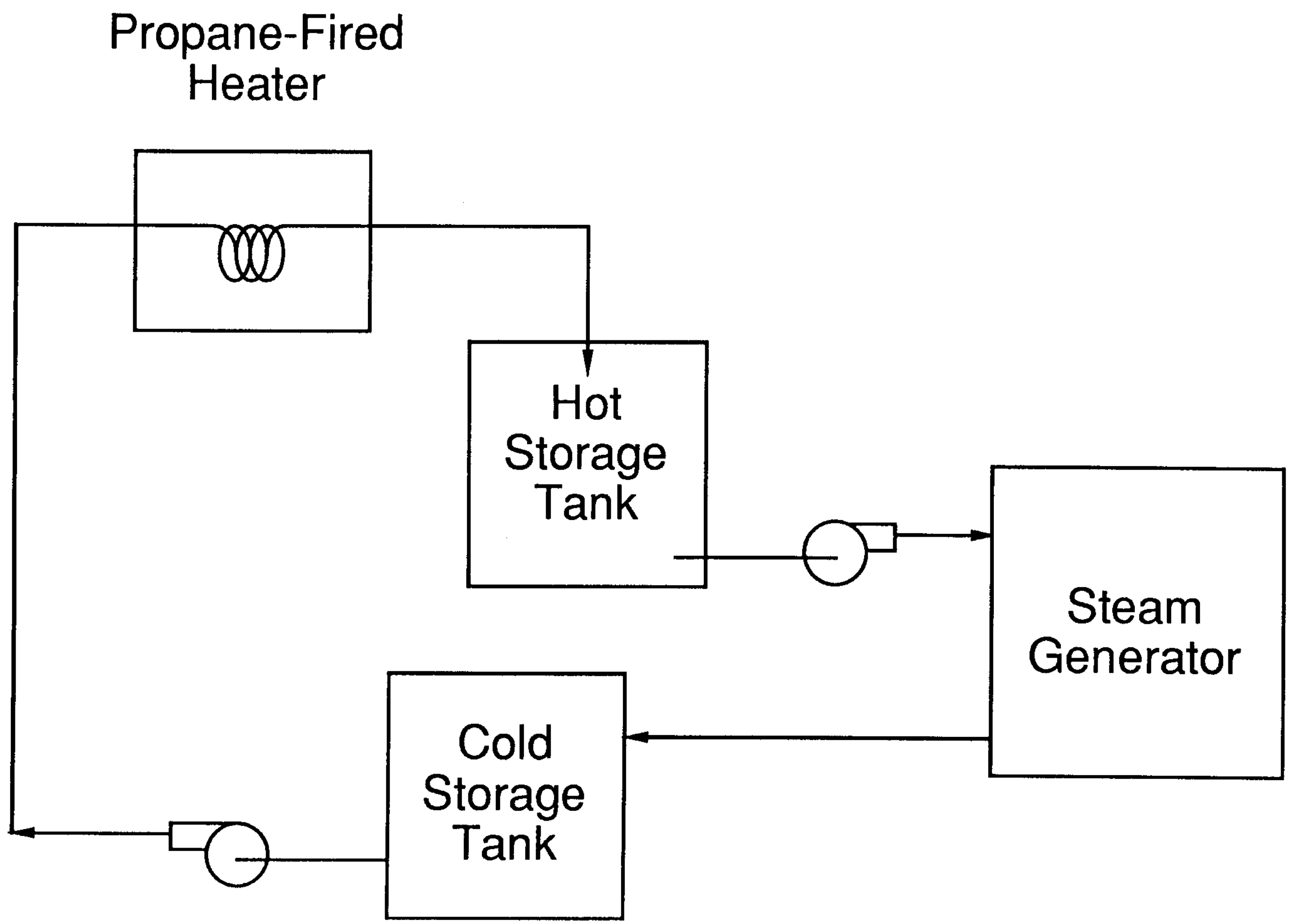
- Two tank storage system
- Nitrate salt
- Hot tank - 1050°F (565°C), 7 MWh_{th}
- Cold tank - 550°F (288°C)
- Test objectives
  - determine if thermal performance degraded since installation in 1982
  - validate computer model
  - estimate efficiency of 1200 MWh_t system
  - compare performance with 2 European systems

Molten Salt Storage Tests at CRTF

1987 (continued)

- Results
  - hot tank losses same as in 1982
  - cold tank losses were less due to wet insulation in 1982
  - computer model gives good prediction of tank performance
  - efficiency of 1200 MWh_t system is $98\%^+$
  - thermal performance of test system was similar to the European systems
  - demonstrates technical feasibility
- SAND87-3002

CRTF Thermal Storage System



M4-CD-G0351702

Comparative Ranking of Thermal Storage Systems

1983

- Comparison of 3 storage systems for Shenandoah-type plant
  - Syltherm/taconite trickle charge
  - Hitec 2-tank
  - direct contact phase change
- Results
  - Syltherm trickle charge is best for <7 hours storage
  - phase change is best for >7 hours
- Caveats/issues
  - compatibility between Syltherm and taconite
  - phase change system has not been proven experimentally
- SERI/TR-631-1283, by Stearns-Roger Services, Inc.
- SERI/STR-230-2065 describes direct-contact phase-change research by Grumman Aerospace Corp.

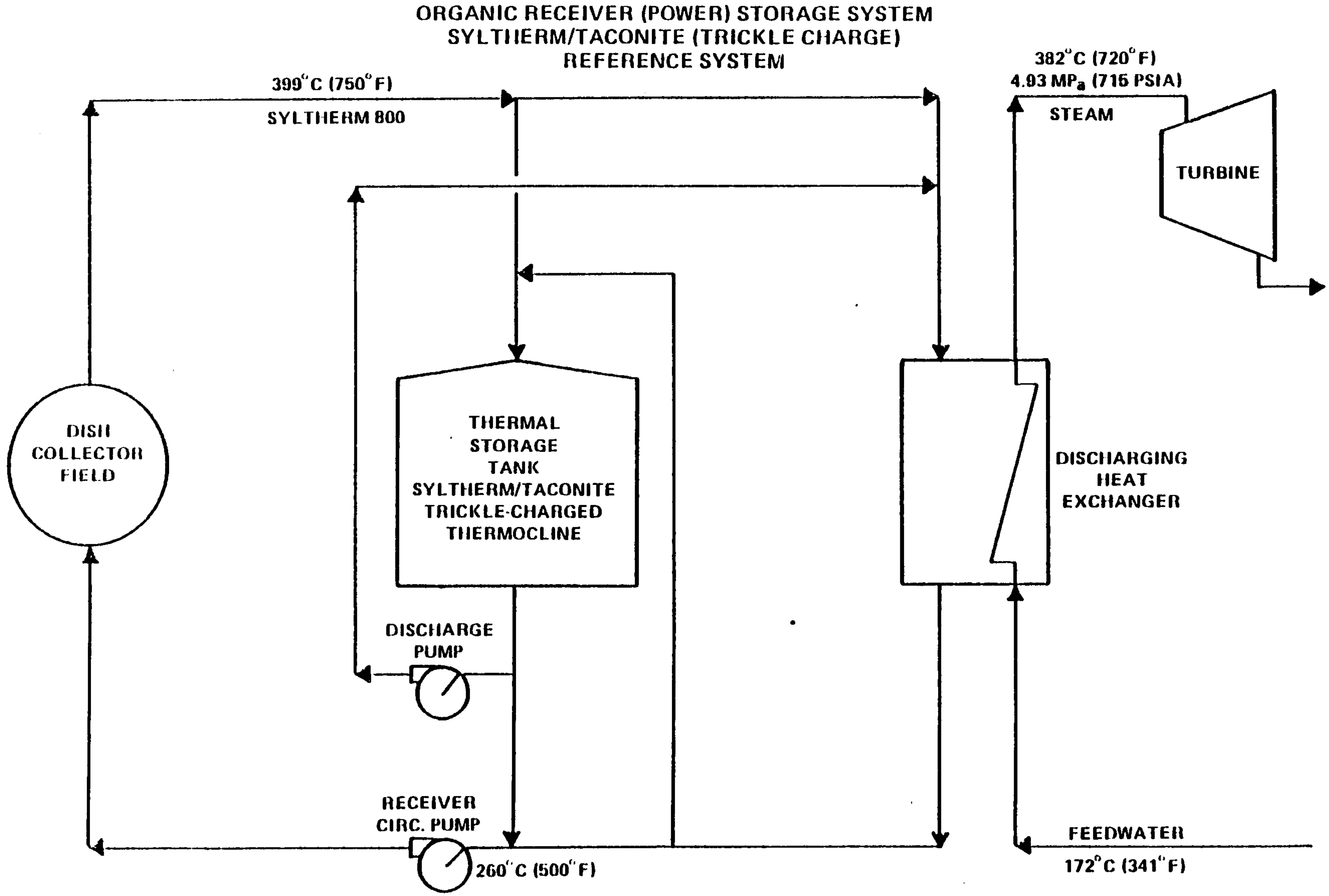


Figure 3–27. THERMAL STORAGE SYSTEM
SYLTHERM/TACONITE (TRICKLE CHARGE) (REFERENCE SYSTEM)

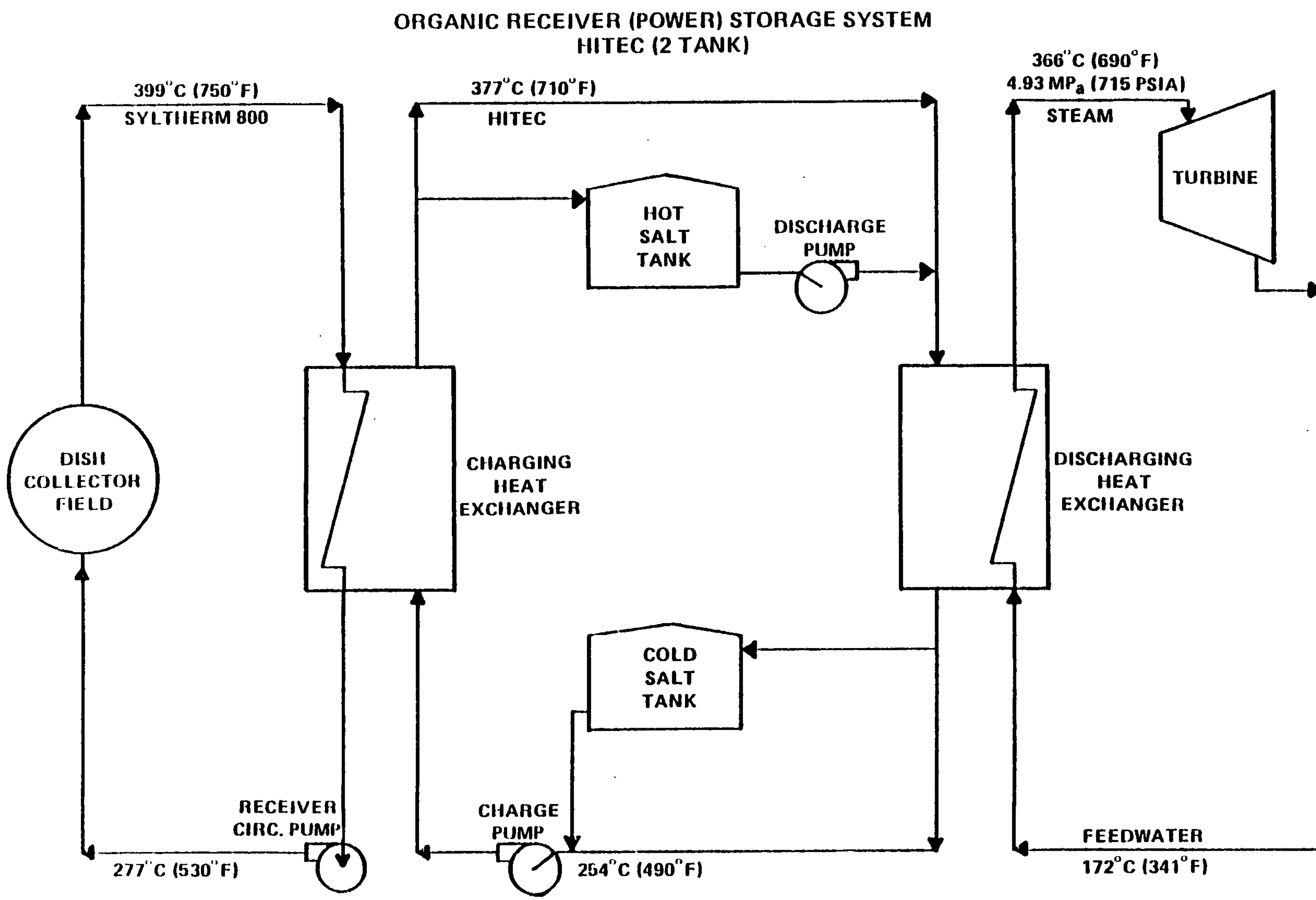


Figure 3–29. THERMAL STORAGE SYSTEM
HITEC (2 TANK)

A-8.80.044

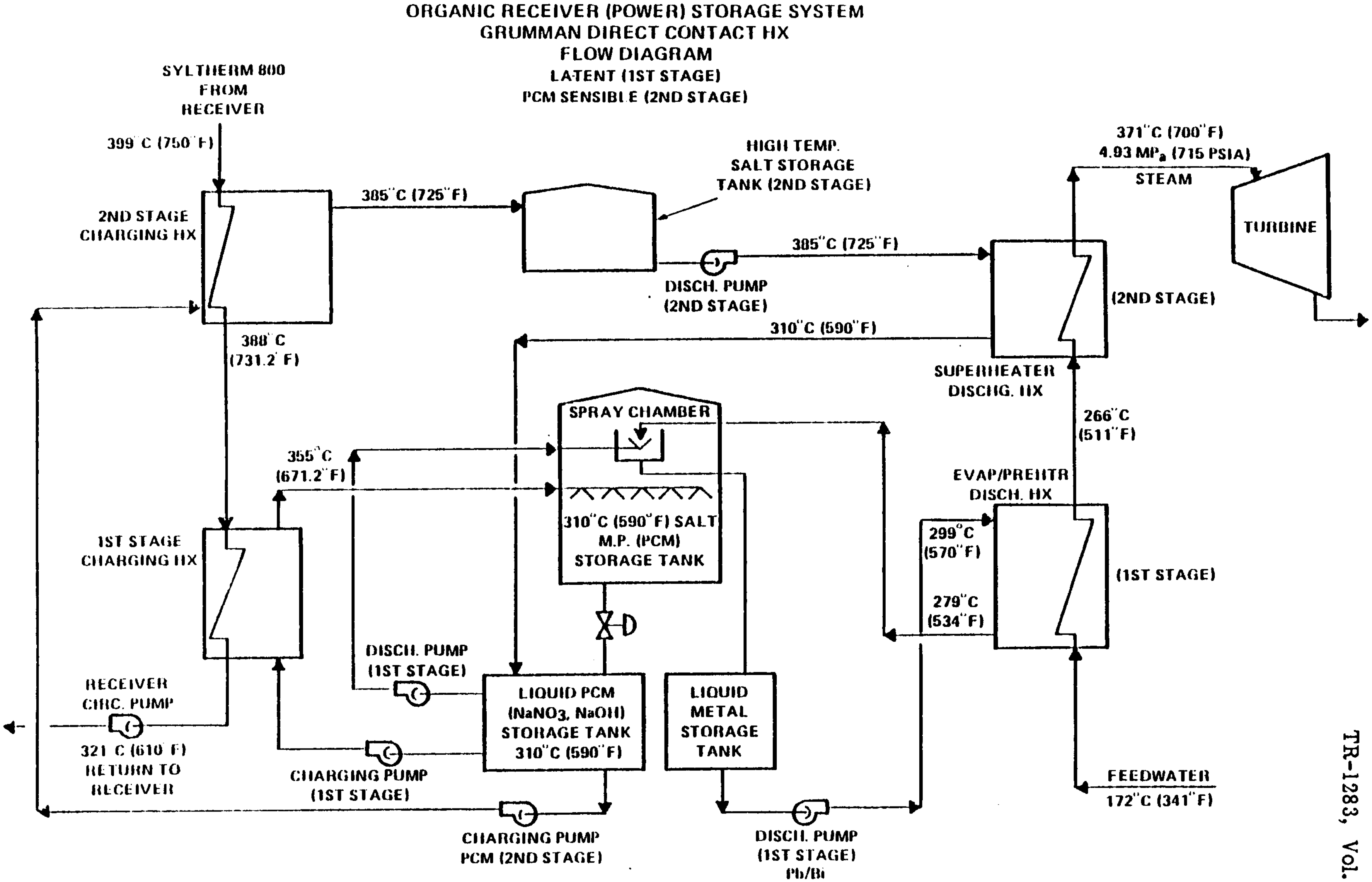


Figure 3–31. THERMAL STORAGE SYSTEM
LATENT, DIRECT CONTACT - PCM (2-STAGE)

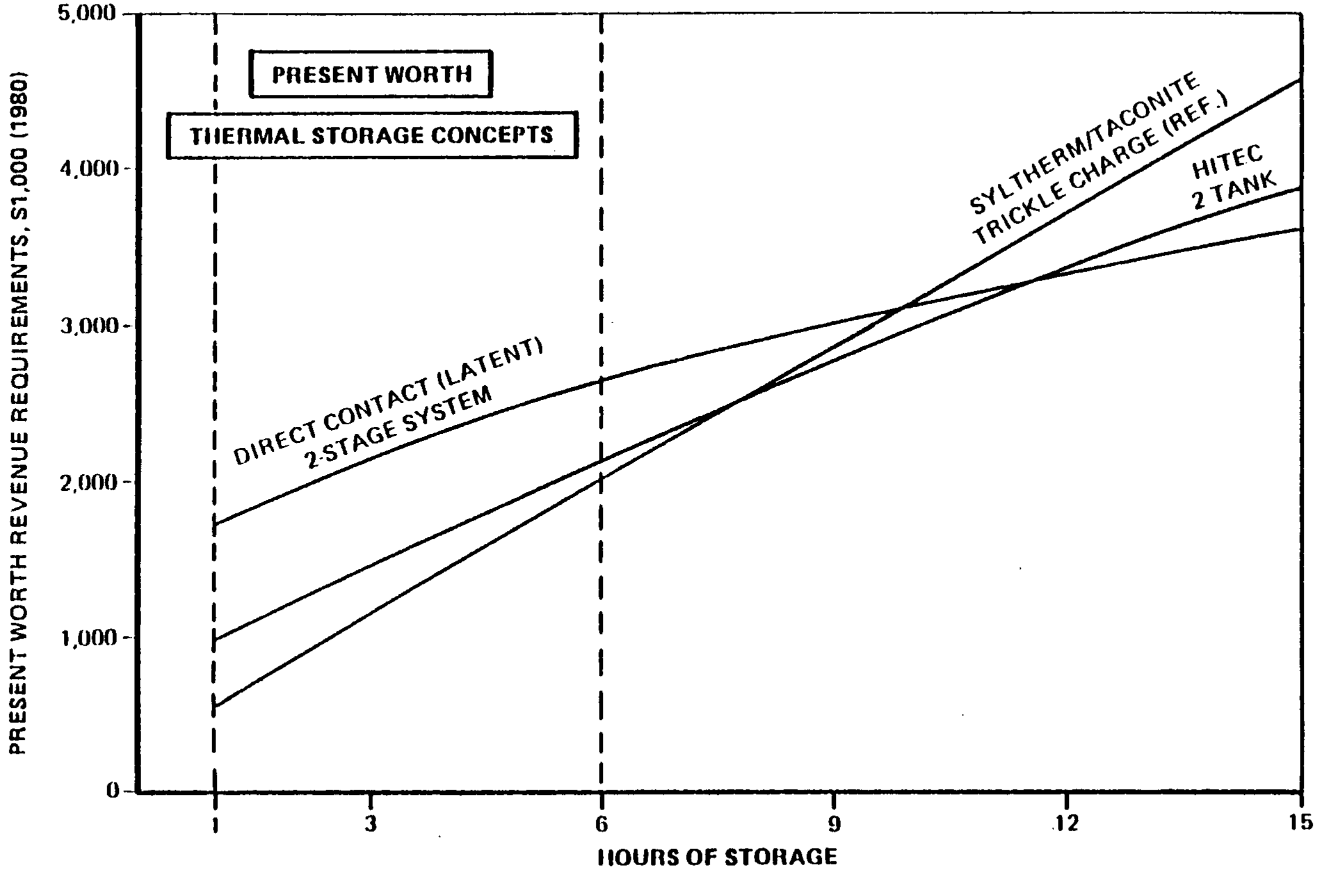


Figure 4–8. PRESENT WORTH REVENUE REQUIREMENTS, ORGANIC FLUID RECEIVER (POWER)

Conclusions

Considerable solar-related experience with various storage systems in temperature range of interest

- Thermocline systems
  - adequate field experience, but requires large quantities of HTF
  - probably not cost effective for Syltherm-based systems
- Trickle charge
  - possibly most cost effective for short duration storage (<6 hours)
  - no technology development required
- Two-tank, salt
  - good field experience
  - most cost effective solution over narrow range of duration (8-12 hours)

Conclusions
(continued)

- Phase change
  - many possible configurations
  - no field experience
  - development required
  - good potential for cost effective long-term storage ($>$15 hours)

AN OVERVIEW OF ORNL TES WORK AND ITS APPLICABILITY TO LUZ SOLAR ELECTRIC NEEDS

M. Olszewski
J. J. Tomlinson
Oak Ridge National Laboratory

Prepared for
EXPERT'S MEETING

October 19 - 20, 1988

APPLICABLE TES TECHNOLOGY HAS BEEN DEVELOPED THROUGH A NUMBER OF PROGRAMS AT ORNL

- DOE Thermal Energy Storage Program
    - building applications with applicable temperature range of -20C to 200C
    - industrial applications covering temperature range of 100C to 1100C

- Burst Power Reject Heat Management for SDI
    - low (30C) and high (400C to 800C) needs

- Dynamic Solar Power System TES for NASA Space Station
    - development of performance model
    - advanced metal PCM development

WIDE VARIETY OF TECHNOLOGIES ARE BEING (OR HAVE BEEN) DEVELOPED IN THE DOE PROGRAM

- Salt PCM Systems with Shell and Tube Heat Exchangers
- Thermocline Sensible Heat Storage
- Slurry Heat Transport and Storage Systems
- Form-Stable Composite Media
- Encapsulated Metal Alloy Storage Media
- Chemical Reaction Systems Using Complex Compounds

MANY SHELL AND TUBE CONCEPTS HAVE BEEN STUDIED

- The primary issue with shell and tube designs is that reduction in conductance due to increasing solid salt layer leads to large surface area requirements

- Techniques studied include

    - scrapers to keep solid from adhering to heat exchange surface
    - finned surfaces that extend beyond the solid salt layer
    - reticulated metal foams to provide continuous conduction path to the liquid
    - vibrating heat transfer surface to prevent adhesion of solidifying salt

- In general results were not greatly positive
    - mechanical means for removing solid salt from HX surface did not work well
    - finned surfaces enhance conductivity by about 25%
    - reticulated metal foams had higher conductivity enhancements (about 35 to 45%) if good contact was made with heat transfer tubes

- Even with conductivity enhancement shell and tube concepts require rather large surface areas

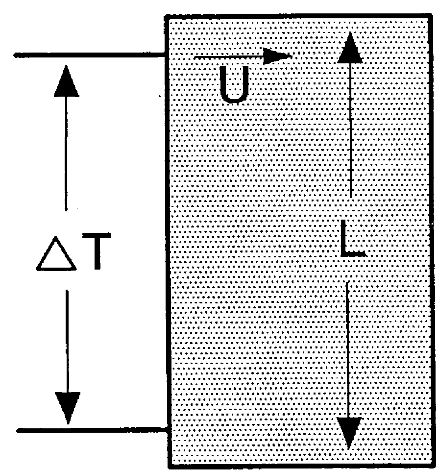
THERMOCLINE SYSTEM STUDIES BY DOE HAVE PROVIDED TECHNICAL BASIS FOR SENSIBLE HEAT STORAGE DESIGN

- Thermocline TES design benefits include
  - single tank resulting in low system cost and reduced heat losses
  - high volumetric efficiency
  - textbook knowledge developed for diffuser design
  - no need for membrane

- Richardson number identified as nondimensional stratification parameter

$$Ri = \frac{[g\ \beta \Delta T]L}{U^2}$$

For stratification, $Ri \geq 1/4$



- Sharp thermoclines achieved in chilled water systems; better performance expected with SEGS TES

  Rationale: $\beta_{oil} \approx 20\ \beta_{H_2O}$

PUMPED PCM SLURRY INITIALLY STUDIED BY DOE MAY BE AN OPTION

- Application in collector loop

- Potential benefits include

  - increased heat transport through latent heat
  - smaller pipes and pumps
  - greater thermodynamic availability especially in small ΔT systems such as SEGS

- Attractive features include

  - extensive SEGS collector loop volume serves two roles: heat transport and TES
  - slurry solids displace expensive heat transfer oil

- Problems

  - PCM slurry material not available
  - slurry management and control

OPEN COMPOSITES HAVE BEEN DEVELOPED FOR INDUSTRIAL REJECT HEAT RECOVERY APPLICATIONS

- Concept uses a PCM immobilized within a ceramic matrix
- Composition using Na_2CO_3-$BaCO_3$/MgO was focus of development work
- Cold-pressing and extrusion processes developed that produced pellets with density of 92% T.D.
- Pellets typically 50 to 60% PCM by weight (heat of fusion of Na_2CO_3-$BaCO_3$ is 172 KJ/KG)
- Performance test of 160 thermal cycles (>3500 hours) showed good media stability with only about 1% weight loss and no significant cracking
- At lower temperatures concept has not been as successful
  - nitrates and chlorides
  - density and PCM content have been lower than that achieved with carbonates
  - weight losses have been high

Thermodynamic and practical advantages of packed bed of PCM pellets long-recognized by DOE and others as useful in low ΔT TES systems

- Central issue: development of PCM coating that is

  - economic
  - probably seamless
  - chemically stable
  - strong enough

- DOE-sponsored work (through OSU) focused on development of integral shell

  - by controlled quenching of Si-Al hypereutectic to form Si shell (Si-Al eutectic m.p. = 577C)
  - by aluminothermic reaction coating (alloy reacts with SiO_2 to form Al_2O_3)
  - by packed bed cementation siliconizing
  - results only partially successful
  - further work at ORNL on Si-Al hypereutectic showed that Si shell not stable above 600C

- Joint venture between Lanxide and DuPont formed to continue coating development and applications work

- PCM coating processes now being developed at lower temperatures by others.

Thermochemical reactions currently being studied by DOE for chill storage applications may be useful in SEGS TES

- Reaction:

salts(s) + ligand (g) $\rightleftharpoons$ complex compound(s) + ΔH

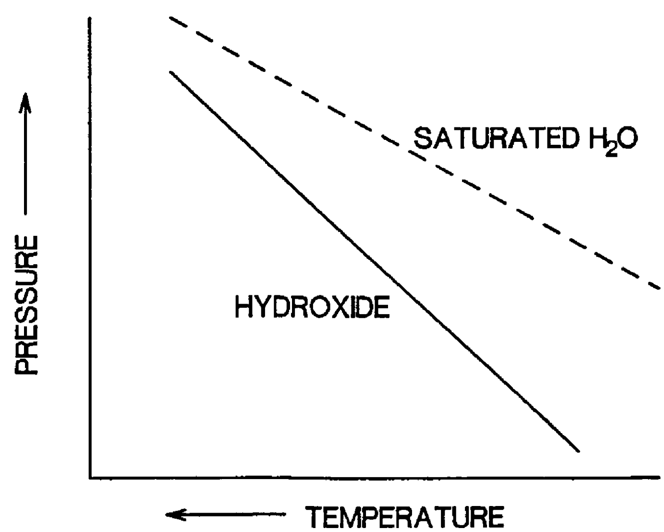
  - chill storage ligand is ammonia
  - chill storage salt: metal halides

- For SEGS , metal oxide - hydroxide reactions such as

$$CaO(s) + H_2O(g) \rightarrow Ca(OH)_2(s) + \Delta h$$

  appear promising.

- System based on transfer of ligand (H_2O) between two containers



SDI ACTIVITIES HAVE FOCUSED ON BURST POWER APPLICATIONS

- Large amounts of reject heat generated for only a small portion of the orbit

- High-temperature need for prime power system uses LiH

    - between 700K and 1100K storage density is >4 MJ/KG
    - encapsulate LiH spheres with metal shell
    - shells of 304L SS (7-mil) and MOLY (5-mil) have been used

- Lower temperature (300K) needs have been met using complex compounds

    - use ammines or hydrates
    - storage unit acts as heat pump and storage system
    - can get lifts exceeding 100K in a single stage unit

ASSESSMENT ACTIVITIES PARALLEL THE HARDWARE DEVELOPMENT

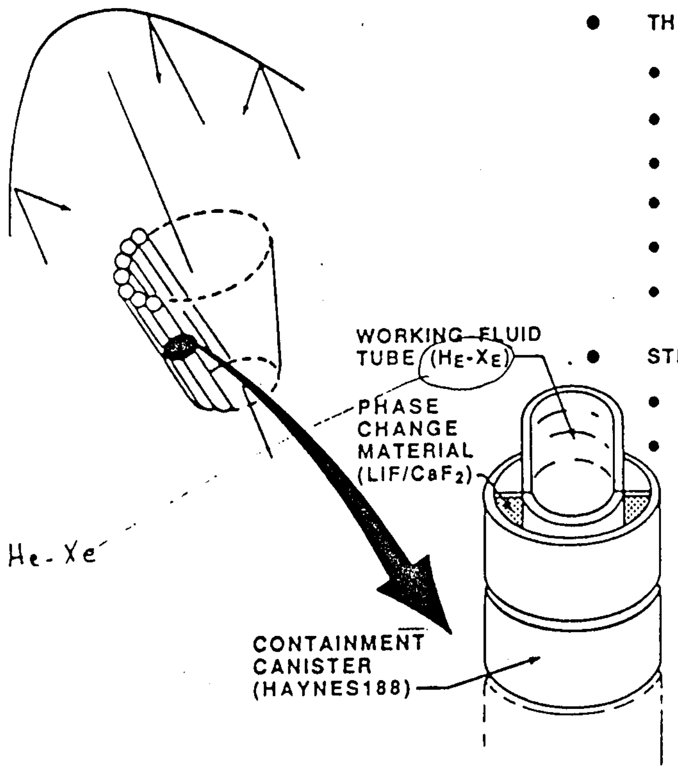
- Examined thermal performance of five candidate storage unit designs

  - shell and tube PCM tube side
  - shell and tube PCM shell side
  - concentric annular regions
  - parallel slabs
  - packed bed

- Assessment based on specific mass (KW/KG) basis

- Thermal performance results indicated that mass of encapsulating material and thermal conductivity of PCM were critical parameters

NEW INITIATIVE SUPPORTS DEVELOPMENT OF SOLAR RECEIVER FOR NASA SPACE STATION POWER SUPPLY



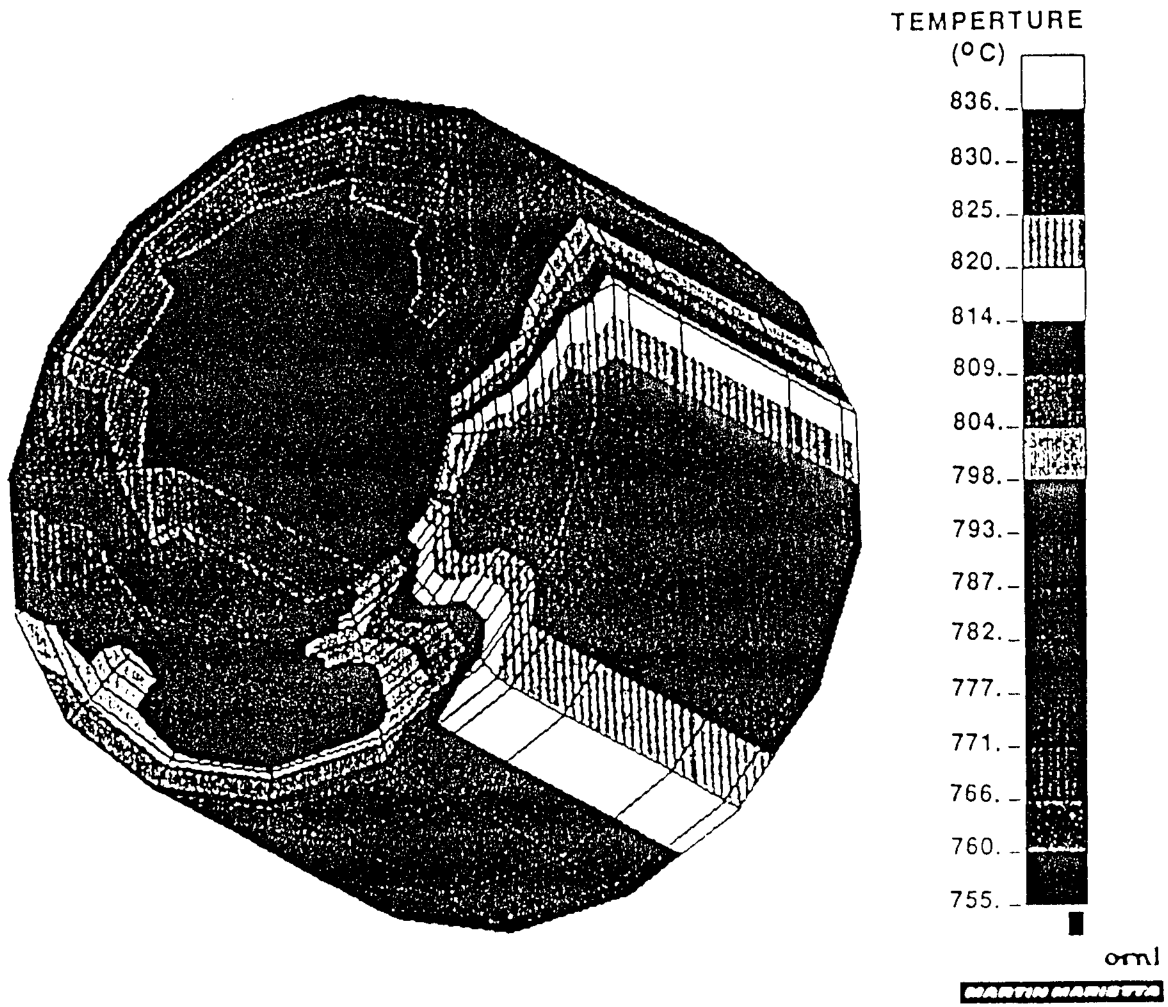
- THERMAL ANALYSIS (QUASI 3-D)
  - CONDUCTION (r,θ) : SALT (SOLID), CANISTER
  - CONVECTION : SALT (LIQUID) { 1-G : BUOYANCY; 0-G : MARANGONI
  - VOID : SIZE, SHAPE, GROWTH, LOCATIOI
  - RADIATION ACROSS VOID
  - MELT/FREEZE BOUNDARY MOVEMENT
  - TIME-DEPENDENT, ASYMMETRIC B. C.'s
- STRESS ANALYSIS (ADINA)
  - THERMAL STRESS (CANISTER)
  - TRACTIVE FORCE (SALT-METAL INTERFACE)

om

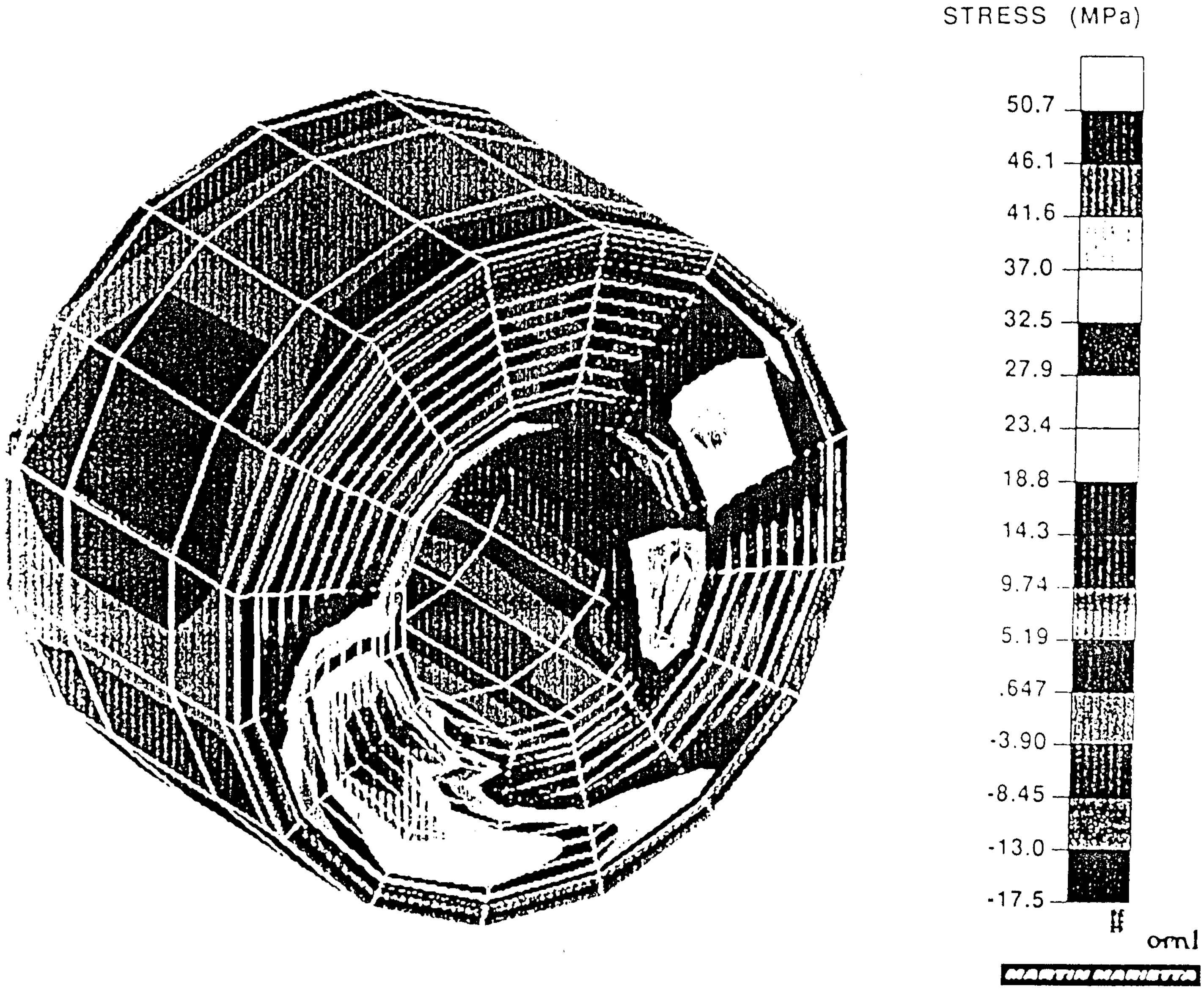
MARTIN MARIETTA

MARTIN MARIETTA ENERGY SYSTEMS

CANISTER TEMPERATURE PATTERN AT 5-min PRIOR TO ECLIPSE (LiF/CaF_2 EUTECTIC; NORMAL GRAVITY; 2-D)



MAXIMUM STRESS IN CANISTER SIDE/END WALLS AT 30 MINUTES (ADINA 3-D CALCULATION)



DEVELOPMENT OF ADVANCED TES MEDIA FOR SPACE APPLICATIONS FOCUSES ON METALLIC PCM

- Fluoride salts (used in baseline system concepts) have problems associated with

  - low conductivity
  - restricted melt temperatures
  - large thermal expansion (20% to 30%)

- Advanced concepts will use metallic PCM's to overcome problems of salt systems

  - higher conductivity
  - alloy compositions available with melt temperatures spanning the operating temperature range of interest (1100 to 1500K)
  - thermal expansion problem greatly mitigated
  - higher latent heat

- Silicon-based compositions under study include

  - germanium - silicon solutions (1211 to 1687K)
  - eutectics with "iron" group
    Ni-Si eutectic (1239K)
  - eutectics with alkaline earth group
    Be-Si eutectic (1363K)

- Key technology issue is encapsulation of PCM

THERE ARE A RELATIVELY FEW MEDIA THAT DESERVE ATTENTION

- Within the 318C to 370C range there are about 500 potential PCM's

- Screening was done using the following criteria

  - cost
  - property data availability
  - toxicity

- We looked at

  - salts
  - metallic compounds
  - brazes and solders
  - organics

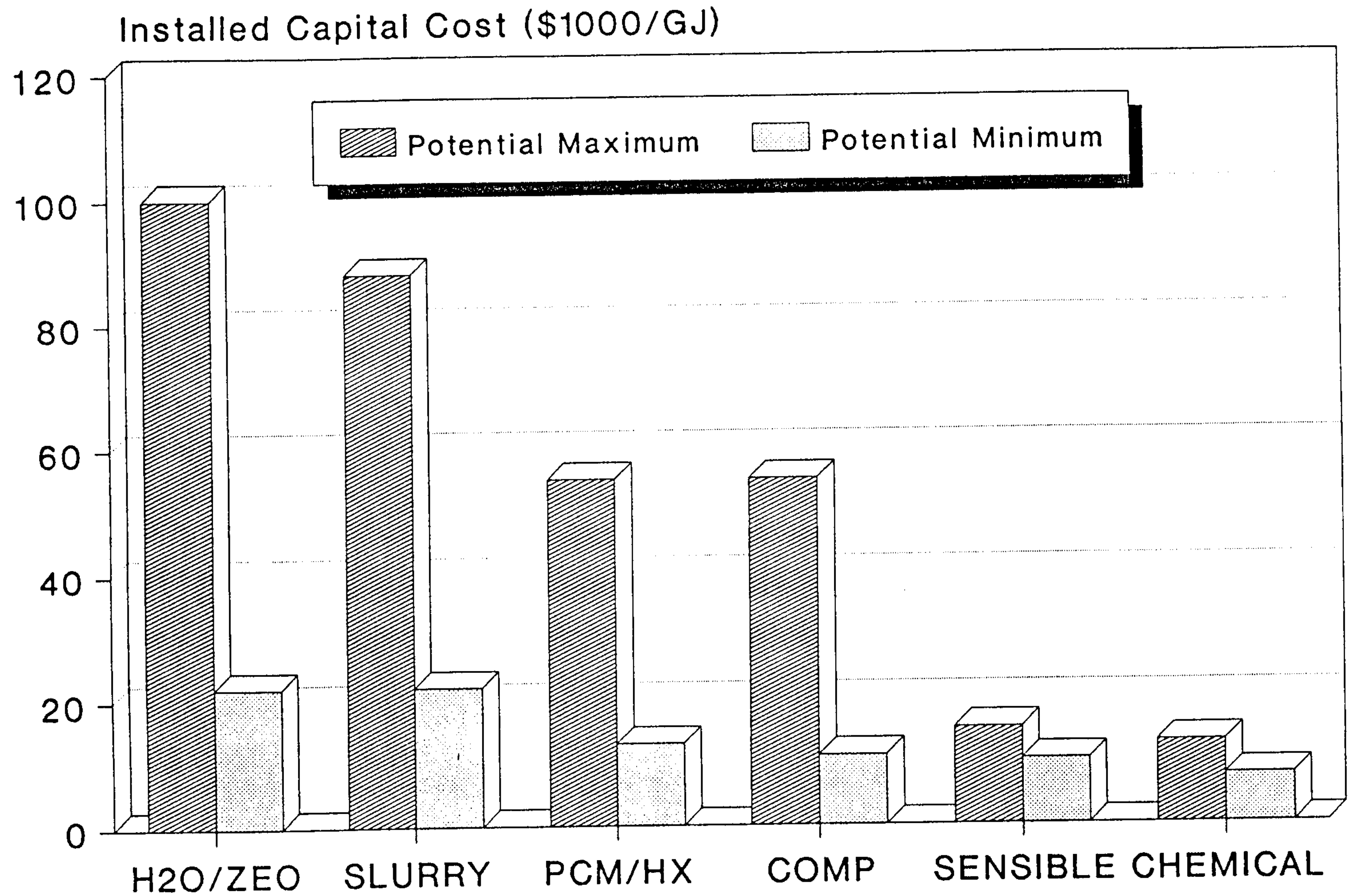
- Potential candidates are in following families

  - hydroxides
  - chlorides
  - fluorides
  - nitrates

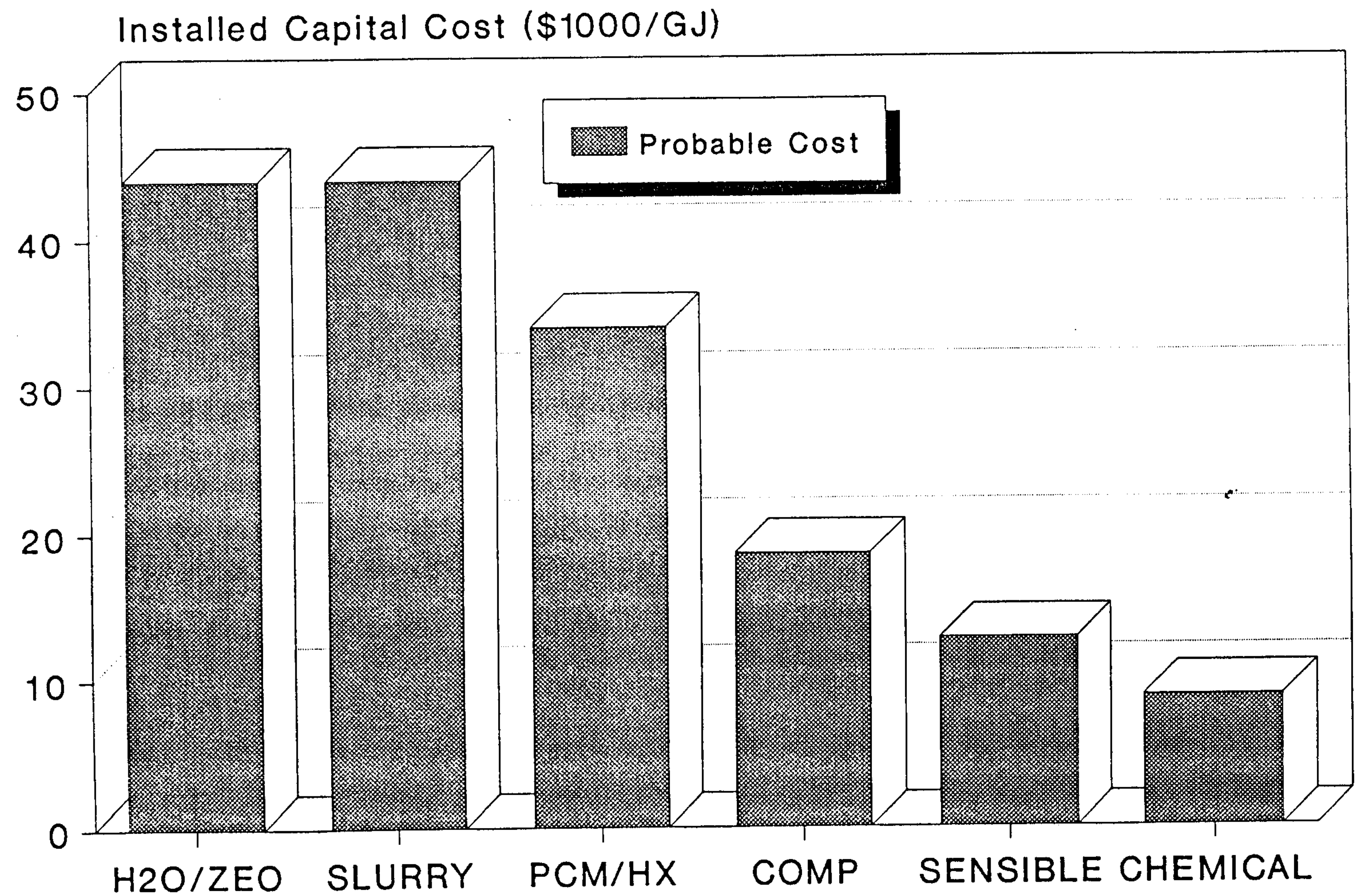
BASED ON PREVIOUS WORK IT APPEARS THAT
SEVERAL CONCEPTS ARE CANDIDATES
FOR THE LUZ SOLAR APPLICATION

- Evaporating water and storing the vapor in zeolite
- Slurry heat transport system using microencapsulated PCM
- Shell and tube system
- Open composite media in packed bed
- Sensible heat storage using thermocline tank
- Chemical means using hydrated complex compound or hydroxide/oxide reaction

THE UNCERTAINTY REGARDING INSTALLED CAPITAL COST IS HIGH FOR MOST OF THE SYSTEMS EXAMINED



SEVERAL, HOWEVER, APPEAR REASONABLY PROMISING



IN SUMMARY

- Many of the technologies developed by the DOE/ESD TES program are applicable to the LUZ application

- PCM is limited to a few salts

- Technologies potentially attractive include sensible, phase change, and chemical concepts

  - one-tank thermocline
  - PCM slurry
  - open composite
  - reversible reaction/hydrated complex compound

- More detailed studies will be required before conclusion can be reached

- LUZ application could be addressed with some restructuring of current DOE/ESD TES program

DFVLR/CIEMAT Study on Thermal Energy Storage for Commercial Applications

Presentation for Phase Change Thermal Energy Storage Symposium

October 19-20
Inn at Silver Lakes
Helendale, California

by

Dr. Michael Geyer
Platforma Solar de Almeria
Aptdo. 7
Tabernas (Almeria) 04200
Spain

October 19, 1988

SOLID SALT STORAGE

Preliminary Cost Analysis

Pipes:	760 000 m 304 m per stack	DM	2 049 000
Salt:	8300 m^3 1000 plates (8,3t) including melting and forms and assembly		14 896 000
Insulation Concrete (5600 m^2) and steel cladding (17 000 m^2) and rockwool insulation (19 550 m^2)			4 065 000
Oil:	315 m^3 x 4 000 DM		1 260 000
		TOTAL DM	22 270 000
	Rate 1.85	US	12 037 000

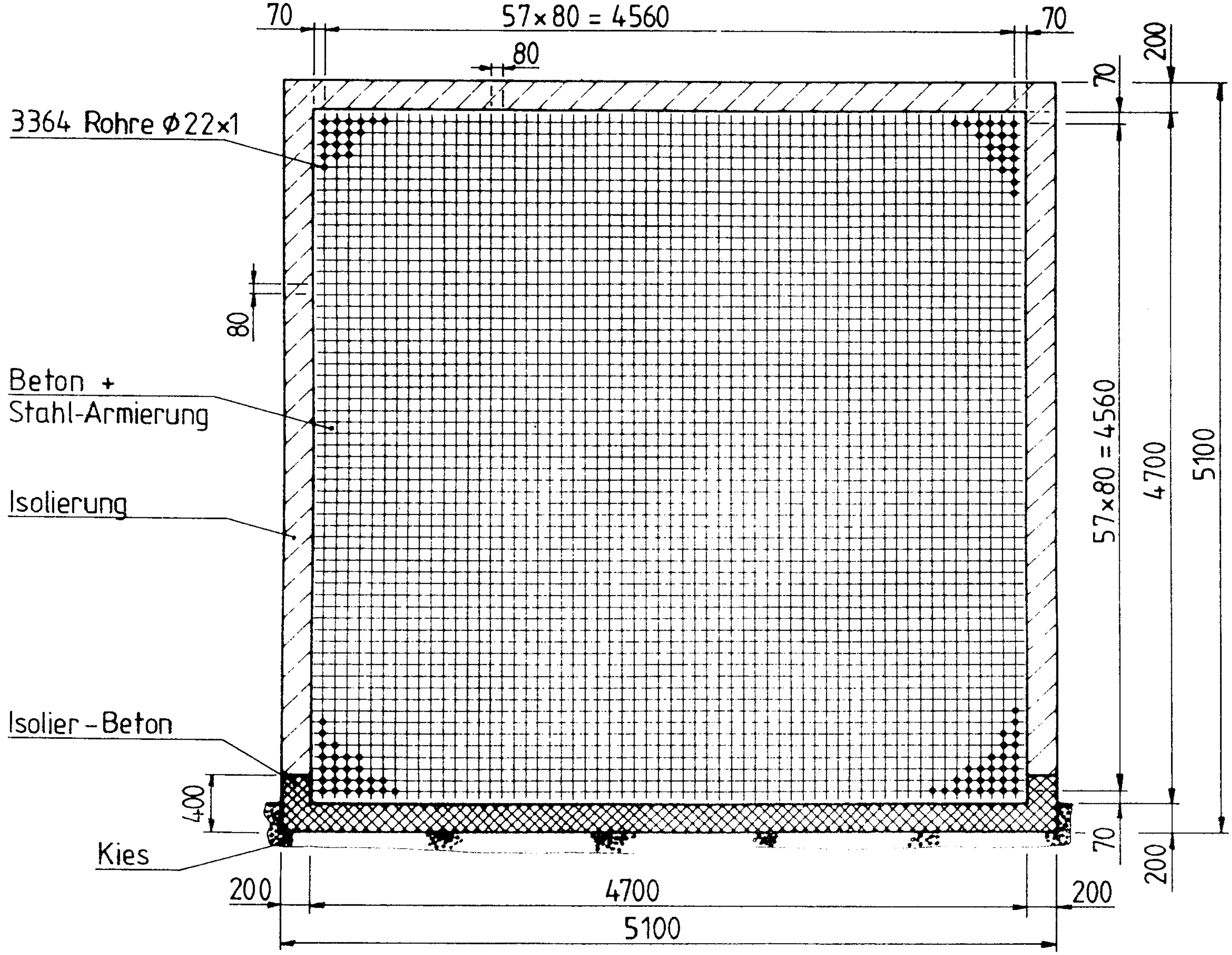
CONCRETE STORAGE

PRELIMINARY COST ANALYSIS

Pipes	1650000 m	diameter 22 mm outside 20 mm inside		
	welded, mounted into the form work including 10110 tube turns including 2 orbital welding machines and 1 pipe bending machine including 6 distributors		DM	4 255 000
Concrete	10000 m^3 and 330 t reinforcement steel mounted including insulation concrete		DM	2 716 000
Outside insulation:	200 mm rock wool plate clodded 7 500 m^2		DM	1 125 000
Oil	520 m^3 Monsanto		DM	2 080 000
		Total	DM	10 176 000
	Exchange rate: 1 US $ equal to DM 1,85			
		Total	US$	5 500 000

07.10.1988
TFE/Be/Blo.

Schnitt Beton-Speicher

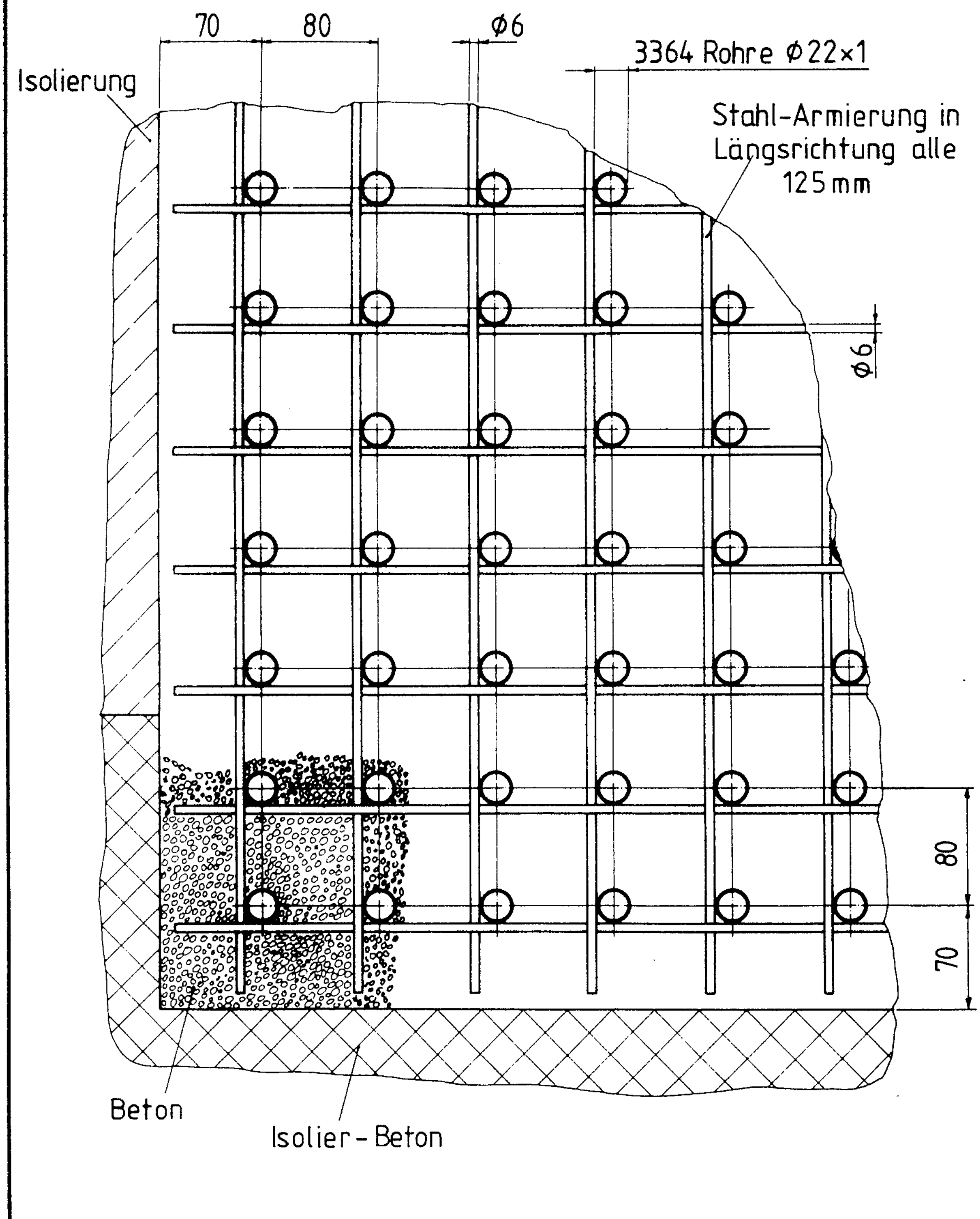


Datum 07.10.88

Siempelkamp Giesserei GmbH & Co. Krefeld
Abteilung Reaktortechnik

Blatt Nr. TFF 1726

Detail Beton - Speicher

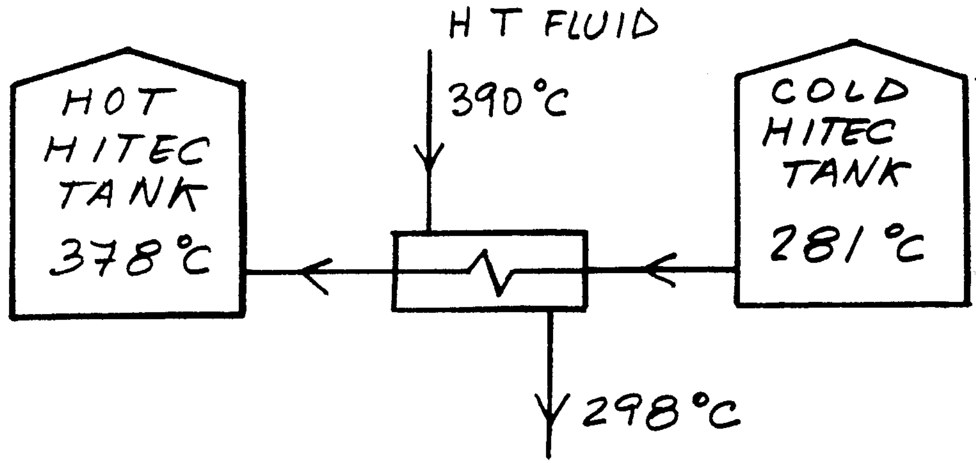


Datum 07.10.88	Siempelkamp Giesserei GmbH & Co. · Krefeld Abteilung Reaktortechnik	Blatt Nr. TFE 1227

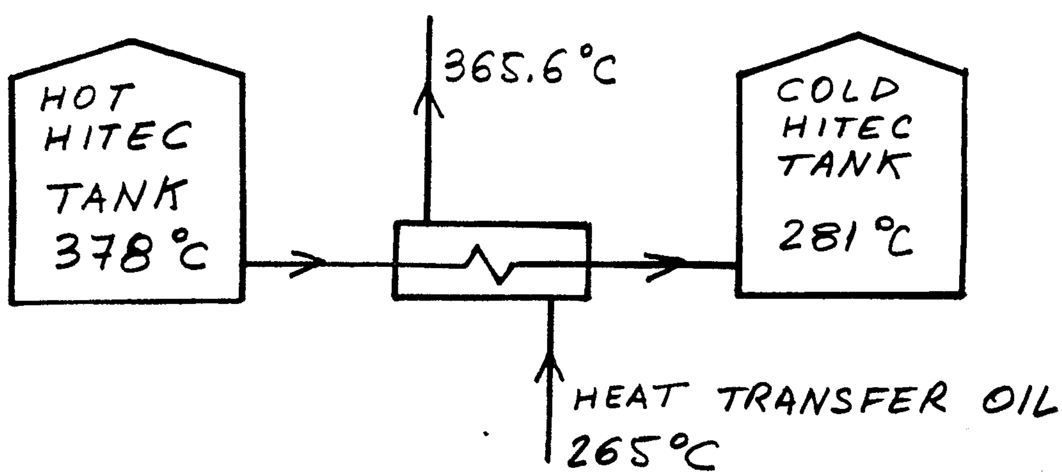
ADVANTAGES OF HITEC

- Thermal stability
- Industrial experience
- Well known physical properties
- Commercial availability
- Tested Heat transfer coefficients
- Existent corrosion data
- Not very expensive (0.74 $/Kg)

CHARGING



DISCHARGING



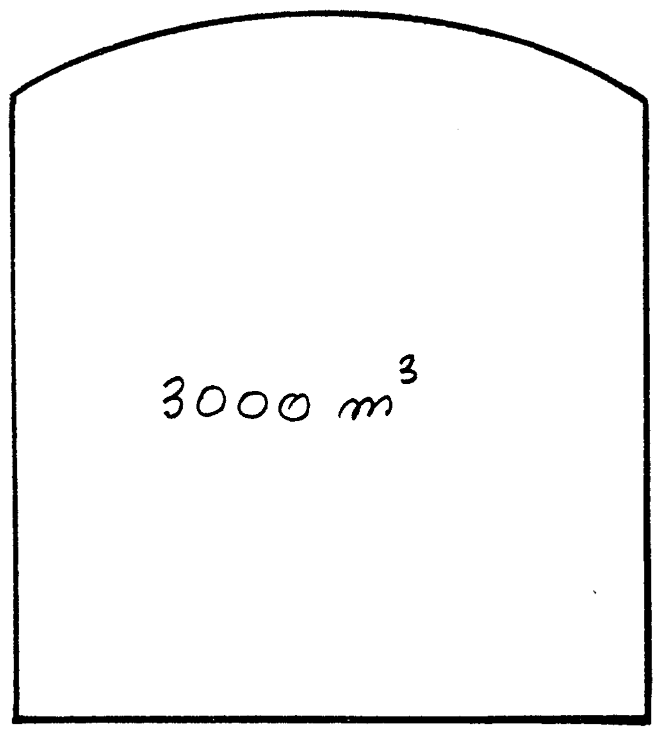
HEAT EXCHANGERS

	Charging	Discharging
Load (MW)	187.1	198
LMTD (°C)	14.4	14.1
HTC $\left(\frac{W}{m^2\,°C}\right)$	695	695
S (m^2)	18754	$\boxed{20171}$

Cost : 160 \$/m^2 (C.S.)

Price : 3.23 MM \$

TWO TANKS



Ø = 16460 mm
h = 16460 mm
Thicknesses :
Shell 20 to 8 mm
Roof 6 mm
Bottom 20 mm
Weight : 420 metric tons each
Material : Carbon Steel
Price : 0.66 MM $ Each
TOTAL PRICE = 1.32 MM $

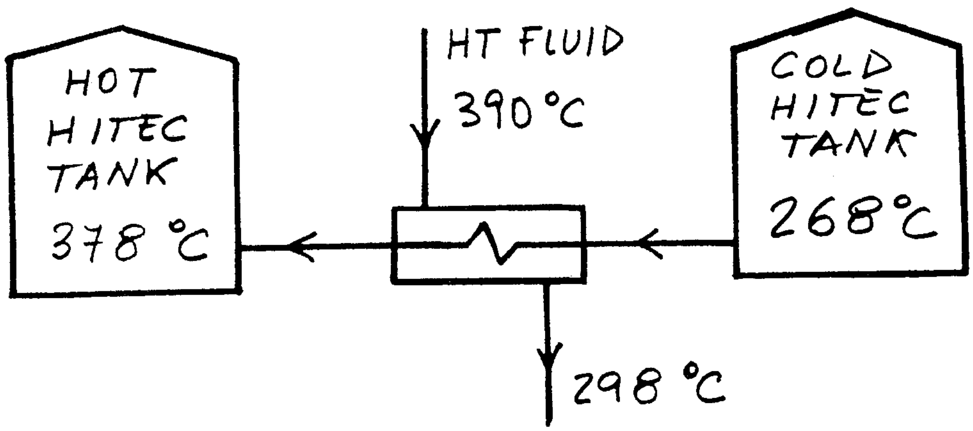
OVERALL COST

- SALT(**)	3.65
- HE's	3.23
- TANKS	1.32
- OTHER*	1.5
	9.7 MM $ USA

(*) Foundations, piping, valves, pumps, instrumentation, inert gas system, isolation, tracing, construction, etc.

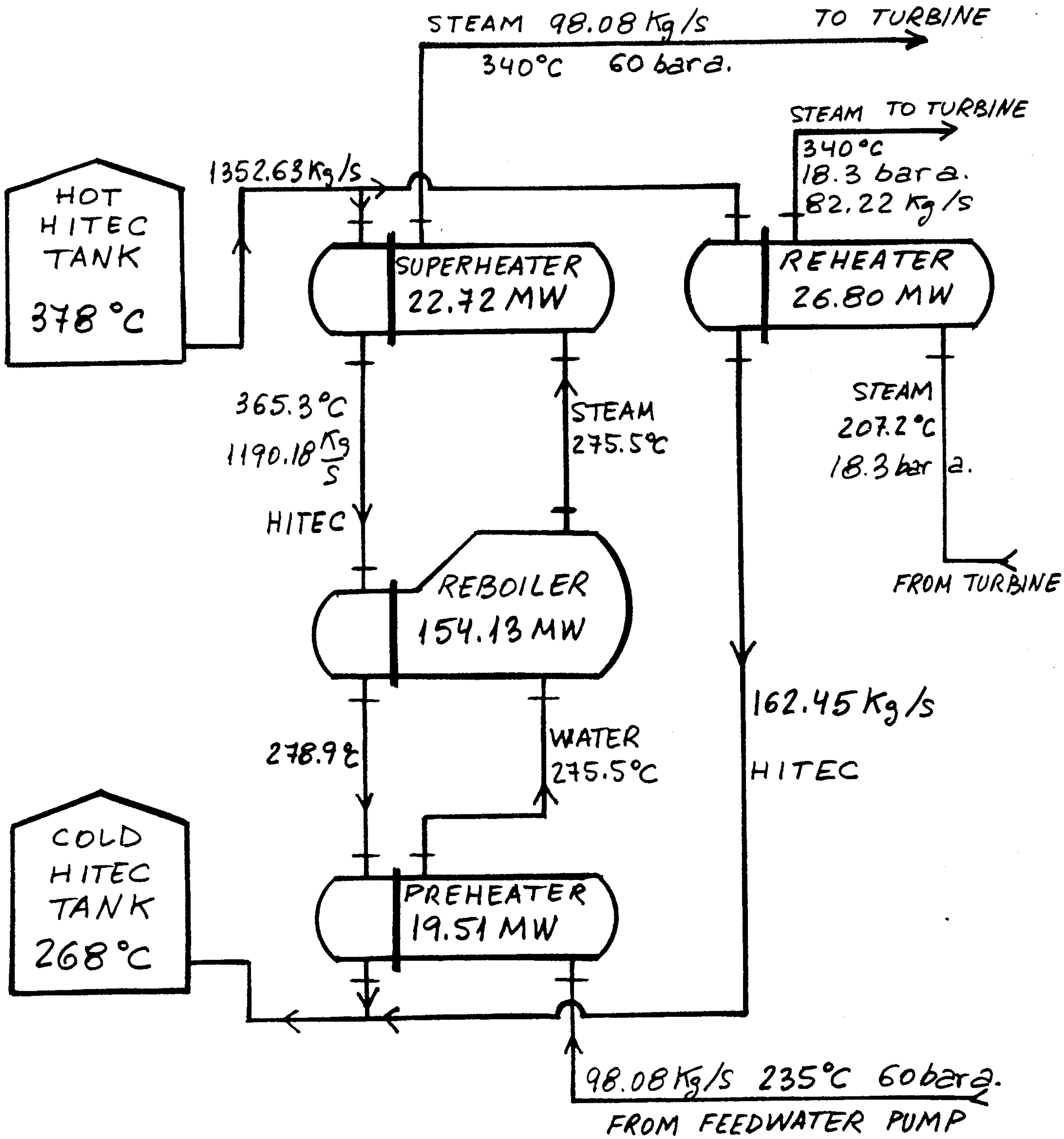
(**) 4936 metric tons.

CHARGING



CHARGING TIME : 3 HOURS
H.T. COEFFICIENT : 695 W/m^2 °C
LOAD : 67 MW
LMTD = 19.6 °C
SURFACE : 4907 m^2
COST : 0.785 MM \$

STEAM GENERATION SYSTEM

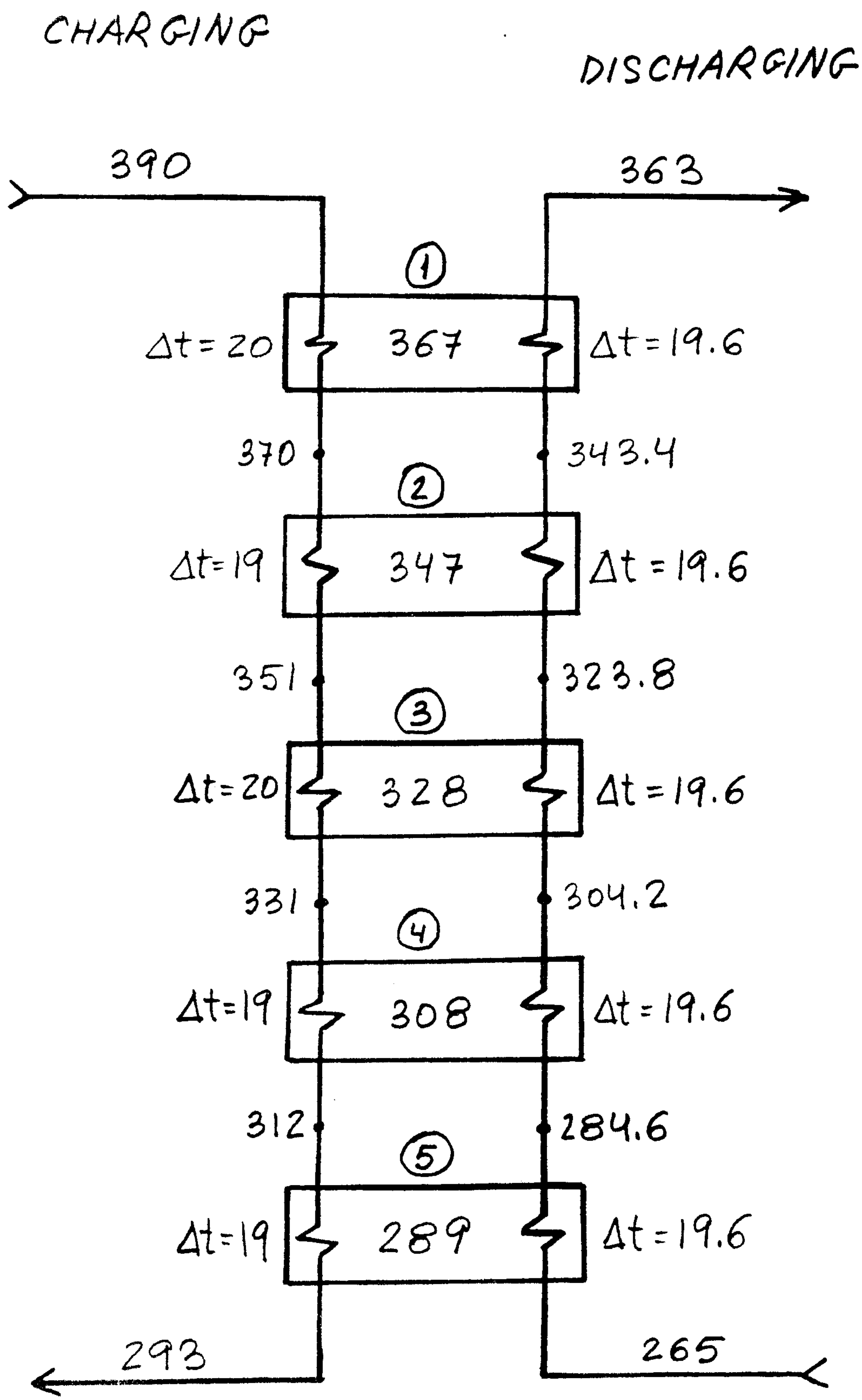


OVERALL COST

SALT (4364 MT)	3.23
CHARGING HE'S	0.785
DISCHARG. HE'S	2.00
TANKS	1.22
OTHER	1.5
	8.735 MM $

LUZ'S PROPOSAL

TEMP. IN DEGREES C.



HEAT LOADS (MW)

CHARGING		DISCHARGING
→ 42.26	1	40.26
39.33	2	39.42 ←
→ 40.54	3	38.51
→ 37.67	4	37.66
→ 36.84	5	36.81

OVERALL LOAD : 196.73 MW

HE's SURFACE (m^2)

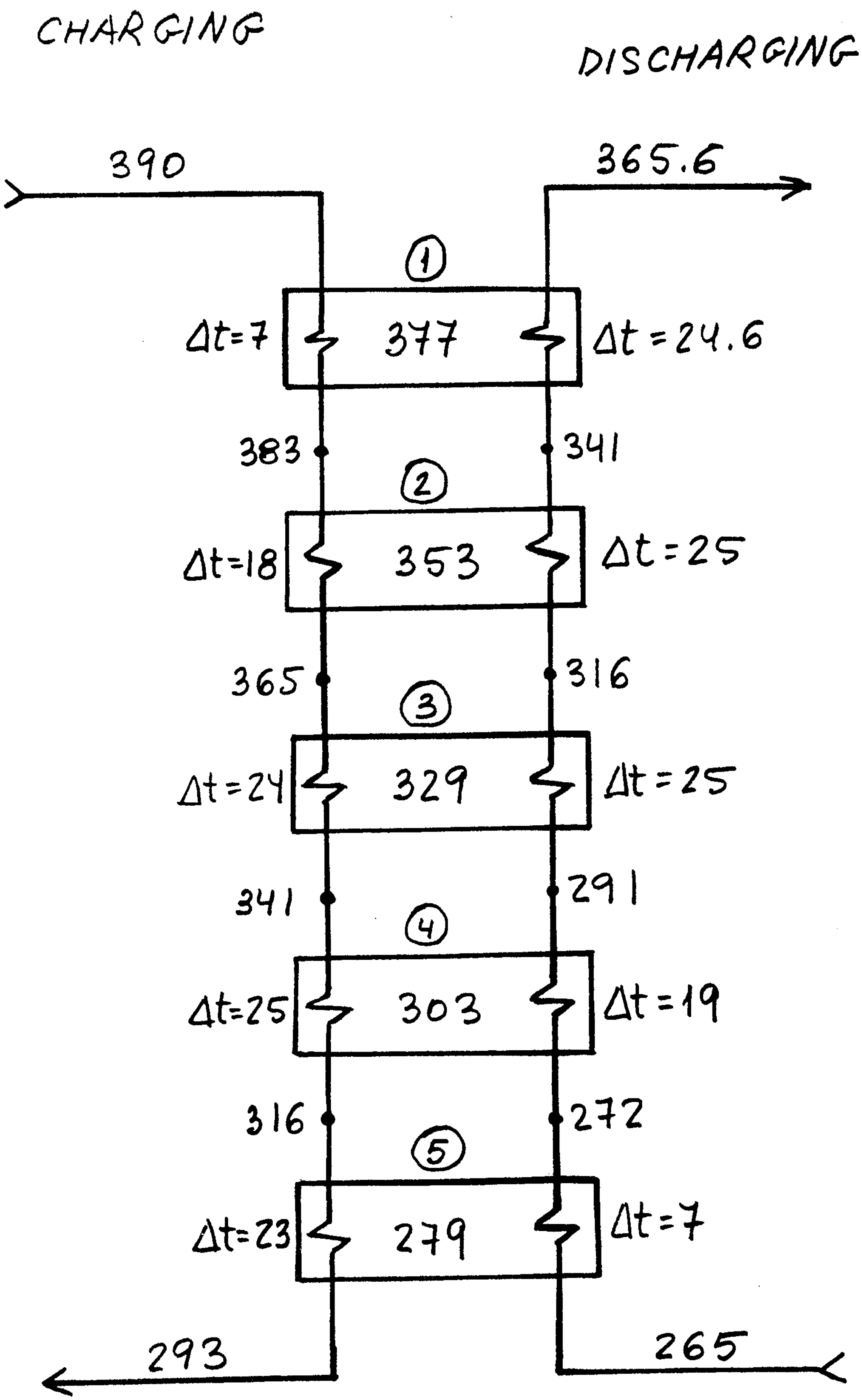
(H T coefficient = 414 W/m^2°C)

CHARGING		DISCHARGING
→ 10395	1	8806
8746	2	9051 ←
→ 9973	3	8231
8378	4	8436 ←
→ 8193	5	7696

TOTAL SURFACE = 46048 m^2

ALTERNATIVE

TEMP. IN DEGREES C.



HEAT LOADS (MW)

CHARGING		DISCHARGING
14.89	1	50.54 ←
37.79	2	49.99 ←
→ 49.29	3	48.53
→ 49.99	4	35.97
→ 44.71	5	19.80

TOTAL LOAD = 244.52 MW

HE's SURFACE (m^2)

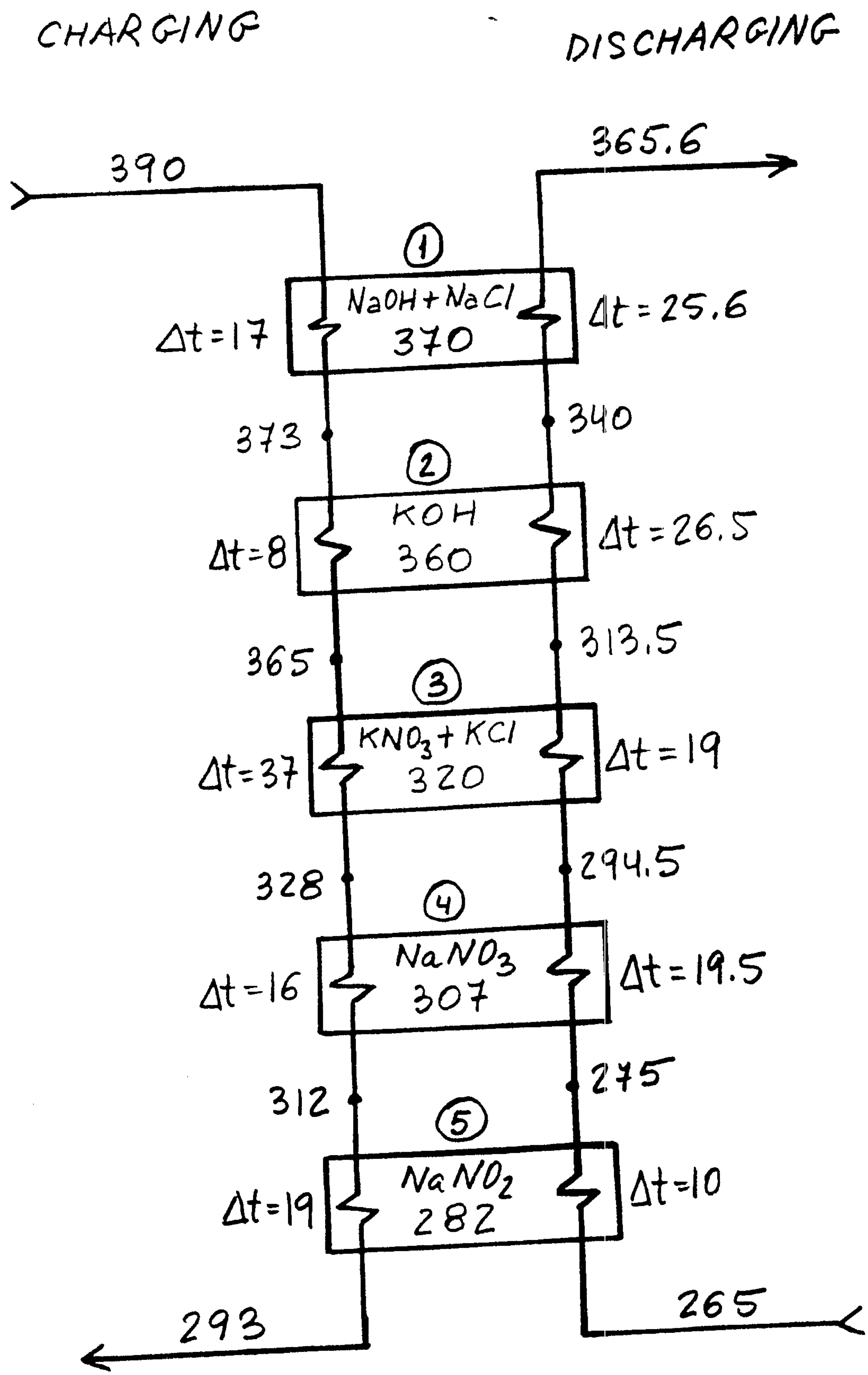
CHARGING		DISCHARGING
3973	1	5706 ←
4647	2	5438 ←
→ 5450	3	5030
→ 5181	4	4340
→ 4563	5	3120

TOTAL SURFACE = 26338

SALT	MELTING POINT °C	LATENT HEAT $\frac{kJ}{kg}$	PRICE $\frac{\$}{kg}$
NaOH (73.2%) + NaCl (26.8%)	370	370	0.46
KOH	360	167	0.92
KNO_3 (95.5%) + KCl (4.5%)	320	150	0.63
$NaNO_3$	307	174	0.64
$NaNO_2$	282	212	0.56

CHOOSEN SALTS

TEMP. IN DEGREES C.



HEAT LOADS (MW)

CHARGING		DISCHARGING
35.98	1	52.56 ←
16.71	2	52.89 ←
→ 75.45	3	36.90
31.66	4	37.05 ←
→ 36.84	5	18.67

TOTAL LOAD = 254.79 MW

HE's SURFACE (m^2)

CHARGING		DISCHARGING
→ 9698	1	9520
→ 4821	2	4067
→ 8508	3	6413
→ 6860	4	4313
→ 4699	5	4002

TOTAL SURFACE = 34586 m^2

COST = 5.53 MM $

OVERALL COST

SALTS	3.27
HE's	5.53
TANKS	0.288
OTHER	0.60
	9.688 MM $USA

Advanced Energy Transmission Fluids for Thermal Systems

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Scope

Develop phenomenological understanding and engineering information for the use of phase change slurries (PCSs) and friction-reducing additives (FRAs) in thermal systems to improve thermal-hydraulic performance

Justification

- Significant potential exists for improving a thermal system's overall performance through
  - higher end-use temperatures
  - reduced flow, allowing smaller pipes and pumps
  - improved system thermal storage
  - reduced system weight
  - increased heat transfer, allowing reduced heat exchanger size
- Lack of data on heat transfer, fluid mechanics, and system performance hinders implementation of the PCS and FRA concepts

Advanced fluids concepts identified at ANL

- Low concentrations (20-200 wppm) of non-Newtonian additives (high-molecular-weight linear polymers, surfactants, synthetic fibers) to reduce frictional flow losses

- Phase-change (melting⇔freezing) particulate slurries (cross-linked high-density polyethylene, ice slurries, waxes) to enhance bulk convective energy transport and heat transfer coefficients

- Combining above concepts to achieve maximum benefits

Technical Issues

- Can robust FRAs and PCSs be identified which are resistant to flow shear and compatible with temperatures of various thermal systems?
- How much do FRAs reduce heat transfer?
- How much do PCSs increase pressure drop?
- Are FRAs effective when combined with a PCS?
- What are the mechanisms and parameters dictating FRA and PCS performance?
- How do advanced fluids interact with thermal system components (pumps, heat exchangers, piping, valves, etc.)?

Benefits

- *Flow rate* reduction due to PCS latent heat

  - Heating $0.6\ Q_o$
  - Cooling $0.2\ Q_o$

- System *pressure drop* and *pumping power* reductions due to FRA and PCS

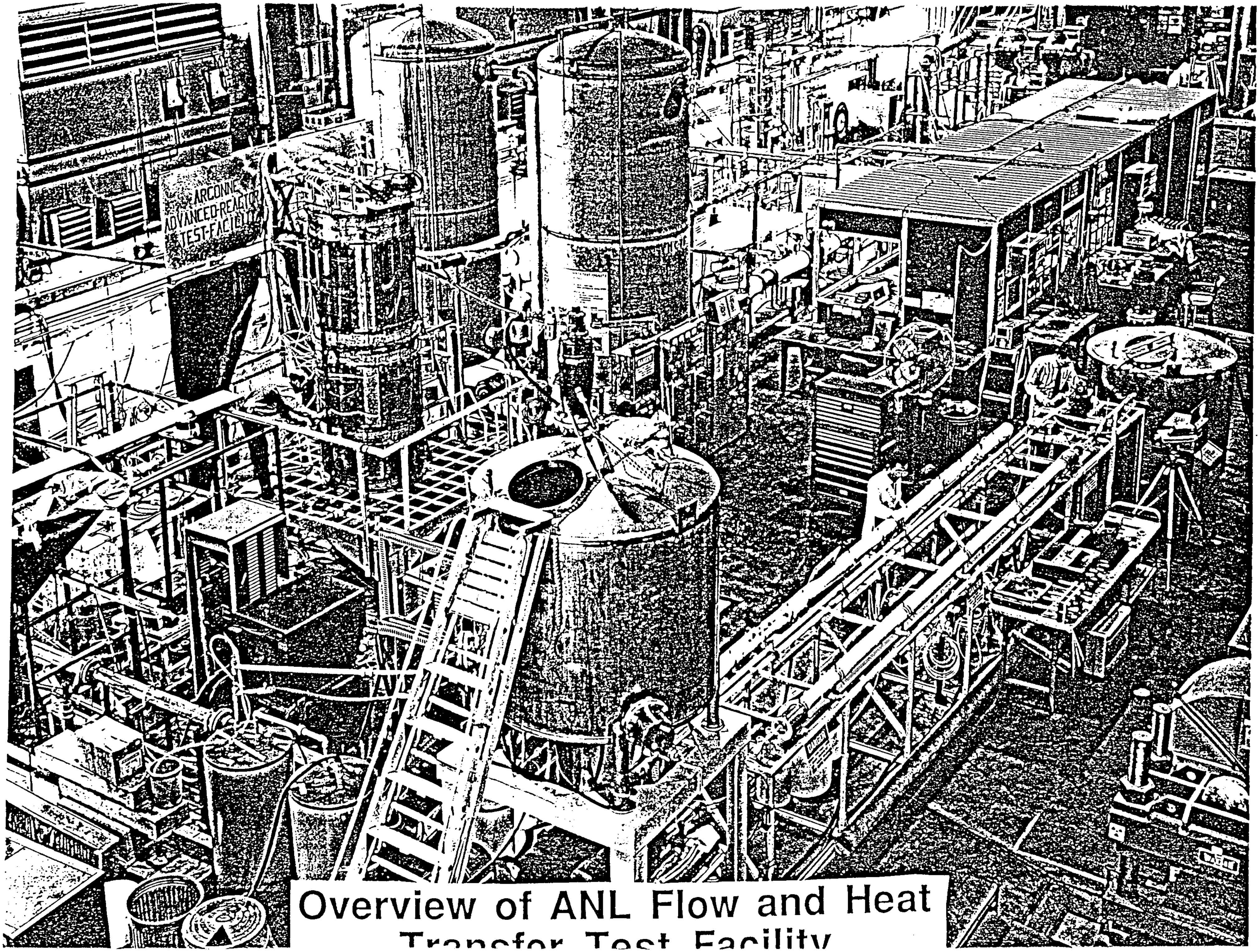
  - Heating $0.1 \Delta P_o\ (W_o)$
  - Cooling $0.01 \Delta P_o\ (W_o)$

- *Pipe size* reductions due to combined use of both concepts

  - Heating $0.5 D_o$
  - Cooling $0.3 D_o$

- Energy storage *tank volume* reductions due to PCS

  - Heating $0.4\ V_o$
  - Cooling $0.1\ V_o$

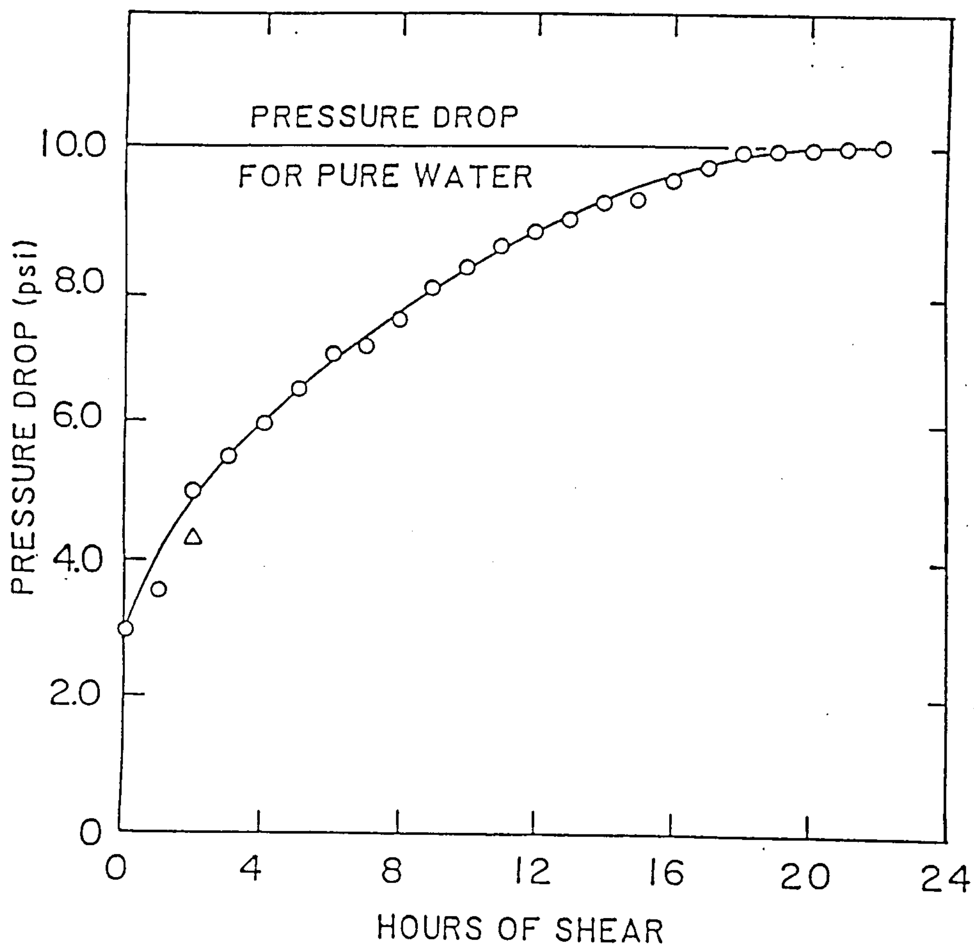


Overview of ANL Flow and Heat Transfer Test Facility

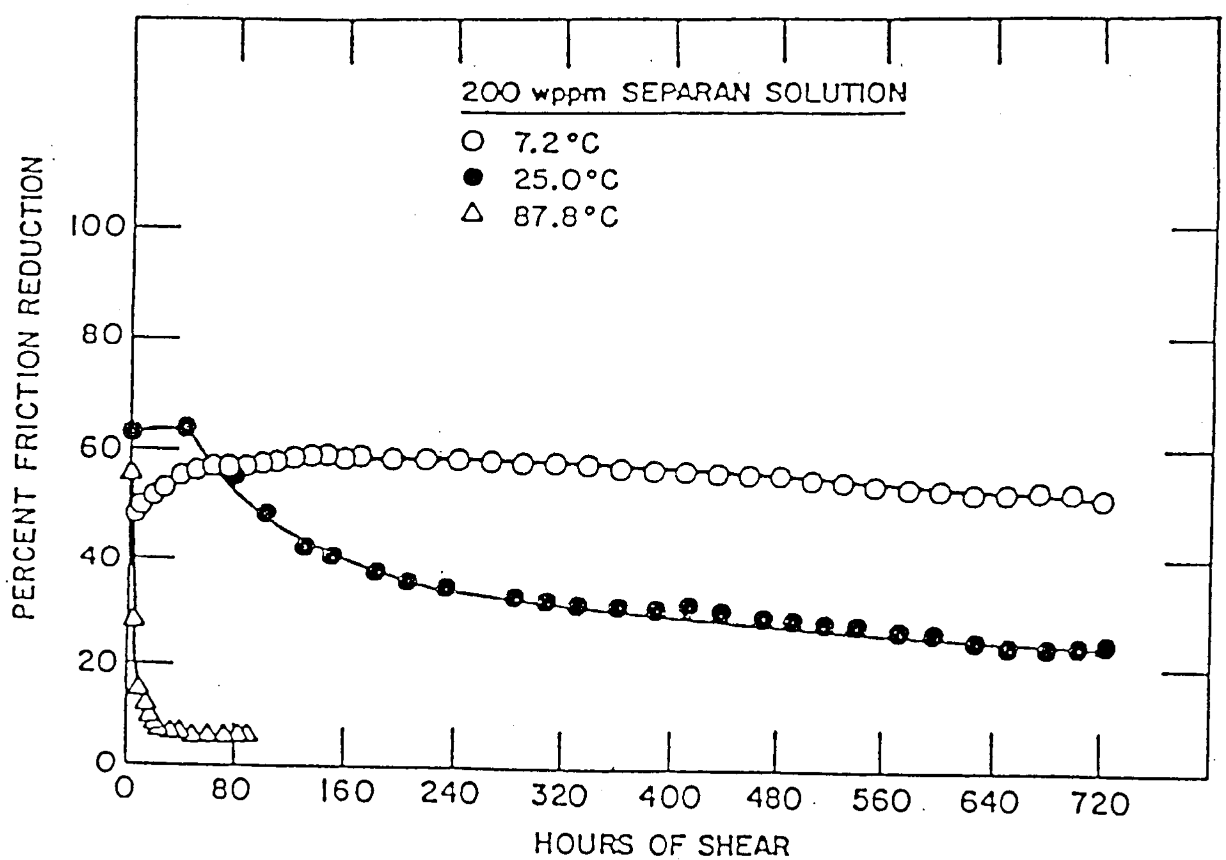
Friction-Reducing Additives

Additives Tested:	Dilute aqueous solutions of high-molecular weight linear polymers • Polyox • Separan • Guar gum Aqueous suspensions of large–aspect–ratio synthetic fibers • Nylon • Fiberglass • Polyester • Iron Whiskers
Conditions:	• Temperatures of 45-200°F • Prototypic turbulent piping flow shear • Fresh solutions in various viscometers and long-term recirculatory flow
Parameters Measured:	• Pressure drop • Viscosity • Heat transfer • Degradation rate
Outcome:	Separan and nylon fibers identified as candidates for further testing

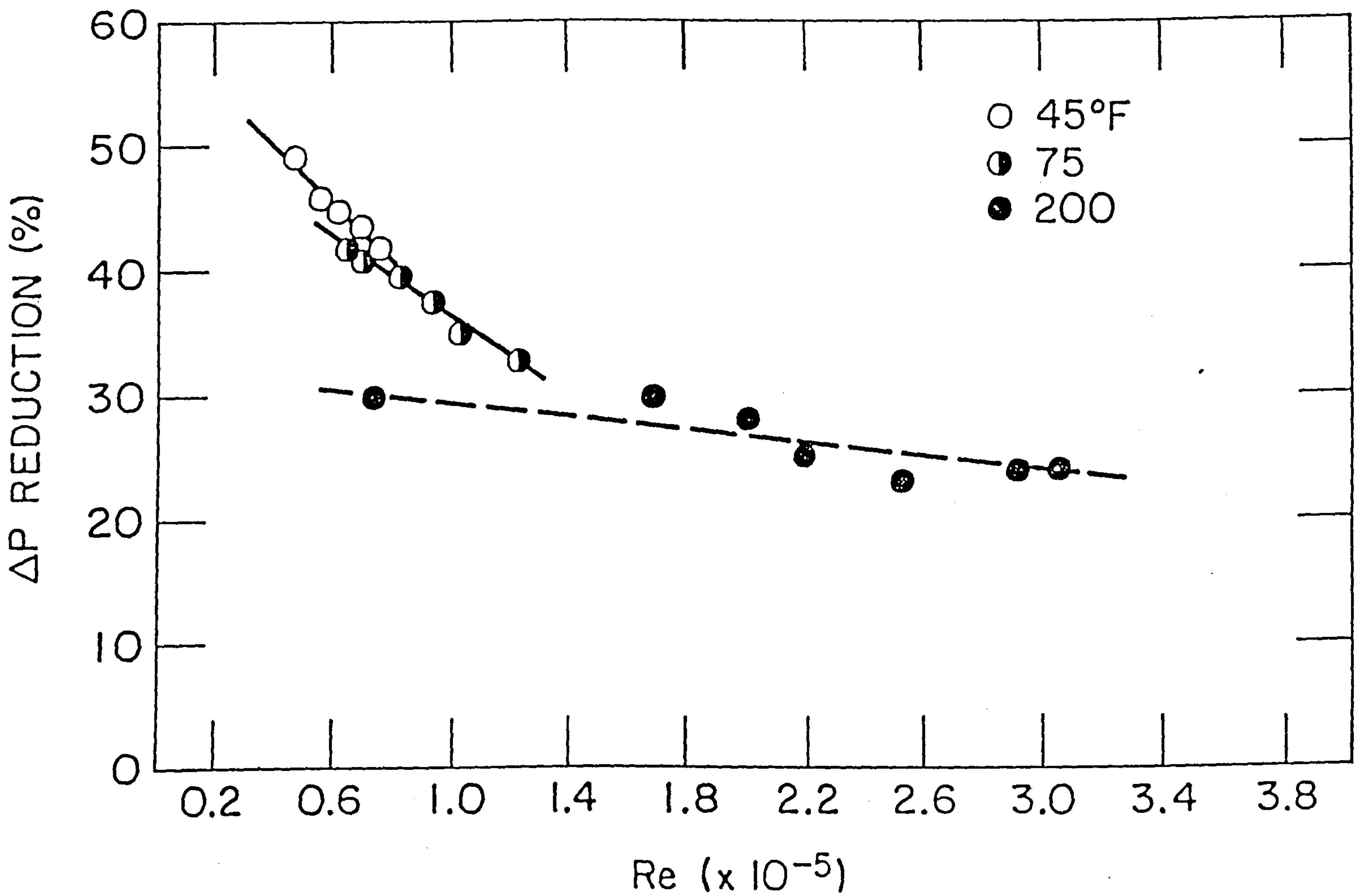
Effect of recirculation of 200-wppm Polyox solution at 25°C on pressure drop



Effect of temperature on friction reduction as a function of circulation time for 200-wppm Separan solution



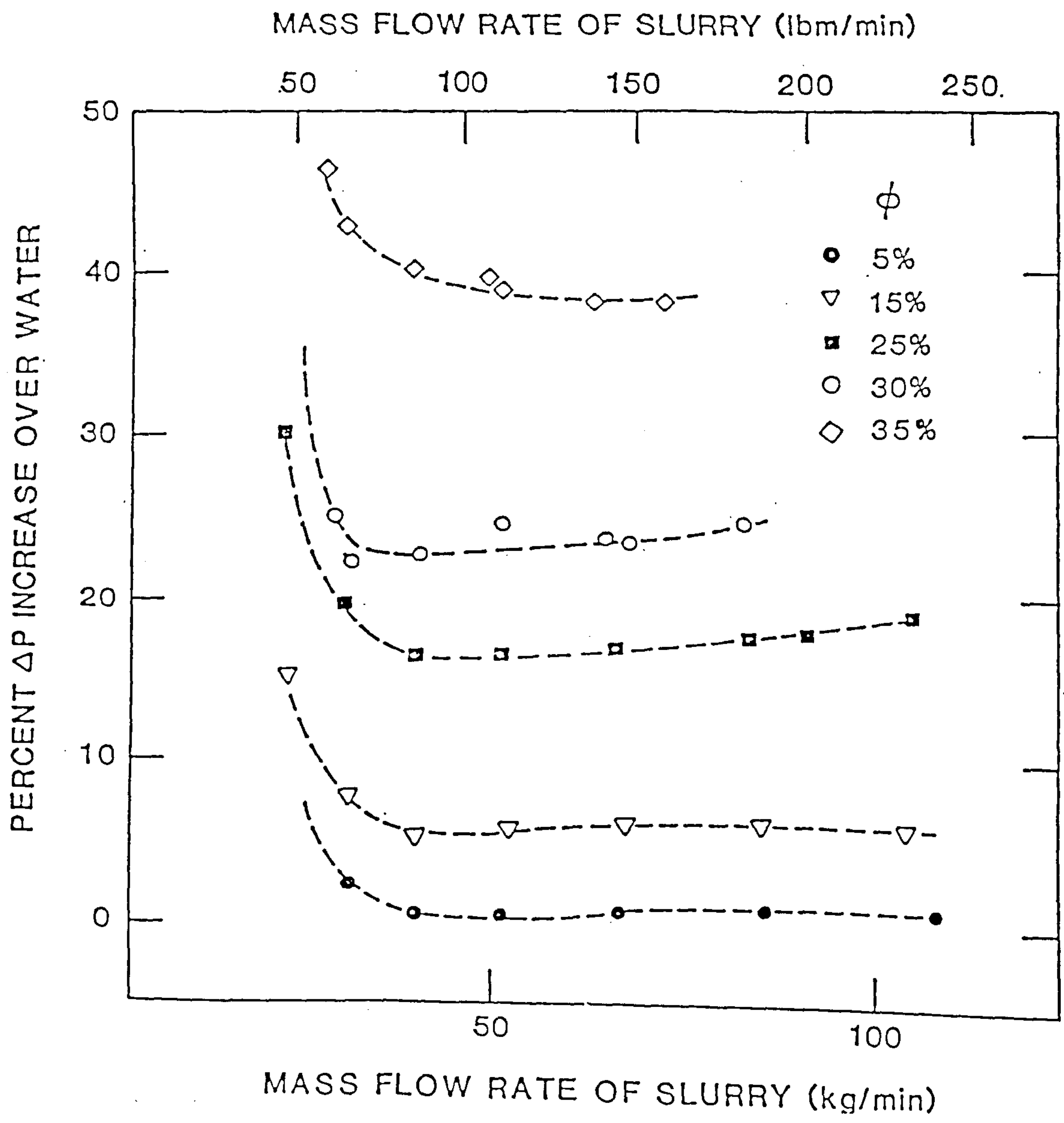
Percent pressure drop reduction versus Reynolds number for an aqueous suspension of nylon fibers (L/D = 50, L = 1 mm) at 5% loading for various temperatures



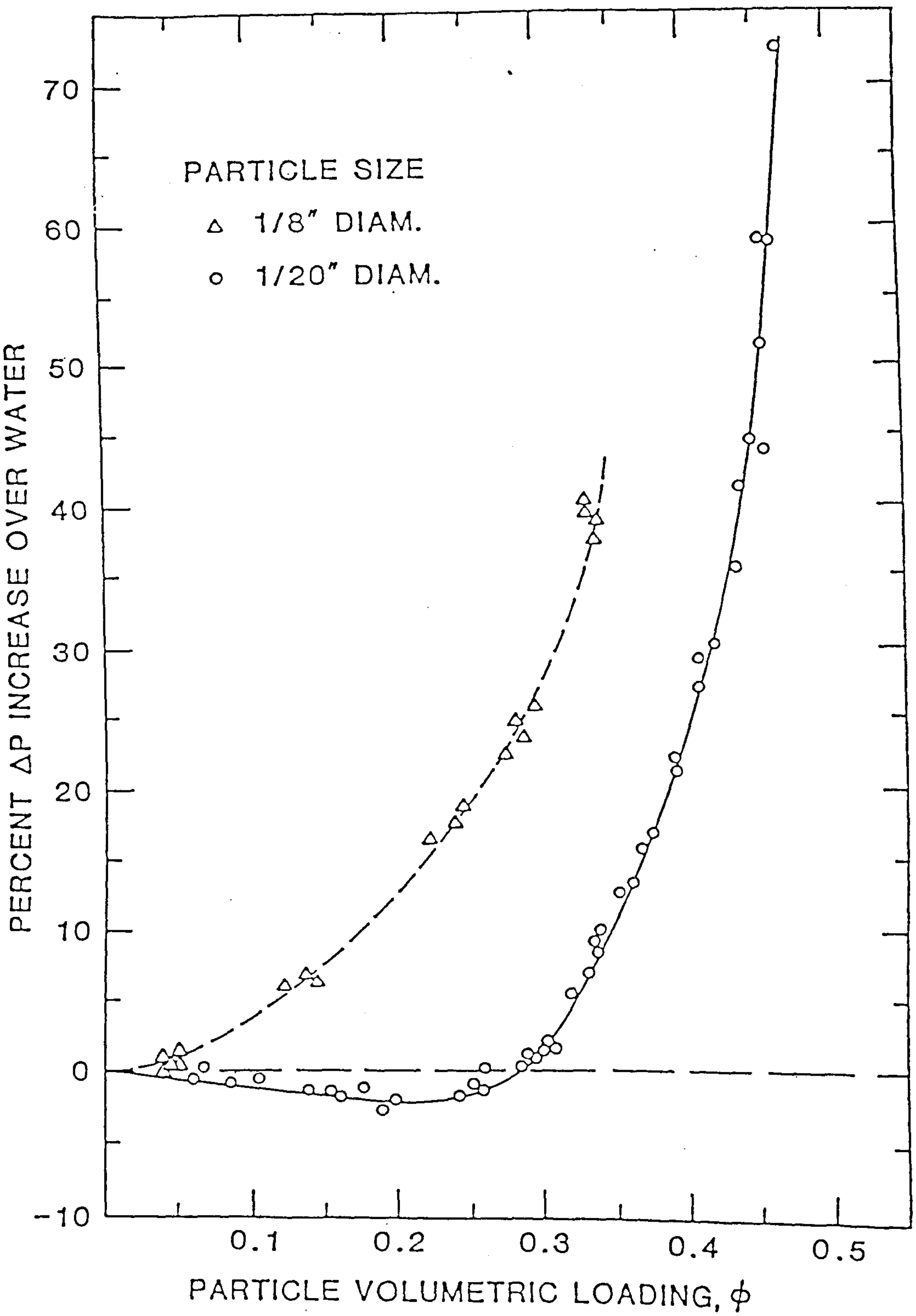
Phase Change Slurries

Slurries tested:	• Cross-linked high-density polyethylene (X-HDPE) • Ice crystals
Conditions:	• Temperatures of 32-285°F • Turbulent flow • Loadings of 0-45 vol.% • Particle sizes of 1/8 and 1/20 in.
Parameters Measured:	• Pressure drop • Temperature profiles • Heat transfer
Outcome:	• Highly loaded slurries under certain conditions can be pumped with only marginal pumping power increases and exhibit increased heat transfer relative to pure water • Ice slurry and X-HDPE have similar effects on pressure drop • Pressure drop and heat transfer are strong functions of particle diameter • Existing correlations are inadequate for design

Effect of particle loading on pressure drop for X-HDPE slurries with 1/8"-diam particles at different flow rates



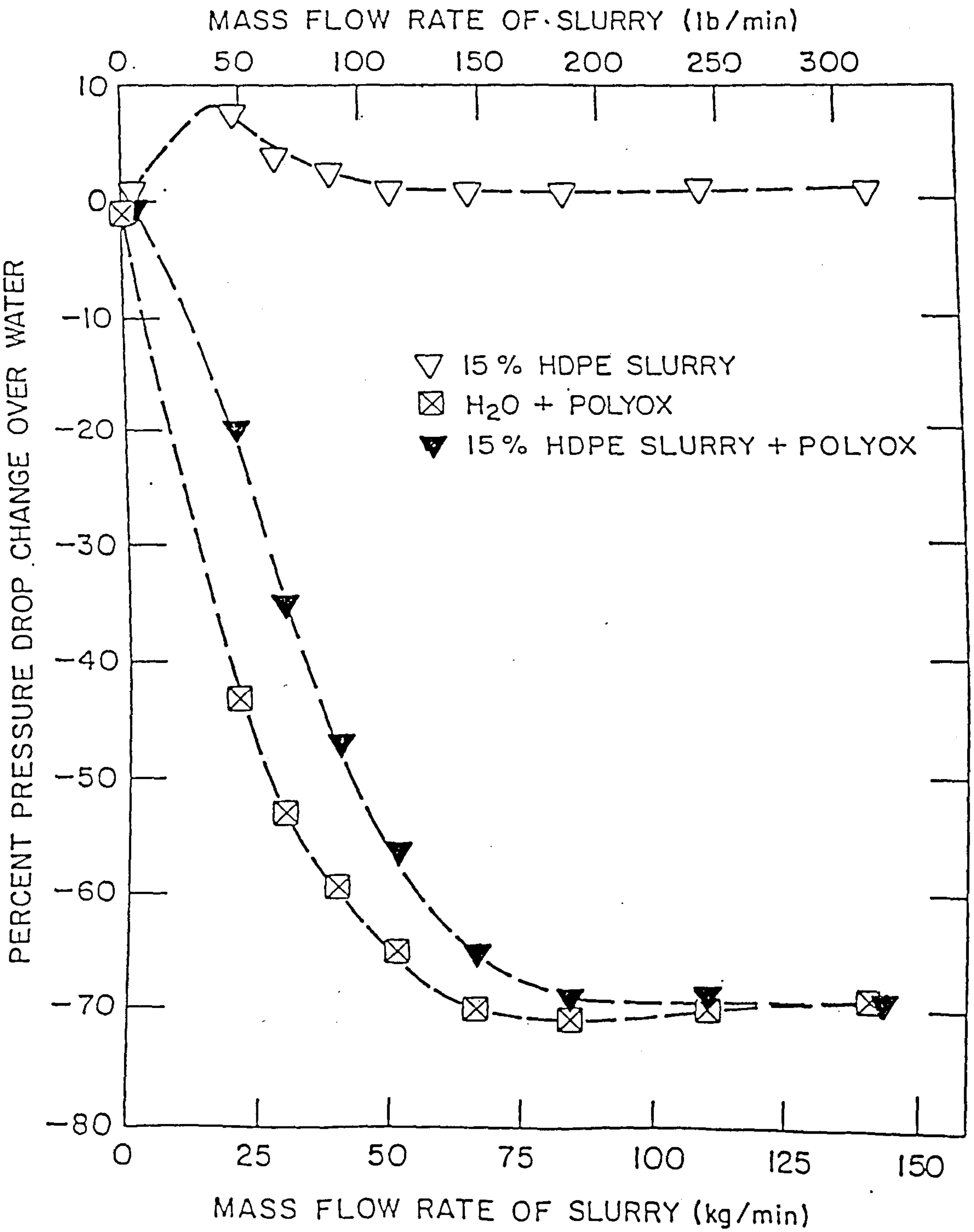
Effect of X-HDPE particle size and loading on pressure drop



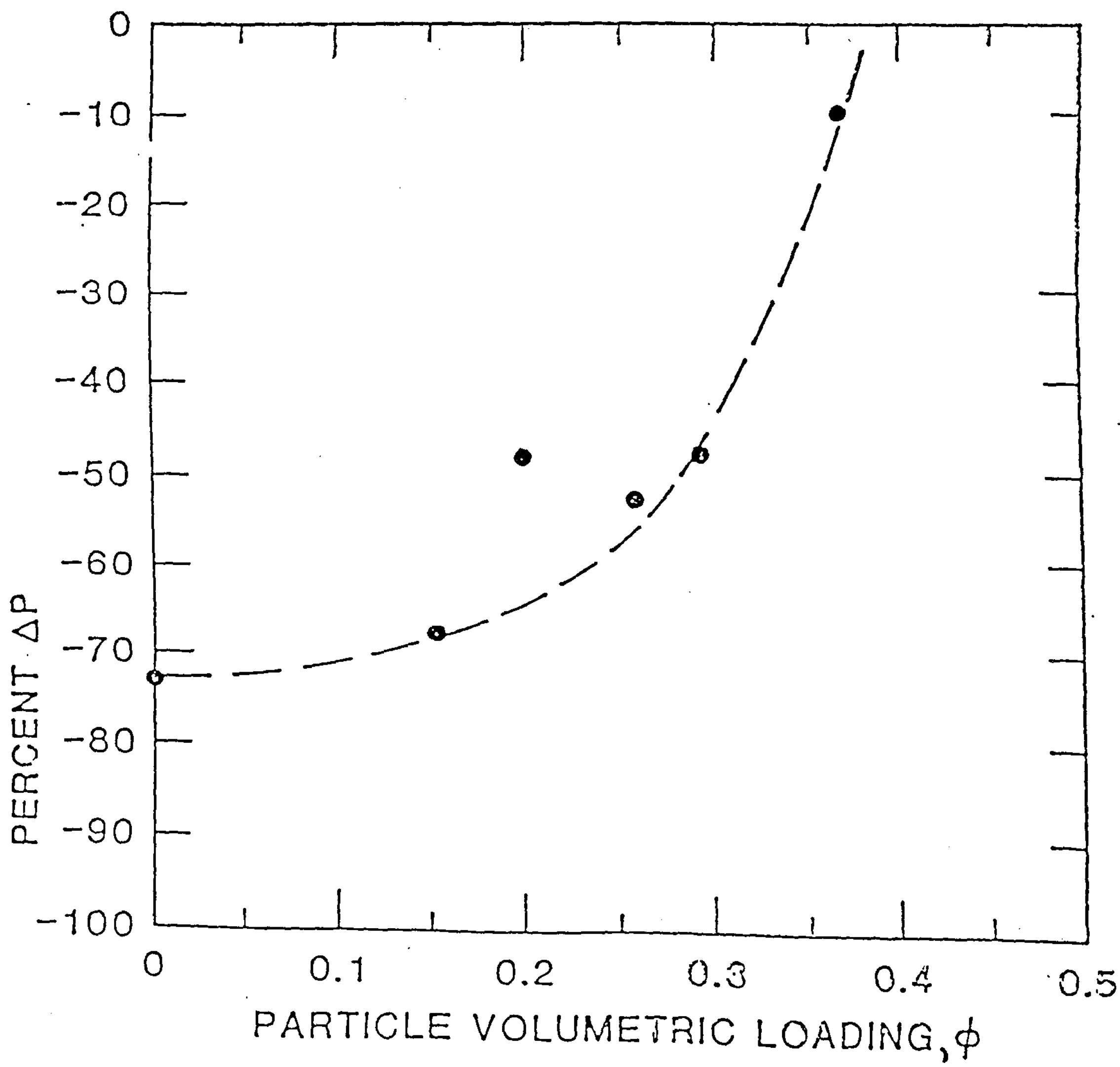
Combined-Concept Fluids

Materials Tested:	X-HDPE + water + Polyox
Conditions:	• Temperature of 75°F • Turbulent flow • Loadings of 0-35 vol.% X-HDPE, 200 wppm Polyox • Particle sizes of 1/8", 1/20"
Parameters Measured:	• Pressure drop • Temperature profiles
Outcome:	A friction-reducing additive can significantly reduce the pressure drop for a slurry with < 30% particle loading

Effect of mass flow rate of slurry on pressure drop with and without FRA



Effect of particle loading on pressure drop for combined–concept slurries with 1/20"-diam particles



Conclusions

- Testing of Advanced Energy Transmission Fluids has established their feasibility
- Improved thermal-hydraulic performance and component cost reductions can be realized
- Further testing is needed to evaluate performance in prototypic systems and identify additives for various operating conditions
- An engineering thermal-hydraulic data base must be generated when enhancement mechanisms are better understood

Modeling of Fixed Bed Heat Storage Units Utilizing Phase Change Materials

V. ANANTHANARAYANAN, Y. SAHAI, C. E. MOBLEY, and R. A. RAPP

A computer model has been developed for the calculation of the heat exchanged and temperature profiles in a packed bed containing a phase change material. The packed bed is intended as a heat storage unit in which an inert fluid flowing through the bed exchanges heat with an encapsulated spherical shot of the phase change (melting and freezing) material. Examples of predicted bed temperature profiles during heat storage and utilization cycles are given. For Al-12 wt pct Si and Al-30 wt pct Si shot, a sequence of storage and utilization cycles with cyclic cocurrent fluid flow was found to utilize the high latent heat of fusion of the shot efficiently and permit the utilization of the bed as a near isothermal (577 °C) heat recuperator.

I. INTRODUCTION

ECONOMIC heat storage systems are used for heat recovery and for load leveling under circumstances where the demand for and availability of energy do not coincide chronologically. Consequently, load leveling in a power plant with the utilization of stored heat for power generation during peak demand hours, utilization of alternative sources of energy (*e.g.*, solar), and waste heat recovery are areas with potential for cost reduction using efficient heat storage.

Heat storage systems that utilize only the sensible heat of a storage material (no phase change) may be one of two types. The first one is a system in which the energy transporting fluid itself serves as the storage medium. The other system has an enthalpy transporting fluid which exchanges heat with a separate storage medium. Domestic hot water heating systems using water as both the transporting and heat storing fluid fall into the first category. An example of the second type is a system utilizing the sensible heat of solids such as a firebrick checkerwork. A storage medium utilizing sensible heat should have high values for its heat capacity per unit volume and for thermal diffusivity; it should be chemically and geometrically stable under conditions of reversible heating and cooling. It should be noncombustible and nontoxic, have a low vapor pressure, and be inexpensive.[1]

Storage systems that utilize the latent heat of transformation are currently receiving considerable attention. The storage media used by these systems, called Phase Change Materials (PCMs), offer advantages such as a small temperature difference between the storage and retrieval cycles, small unit sizes, and low weight per unit storage capacity. Selection of the storage material depends largely on the mean storage temperature. Some desirable characteristics of a PCM for use as a heat storage medium are a high latent heat of transformation (usually fusion), a narrow freezing range or a congruent melting point, nontoxicity, long term chemical stability, inertness with respect to a suitable container material, low cost, and ready availability.[1]

Inorganic salts such as halides, nitrates, sulfates, carbonates, *etc.* in multicomponent eutectic systems have been studied for a long time as PCM alternatives to sensible heat storage in water, fused salts, or bricks. Tye, Bowine, and Desjarlis[2] specified PCM salts with temperature ranges to match principal heat generating sources: $LiNO_3$ at 527 K (254 °C) for a pressurized water reactor, 63LiOH-37LiCl at 533 K (260 °C) for a boiling water reactor, LiOH at 743 K (470 °C) for a fossil-fueled supercritical steam reactor, and $Na_2B_4O_7$ at 1015 K (742 °C) for a high-temperature gas-cooled graphite moderated reactor. Thus lithium salts were the basis for most workable PCM materials in that study.

Birchenall and Riechman[3] and Farkas and Birchenall[4] have surveyed the potential of metallic eutectics and congruently melting intermetallic compounds for heat storage. They showed that the heat of fusion of a heat storage alloy can be maximized by the use of a large number of components of high heats of fusion in nearly equal proportions in the alloy. They found that alloys rich in the relatively plentiful element Si offer high heat storage densities.

Research has been in progress at The Ohio State University toward the development and fabrication of spherical self-encapsulated phase change material shot, which can be brought into direct contact with an energy transporting fluid in a ceramic lined column, obviating the need for an expensive and corrosion-resistant heat exchanger. The heat storage shot would have a relatively high melting, corrosion resistant outer shell that would enclose and contain a lower melting heat storing eutectic core.

The fabrication of self-encapsulated PCM shot as described above is being considered through (i) controlled cooling of a hypereutectic Al-Si shot in the temperature range between the liquidus and the eutectic, (ii) chemical oxidation/anodizing, and (iii) pack cementation siliconizing. The shot as fabricated would have a shrinkage cavity at its center that would accommodate the expansion upon melting of the shot core during temperature cycling.

The purpose of this work was to develop a mathematical model that would describe the thermal response of packed beds which utilize encapsulated eutectic or hypereutectic Al-Si PCM shot as a heat storage medium. Models available in the literature on heat exchange in packed beds adequately cover sensible heat storage without a phase change. These models were extended to include the latent heat of fusion for the PCM shot in addition to differing values for the specific heat above and below the transformation temperature. Figure 1 shows the Al-Si equilibrium phase diagram.[5] Figure 2 shows a schematic representation of the shot and

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Manuscript submitted January 8, 1986.

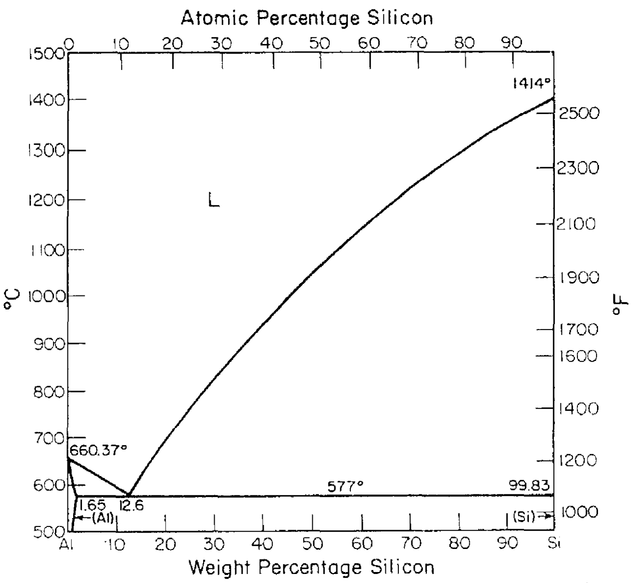

Fig. 1 — Aluminum-silicon phase diagram.

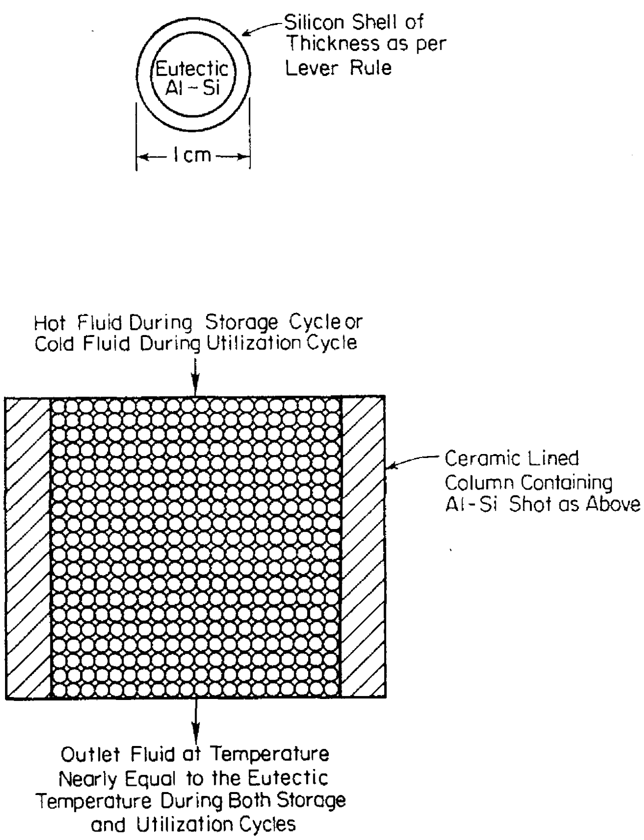

Fig. 2 — Schematic figure showing Al-Si shot with shell and a ceramic lined column containing the shot.

the mode in which the shot may be used in a ceramic-lined column based on this study.

Such a bed could be operated above and below the transformation temperature as a near-isothermal recuperator to utilize the high latent heat of fusion of the PCM shot. The model described here was developed to devise modes of operating the bed in a most efficient manner.

II. BACKGROUND

Two models are conventionally used to describe the transient response of a packed bed heat storage unit. One is the single-phase conductivity model which is based on the assumption that the temperatures of the fluid and solid are equal at any given axial location.

The energy balance equation for the single phase model is

$$U_f \rho_f C_f \frac{\partial T}{\partial x} + \rho_b C_b (1 - \varepsilon) \frac{\partial T}{\partial t} = k_b \frac{\partial^2 T}{\partial x^2} \quad [1]$$

The use of dimensionless parameters describing the response of the packed bed results in simplified differential equations and general solutions valid for many different combinations of independent variables involved.

Riaz[7] provided solutions of the conductivity model, plotting dimensionless temperature as a function of dimensionless distance and time, defined as below:

dimensionless distance

$$\xi = x k_b / U_f \rho_f C_f \quad [2]$$

dimensionless temperature

$$\theta = (T_f(\text{initial}) - T_b)/(T_f(\text{initial}) - T_b(\text{initial})) \quad [3]$$

dimensionless time

$$\tau = t k_b \rho_b C_b / (\rho_f C_f U_f)^2 \quad [4]$$

The nondimensional energy equation became

$$\frac{\partial \theta}{\partial \xi} + \frac{\partial \theta}{\partial \tau} = \frac{\partial^2 \theta}{\partial \xi^2} \quad [5]$$

The alternative Schumann model for the solid/fluid energy balance assumes infinite thermal conductivity in the transverse direction, no axial heat conduction, perfectly insulated container walls, temperature-independent physical and thermal properties, constant fluid flow velocity along the length of the bed, and negligible radiation effects. The basic differential equation for the energy balance for the fluid is:

$$\dot{m}_f C_f L / h A_h \frac{\partial T_f}{\partial x} = T_b - T_f \quad [6]$$

The equivalent equation for the storage medium is

$$[A(1 - \varepsilon)\rho_b C_b L / h A_h] \frac{\partial T_b}{\partial t} = T_f - T_b \quad [7]$$

Riaz compared the results of the two-phase Schumann model with those obtained using the conductivity model and indicated that the two models agreed within errors of less than 10 pct for τ less than 10.

Jefferson[8] presented a detailed evaluation and comparison of the various methods for the determination of the transient response of packed beds. He found that Biot number, thermal capacity ratio, and Peclet number as defined below were significant in determining the conditions under which the simplified two-phase model could be modified to account for intraparticle conduction and axial fluid dispersion. The dispersion effect is the mixing action within the fluid that results from the eddy currents created as the fluid flows through a complex set of passages.

Biot number

$$B_i = hd/2k_b \quad [8]$$

Heat capacity ratio

$$V_H = \rho_b C_b(1 - \varepsilon)/\rho_f C_f \varepsilon \quad [9]$$

Thermal capacity ratio

$$\beta = V_H/(V_H + 1) \quad [10]$$

Peclet number

$$P_e = (\rho_f C_f U_i)^2 AL\varepsilon/k_f A_h \quad [11]$$

The Biot number was found to provide the sole criterion for estimating the relative importance of intraparticle conduction. For a storage medium with a high thermal conductivity, the Biot number is small and the storage medium will have a uniform temperature within each particle. At large values of V_H, Jefferson lumped together axial dispersion and intraparticle effects to obtain an effective convective film heat transfer coefficient h_e to be used with the Schumann model.

$$1/h_e = \frac{1}{h}\left(1 + \frac{B_i}{5}\right)\beta^2 + \frac{d}{LP_e} \quad [12]$$

Schmidt and Willmott[1] evaluated h_e using the above expression in typical beds of steel shot with air as the fluid and showed that the difference between h and h_e is small.

None of these previously available solutions accommodates a phase change in the shot. To generate temperature profiles for a bed of PCM shot shown in Figure 2, these models must be extended to include in the calculations an expression for the latent heat of transformation. The purpose of this work was to develop such a model. Since temperature profiles in a bed of Al-Si shot of high thermal conductivity heated or cooled by air are proposed to be generated, two simplifications become clear. The high thermal conductivity of the shot makes the Biot number small and the assumption of uniform temperature in the transverse direction becomes reasonable. Secondly, for fluids such as air with high values of V_H, the use of a modified heat transfer coefficient in a Schumann-type model, as proposed by Jefferson, becomes applicable. However, as the change in the heat transfer coefficient due to such modification has been shown to be small,[1] a Schumann model with incorporation of terms for the phase change in the energy equation appears to be satisfactory. Regarding other simplifying assumptions that may be made, the assumption of negligible axial conduction appears to be reasonable as the shot are only in point contact. Since it is proposed to use the bed of Al-Si shot around the eutectic temperature of 577 °C, the operating temperatures are not high enough to make radiation effects appreciable. However, the model developed for the Al-Si shot should agree with the Schumann model below the transformation temperature. For short dimensionless times less than ten, the Schumann model agrees with curves published by Riaz,[7] which can be used to check the validity of the model.

III. MODEL DESCRIPTION

The computer program (herein called the model) was developed for the estimation of temperature profiles of the solid and the fluid along the length of a packed bed of self-encapsulated PCM shot as functions of distance along the bed and time during a series of heat storage and utilization cycles. The model ignores the thin encapsulation shell on the PCM and considers only the heat storing core of the shot in the calculations. In this two-phase model, an energy balance is established between the fluid and the storage material. The bed is divided into a series of small height segments within which both the solid and fluid temperatures are assumed to be uniform within each phase. The model assumes infinite thermal conductivity in the transverse direction, no axial heat conduction, a perfectly insulated container wall, negligible radiation effects, constant fluid flow velocity along the length of the bed, and no axial dispersion effects in the fluid. Temperature-dependent properties of the fluid are used in the calculations.

In a given height segment, heat exchanged between the shot and a small amount of fluid that enters the bed during an incremental period of X_s/U_f is considered. The heat transfer coefficient for heat exchange between the fluid and the height segment nearest to the inlet end is first calculated according to the following expressions proposed by Baumeister and Bennet:[9]

$$J_h = aN_{\mathrm{Re}}^z \quad [13]$$

where a and z are given in Table I.[9]

The Ergun analogy factor J_h represents an analogy between the friction factor and the heat transfer coefficient. In fact, J_h is proportional to the friction factor.

$$h = J_h U_f \rho_f C_f / N_{\mathrm{Pr}}^{0.67} \quad [14]$$

$$h_v = 6h/d \quad [15]$$

The heat exchanged from the fluid to the solid is then calculated as:

$$\dot{H}(m,n) = h(m,n)A_h[T_f(m,n) - T_b(m,n)] \quad [16]$$

where m and n are the indices for the mth time increment and the nth height segment of the bed, respectively. The temperature change in the fluid resulting from passage through the segment is given by:

$$\Delta T_f(m,n) = -\dot{H}(m,n)/U_f \rho_f A C_f \quad [17]$$

The corresponding temperature change in the shot is given by:

$$\Delta T_b(m,n) = X_s \dot{H}(m,n)/m_s C_b U_f \quad [18]$$

The temperature of fluid entering the next height segment is given by:

$$T_f(m, n+1) = T_f(m,n) + \Delta T_f(m,n) \quad [19]$$

The temperature of the bed for the next quantity of fluid that enters the bed during the next period X_s/U_f is given by:

$$T_b(m+1, n) = T_b(m,n) + \Delta T_b(m,n) \quad [20]$$

Table I. Constants Used in the Calculation of J_h[9]

D_b/d	a	z
10.7	1.58	−0.40
16.0	0.95	−0.30
25.7	0.92	−0.28
>30	0.90	−0.28

During a storage cycle, $\Delta T_f(m, n)$ is negative and $\Delta T_b(m, n)$ is positive, with opposite signs during a utilization cycle. The flowing fluid with the revised temperature then exchanges heat with the next height segment, which is again calculated as per Eqs. [13] through [20].

When the temperature of the shot reaches the eutectic temperature in any segment, its temperature is not changed until the latent heat of fusion of the shot in the segment is absorbed by the shot. During this period, the percentage of shot melted in a given segment is calculated as the percentage of the heat of fusion absorbed by the segment.

The model accounts for the time element by adding X_s/U_f to the time elapsed for each incremental volume of fluid that passes through the bed. The output variables are nondimensionalized as in Eqs. [21] through [23]. However, it should be noted that a change in the inlet fluid temperature relative to the PCM eutectic or transformation temperature would change the profiles.

$$\xi' = (L - x)/L \qquad [21]$$

$$\theta = [T_f(1,1) - T_b(m,n)]/[T_f(1,1) - T_b(1,1)] \qquad [22]$$

$$\tau' = th_v/\rho_b C_b \qquad [23]$$

The instantaneous rate of heat storage is calculated as:

$$\dot{Q} = \sum_{i=1}^{y} \dot{H} \qquad [24]$$

where y is the number of height segments into which the bed is divided and $\dot{Q}$ is the instantaneous rate of heat storage in the bed. During a utilization cycle, $\dot{Q}$ has a negative value since heat is removed from the bed. The $\dot{Q}$ values for the entire duration of a storage or utilization cycle are summed up to calculate Q, the total heat stored in or removed from the bed during the cycle, as follows:

$$Q = \sum_{j=1}^{N} \dot{Q}X_s/U_f \qquad [25]$$

where N is the number of fluid elements that pass through the bed during the cycle. The bed utilization factor is evaluated as:

$$\mathrm{BUF} = Q/ym_s\left(\int_{T_{b(1,1)}}^{T_E} C_b\,dT + HF + \int_{T_E}^{T_{f(1,1)}} C_b'\,dT\right) \qquad [26]$$

The above model was used to generate temperature profiles in a bed of Al-Si shot as described in Figure 2. Inlet fluid temperatures of 750 °C during storage cycles and 27 °C during utilization cycles were used in the calculations. The physical properties required for the calculations are presented in Tables II and III. The profiles generated and the modes of heating and cooling were then examined to devise modes of operating the bed as a near isothermal source of heat during both storage and utilization cycles.

IV. RESULTS AND DISCUSSION

Program runs were first made with dimensionless parameters calculated using Eqs. [4], [5], and [6] for comparison of temperature profiles prior to the onset of phase change in the PCM shot, *i.e.*, considering only sensible heat exchange. Agreement within approximately 5 pct between the temperature profiles generated by the present model and those published by Riaz was observed as shown in Figure 3. The calculations of the present model had been carried out with a step height of 2.5×10^{-4} meter.

Figure 4 is a plot of dimensionless temperature *vs* dimensionless distance for a bed of eutectic 1×10^{-2} meter diameter Al-12 wt pct Si alloy shot at different times during an initial heating cycle for a bed from a uniform initial temperature of 26.7 °C (80 °F). The heat exchange between the fluid and the shot is very fast as expected for a packed bed owing to the high heat transfer surface area to volume ratio. The temperature of the bed at and near the top (inlet) quickly reaches the bed eutectic temperature (750 °C or 1382 °F), while the bottom of the bed is still at lower temperatures. Hence, if the latent heat of the

Table II. Physical Properties Used in Calculations

	Al-12 Si Shot	Al-30 Si Shot	Air
Density (Kg/m^3)	2.34×10^3	2.34×10^3	1.281
Heat capacity (Joules/Kg-C)	8.87×10^2	8.87×10^2 for $T_b < 577$ °C 2.415×10^3 for $T_b > 577$ °C	
Heat of fusion (Joules/Kg)	5.16×10^5	4.13×10^5	

The other physical properties of air that were used are given in Table III.

Table III. Physical Properties of Air Used in Calculations

T_f (°C)	μ_f ($\times 10^{-6}$ Poise)	C_f ($\times 10^3$ Joules/Kg-C)
22.6 to 126.6	184	1.005
126.6 to 226.6	184	1.005
226.6 to 326.6	227	1.014
326.6 to 426.6	265	1.030
426.6 to 526.6	299	1.051
526.6 to 626.6	331	1.075
626.6 to 726.6	362	1.099
726.6 to 826.6	391	1.122
826.6 to 926.6	419	1.143
926.6 to 1026.6	445	1.161

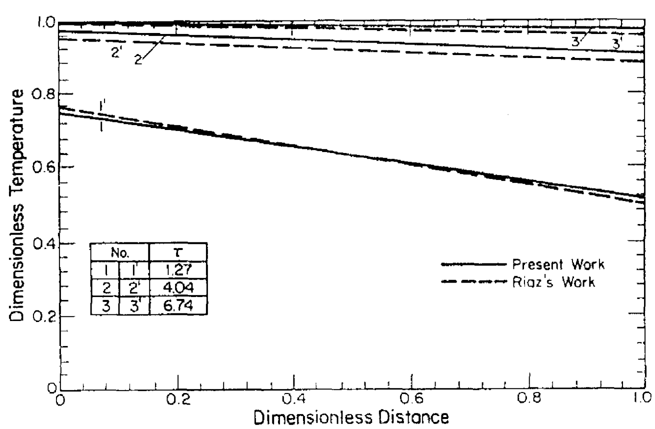

Fig. 3—Comparison of temperature profiles generated by present model with those of Riaz.[7]

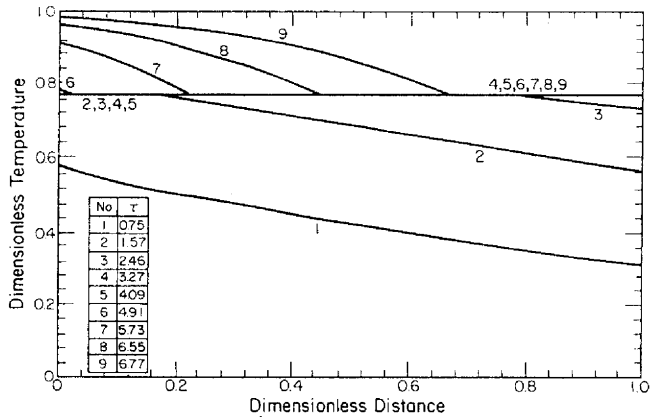

Fig. 4—Profiles in a bed of eutectic Al-12Si alloy shot during the first heating cycle. Hot inlet fluid flows from left to right.

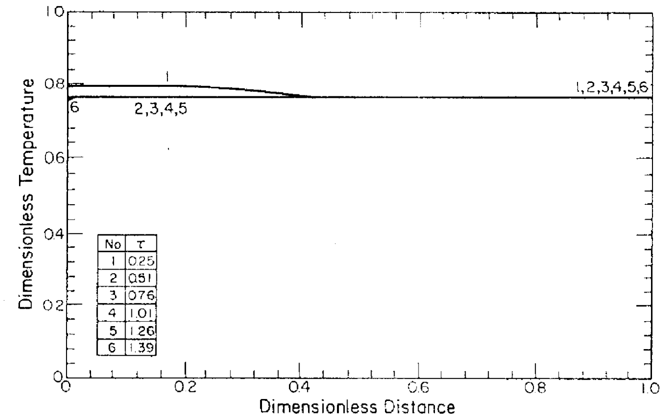

Fig. 6—Profiles in a bed of eutectic Al-12Si alloy shot during a cocurrent cooling cycle following the heating cycle of Fig. 4. Cool inlet fluid flows from left to right.

shot is to be efficiently utilized by raising the outlet of the bed to the eutectic temperature, the bed inlet needs to approach the inlet fluid temperature. If conventional cyclic *countercurrent* cooling of the bed were done after the first storage cycle, the outlet would cool quickly and generate steep temperature gradients in the bed for the subsequent heating cycle, as seen in Figure 5. Hence, the efficient utilization of the latent heat of fusion would not be realized with the scheme of cyclic countercurrent heating and cooling.

Therefore, the program was run to generate temperature profiles during a cyclic *cocurrent* cooling cycle for the bed, starting from the profile at the end of the initial heating cycle shown in Figure 4. The intention was to transfer heat from the hotter inlet of the bed to the cooler outlet of the bed and thereby raise the temperature of most of the bed to the eutectic temperature. Figure 6 is a plot of dimensionless temperature *vs* dimensionless distance for different dimensionless times during the first cocurrent cooling cycle following the storage cycle of Figure 4. At the end of this cycle, essentially all of the bed had been brought to the eutectic temperature, as desired.

Figure 7 is a plot of temperature profiles in the bed at different dimensionless times during the subsequent heating cycle starting from the profile at the end of the cocurrent cooling cycle shown in Figure 6. Through step 5, a major portion of the bed is at the eutectic temperature and the heat input is utilized mainly to provide the latent heat of fusion for the shot, while the fluid outlet temperature remains at or near the eutectic temperature.

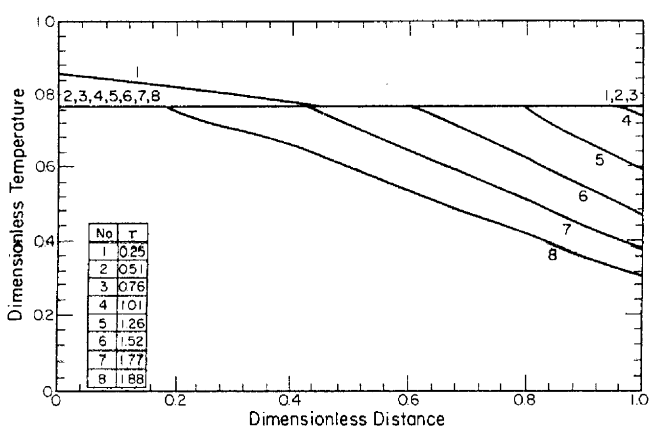

Fig. 5—Profiles in a bed of eutectic Al-12Si alloy shot during a subsequent countercurrent cooling cycle. Cool inlet fluid flows from right to left.

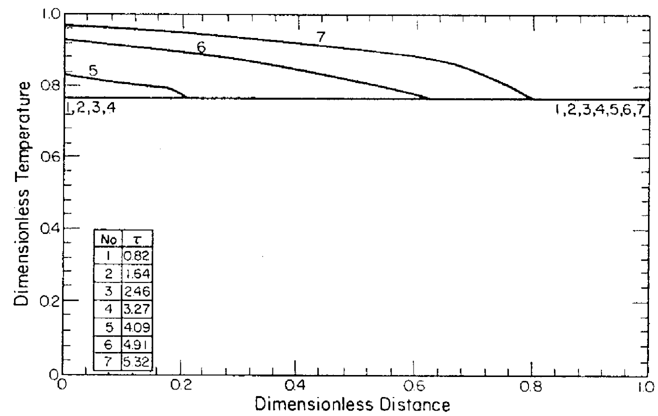

Fig. 7—Profiles in a bed of eutectic Al-12Si alloy shot during the second heating cycle after the cocurrent cooling cycle of Fig. 6. Hot fluid flows from left to right.

For all subsequent cyclic cocurrent cooling and heating cycles, about 75 pct of the bed remains at the eutectic temperature with the shot at each height exhibiting a differing melted fraction, while the bed inlet temperature cycles between the two temperature extremes, as shown in Figures 8 and 9.

Figures 10 and 11 present temperature profiles for the hypereutectic Al-30 wt pct Si alloy. This hypereutectic alloy is chosen as a composition for which the outer containment shell could be pure Si. The shell thickness would vary according to the lever rule from the phase diagram. By the use of fabrication procedures for the shot as suggested earlier and the selection of cycling temperatures, a typically minimum shell thickness of 1×10^{-3} meter would be maintained. The melting of the hypereutectic alloy has been treated to provide an effective (average) specific heat above the eutectic temperature. This was done by taking into account the heat of fusion of silicon as it progressively melts above the eutectic temperature for Al-30 wt pct Si alloy. Upon comparing Figure 10 with Figure 4, the inlet of the bed of Al-30 wt pct Si shot is not heated up quite as much as the inlet of the bed with Al-12 wt pct Si shot, because the effective specific heat for the Al-30 wt pct Si alloy above the eutectic temperature is 2.415×10^3 Joules/Kg-C as compared with 8.87×10^2 Joules/Kg-C for the Al-12 wt pct Si alloy.

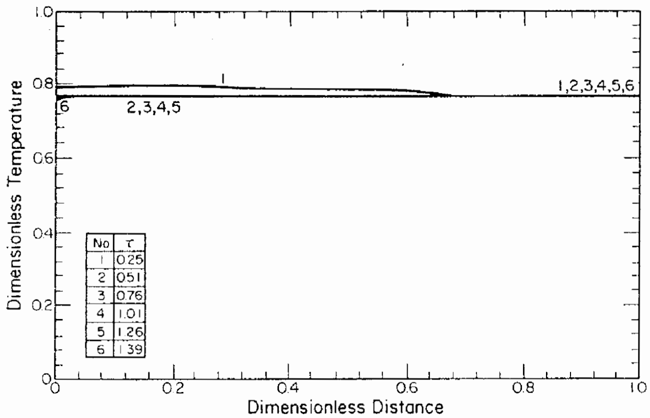

Fig. 8 — Profiles in a bed of eutectic Al-12Si alloy shot during the second cocurrent cooling cycle following storage cycle of Fig. 7. Cool fluid flows from left to right.

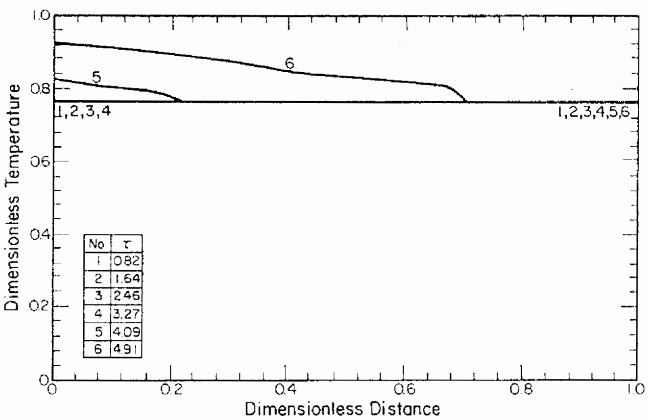

Fig. 9 — Profiles in a bed of eutectic Al-12Si alloy shot during the third heating cycle following utilization cycle of Fig. 8. Hot fluid flows from left to right.

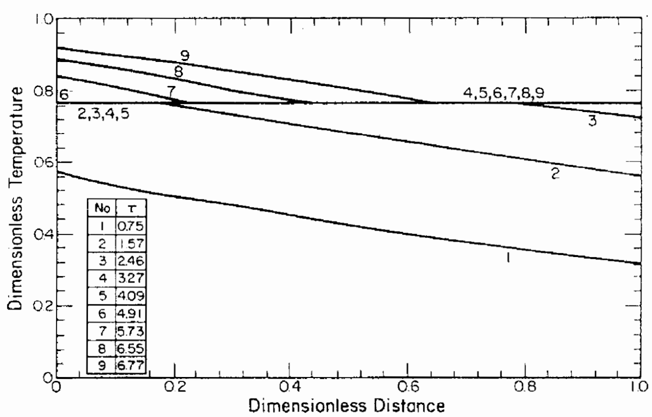

Fig. 10 — Profiles in a bed of hypereutectic Al-30Si alloy shot during the first heating cycle. Hot fluid flows from left to right.

Figure 11 shows profiles for the Al-30 wt pct Si alloy after the third heating cycle combined with cocurrent cooling, similar to the curves shown in Figure 9 for the Al-12 wt pct Si alloy. Figure 11 further illustrates that only the inlet of the bed cycles in temperature while the bed effectively provides an isothermal reservoir of heat at the eutectic temperature. Computer runs for the Al-30 wt pct alloy corresponding to successive cycles, such as in Fig-

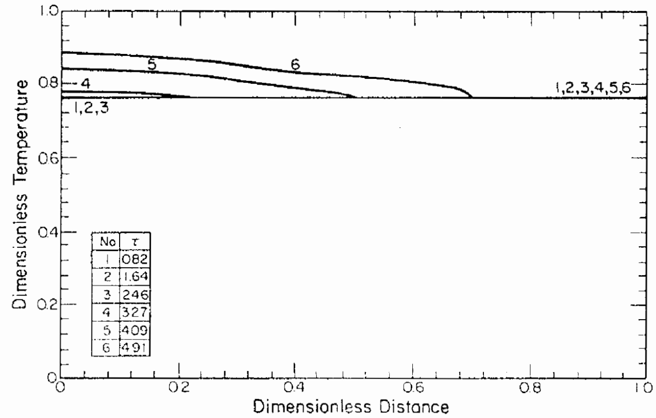

Fig. 11 — Profiles in a bed of hypereutectic Al-30Si alloy shot during the third heating cycle following the same heating and cooling cycles as in Figs. 4 through 9. (This figure corresponds to Fig. 9 for the Al-12 wt pct Si alloy.)

ures 5 through 8 for the Al-12 wt pct alloy, resulted in similar profiles.

Figure 12 is a plot of the instantaneous rate of heat storage in the bed during successive heating and cocurrent cooling cycles in a bed of Al-12 wt pct Si shot. After a few initial cycles of heating and cooling, the amount of heat stored in the bed during each heating cycle (area under curve) and that removed from the bed during each cooling cycle are nearly constant. The model can force the areas under the curve to be equal for each successive heating and cooling cycle by continuing a given heating or cooling cycle until a specified value of BUF is reached. This would ensure that the total amount of heat stored in the bed during a heating cycle exactly equals the heat removed during the succeeding cooling cycle. The model can also provide the relative periods of heating and cooling needed to maintain such equality for a given set of hot and cold fluid inlet temperatures.

For an industrial system comprised of two identical columns which are operated out-of-phase for constant time periods, the hot inlet process temperature would be fixed. The thermal balance could then be satisfied most readily by adjustment of the flow rate of the cool inlet stream or/and adjustment (raising) of the temperature of the cool inlet stream *via* heat gained from an auxiliary conventional heat exchanger.

The use of a balanced pair of heat storage units, each utilizing a sequence of different PCM shot with different

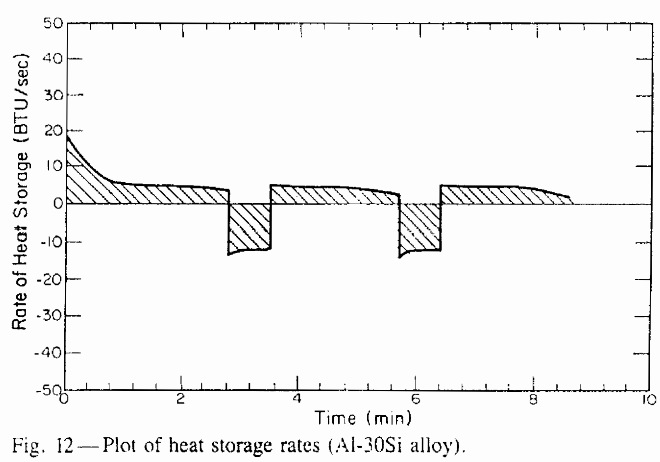

Fig. 12 — Plot of heat storage rates (Al-30Si alloy).

transformation temperatures, could yield a set of outlet fluids with different, but nearly constant, temperatures for power generation or other purposes. A schematic representation of such a system is shown in Figure 13. Indeed, other eutectic alloys high in Si have been proposed for heat storage at various temperatures.[12]

V. CONCLUSIONS

A computer model has been developed for the estimation of temperature profiles of PCM shot in a packed bed in contact with a hot or cold inert flowing fluid as functions of distance along the bed and time during successive heating and cocurrent cooling cycles. Successive cyclic cocurrent heating and cooling cycles were shown to maintain a major portion of the bed at or near the transformation temperature, so that heat gained by or removed from the bed contributed largely only to a change in the percentage of shot melted. Such cycles were also shown to provide a nearly constant outlet fluid temperature equal to the eutectic temperature. The model can specify relative periods of heating and cooling cycles needed to make the heat removed during a cooling cycle equal the heat stored during a heating cycle. This is done by specifying a desired bed utilization factor for each heating and cooling cycle that would enable the continued operation of a major portion of the bed at or near the eutectic temperature after the initial few transient cycles. The model was found to compare favorably with results published in the literature for temperatures below the onset of melting in the PCM shot. A sequence of such heat storage beds involving different PCMs with different eutectic temperatures could provide isothermal streams of waste heat at several levels of temperature.

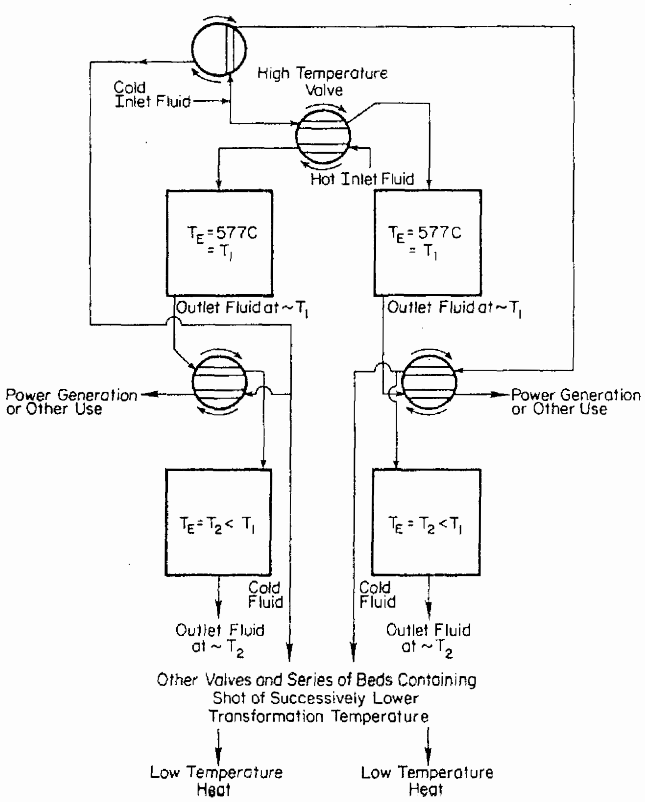

Fig. 13—A schematic representation of a balanced pair of sequential packed beds utilizing PCM shot. Indicated valve positions provide heat storage for beds on left and utilization on right. Rotation of all valves 90 deg clockwise provides opposite functions.

NOTATION

A	Area of cross-section of the bed (m^2)
A_h	Heat transfer surface area in each height segment (m^2)
B_i	Biot number (hd/k_b)
BUF	Bed utilization factor (fraction)
C	Specific heat at constant pressure (Joules/Kg-C)
C_b'	Specific heat at constant pressure of storage medium above the eutectic temperature (Joules/Kg-C)
d	Diameter of shot in the bed (m)
D_b	Diameter of the bed (m)
$\dot{H}$	Rate of heat exchange (Joules/sec)
HF	Heat of fusion of the shot core material (Joules/Kg)
h	Convective film heat transfer coefficient (Joules/m^2-C-sec)
h_e	Effective film heat transfer coefficient (Joules/m^2-C-sec)
h_v	Volumetric heat transfer coefficient (Joules/m^3-C-sec)
J_h	Ergun analogy factor
k	Thermal conductivity (Joules/(sec) (m) (°C))
L	Length of the bed (m)
$\dot{m}_f$	Mass rate of flow (m/sec)
m_s	Weight of shots in a segment (Kg)
N_{Pr}	Prandtl number ($C_f \mu_f / k_f$)
N_{Re}	Reynolds number ($\rho_f d U_i / \mu_f$)
(m, n)	Represent the nth height segment and the mth time element
P_e	Peclet number $(\rho_f C_f U_i)^2 AL\varepsilon / k_f A_h$
Q	Heat stored in or removed from the bed in a storage or utilization cycle (Joules)
$\dot{Q}$	Rate of heat storage or removal (Joules/sec)
t	Time (sec)
T_E	Eutectic temperature (C)
T	Temperature (C)
ΔT	Temperature change (C)
U_f	Superficial velocity of fluid (m/sec)
U_i	Interstitial fluid velocity (m/sec)
V_H	Heat capacity ratio $[\rho_b C_b(1 - \varepsilon)/\rho_f C_f]$
V_s	Volume of shot in a segment (m^3)
x	Distance from heating fluid inlet (m)
X_s	Length of a height segment (m)
y	Number of height segments into which bed is divided

Greek Letters

β	Thermal capacity ratio ($V_H/V_H + 1$)
τ	Dimensionless time as used in Riaz's work[7] $[tk_b\rho_b C_b/(\rho_f C_f U_f)^2]$
τ'	Dimensionless time ($th_V/\rho_b C_b$)
ε	Porosity of the bed (fraction)
ρ	Density (Kg/m^3)
ξ	Dimensionless distance as used in Riaz's work[7] $(xk_b/U_f\rho_f C_f)$
ξ'	Dimensionless distance $(L - X)/L$
θ	Dimensionless temperature $[T_f(1, 1) - T_b(m, n)]/[T_f(1, 1) - T_b(1, 1)]$

Subscripts

f Fluid
b Storage medium

ACKNOWLEDGMENTS

Financial support from the Department of Energy Subcontract No. 19X-43394C from Martin Marietta Energy Systems, Inc., Oak Ridge, Tennessee 37831, is gratefully acknowledged. The authors appreciate technical discussions with M. Olszewski, J. Martin, and L. S. Fan.

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LATENT HEAT STORAGE

FOR

SOLAR THERMAL POWER

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Prepared for LUZ-DOE-SERI Workshop,
Victorville, California, October 1988.

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ABSTRACT

Existing tools for design and performance calculations for passive latent heat storage heat exchangers are summarized. The tools are adequate to treat the more critical stage, namely, the heat recovery stage, for shell/tube heat exchangers. Additional development work is necessary to address the storage stage, viscous heat transfer fluids, finned tubes and system optimization.

SCOPE

Thermal Analysis, Performance Calculations,
Thermal Design Considerations and Methods

TYPES OF LATENT HEAT STORAGE UNITS

Shell-and-tube : (a) single pass -- multiple pass
(b) finned -- unfinned
(c) PCM in shell -- PCM in tubes

Other types -- plate-fin, direct-contact, etc.

DESIGN AND ANALYSIS OF PERFORMANCE

Storage Unit in Discharge Mode - Storage Mode
Flowrate and Inlet Temperature of Fluid Vary
in Time in a Prescribed Manner,may have Jumps

BASIC CONSIDERATIONS

1. Latent Heat Storage is NOT Isothermal : Temp. Diff. needed for Conduction, Convection
2. Freezing/Melting will probably NOT be Axially Uniform
3. Double and Multiple Tube Passes of the Fluid-Fluid Type to be Avoided. Uniform phase growth not desirable
4. Fins can Provide Significant Improvement in Performance, close to the Point of Isothermal Operation
5. Volumetric Heat Capacity is More Important than Good Conductivity in PCM Selection
6. Melting is not always dominated by Convection

TOOLS AVAILABLE

Effectiveness -- NTU charts

Computer program for calculating effectiveness.
Handles freezing and melting on
unfinned tubes, time-dependent HTF flow
and inlet temperature

Computer program for finned tubes, with
constant HTF flow and T-inlet

Design program (details next)

FEM code for single tube, used as diagnostic
tool for simple models

Simulation subroutine for heat recovery

Shrinkage cavity model (experimentally verified)

DESIGN METHOD FOR

LATENT HEAT STORAGE UNITS

1. Select PCM with melting point slightly below storing temperature.
2. Decide upon maximum and minimum outlet temperatures during heat recovery.
3. Collect thermal properties of fluid and PCM.
4. Run design program (any PC, VAX, etc.)
5. Examine output design parameters from program and redesign if necessary.

Limitations of Existing Design Software:

1. Heat recovery only.
2. No fins.
3. Heat transfer coefficient uniform -- not valid for viscous HTF
4. Constant Load

These limitations DO NOT apply to models and analysis software.

WORK TO BE DONE

Include melting, finned tubes and
  time-dependent HTF flow in design tool

Develop model for developing flow for
  use with viscous HTFs

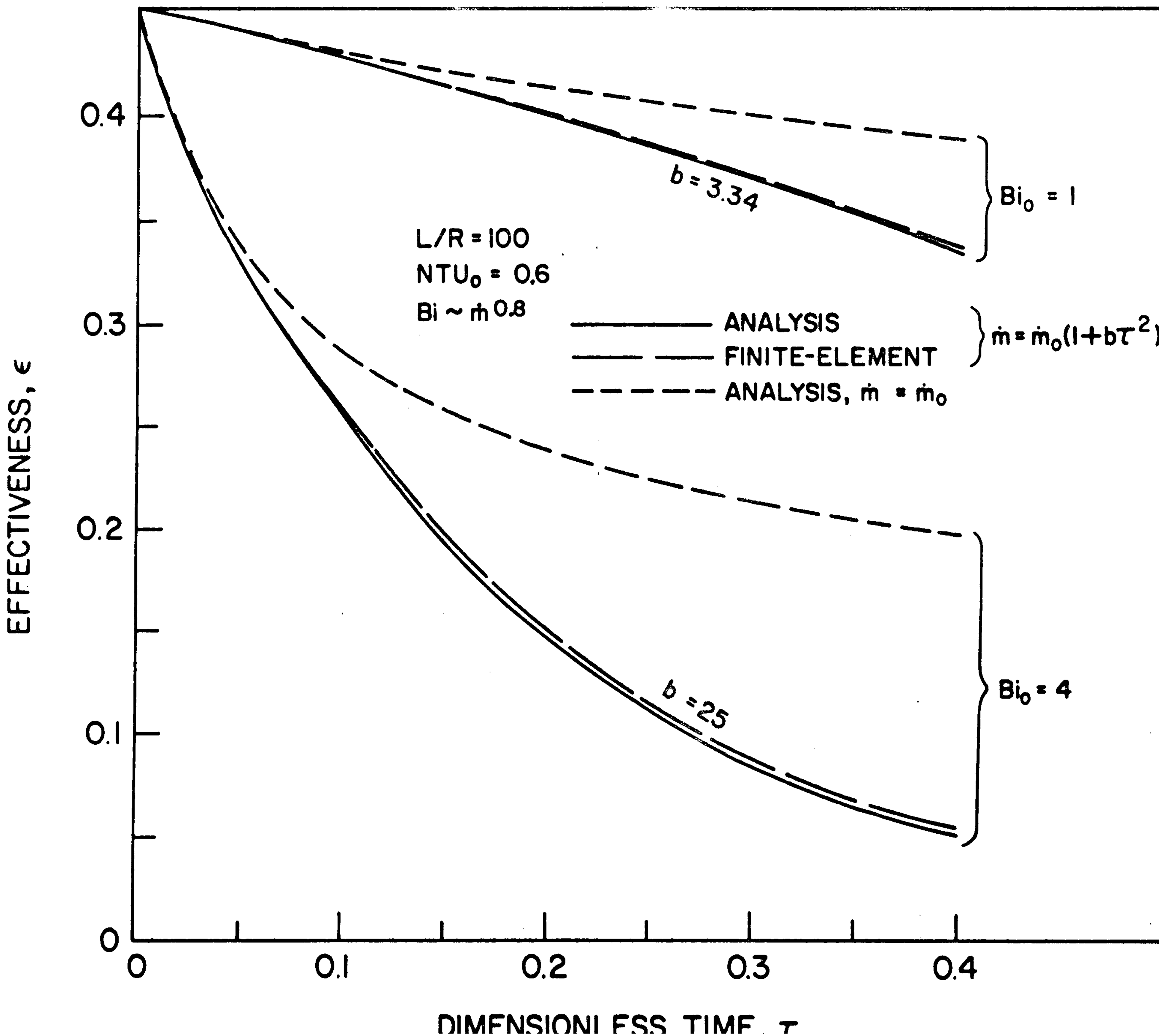
Verify melting model by FEM

Verify fin model by FEM

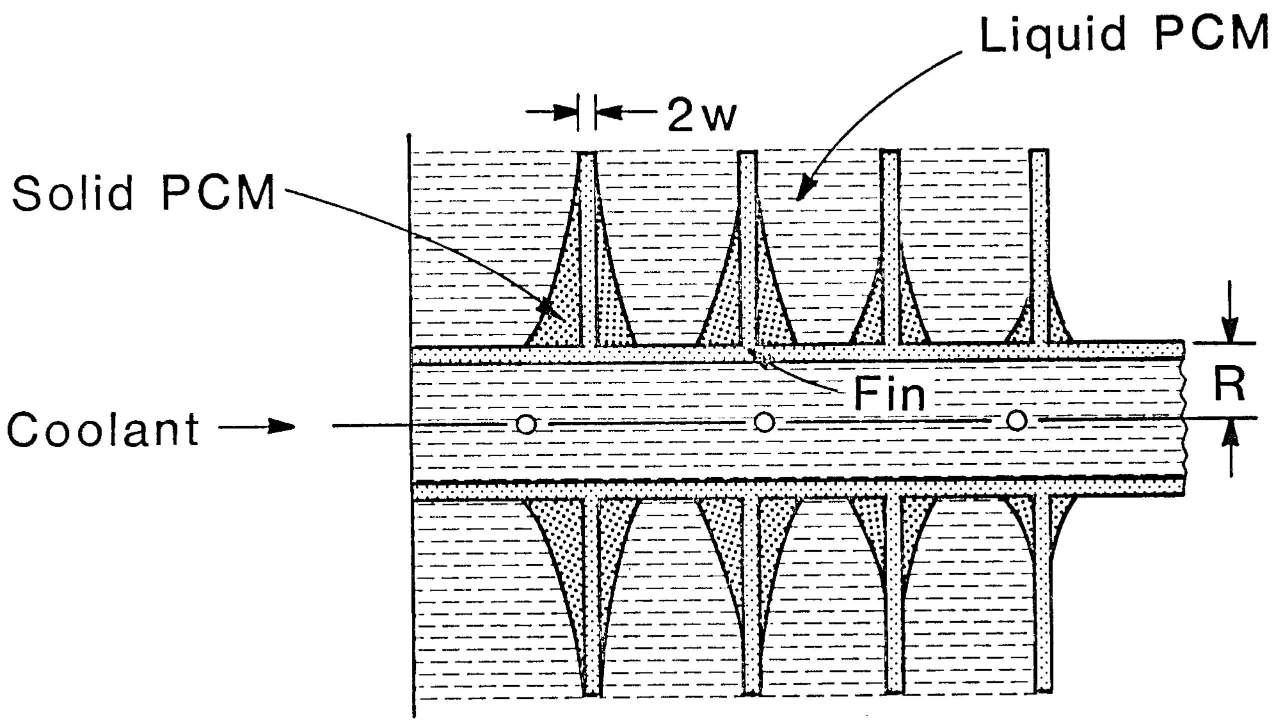
Merge storage simulation subroutine with
  solar system simulator, optimize system

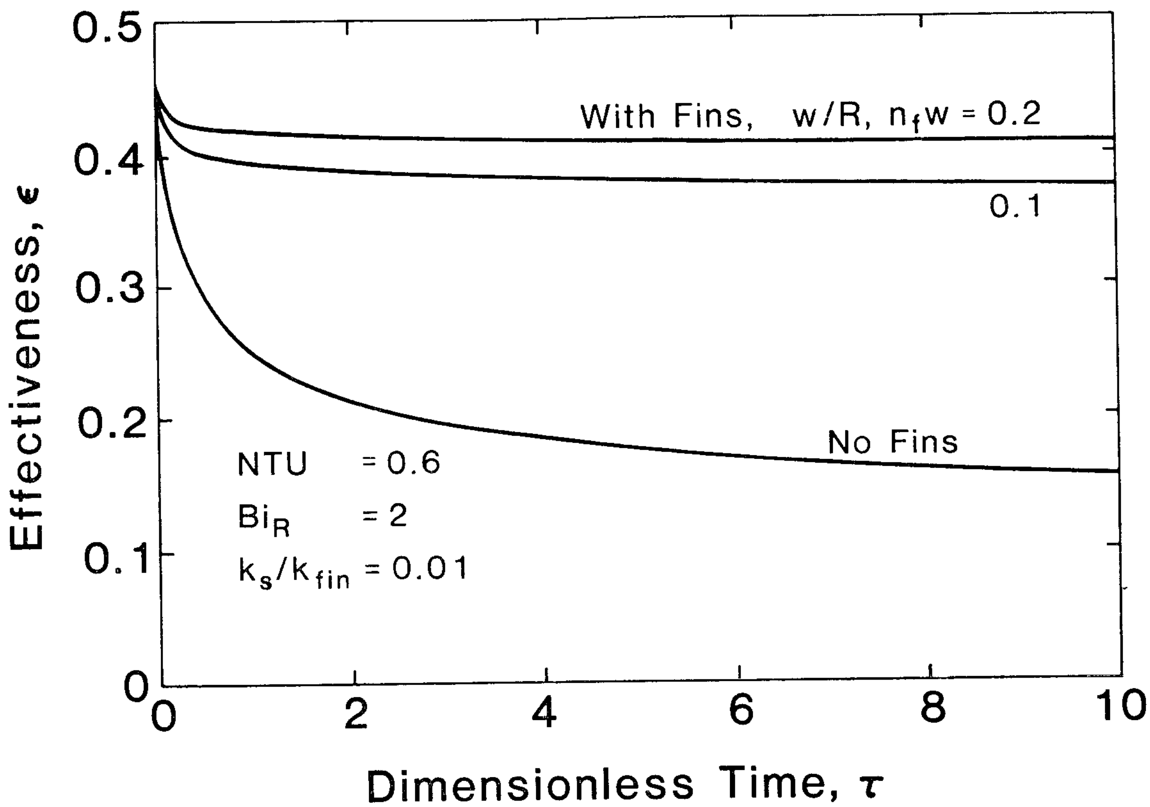
Include melting, finned tubes, holding
  stage into simulator

Cost optimization, structural/safety needs

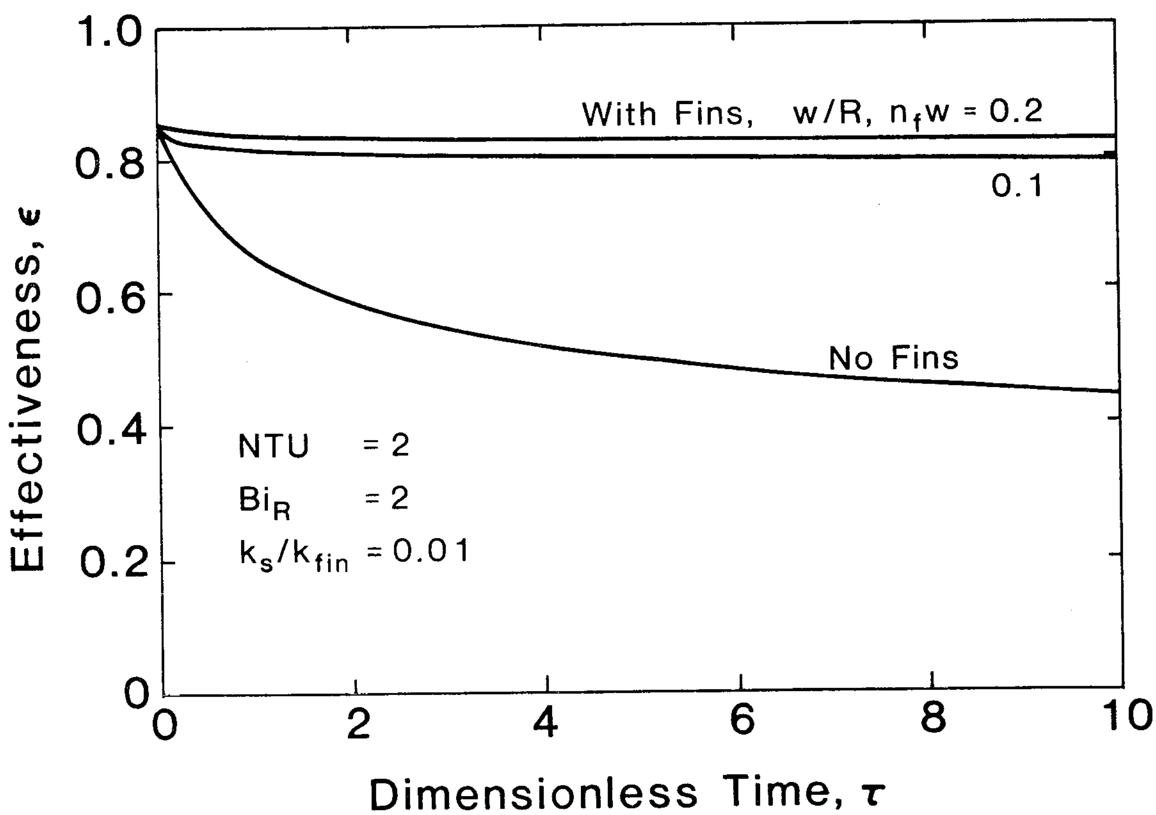


EFFECTIVENESS, ε
DIMENSIONLESS TIME, τ
0
0.1
0.2
0.3
0.4
L/R = 100
NTU₀ = 0.6
Bi ~ ṁ^0.8
ANALYSIS
FINITE-ELEMENT
ANALYSIS, ṁ = ṁ₀
ṁ = ṁ₀(1+bτ²)
b = 3.34
b = 25
Bi₀ = 1
Bi₀ = 4

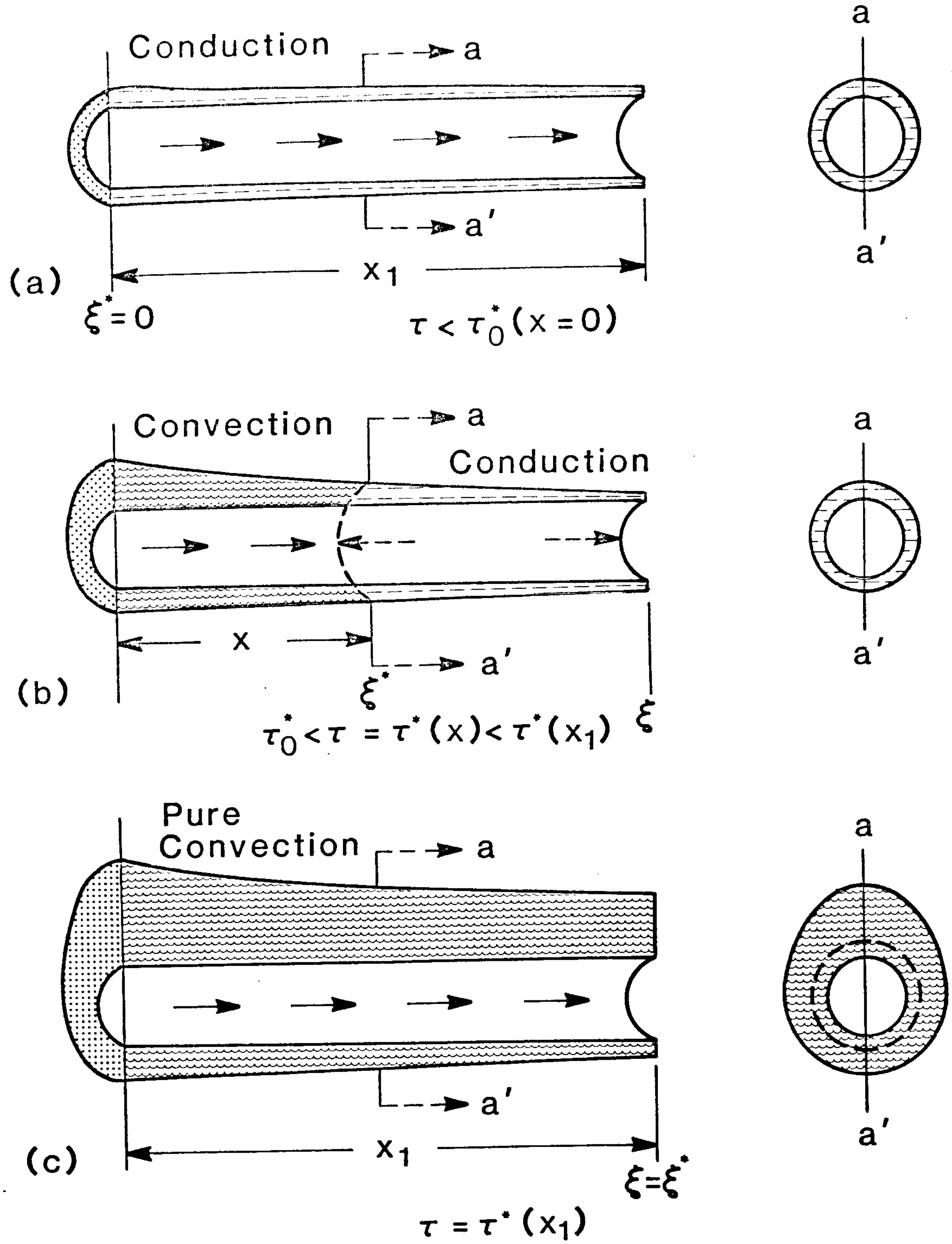

Liquid PCM
2w
Solid PCM
R
Fin
Coolant

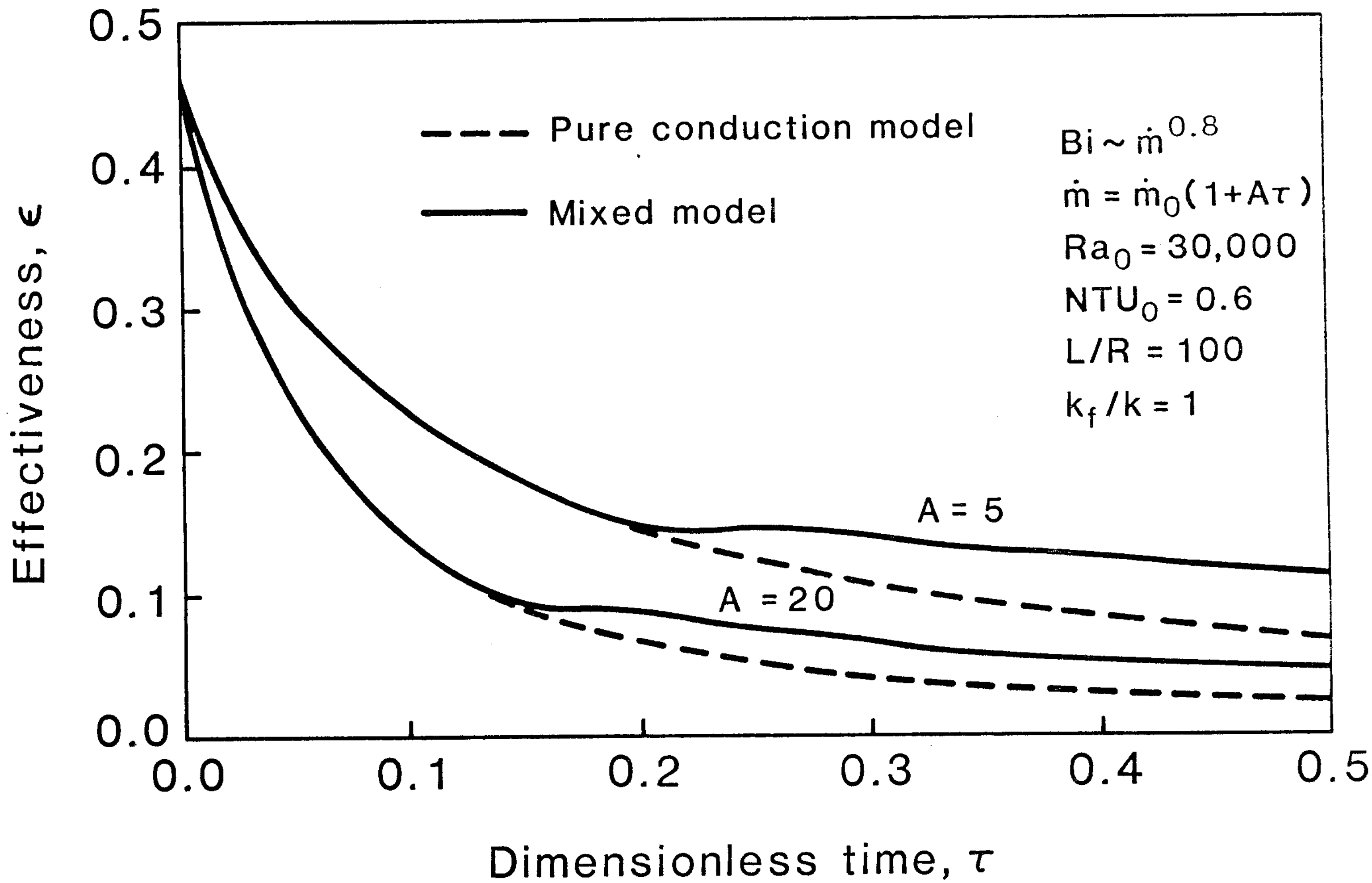


0.5
0.4
0.3
0.2
0.1
0
Effectiveness, ε
With Fins, w/R, n_f w = 0.2
0.1
No Fins
NTU = 0.6
Bi_R = 2
k_s/k_fin = 0.01
0
2
4
6
8
10
Dimensionless Time, τ

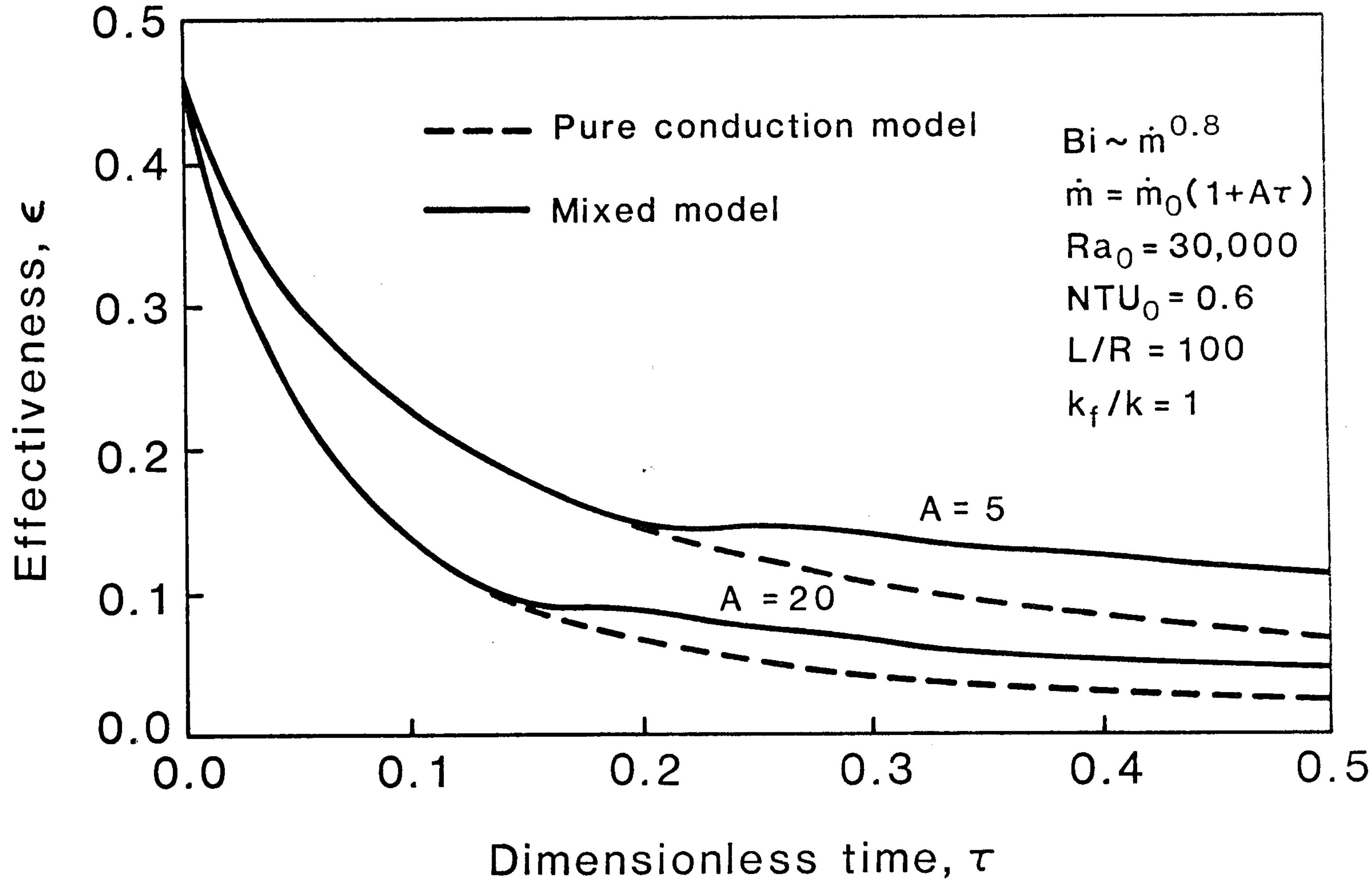


1.0
0.8
0.6
0.4
0.2
0
Effectiveness, ε
With Fins, w/R, n_f w = 0.2
0.1
No Fins
NTU = 2
Bi_R = 2
k_s/k_fin = 0.01
0
2
4
6
8
10
Dimensionless Time, τ


Conduction
a
a'
(a)
x_1
$\xi^* = 0$
$\tau < \tau_0^*(x=0)$
Convection
Conduction
x
(b)
ξ^*
ξ
$\tau_0^* < \tau = \tau^*(x) < \tau^*(x_1)$
Pure Convection
(c)
x_1
$\xi = \xi^*$
$\tau = \tau^*(x_1)$



0.5
0.4
0.3
0.2
0.1
0.0
Effectiveness, ε
Pure conduction model
Mixed model
Bi ~ ṁ^0.8
ṁ = ṁ0(1+Aτ)
Ra0 = 30,000
NTU0 = 0.6
L/R = 100
kf/k = 1
A = 5
A = 20
0.0
0.1
0.2
0.3
0.4
0.5
Dimensionless time, τ



0.5
0.4
0.3
0.2
0.1
0.0
Effectiveness, ϵ
Pure conduction model
Mixed model
Bi ~ ṁ^0.8
ṁ = ṁ0(1+Aτ)
Ra0 = 30,000
NTU0 = 0.6
L/R = 100
kf /k = 1
A = 5
A = 20
0.0
0.1
0.2
0.3
0.4
0.5
Dimensionless time, τ

APPENDIX C

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Document Control Page	1. SERI Report No. SERI/STR-250-3516	2. NTIS Accession No. DE89009426	3. Recipient's Accession No.
4. Title and Subtitle Phase-Change Thermal Energy Storage: Final Subcontract Report on the Symposium Held October 19-20, 1988, Helendale, California			5. Publication Date November 1989
			6.
7. Author(s) NA			8. Performing Organization Rept. No.
9. Performing Organization Name and Address Luz International Ltd. 924 Westwood Blvd. Los Angeles, CA 92024			10. Project/Task/Work Unit No. ST91 7001
			11. Contract (C) or Grant (G) No. (C) HH-9-18108-1 (G)
12. Sponsoring Organization Name and Address Solar Energy Research Institute 1617 Cole Blvd. Golden, CO 80401-3393			13. Type of Report & Period Covered Technical Report
			14.

15. Supplementary Notes
SERI Technical Monitors: Russell Hewitt and Bimleshwar Gupta

16. Abstract (Limit: 200 words) This document reports on the symposium held October 19-20, 1988, at Helendale, Calif., on phase-change thermal energy storage. Thermal energy storage is important to solar electric power plants, but currently there is no cost-effective reliable storage system that will work at 735°F (397°C), the current operating temperature of the Luz International Ltd. Solar Electric Generating Systems (SEGS). As a possible solution, Luz developed two storage designs using phase-change materials and asked symposium participants to advise on the feasibility of using these materials in SEGS-type facilities.

Symposium participants concluded that phase-change materials would probably not meet the cost goals in the immediate future. However, two alternative storage options emerged: encapsulation of phase-change salts and chemical energy storage using hydroxide/oxide reactions. Participants recommended that the most promising options be evaluated and that schedules for applications by 1992 or beyond be established. These evaluations will provide the technical and economic bases for further efforts, including designing and installing prototype field systems and detailed engineering design studies with supporting R&D activities.

17. Document Analysis
a. Descriptors Phase-change materials; sensible heat storage; solar thermal power plants; energy storage systems; energy storage.

b. Identifiers/Open-Ended Terms

c. UC Categories
202

18. Availability Statement	19. No. of Pages
National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, Virginia 22161	155
	20. Price A08

Form No 0069 (3-25-82)