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SOLAR PILOT PLANT, PHASE 1. PRELIMINARY DESIGN REPORT

Volume 5. Thermal Storage Subsystem. CDRL Item 2

MASTER

May 1, 1977

Work Performed under Contract No. EY-76-C-03-1109

Energy Resources Center
Honeywell, Incorporated
Minneapolis, Minnesota

U.S. Department of Energy

Solar Energy

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ERDA Contract No. E(04-3)-1109

1 MAY 1977

SOLAR PILOT PLANT
PHASE I

PRELIMINARY DESIGN REPORT

VOLUME V
THERMAL STORAGE SUBSYSTEM
CDRL Item 2

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FOREWORD

This is the initial submittal of the Solar Pilot Plant Preliminary Design Report per Contract Data Requirement List Item 2 of ERDA Contract E(04-3)-1109. This report is submitted for review and approval by ERDA. This is Volume V of seven volumes.

10 MEGAWATT SOLAR PILOT PLANT
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

ABSTRACT

THERMAL STORAGE SUBSYSTEM

The Honeywell thermal storage subsystem design features a sensible heat storage arrangement using proven equipment and materials. The subsystem consists of a main storage containing oil and rock, two buried superheater tanks containing inorganic salts (Hitec), and the necessary piping, instrumentation, controls, and safety devices. The subsystem can provide 7 MW (e) for three hours after twenty hours of hold. It can be charged in approximately four hours. Storage for the commercial-scale plant consists of the same elements appropriately scaled up. This volume contains a description of the subsystem design methodology and evolution and the subsystem operation and performance.

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GLOSSARY
OF
DEFINITIONS AND SYMBOLS

Additional definitions and symbols not included in the text are listed below:

HB	High Boiler--Fluid components with a boiling point higher than the bulk fresh fluid.
LB	Low Boiler--Fluid components with a boiling point lower than the bulk fluid.
ACV	Automatic Proportional Control Valve
GV	Solenoid operated gate valve
HH	Handholes--below-ground electrical terminations with hand access.
Hitec	Trade name for the heat transfer salt used in the storage superheater loop
OPT	Optimum
G	Superficial mass velocity=mass flow/cross section area
C_f , C_{pf}	Heat capacity of fluid
C_s , C_{ps}	Heat capacity of solid
Caloria	Exxon petroleum company trade name for a series of high temperature heat transfer oils. In this document used specifically for HT 43 Caloria.
SH	Superheater
H. R.	Heat Rate
C. S.	Carbon Steel
L. A. C. S.	Low Alloy Carbon Steel
H/A	Hand and automatic
K	Proportional gain
I	Integration
X	A multiplication is used

Δ

Delta or change in error

H/D=B Height divided by diameter

Pinch Point Minimum temperature difference between fluid streams
within a heat exchanger.

Utilization Factor-UF Ratio of thermal energy charged and discharged
from main storage tank between the design fluid temperatures
out of the tank of 300°C (572°F) and 253°C (554°F), to the thermal
energy stored between 303°C (578°F) and 249°C (480°F).

SECTION 1 INTRODUCTION

BACKGROUND

Supplies of most conventional fuels are being depleted rapidly. Consequently, it is necessary to identify alternate sources of energy and to develop the most promising to ensure availability when needed.

An alternative with great potential is the conversion of sunlight to energy. One aspect of this usage is generating electricity through solar energy. A goal of the national energy program is to demonstrate the technical and economic feasibility of a central receiver solar power plant for generating electricity. Pursuant to that goal, the Energy Research and Development Administration (ERDA), on 1 July 1975, awarded Honeywell Inc. a two-year contract for Phase I of such a program.

The initial program phase, which is the subject of this report, consisted of developing a preliminary design for a 10 MW(e) proof-of-concept solar pilot plant. The second phase will consist of building and operating the pilot plant and projecting the information gained to larger-scale plants. This phase is scheduled to be completed in the early 1980's. The third phase will consist of designing, building, and operating two 50-100 MW(e) demonstration plants. The final phase will consist of building and operating plants in the 100-300 MW(e) range.

PHASE I PROGRAM SCOPE

The Phase I program consisted of developing a pilot plant preliminary design by first developing a preliminary baseline design to meet specified

and assumed performance requirements. The baseline was then refined through analysis and experimentation, and evaluated by testing key subsystems, i.e., collector, steam generator, and thermal energy storage.

The complexity of the undertaking dictated a team approach to provide the technical and managerial skills required. The Honeywell team is identified in Figure 1-1.

Figure 1-1. Honeywell Team for Phase I Solar Pilot Plant Program.

A unique feature of the test plan was the use of selected facilities of an operating power plant, Northern States Power's Riverside Plant in Minneapolis, Minnesota, to test the steam generator and thermal energy storage subsystems. An ERDA-directed change from latent heat (phase change) storage to sensible heat storage cancelled the storage portion of the test

plan. The steam generator was tested using a solar array to simulate the insolation required to generate steam. The collector subsystem hardware, one mobile and three stationary, full-scale, four-mirror units, was field tested for performance and reaction to operating environments at Honeywell's Avionics Division facility in St. Petersburg, Florida.

The information obtained from the subsystems tests was used to complete the pilot plant preliminary design, and to project performance and cost of a 100 MW(e) plant to facilitate long-range planning.

The chronology of the work done in Phase I is summarized in Figure 1-2.

Figure 1-2. Chronology of Phase I Solar Pilot Plant Program

ORGANIZATION OF THE PRELIMINARY DESIGN REPORT

The preliminary design and supportive data resulting from the Phase I work are presented in seven volumes:

- I - Executive Overview
- II - System Description and System Analysis (3 books)*
- III - Collector Subsystem
- IV - Receiver Subsystem
- V - Thermal Storage Subsystem
- VI - Electrical Power Generation/Master Control Subsystems and Balance of Plant
- VII - Pilot Plant Cost/Commercial Plant Cost and Performance

Abstracts of volumes other than the one in hand and Volumes I and VII are on the following pages.

*Book 2 is Central Receiver Optical Model Users Manual

Book 3 is Dynamic Simulation Model and Computer Program Descriptions

ABSTRACTS

Vol. II - SYSTEM ANALYSIS AND SYSTEM DESCRIPTION

Honeywell conducted a parametric analysis of the 10 MW(e) solar pilot plant requirements and expected performance and established an optimum system design. The main analytical simulation tools were the optical (ray trace) and the dynamic simulation models. These are described in detail in Books 2 and 3 of this volume under separate cover. In making design decisions, available performance and cost data were used to provide a design reflecting the overall requirements and economics of a commercial-scale plant. This volume contains a description of this analysis/design process and resultant system/subsystem design and performance.

Vol. III - COLLECTOR SUBSYSTEM

The Honeywell collector subsystem features a low-profile, multifaceted heliostat designed to provide high reflectivity and accurate angular and spatial positioning of the redirected solar energy under all conditions of wind load and mirror attitude within the design operational envelope. The heliostats are arranged in a circular field around a cavity receiver on a tower halfway south of the field center. A calibration array mounted on the receiver tower provides capability to measure individual heliostat beam location and energy periodically. This information and weather data from the collector field are transmitted to a computerized control subsystem that addresses the individual heliostat to correct

pointing errors and determine when the mirrors need cleaning. This volume contains a detailed subsystem design description, a presentation of the design process, and the results of the SRE heliostat test program.

Vol. IV - RECEIVER SUBSYSTEM

The Honeywell receiver subsystem design uses well established fossil technology and consists of a cavity receiver housing, a steam generator, a cavity barrier, piping, and a support tower. The steam generator absorbs the redirected solar energy from the collector subsystem and converts it to superheated steam which drives the turbine. The receiver is adequately shielded to protect personnel and equipment. A cavity barrier is lowered at night to conserve heat and expedite startup the following day. This volume contains the subsystem design and methodology and the correlation with the design and performance characteristics of the SRE steam generator which was fabricated and successfully tested during the program.

Vol. VI - ELECTRICAL POWER GENERATION SUBSYSTEM, CONTROLS, AND BALANCE-OF-PLANT

The Honeywell electrical power generation subsystem centers on a General Electric dual admission, triple extraction turbine generator sized to the output requirements of the Pilot Plant. The turbine receives steam from the receiver subsystem and/or the thermal storage subsystem and supplies those subsystems with feedwater. The turbine condensor is wet cooled. The plant control system consists of a coordinated digital master and subsystem digital/analog controls.

The remainder of the plant, work spaces, maintenance areas, roads, and reception area are laid out to provide maximum convenience compatible with utility and safety. Most of the activities are housed in a complex around the base of the receiver tower. This volume contains a description of the relationship of the electrical power generation subsystem to the rest of the plant, the design methodology and evolution, the interface integration and control, and the operation and maintenance procedures.

SECTION 2

SUMMARY STORAGE SUBSYSTEM DESCRIPTION

CONCEPT MECHANIZATION

Honeywell has selected a two-stage sensible heat storage system utilizing rock and oil in the main stage and an inorganic salt mixture for the super-heat storage. An artist's conception of the proposed Pilot Plant configuration is shown in Figure 2-1.

Design Basis

Honeywell originally proposed a latent heat storage subsystem and had developed a conceptual design for the pilot plant. In addition, a Subsystem Research Experiment (SRE) was designed, fabricated and assembled. Honeywell was directed to cease work on the latent heat concept and to proceed with a preliminary design based on a near-term sensible heat storage. It was determined that such a system must contain materials and equipment demonstrated by contractor SREs. Consequently, a candidate system must contain oil, rock and oil, and/or Hitec salt as the thermal storage material.

Design Basis Selection

Honeywell conducted plant performance and economic analysis to determine a basis for the heat storage mechanization. These analyses indicated that for a sensible heat system a minimum bus bar energy costs, mils/kWh (e), would be achieved when the ratio between the turbine primary and secondary

Figure 2-1. Artist's Concept of the Proposed Pilot Plant Configuration

admission port pressures were approximately 0.3. The corresponding value for a latent heat system was approximately 0.5. These comparisons are shown in Figure 2-2. The differences reflect reduced heat losses, reduced fluid makeup and the inherent capability of the latent heat system to be discharged at a higher energy level than the sensible heat systems. Based on minimum bus bar costs and turbine design considerations the best receiver operating state was determined to be 10100 kPa and 510°C. This state point is shown as the receiver inlet on Figure 2-3. To assure maximum flexibility when switching from receiver to storage-derived steam and to promote long life for the turbine and components, the storage steam is admitted to the turbine at conditions which match the resident state conditions when operating from receiver steam. This Honeywell-imposed requirement coupled with the optimum pressure ratio of 0.3 for minimum plant electrical production costs sets the storage discharge state conditions into the turbine of 3270 kPa/388°C as shown. Accounting for energy loss from storage to the turbine the state conditions at the storage discharge becomes 3620 kPa/390°C.

With the cycle conditions determined, the three candidate mechanizations shown on Figure 2-4 were evaluated. Cost comparisons shown were made on the basis of installed capital plus recurring oil maintenance and makeup costs. The oil and Hitec system did not appear to have an attractive near-term economic advantage due to the oil degradation problem. As a matter of fact, this system with the large volumes of energy-intensive oil required did not represent a significantly lower technical risk. The Partherm 450 and Taconite, while offering some potential economic and performance advantages, was not selected because these materials have not been demonstrated in a SRE program. Honeywell is reasonably satisfied that the thermocline principle has been adequately demonstrated and that the rock does not adversely influence the long-term stability of the oil at temperatures less than 304°C. Consequently, a system consisting of rock and oil in the main stage was selected.

Figure 2-2. Main Storage Design Point Selection

Figure 2-3. Mollier Diagram Turbine Admission Conditions

Figure 2-4. Cost Comparison for Three Alternative Near Term Sensible Heat Storage System for Solar Pilot Plant Application

Comparison of candidate materials for heat transfer into and out of superheater storage is shown in Figure 2-5. The comparative cost of electricity for each candidate is plotted versus the amount of superheat provided by the system. Hydro-carbon oils, although less expensive than synthetics are limited to 316°C maximum due to thermal cracking and the attendant copious make-up required. Above 316°C synthetics can be used but are extremely expensive. On the other hand the high-temperature sensible-heat capability of inorganic salts at temperatures to 482°C is free from thermal decomposition and will provide lower costs for electrical power than either synthetic or hydrocarbon oils. The latent heat salt represents a heat exchanger tube intensive system. Although it optimizes with somewhat lower plant power costs it is not cost effective for matching the turbine inlet temperature of 388°C (144°C superheat). Consequently, a superheater system consisting of Hitec or Partherm 290 designed to provide matching steam temperatures at the turbine was selected.

SUMMARY DESCRIPTION

Configuration

The Honeywell Storage Subsystem consists of two sensible heat stages. The first or main stage contains a rock and oil tank to store thermal energy and is equipped with interconnecting flow loops to transport this energy. The second stage consists of two transfer tanks equipped with interconnecting flow loops to transport this energy. Tube and shell-type heat exchangers are used to couple the storage fluid loops to the plant steam cycle for the thermal energy transfer. Figure 2-6 shows the flow schematic for the pilot plant.

Charging thermal storage is accomplished by desuperheating receiver steam for supplying the second stage and condensing and subcooling the

Figure 2-5. Superheater Storage Design Point Selection

Figure 2-6. Pilot Plant Flow Schematic

steam for main stage supply. The condensate is returned to the plant deaerator. The system, which has been designed to accept large variations in receiver steam supply conditions, has a self-adjusting steam flow control feature based on oil heat rates.

Discharging Thermal Storage is accomplished by preheating and boiling feedwater in the main stage and superheating the steam in the second stage.

During hold periods the main storage is used to supply steam to the turbine for sealing purposes and to second stage for trace heating of the salt lines and equipment to prevent freezing of the salt. Electric tracing is also provided on valves and selected equipment. Stainless steels are used as material of construction in the second stage tankage and in the molten salt loops. Low alloy and carbon steels are used on the steam charge and discharge side, respectively. Low alloy steels are used in the main storage tankage and on steam side and carbon steels in the oil flow loops.

The main tank contains a packed bed of nominal 12.7 mm (0.5 inch) diameter granite pebbles with oil flow manifolds at the top and bottom. Oil fills the voids in the bed and serves as the heat transfer medium. A single (dual-parallel for commercial) tank is possible because a thermocline is set up and this enables a high degree of temperature stratification to be

maintained in the 18 meter diameter tank. The bed height is 14.4 meters (47 feet). This is sufficient to ensure twenty hours of sealing and tracing steam during hold, accommodate the heat losses and to supply the required steam power through the second stage to the turbine. The main storage tank is charged when the outlet temperature at the lower manifold indicates 290°C (554°F). The tank is discharged when the outlet temperature at the upper manifold indicates 300°C (572°F). The energy utilization factor is 77.4 percent.

Storage Control

A total of only 13 control loops are used for the charge and discharge cycles in storage. These 13 control loops are shown in Figure 2-7 with the principal parameters needed to provide the feedbacks to these controls.

The purpose of control (C-1) is to control the temperature of the incoming steam so that it is compatible with the upper limits of the Hitec. Since sodium nitrite decomposes appreciably at temperatures over 455°C (850°F) the attemperator reduces the temperature of the incoming steam to more reasonable limits. In similar fashion, the control C-2 reduces the steam temperature to match the 316°C upper limits of the Caloria HT-43 oil.

Control C-3 is used for controlling the flow of Hitec to the second-stage storage. C-4 controls flow through the subcooler and condensate receiver as a function of receiver level. The flow of oil to storage and through the condenser is regulated by C-5.

Due to the high operating temperatures, an inert atmosphere is maintained in the oil and Hitec tanks by the controls C-6 and C-7. The control of the nitrogen to the Hitec tank is more demanding since there is flow from the hot to the cold tank and a balance must be maintained in the ullage space.

On the discharging side, control C-8 is used to regulate the flow through the preheater and boiler. In similar fashion the Hitec flow through the superheater is controlled by C-9.

Boiler drum level is maintained by C-10 and C-11. Under normal demand, the C-10 control regulates the flow of feedwater while under very low demand, the auxiliary system C-11 is used.

Figure 2-7. Pilot Plant Control Loop Scheme

The Hitec eutectic salt freezes at 142°C. Therefore, external heating is required to maintain the salt in a molten state. In order to provide this heat to the lines, pumps and Hitec storage tanks, steam from either the receiver or the main storage sealing and tracing system is used. Control C-12 regulates the flow of this steam to the various units as a function of pressure. This pressure should enter the pump housing and heating lines at pressures not over 1720 kPa.

The last control (C-13) is used to regulate the oil to the maintenance unit.

For all of the control loops described, the control valves, positioners, electronic controllers and other components have been carefully selected. Valves with the proper valve coefficients, high temperature steels and pneumatic controllers have been identified for each circuit. Controllers have the proportional, integral and summing characteristics included in the electronic amplifiers that drive the pneumatic actuators. The use of proportional, set points, integral control and summing provides the necessary long-term stability for all the subsystems. Control philosophy has been verified in a computer simulation of the charge and discharge system.

Data Acquisition

The major goals for the pilot plant regarding data acquisition are (1) to acquire data that will permit commercial plant specification; and (2) to determine how and to what extent the commercial plant ought to be automated.

The data acquisition and computing equipment required for thermal storage is designed into the master computer system at the plant central control; similarly, for the applicable software. This system will accumulate both process and test data over a two-year period, and will be used to verify predicted performance and in particular to evaluate the oil/rock thermocline storage concept.

Instrumentation

The thermal storage system instrumentation consists of standard off-the-shelf, highly reliable electronics for process and test purposes. The transmission of signals to data acquisition has been configured to both minimize personnel troubleshooting and implementation costs. The oil/rock tank instrumentation incorporates a unique scheme for reference junction compensation, conditioning and linealizing of some 500 thermocouple signals and transmitting signals over a single twisted pair line directly to the data acquisition computer for off-line data reduction. Implementation of this scheme includes a data logger and serial multiplexer and incorporates either local or remote operation, variable sampling rates, and hardcopy printout.

The process instrumentation is designed and configured to condition most low-level signals to 4-20 ma outputs prior to transmission. This feature allows maintenance flexibility for the routing and distributing of signal lines. Also, long cable runs are kept to a minimum where possible so that junction boxes provide access to signals and circuits.

For the pilot plant, both process instrumentation and special test instrumentation is implemented to provide sufficient data to fully determine and understand the performance and dynamics of the concept of oil/rock and Hitec storage and discharge capability. The express purpose here is for building and operating a cost-effective commercial plant in the future.

Fire Protection

The ability to rapidly detect and contain fires in a utility environment is of paramount concern.

A most unique state-of-the-art but proven fire protection system has been designed for both pilot and commercial plants. This consists of ultra-violet (UV) detectors for virtually "instantaneous" response to flame detection. The detectors provide the signals to operate a "light water" agent fluorochemical proportioning system.

The "light water" foam concentrate is a fully biodegradeable chemical and is soluble in water for maintenance and cleanup. Upon activating the proportioning system mixes water and agent in a 97 percent to 3 percent ratio, respectively, and has the capacity for 65 lit/s application for the pilot plant.

MAJOR DESIGN FEATURES

The Honeywell Thermal Storage Subsystem Configuration selection was the result of many tradeoffs and considerations. Table 2-1 lists the most significant ones, also discussed in the succeeding paragraphs.

Design Scaling

The objectives of the solar pilot plant are to 1) establish the technical feasibility of a solar thermal power plant of the central receiver type with significant commercial potential, and 2) to obtain sufficient development, production and operating data to indicate the economics operation for commercial power plants of similar design. This requires similitude in terms of design, performance and cost.

Figure 2-8 shows the design for the pilot plant and Figure 2-9 the 100 MW(e) commercial plant. The P.P. boiler/condenser heat exchanger sizes approach the largest single module that is economically truck transportable. Units

Table 2-1. Design Selection

Consideration	Honeywell Storage Configuration Feature
Scaling pilot plant results	<ul style="list-style-type: none"> • modular heat exchangers • scale for capacity • adequate data collection
Low capital and operating costs	<ul style="list-style-type: none"> • rock and oil main storage • 10,100 kPa/510°C charge and • 3620 kPa/390°C discharge cycle
Steam switching capability	<ul style="list-style-type: none"> • matching turbine admission at design • inorganic salt superheater storage
Flexible operating strategies	<ul style="list-style-type: none"> • simultaneous charge and discharge • variable charge capacity
Development risk	<ul style="list-style-type: none"> • Standard equipment
Thermal cycling of tankage	<ul style="list-style-type: none"> • below ground superheater tanks • low alloy steel knuckle design to avoid thermal ratcheting of rock and oil tank
Main storage packed bed and design and performance	<ul style="list-style-type: none"> • developed modeling technique • utilization efficiency of "used" bed
Storage control and automation	<ul style="list-style-type: none"> • analog/digital hybrid control
Oil degradation at temperature	<ul style="list-style-type: none"> • oil distillation

Figure 2-8. Thermal Storage Subsystem Commercial Plant Design

Figure 2-9. 100 MW_e Commercial Pilot Plant with Pilot Plant Overlay (Black)

significantly larger than this would required special design for transport, assembly and testing at the site.* The boiler size is limited by the transportable weight and cost for the high-pressure shell and the condenser by the maximum transportable length and cost of the high-pressure tube bundle. Therefore, the most economical commercial plant configuration would contain eight boilers and six condensers of approximately the pilot plant size. The other heat exchangers, at the pilot plant scale, are somewhat smaller than the required economic size for the commercial plant. Therefore these units will be scaled up for capacity. Likewise the tankage is simply scaled up to obtain the required capacity. Dual tanks are used in the 100 MW(e) commercial plant since a tank 34.8m in diameter is the maximum size rock tank size based on low-cost available manufacturing techniques and field heat treating practices. In all cases when scaling is required it is absolutely necessary to conduct rigorous engineering design and performance tests so as to collect sufficient data to specify these scaled-up equipments.

Capital and Operating Cost

Honeywell is convinced that, when viewed in terms of the commercial plant, the rock and oil sensible-heat main storage will produce the lowest bus bar energy costs from among the near-term alternatives. Plant economic studies have indicated that turbine operating cycles of 10100 kPa/510°C (1465 psia/950°F) and 3270 kPa/388°C (475 psia/730°F) for primary and secondary admission conditions results in the most favorable overall capital and annual energy costs.

*An additional important factor is the maintenance required and in pulling of the tubes bundle for inspection or cleaning.

Steam Switching Capability

To take maximum advantage of thermal storage it must not only be ready at a moment's notice but also be able to pick up a portion or all of the turbine load in a matter of seconds. When operating the turbine from receiver steam the state conditions at the storage admission port are as follows:

Receiver Flow	<u>Storage Admission</u>	
	Temperature	Pressure
100% of design	390°C	3620 kPa
50% of design	410°C	3620 kPa
25% of design	443°C	3620 kPa

Honeywell's approach for instantaneous transfer is to match the turbine secondary admission conditions with storage steam at the design flow. When switching the turbine from receiver steam in a deep throttle position to thermal storage steam the temperature mismatch will not exceed 56 C° (100 F°). The turbine manufacturer has indicated that this degree of temperature matching will give long-life turbine performance.

The amount of superheat required to accomplish this is approximately 142 C° (255 F°). The most cost effective, near-term sensible-heat storage material for this is an inorganic salt mixture referred to as Hitec or Partherm 290. This material has been selected for the Thermal Storage Second Stage.

Flexible Operating Strategies

One of the major goals for the operation of pilot plant is to evaluate the usefulness of alternative modes in determining storage requirements for commercial plants. For example, during periods of intermittent cloud cover it may be determined that the plant should be operated in a storage-following mode. In this case all the receiver input would be run through storage. Consequently, storage will be simultaneously charging and discharging.

The variations in heat rate capability of the Receiver steam generator from sunrise to sunset dictate that the storage charging system accept a wide range of inlet conditions. Honeywell has designed a charging system that will handle a variable charge to full charge as specified. This is evident in proper attemperatur design. This same system can also accept low-grade steam in either pressure or temperature if at reduced flows.

Development Risk

In order to demonstrate the viability of central receiver solar power for the near term it is necessary to minimize the risks associated with its development.

Honeywell's approach to help achieve this goal is to select standard, proven hardware. The tankage, heat exchangers, pumps, valves and transducers were all selected with this in mind.

In addition, packaged units for usage, oil and salt maintenance were used based on the industry's long-standing experience in providing such low-maintenance, high-performance equipment.

Thermal Cycling of Tankage

Undue material stresses and metal fatigue can result from improper design of the storage tankage. Daily charging and discharging of storage poses severe temperature cycling conditions on the superheater storage tankage. Below-ground storage of the two tanks provides not only the best economical and technical solution for minimizing temperature cycling but assures safe separation of oil and salt in the event of a spill.

The main oil and rock tank design is predicated on avoiding thermal ratcheting. This phenomenon would manifest itself after repeated cooldowns from operating temperature to ambient. Honeywell has selected a high-yield strength low-alloy tank material which will preclude thermal ratcheting and allow repeated cooldowns over its design service life.

Main Storage Bed Design and Performance

Transferring heat to or from a fluid stream to beds of broken solid materials is one of the commonest of industrial processes. Honeywell has taken advantage of the wealth of technical data from the literature and has developed a mathematical model to approximate the processes taking place in the main storage packed bed of granite pebbles. This model is deemed to be completely adequate for specifying this design. Using this model Honeywell was able to run a large number of charge, discharge and hold modes with sealing and tracing steam flow and has determined the proper bed design conditions to meet the specification for a 30-year operating life.

Storage Control and Automation

A basic question to be resolved in the pilot plant is to what degree should storage control be automated? To help solve this problem Honeywell has provided both the standard analog loops process control and a digital data acquisition system for collecting the requisite engineering data for equipment evaluation. These two necessary elements, when coupled together, serve a unique purpose - the means to determine the amount of automatic control.

Oil Degradation at Temperature

One of the factors that influenced the selection of rock and oil over oil alone was the lower expected installed and operating costs due to the smaller size of the system and the volume rate of oil replacement. However, Honeywell is concerned about the lack of quantitative long-term, large bulk test data on the degradation of oils over the expected operating temperature range and the influence of rocks and metals at those temperatures on the stability and behavior of the selected oil. Although Honeywell has not performed any significant testing on these oils, many industrial and laboratory contacts were made to keep abreast of available ongoing testing. Considering the uncertainties stated above and in the interest of maintaining a low-risk profile in all critical areas Honeywell has taken a conservative design approach for the pilot plant.

This requires that the design be based on the more severe oil degradation data documented in the technical literature. Although, this may result in a higher level cost for the pilot plant, it seems to reflect the purpose of the pilot plant more accurately.

DESIGN CHARACTERISTICS AND PERFORMANCE

The thermal storage design and performance characteristics are summarized in Tables 2-2 and 2-3 for the pilot and commercial scale plants.

Design Characteristics (Refer to Table 2-2)

Approximately 83 percent of the storage capacity is allocated to the main stage and 17 percent to the second stage. Caloria HT-43, an aliphatic petroleum oil, was selected as the main-stage heat-transfer fluid. This selection was based on the results of the testing at Sandia Laboratories¹ and from information supplied by McDonnell-Douglas and Martin Marietta. Granite rock pebbles nominally 12.7mm in diameter meeting ASTM grade 6 are the packed bed material. A mixture of inorganic salts consisting of 7% NaNO_3 , 53% KNO_3 and 40% NaNO_2 melting at 142°C (288°F) is the heat-transfer fluid for the superheater or second stage.

Either Hitec or Partherm 290 are the industrial products which satisfy the design requirements.

The operational readiness or availability has been estimated to be 0.985. The mean time between failures is 1094 hr and the mean time to repair is 14.8 hr. Refer to Appendix F for details.

The heat loss rate of 5 percent per day from storage is broken down as shown on Table 2-4.

The difference in sealing and tracing steam requirements for the pilot and commercial plants reflects economy of scale.

¹Communication from Mr. Barolla of Sandia Livermore Labs.

Table 2-2. Thermal Storage Baseline Characteristics - Design

Parameter	Pilot Plant	Commerical Plant
Storage Capacity, MWH(t)	133	961
Main Storage, MWH(t)	116	831
SH Storage, MWH(t)	17	130
Main Storage Media	Caloria Oil/Rocks	Caloria Oil/Rocks
Operational Availability	98%	98%
SH Storage Medium	Hitec Salt	Hitec Salt
Main Storage Tankage-Quantity	One	Two
Diameter, Meters	18.3	34.8
Wall Height, Meters	14.6	14.6
SH Storage Tankage	Two cylindrical tanks with dished heads - below ground.	
Diameter, Meters	6.1	12.2
Wall Height, Meters	4.9	9.8
Heat Loss Rate, %Capacity/Day	5	5
Operating Temperatures		
Main Storage, °C	303→249	303→249
Min. Oil Temperature When Charged, °C	300	300
Discharged, °C	249	249
SH Storage, °C	454→299	454→299
Sealing & Tracing Steam, % of Capacity	6.0	2.3

Table 2-3. Thermal Storage Baseline Characteristics - Performance

Parameter	Pilot Plant	Commercial Plant
Net Elect. Output, MW(e)	7.0	70.0
Duration, hours	3	3
Charge P/T, kPa/°C	1010 ⁰ /510	1010 ⁰ /510
Discharge P/T, kPa/°C	3620/390	3620/390
Gross turbine H. R. WH(t)/ WH(e)	3.512	3.145
Gross thermal efficiency	0.285	0.318
Net thermal efficiency	.221	.291
Max. Discharge Rate, MW(t)	31.6	284.5
Gross Charge Input Rate, MW(t)	37.7	247.3
Max. Charge Rate, MW(t)	31.6	207.2
Charge Efficiency	0.838	0.838
Thermocline Utilization Efficiency-MS (including 20 hours of hold)	0.774	0.774
Feedwater Temperature, °C	205	190.5
Feedwater Flow, kg/h	49,025	411,135

Table 2-4. Thermal Storage Heat Losses
(Percent per 100 hour basis)

Item	Percentage of		
	Main Storage Capacity	Superheater Storage Capacity	Total Capacity
Tankage	11.6	16.9	12.3
Piping	3.2	6.4	3.6
Heat Exchangers	2.5	2.7	2.5
Steam Lines	1.4	9.6	2.4
TOTAL	18.7	35.6	20.8

The minimum oil temperature at main storage charge outlet when fully charged corresponds to a charge time of approximately four hours based on a constant oil flow rate and condenser outlet temperature. The minimum oil temperature of 290°C at main storage discharge outlet when fully discharged corresponds to 3 hours, based on a constant heat rate. The condenser and subcooler design is based on initial maximum heat rate and the boiler and preheater are sized to handle the end point condition.

Table 2-5 lists the materials of construction for the thermal storage.

Table 2-5. Materials of Construction

	Main Storage	SH Storage
Tankage & Columns	low alloy steel (SA-533 Class II)	stainless steel
Heat Exchangers	carbon & low alloy steels	stainless steel
Piping	carbon & low alloy steels C.S. /L.A.C.S.	stainless steel
Insulation	Foam Glass	Foam Glass

Performance Characteristics (Table 2-2)

The Pilot Plant Thermal Storage will produce 7 MW(e) net for three hours after 20 hours of hold. During the hold time storage will provide 680 kg/h at 239 kPa and 121°C for turbine sealing and second-stage tracing. The net storage thermal efficiency will be 22%. The gross thermal-to-electrical energy conversion (gross turbine heat rate) ratio is 3.512 kWh (t)/kWh(e). The maximum discharge rate from storage is 31.6 MW(t). Main storage contributes 83 percent and the superheater stage supplies the rest. The estimated maximum time from hot standby to rated power is less than one minute. Return to standby can be achieved in approximately the same time.

The Pilot Plant Thermal Storage can be charged in approximately four hours. The charging efficiency with the subcooler is 83.8 percent, based on a gross charge input rate from the Receiver of 37.7 MW(t). This level of efficiency represents a minimum plant installed and operating cost.

The thermocline utilization efficiency, based on a 3-hour discharge preceded by 20 hours of sealing and tracing steam with an end-point temperature of 300°C and a nominal 4-hour charge with an end-point temperature of 290°C, is 77.4 percent which is equivalent to a charge utilization efficiency of 98 percent, with a growth of 3% during discharge.

The feedwater temperature variation with boiler feed pump mass flow is given in Figure 2-10 for steady-state conditions.

In the plant operating modes in which the turbine is being driven by steam from the receiver or thermal storage, the temperature and mass flow of the feedwater indicated by the curve labeled "Receiver and/or Thermal Storage Driving Turbine" are the appropriate values at the inlet to the receiver or thermal storage, respectively. For example, if the receiver alone is supplying 18,181 kg/hr of steam to the turbine, the temperature of the feedwater supplied to the receiver drum is 157°C.

For the turbine operation on receiver and thermal storage steam simultaneously, the feedwater temperature at the inlet to the receiver and thermal storage is determined on the basis of the total steam flow to the turbine (throttle plus admission). For example, if the receiver is supplying 18,181 kg/hr of steam to the turbine and thermal storage is simultaneously supplying 27,273 kg/hr of steam to the turbine, the temperature of the feedwater supplied to the receiver drum and to the thermal storage boiler inlet is 202°C corresponding to the booster pump flow of 45,455 kg/hr.

Figure 2-10. Feedwater Temperature versus Feedwater Flow

In the plant-operating mode of the receiver-charging thermal storage with the turbine in the standby mode, the temperature of the feedwater entering the receiver drum is 172°C and does not vary with feedwater flow over the range indicated in the figure.

In the plant-operating mode of the receiver charging thermal storage while the turbine is being driven by receiver steam and/or thermal storage steam, the feedwater temperature at the inlet to the receiver or thermal storage corresponds to a point in the shaded area of the curve at the mass flow of the booster pump. The precise temperature is determined by the relative amounts of steam charging storage and driving the turbine. The feedwater temperature corresponds to the value indicated on the curve labeled "Receiver and/or Thermal Storage Driving Turbine" at the feedwater flow corresponding to the total (throttle plus admission) steam flow to the turbine.

SECTION 3

DETAILED SUBSYSTEM DESCRIPTION

PILOT PLANT PRELIMINARY DESIGN

The Honeywell Thermal Storage Subsystem design is responsive to all requirements and specifications as they are understood.

The preliminary design described in this section is the precursor of large scale commercial power plant thermal storage systems of the near future.

The design elements are shown on Figure 3-1. These 13 hardware oriented elements are described in subsequent paragraphs and sections. The commercial plant consists of the same elements but with different numbers or sizes of equipment.

Subsystem Site Plan

The thermal storage subsystem equipment is located within the Central Plant complex in the northeast section as shown on Figure 3-2. Equipment controllers and data acquisition terminals are located in the control and computer rooms respectively. Inorganic salts and spare items will be stored on pallets in the General Services Building. The turbine building will contain the mechanical and electrical repair shop, where overhaul and repair of selected equipments will be performed.

The storage equipment site plan is shown on Figure 3-3. Approximately 372 m² are required to contain this equipment. The storage equipment is located outside the area 20 m from the center of the tower to preclude

Figure 3-1. Thermal Storage Subsystem Design Elements

3-3

Figure 3-2. Central Plant Complex

Figure 3-3. Storage Equipment Site Plan

interference between the tower foundation and storage tank foundation. A foundation separation distance of 1.5 m is maintained to minimize the influence of adjacent structures on storage tank heat loss. A berm, completely isolating the oil/rock storage tank, is sized to contain all of the oil. A low area drain will enable spilled oil to be returned to the makeup oil storage tank where it can be pumped into mobile trailer trucks for temporary storage. In the event that the spill involves hot oil, a fire may ensue. The fire protection system provides automatic dispensing of light water foam on the tank and within the berm. The light water foam is biodegradeable and this will greatly simplify the post spill cleanup process. Notice that the inorganic salt (HITEC) storage tanks are located on the opposite end of the storage field and are below ground. The hot oil and hot salts are not compatible and present a general safety hazard. However, with such an arrangement, the personnel and equipment safety is assured for all except the most devastating ground zero earthquakes, well beyond the design level. The heat exchangers are arranged and spaced to allow the tubes to be pulled for inspection and maintenance.

Fluid lines to the central complex from storage are on a line approximately 35 degrees east of north, 2.4 m above grade. Power distribution and control signal lines will be routed below ground to the Local Control Station. The Local Control Station contains switchgear, a status panel and annunciator panel and local controls for operating/securing various equipment for maintenance or for special tests.

Materials of Construction -- The materials used in all the storage equipments are of common, commercially available types. No exotic materials are required for construction. The structural materials are mild, low alloy and stainless steels. Table 3-1 shows a summary of these material types for the major equipments. The basis for selection of major use materials is discussed below.

Table 3-1. Thermal Storage Subsystem Materials of Construction

Equipment/Item	Material of Construction
<u>Rock & Oil Tank</u>	
Shell & Bot. w/knuckle	A533 Class 2 Grade A
Top (top knuckle)	A516-60
Nozzle Neck A106	Flange A105
Manway Neck A106	Flange A516-60 Cover A516-60
Reinforcing Pads	A533 Class 2 Grade A (A516-60)
Couplings	A105
Bolting	Bolts A193-B7 Nuts A194-2H
Gaskets	Compressed Asbestos
Structural	A36
Electrodes (welding)	E9018-D1 A533 Class 2 Grade A E60XX or E70XX A516-60
<u>Hitec Tank</u>	
Shell	A240-304
Heads	A240-304
Nozzle	Neck A312-304 Flange A182-F-304
Manway	Neck A240-304 Flange A240-304 Cover A240-304
Reinforcing Pads	A240-304
Stiffener Rings	A240-304
Bolting	Bolts A193-B8 Nuts A193-8
Gaskets	Compressed Asbestos
Structural	A276-304
Electrodes (welding)	E308

Table 3-1. Thermal Storage Subsystem Materials of Construction (Continued)

Equipment/Item	Material of Construction
<u>Pumps</u>	
Main Oil Pumps	
Casing	STL
Impeller	CI
Case Rings	Iron
Pump Shaft	STL
Shaft Sleeve	316-SS
Packing Gland	S & I
Base Plate	C. I.
Coupling	Falk
Coupling Guard	S & I
Stuffing Box Sealing	S & I 240
Main Hitec Pumps	M & I Class 50
Casing	316 - SS
Impeller	316 - SS
Case Rings	316 - SS
Pump Shaft	316 - SS
Shaft Sleeve	316 - SS
Packing Gland	316 - SS
Base Plate	S & I
Coupling	Falk
Coupling Guard	S & I
Stuffing Box Sealing	Graph Oil

Table 3-1. Thermal Storage Subsystem Materials of Construction (Continued)

Equipment/Item	Material of Construction
<u>Heat Exchangers</u>	
Item No. HE-1 (Charging Hitec)	
Tubes	304 ss welded
Shell	304 ss
Bonnets	304 ss
Tube Sheets	304 ss
Baffles	304 ss
Item No. HE-2 (Charging Oil Condenser)	
Shell	Carbon Steel (CS)
Tubes	A204 CS welded
Bonnets	CS
Tube Sheets	CS
Baffles	CS
Item No. HE-3a (Oil Discharge (preheat))	
Shell	CS
Tubes	A204 CS welded
Bonnets	CS
Tube Sheets	CS
Baffles	CS
Item No. HE3b (Oil Discharge Boiler)	
Tubes	A204 CS (welded)
Shell	CS
Bonnets	CS
Tube Sheets	CS
Baffles	--

Table 3-1. Thermal Storage Subsystem Materials of Construction (Continued)

Equipment/Item	Material of Construction
Item No. HE-4 (Hitec Discharge)	
Tubes	304 ss welded
Shell	304 ss
Bonnets	CS
Tube Sheets	304 ss
Baffles	304 ss
Unit (Subcooler)	
Tubes	304 ss A249
Shell	CS
Bonnets	CS
Tube Sheets	CS
Baffles	CS

Salt Storage, Heat Exchanges, Charge and Discharge Flow Loops -- The compatibility of Hitec salts with materials of construction has been documented by M. D. Silverman and J. R. Engle¹. For operation at temperatures less than or equal to 450°C practically all systems containing Hitec have been built of carbon steel and the corrosion rates, although relatively high (less than or equal to 0.12 to 0.25 mm/yr), have been tolerated because of short equipment depreciation schedules. However, at temperatures greater than 450°C the corrosion rate for Hitec in carbon steel rises appreciably and is considered unsatisfactory for long term operation. This necessitates the use of stainless steels for containment and transfer. Some Russian data² obtained from 700 hour tests at 500°C with a stainless steel (0.1%C, 18%Cr, 9%Ni and a small percentage of Ti) yielded a corrosion rate of 0.06 mm/yr. However, it was found that under stress this type of steel was subject to intergranular corrosion. More recent Russian work³ showed

specimens, of another stainless steel (18%Cr, 10%Ni and a small amount of Ti) exposed to Hitec at 500°C for 600 hours. This same steel was used in open air plant baths for more than four years at 450 to 500°C with essentially no corrosion damage. The Honeywell design operates in the range of 299°C to 454°C and the Hitec is maintained under a blanket of inert atmosphere (nitrogen). The Russian data on corrosion rates would be acceptable for a 30-year depreciation schedule. Therefore, a stainless steel of type 304 will be used. ASTM material specifications will be selected based on the specific application in the system

Main Storage Tank -- This tank, being filled with granite rock, must withstand the deep thermal cycling that may be encountered over its lifetime. Diurnal variations during charge and discharge of 56°C (100°F) are of no particular concern. However, cycling from 316°C to ambient is of concern because of the thermal ratcheting that will take place. To avoid this a high yield strength, weldable material must be used. The material selected is ASTM A533 Grade A Class 2 with $F_y=405$ MPa at 316°C and $F_y=482$ MPa at 20°C.

Design, Construction Testing Codes -- Consideration has been given to relevant local, state and national codes in the design and construction of the thermal storage subsystem. In addition, certain standards, guides and regulations are employed based on long standing industrial experience. Equipments will be designed, constructed and tested in accordance with appropriate sections of the documents shown on Table 3-2.

Piping and Instrumentation

Figures 3-4 and 3-5 show the piping and instrumentation required for the pilot plant. Table 3-3 gives the list of symbols used in the diagrams.

Table 3-2. Equipment Design Construction and Test Codes

Item	Governing Document											
	ASTM	ASME	TEMA	NEMA	ISA	API	OSHA	UBC	NEC	AINS	ANSI	ASA
Heat Exchangers	II VIII	C VIII	C						X			
Piping, Flanges and Fittings	X	II				X	X				X	X
Storage Materials	X						X	X				
Foundations	X					X						
Tankage		II				620 650	X	X				
Columns		II VIII					X	X				
Pumps	X	X				X	X					
Motors				X					X			
Electrical							X	X	X			
Welding							X			X		
Instruments					X							

The design of the piping for the system is based on the applicable codes of the Power Boiler Section of the ASME Boiler Code, the ASA code for Pressure Piping, ASTM and API codes. The maximum allowable working stress vs temperature is determined for all piping applications. The corrosion allowance was 1.65 mm (0.065 inch). The pressure to stress ratio was determined for piping wall thickness. Piping tests and data sheets are given in Section 6. Piping thermal expansion will be accomplished by piping flexibility and expansion joints will be minimized. All piping systems will be insulated and jacketed with flashing. The piping will be supported above ground in pipe racks with rollers and anchors. The various elements given on this diagram are described in succeeding paragraphs and sections of the document.

Figure 3-4. Piping and Instrument Diagram - Main Storage

Table 3-3. Piping and Instrumentation Diagrams - Nomenclature

The succeeding symbols, terms, and acronyms refer to those used specifically in the accompanying Piping and Instrumentation Diagrams, and Electrical Site Plan and One-Line Diagrams.

<u>Symbol/Term/Acronym</u>	<u>Explanation</u>
PT	Pressure transmitter including the sensor element (4-20 ma output).
TT	Temperature Transmitter 4-20 ma output).
TE	Temperature element - the hot junction weld of the thermocouple.
TW	Temperature element test well - for insertion of and protection of the temperature element.
FE	Flow element consisting of a calibrated orifice plate and flange assembly.
FT	Flow transmitter (4-20 ma output).
LT	Level transmitter - includes the level sensor, hardware, and associated electronics for 4-20 ma output.
ACV	Automatic Control Valve, pneumatically operated, electrically actuated (proportional-type).
GV	Gate Valve - solenoid operated.
LI	Level indicator and readout (in local control or on-site)
HLA	High level alarm.
LLA	Low level alarm.
FI	Flow indicator (in local control or on-site).
PI	Pressure indicator (in local control or on-site).
TI	Temperature indicator (in local control or on-site).
MDP	Main discharge pump
MCP	Main charge pump

Table 3-3. Piping and Instrumentation Diagrams -
Nomenclature (Continued)

<u>Symbol/Term/Acronym</u>	<u>Explanation</u>
AMDP	Auxiliary main discharge pump
HCP	Hitec charge pump
HDP	Hitec discharge pump
HDCV	Hitec discharge control valve
LBP	Low boiler pump
MOP	Makeup oil pump
OMRP	Oil makeup reboiler pump
ROP	Reboiler oil pump - condenser
OMP	Oil main pump
HH	Hand holes
TC1	Terminal cabinet number 1
TC2	Terminal cabinet number 2
J	Junction box
CONT	Control
RCD	Record
CMP	Computer
ATT	Attemperator
Locally mounted mechanical device
Locally mounted electronic device sensor
Locally mounted pneumatic, solenoid or proportional device
Locally mounted electronic transmitter
Gate valve or isolation valve - manual
Globe valve
Safety or relief valve
Motor operated valve

Table 3-3. Piping and Instrumentation Diagrams -
Nomenclature (Continued)

<u>Symbol/Term/Acronym</u>	<u>Explanation</u>
Solenoid operated
Diaphragm operated valve
Automatic proportioning control valve - diaphragm operated
Strainer, duplex basket type
Trap

Tankage and Foundation

Superheater Storage -- Thermal design based on system tradeoff studies it was determined that the superheater storage would use the sensible heat in an inorganic salt mixture such as Hitec or Partherm 290 over the temperature range of 293°C to 454°C. To charge and discharge the storage two separate tanks are required to effect the transfer. A single tank containing rocks or taconite and utilizing the thermocline principle was reviewed. This approach may offer significant attractive features and represents a potentially lower installed cost system. However, the compatibility of these materials at the operating temperature is unknown and no SRE configurations were tested. Therefore, the dual tankage using the sensible heat in the inorganic salts was selected.

Thermal analysis revealed that during diurnal operations the temperature in the empty molten salt tank would decay to ambient in less than 20 hours. This analysis is shown on Figure 3-6. This deep thermal cycling must be avoided to insure long term structural integrity of the tankage and eliminate the need for continuous tracing on the tank to prevent freezing the salt

Figure 3-6. Temperature Decay in Hitec Tanks

mixture (143°C). These conditions coupled with safety and earthquake considerations dictated that the tankage be placed in a vault below ground. This represents the most cost-effective solution for the design. The vault area general arrangement with the tankage in place is shown in Figure 3-7. The section view given in Figure 3-8 shows the roof structure to support the insulation modules. These modules can be removed and then tanks can be installed or removed as required.

Heat Loss from Hitec Storage --

- Storage Pit Dimensions -- 7.6 mW x 14.6 mL x 9.1 mD (25' W x 48' L 30' D)
- Hot Storage Tank Temperature -- 454°C (850°F)
- Cold Storage Tank Temperature -- 299°C (570°F)

Figure 3-7. Molten Salt Storage Vault

Figure 3-8. Molten Salt Storage Vault Section View

● Soil Thermal Conductivities (*)

<u>Soil Type</u>	<u>W/M°C</u>	<u>Btu/hr ft°F</u>
Soil, dry	0.13	0.08
Soil, dry plus stones	0.5	0.3
Sand, dry	0.33	0.19
Gravel	0.38	0.22
Earth plus 42% water	1.0	0.6

To obtain an order-of-magnitude estimate of the heat losses, each half of the pit (the hot tank and cold tank areas) was approximated by a right circular cylinder of equal inside area. A closed form solution for heat loss from a cylinder buried in a semi-infinite media (the earth) is presented in Reference 4.

$$q = \frac{2\pi}{\ln(4L/D)} KL (T_1 - T_S)$$

where:

D = diameter

L = length

K = soil thermal conductivity

T₁ = cylinder surface temperature

T_S = earth surface temperature

ln = natural logarithm

Assuming that the inside wall of the pit is the same as the tank temperature and that the soil conductivity is 0.5 W/m°C (0.3 Btu/hr ft°F):

* Mark's Handbook, 7th Edition.

$$Q_{\text{LOSS}}^{\text{(Hot tank)}} = \frac{2\pi}{\ln(4(9.1)/9.51)} \cdot 0.5(9.51)(454 - 0)$$

$$Q_{\text{LOSS}}^{\text{(Hot tank)}} = 10.1 \text{ kW} \quad (34,500 \text{ Btu/hr})$$

$$Q_{\text{LOSS}}^{\text{(Cold tank)}} = 6.7 \text{ kW} \quad (2,300 \text{ Btu/hr})$$

The above solution assumes no loss through the cover of the pit. Here it is assumed that 0.6 m (2 ft) of insulation will be used having a K value of 0.087 W/m²°C (0.05 Btu/hr ft°F).

$$Q_{\text{LOSS}}^{\text{(Cover)}} = KA(T - T_s)/X$$

$$Q_{\text{LOSS}}^{\text{(Hot tank)}} = 0.081 \text{ W/m}^2\text{°C} (55.7 \text{ m}^2) (454 - 0)^{\circ}\text{C} / .6 \text{ m}$$

$$Q_{\text{LOSS}}^{\text{(Hot tank cover)}} = 3.7 \text{ kW} \quad (12,600 \text{ Btu/hr})$$

$$Q_{\text{LOSS}}^{\text{(Cold tank cover)}} = 2.4 \text{ kW} \quad (8,200 \text{ Btu/hr})$$

The hot tank also loses heat to the cold tank through the insulated partition. The hot tank and cold tank exchange heat with the opposite surfaces of the partition mainly by radiation. Assuming tank and partition emittances are equal to 0.9, the iterative solution results in a heat transfer rate of 4.5 kW (15,400 Btu/hr).

The net heat losses from the hot tank and cold tank are obtained by summing the energy losses through the walls and the cover.

$$Q_{\text{L Hot}} = 0.75 Q_{\text{L (Soil)}} = Q_{\text{L (Cover)}} + Q_{\text{L (Cold tank)}}$$

The hot and cold tanks have one wall in common hence they lose only 0.75 of the energy to the soil as a single cylinder would, which was the result of the first calculation.

$$\begin{aligned} Q_L (\text{Hot}) &= 0.75 (10.1 \text{ kW}) + 3.7 \text{ kW} + 4.5 \text{ kW} \\ &= 15.8 \text{ kW} (53,800 \text{ Btu/hr}) \end{aligned}$$

$$\begin{aligned} Q_L (\text{Cold}) &= 0.75 (6.7 \text{ kW}) + 2.4 \text{ kW} - 4.5 \text{ kW} \\ &= 2.9 \text{ kW} (10,000 \text{ Btu/hr}) \end{aligned}$$

The point of concern is how cold could the cold storage tank get if the hot storage tank was kept at 454°C (850°F). Since all of the heat transfer rates are linear functions of temperature the calculation is relatively straight forward. (The radiant transfer coefficient accounts less than 5 percent of the total temperature difference between the hot and cold tanks). The equilibrium temperature of the cold tank would be 246°C (475°F). This is above the freezing point and consequently the hot tank will supply sufficient heat to maintain the cold tank above 475°F (246°C).

No consideration has been given to the thermal response time of the system when the heat capacity of the soil is considered. That calculation would have to be done numerically based upon measured or assumed soil properties and an assumed time temperature history for charging the Hitec tanks.

A comparative heat loss calculation was made to compare heat loss for insulated tank above grade with the below grade tanks.

$$\text{Area of tanks } 152 \text{ m}^2 \text{ each}$$

$$Q_L (\text{Hot tank}) = 15.8 \text{ kW}$$

$$\text{Insulation k value} = 0.0865 \text{ W/m}^\circ\text{C}$$

Equivalent Thickness $X = KA (T - T_a)/Q$

$$X(\text{Hot tank}) = 0.0865 \text{ W/m}^\circ\text{C} (152 \text{ m}^2) (454 - 0)^\circ\text{C}/15800 \text{ W}$$

$$X = 0.3778 \text{ m (1.25 ft)}$$

$$X(\text{Cold tank}) = 0.0865 \text{ W/m}^\circ\text{C} 152 \text{ m}^2 (300 - 0)^\circ\text{C}/2900 \text{ W}$$

$$X = 1.36 \text{ m (4.46 ft)}$$

Structural Design -- A detailed structural analysis of the molten salt storage tank for the pilot plant is contained in Appendix G. The resulting design is shown in Figure 3-9. The earthquake requirements as specified for the Barstow, California area were analyzed using NRC Guide 1.60 for determining the response spectra. Analyses using TID-7024 and UBC were compared and it was determined that TID-7024, the dynamic approach, governed. API 620 code was used with allowable stresses from ASME Section VIII Div. 1. Data on material compatibility⁵, strongly suggests that a stainless steel like type 304 be used. Since no long term corrosion data is available for molten salt and low alloy steel, 304 stainless steel was selected.

The salt tank roof is a spherical dome butt welded to an L2 1/2 x 2 1/2 x 1/4 compression ring located at the top of the cylinder and an 8" x 8" tee plate compression ring at the base of the cylinder to resist the buckling loads. A two course shell is used and an extended full cylindrical skirt transmits the loads to the base ring. The skirt is also 304 ss to eliminate stresses due to differential thermal changes. A machined base ring rides on a lubrite bearing spacer and slotted holes in the ring allow for tank radial growth. The lubrite material is a manganese bronze ASTM B 147 (8B). Sixteen two-inch anchor bolts hold the tank to the foundation.

Figure 3-9. 20' x 18' High Hitec Tank

Main Storage Tankage -- This design considers earthquake, wind, thermal cycling and product loads encountered during startup, operation on a day-to-day basis, shutdown, draining and safe emergency shutdown during seismic disturbances. The design for earthquake loads is based on the UBC which is a more conservative type of analysis than the TID-7024 type analysis. The design for wind loads to 110 mph assures that the tank and shell remain stable. The design for diurnal and deep thermal cycling accounts for the differential expansion and contraction between the steel shell and the granite rocks and eliminates thermal ratcheting. The design for the product head considers the varying oil density, and the compaction and angle of repose of the rock.

Thermal Design -- The thermal cycling of a rock and oil storage tank requires thorough analysis to ensure that such tankage will withstand 30 safe years of operation. Diurnal cycling between 254°C and 304°C over the lifetime produces little design concern. However, deep thermal cycling between 304°C and ambient can result in thermal ratcheting if not recognized and accounted for in the initial design. The thermal ratcheting manifests itself when repeated cooling between 304°C and ambient occurs. Figure 3-10 shows an estimated cooldown curve for the oil/rock tank. It takes approximately four months for the tank to cool down to 38°C. During each cooldown cycle, the shell contracts radially at a faster rate than the granite rock. Since the rock mass and area is so much greater than the shell, the rocks will not be compressed by the inward shrinking of the shell. Therefore, the shell will take the differential expansion. The strain induced into the shell for the cycle amounts to 0.001708 mm/mm. The resulting stress is 341.7 MPa. The allowable stresses for tank design must be in excess of the allowable for thermal cycling. Consequently, a high-yield stress, high-temperature application material is a necessity to avoid thermal ratcheting if repeated operating to ambient cycles are anticipated. The material selected is ASTM A533-73 Class 2.

Figure 3-10. Temperature Decay of Oil/Rock Tank

This material requires a post weld heat treatment at 593°C with a minimum holding time of 1.2 min/mm (1/2 hour/inch) of thickness but not less than 1/2 hour.

Structural Design -- Figure 3-11 summarizes the preliminary design of the rock/oil storage tank for the pilot plant. A detailed structural analysis is contained in Appendix G.

A533 Class 2 Grade A steel is used for the shell, bottom, bottom knuckle, and anchor chairs. It was selected for its high yield strength and weldability. The use of this material permits the thermal and product loads to remain in the elastic range for a complete cooldown cycle. It is to be noted that the use of a material such as taconite in place of granite rock would reduce the thermal stresses due to the differential contraction during the cooldown cycle to practically zero. This would allow for reduced

DATA SHEET	
DESCRIPTION	60' X 48' OIL/RCK TANK
NUMBER REQUIRED	1
CAPACITY	43' OF ROCK @ 12% COMP. & 44' OF OIL
DESIGN PRESSURE	1.25 PSI (ROCK @ 32' H. OIL @ 20' H. OIL)
OPERATING PRESSURE	1.25 PSI
TEST PRESSURE	1.625 PSI (HYDROSTATIC HEAD)
DESIGN TEMPERATURE	60°F
TEST TEMPERATURE	60°F WITH COOLDOWN TO 70°F
JOINT EFFICIENCY	1.0 SHELL
CORROSION ALLOWANCE	NONE
CODE & STAMP	SEE NOTE #2
CUSTOMER SPECIFICATION	EXHIBIT A
MATERIALS	
SHELL & BOTTOM W/ KNUCKLE	A533 CLASS 2 GRADE A
TOP & BOTTOM FLANGE	A516-60
HEADS	N/A
NOZZLE	N/A
MANWAY	N/A
REINFORCING PAWS	A533 CLASS 2 GRADE A
PIPE	A516-60
COUPLINGS	N/A
STIFFENER RINGS	N/A
INTERNAL	N/A
BOLTING	BOLTS A193-B7 NUTS A193-7H STUDS
GASKETS	COMPRESSED ASBESTOS
STRUCTURAL	N/A
ELECTRODES	E 60XX OR E 70XX A516-60
CONSTRUCTION	
STRESS RELIEF	REQUIRED PER API SECTION VIII DIV. 1
CLEANING	ROOM CLEAN AFTER ERECTION
SURFACE PREPARATION	N/A
INTERNAL PAINTING	N/A
EXTERNAL PAINTING	N/A
INSULATION	N/A
LADDERS & PLATFORMS	REQUIRED 9\"/>

NOTES: 1. FLANGE BOLT HOLES STRADDLE TANK VERTICAL & RADIAL CENTER LINES - UNLESS OTHERWISE SPECIFIED.
 2. API-650 APP. D, FOR FABRICATION, ERECTION, TESTING, & EXAMINATION. API-650 APP. D, DESIGN MODIFIED FOR THERMAL LOADS.

Figure 3-11. 60' x 48' High Oil/Rock Tank

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	PURCHASER'S NO.	
	DESCRIPTION 60' X 48' H. OIL/ROCK TANK FOR HONEYWELL	
DRAWING NUMBER 1-12441C-1		REVISION C

material thickness to a level acceptable for seismic and product loads and consequently lower cost and smaller size tankage.

The differential thermal expansion between the steel shell and granite rock has resulted in a slightly heavier shell plate; but, this problem is one that should be considered so that the tank has the ability to safely cooldown to ambient temperatures, 21°C, from the operating temperature of 304°C.

A 516-60 was selected for the roof and roof knuckle for its high temperature properties and weldability. The tank should be post weld heat treated in accordance with ASME Section VIII, Division 1, paragraph UCS-56 since A533 steel is used.

The use of a knuckle at the shell-to-bottom connection has been used to reduce discontinuities and stress concentration and to give the tank more flexibility in that region. The effects of the plastic moment which develops in the bottom of a steel tank setting on concrete foundation has been considered in the stress analysis of the knuckle. The analysis is that of Arturs Kalnins for axisymmetric shells. A description of the program and a summary output from the program, called KSHEL 1 is provided in Appendix E.

Lubrite material will be used under the base plate of the anchor chairs to allow the anchor chairs to slide freely for radial growth of the shell.

The roof is equipped with seven large-diameter openings, one 122 cm Ø at the center and six 61 cm Ø equally spaced on a 9.75 m diameter, for easy access to the manifold and for the initial filling of the tank with rock.

The bottom is sloped towards a drain/sump arrangement for draining of the tank.

Fabrication and Erection -- Approximately six months after the start of detail design prefabricated material can be delivered to Barstow, California, for assembly. Assembly will be per API-650 code. The tank bottom segments will be tacked into place and welded using suitable backup plates. All weld areas will be painted with soap bubble solution and checked for leaks with a vacuum box per API-650. The sump trim will be welded into place. The base knuckle will then be welded to the base plates. Strain gauges will be attached and brought out through suitable raceway. Two 2.13 meter and four 2.44 meter courses will then be welded into place. In process, radiography will insure that each course is satisfactorily inspected prior to proceeding to the next course. The bottom manifold sections will be lowered into the tank and assembled in place. The roof will be assembled in the vicinity, moved by derrick into position and welded into place. Figures 3-12, 3-13, and 3-14 show such typical field operations.

Radiography having been satisfactorily completed, the tank will be prepared for post weld heat treatment (PWHT). Special construction openings will be made in the tank to accommodate the necessary heaters. Thermocouples will be placed on the shell and bottom and temporary insulation will be installed to permit heating the tank to greater than 593°C for 1/2 hour (1 hour for commercial size tanks). Subsequent to the PWHT, the tank will be tested to 11.37 KPa by one of several methods to be determined at a later date. Temporary openings will be closed and local heat treating or non-heat treating materials will be used for closures. Temporary openings in the roof will be made to pass through the sections of the upper manifold and to facilitate the loading of rock.

Rock Loading -- Washed 12.7 mm granite pebbles, meeting ASTM standard for mineral aggregates and concrete, will be delivered to the site. A loading hopper will be placed at the top of the oil/rock tank and mated to the four-foot diameter manhole. Temporary internal truss members will be used to support a portion of the rock filled hopper so as not to exceed the

Figure 3-12. Fifth Course Being Installed

Figure 3-13. Roof Plates Being Assembled

Figure 3-14. Rigging Roof for Placement

roof load design. A power-swung, full-wheel derrick will transfer the rocks from the delivered stowage area to the hopper. An angled tapered chute will control delivery of the rocks and direct the rocks to the area for filling. Rocks 50.8 mm in diameter will be used below the lower manifold to ensure that sufficient void volume is available for easy flow of fines and residuals to the sump area. The tank bottom and concrete pad is sloped so that the sump area is 152.4 mm lower than the opposite side.

A motorized portable spreader will be used to level out the bed to predetermined markers on the sidewall of the tank. Instrumentation rakes will be assembled and laid out at the levels indicated. Continuity will be checked in situ before proceeding to cover the rake with rock. Care must be exercised to ensure that the granite rocks do not tend to be selectively graded in size due to successive handling and piling. Manhole openings are provided to install intake and exhaust fans to provide safe, clean air for the personnel working inside the tank. When the tank is filled with rock to the 14.33 meter level the hopper and associated rock loading equipment will be removed and the temporary truss work dismantled. The upper manifolds will be brought in through the temporary openings made in the roof. During assembly, care must be taken to ensure that the weld slag fines is not allowed to fall into the packed bed. They may subsequently block some of the manifold holes.

The manifold bearing pads will be attached to the corresponding foot pads located at the top course of the tank wall. Radial expansion/contraction is able to take place via the manifold slip joints. The full weight of the upper manifold is designed to be supported by the shell as the bearing capability of the rock bed will diminish during compaction and differential expansion. Top level instrumentation will be installed and temporary openings closed. Insulation of the tank can now begin. 23 cm of foamglas will be laid up in successive courses and expandable bands will hold the insulation in place.

Metal flashing with interlocking ribs will be used to weather seal and protect the entire insulation on the tank.

Tankage Foundation Design -- A ringwall foundation shown on Figure 3-15, with a continuous slab at grade was selected as the best configuration for the soil conditions and seismic disturbances anticipated. The dimensions for the pilot and commercial plant sizes are given in Table 3-4. The ringwall foundation, anchor bolt chair, lower tank knuckle and sump/drain detail are shown on Figure 3-16.

Table 3-4. Main Storage Foundation Sizes

Dimension on Figure 3-15	Pilot Plant Tank	Commercial Plant Tank
B	3.2 m	3.2 m
C	16.15 m	32.61 m
D	18.29 m	34.75 m
E	20.12 m	36.58 m
F	24.38 m	40.84 m
G	7.5°	7.5°

Specific design and analysis details are contained in Appendix G.

The design is based on the following conditions:

- a) Soil bearing capacity of 10,000 PSF at 3.05 below grade.
- b) Tank weight (pilot plant) of 3155 kg/m
- c) Product head weight 87.80 kg/m
- d) Product weight on lower knuckle 18379 kg/ft
- e) Earthquake load ± 49645 kg/m

Figure 3-15. Main Storage Tank Foundation Design

BILL OF MATERIALS FOR DRAWING NO. 77-0441100-2				REV.	QUANTITIES SHOWN ARE FOR	ITEM(S)
SHIPPING	MARK	SHIP	TOTAL			
PIECE	PIECE	ASSEMBLY	QTY	DESCRIPTION	SPECIFICATION	WEIGHT
						LINE NUMBER

Figure 3-16. Oil/Rock Tank

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DRAWN BY & DATE JTO/4/77		BROWN-MINNEAPOLIS TANK	
DESCRIPTION OIL/ROCK TANK FOR HONEYWELL		PURCHASER'S NO.	
DRAWING NUMBER 77-0441101-2		REVISION 0	
ORDER NUMBER		SHEET	

- f) Uplift due to internal pressure 4182 kg/m
- g) Soil density 160 kg/m³
- h) Concrete strength 211 kg/cm²
- i) Reinforcement (A615-60) f_y - 4218 kg/cm²
- j) Vertical acceleration ± 0.25 g

The footing must contain sufficient mass and soil above the footing to resist internal pressure and overturning moment due to an earthquake. The effect of vertical acceleration during the earthquake is considered by using 75 percent of the actual computed footing and soil weight. The pad is uniformly loaded and does not see significant bending effects and can therefore be designed for a minimum of reinforcement steel.

Heat Exchangers

The heat exchangers comprise a significant percentage of the thermal storage capital costs. To obtain a minimum cost thermal storage system, that would meet the overall system requirements, tradeoff studies were performed which considered the variable storage media, tankage costs, turbine efficiency, heat losses, cost of electrical power generated, and heat exchanger costs. The results of these tradeoffs are discussed in Section 4. One of the important results of this study was the establishment of storage system operating temperature and pressure levels and the minimum pinch point temperatures for the heat exchangers.

Figure 3-17 is a temperature enthalpy plot for the thermal storage charge cycle. It very clearly shows the relative amounts of enthalpy that each exchanger extracts from the charging steam/water stream and the minimum approach temperatures of the fluid at the entrance and exit of each heat

Figure 3-17. Thermal Storage Charge Cycle

exchanger, "pinch points." The units of enthalpy apply only to the steam/water in the plot, but the temperature apply to all fluids.

Figure 3-18 is the temperature enthalpy plot for the thermal storage discharge cycle. The main features to compare between Figures 3-17 and 3-18 are the relative importance of the subcooler and preheater in the charging and discharging cycles respectively. The subcooler contributes a much larger percentage (14.1 percent) of the total energy input to storage than the preheater contributes to the energy output (8.2 percent) during discharge. This is a phenomena of the water properties and operating pressures and temperatures, but must be considered when selecting heat exchangers to obtain the optimum thermodynamic performance for the thermal storage system.

Having established the fluids, heat rates, temperature levels, and pinch points, the heat exchangers can be designed. Points that can not be established in a single iteration are the effects of pressure losses, heat losses from exchangers and piping and effects of discreet incremental sizes of materials and equipment such as insulation thicknesses and pipe and valve sizes. The area of largest uncertainty lies in the cost of the heat exchangers which vary widely due to material, stainless steel or carbon steel and pressure level, 10 MPa or 4 MPa. It is felt that the exchangers designed for the pilot plant will meet all thermal requirements but because they are less expensive than originally estimated, may be less than optimal in size. Detailed design will require revisiting the cost tradeoff analysis to fine tune the pinch points and exchanger sizes.

The six heat exchangers that will be discussed in the following paragraphs were designed by Manning & Lewis Engineering Co. using Honeywell fluid property data, temperature, pressure, heat transfer rates and fluid flow

Figure 3-18. Thermal Storage Discharge Cycle

rate data. In the final designs small changes to their designs were made to surface areas to accommodate our latest systems analysis and later fluid property data. All thermal performance parameters were verified using simple heat exchanger heat transfer relations taken from references 6 and 7. (See Heat Exchanger Design Calculations, Section 6 and Data Sheet in Appendix B.

The heat exchanger designs are a compromise between two sets of requirements. One requirement is to model the storage system for a commercial sized plant from a storage media temperature level point of view and the second is to evaluate commercial sized heat exchangers. The heat transfer rate requirements for the pilot plant and commercial plant are such that the pilot plant condenser and boiler are of the commercial plant size. The remaining exchangers are approximately one half of the optimum commercial sized units.

Optimum size in this sense means that exchangers of this size have been and are being built, that they can be shipped by rail or heavy duty truck, and that the cost per unit heat transfer is near minimum.

Some of the features that heat exchangers have in common are that all of the exchangers meet TEMA Mechanical Standards Class "C"; all exchangers are designed to meet ASME Code Section VIII Division I pressure tests requirements, all exchangers use 19 mm O. D. (3/4 in.) tubing placed in a 23.8 mm (15/16 inch) triangular array tube bundle. The two Hitec containing heat exchangers employ 15.8 mm I. D. (16 gauge) stainless steel tubes and the other exchangers use 14.8 mm I. D. (14 gauge) carbon steel tubes. The exception is the subcooler which has high pressure on the outside of the tubes and requires 13.5 mm I. D. (12 gauge) tubes.

The sequence of discussion of all heat exchangers will be in the order that the steam/water flows through the storage system starting with the charge side and progressing through the discharging of steam on the discharge side of storage.

A large amount of the detailed design and performance information on all of the heat exchangers can be found in Section 6 and Appendix B.

CHARGING SIDE

Desuperheater -- The desuperheater is the heat exchanger that removes sensible heat from the charging steam to heat the molten salt high temperature storage system. Both fluids exchange only sensible heat and because they are in counter flow, the exit fluid temperatures cross over such that the cold fluid exits at a temperature nearly 100°C hotter than the exiting "hot" fluid (see Figure 3-17).

The desuperheater operates at the highest temperature and pressure in the thermal storage system. Increased molten salt corrosion rates and reduced strength of carbon steel at high temperatures dictate that this heat exchanger be made entirely of stainless steel. Type 304 stainless steel was selected to meet the strength and corrosion resistance requirements and have the lowest fabrication cost. For high pressure heat exchangers, it is advantageous to keep the high pressure fluid on the inside of the tubes rather than in the shell. Thinner walled tubes can be used with the pressure on the inside rather than on the outside and a high pressure thick walled shell is not required.

The major design limitations to heat transfer imposed upon this heat exchanger are a maximum temperature of 499°C (930°F) for entering steam and a maximum steam velocity of 13.7 m/s (45 ft/s). The temperature limitation is to minimize corrosion and thermal break down of the molten salt (Hitec). The steam velocity limitation is required to prevent erosion of the inside of the tubes.

Condenser -- The condenser is a TEMA type BEM horizontal shell and tube exchanger with the condensation occurring on the inside of the tubes. The steam being at 10 MPa (1435 psia) would require an extremely heavy shell and heavier walled tubes if the condensing was on the outside of the tubes.

This exchanger would perform most effectively when mounted with a slope of approximately 2% to aid in condensate drainage.

The materials of construction of this exchanger are all carbon steel since steam side corrosion rates at this temperature are minimal and negligible for the oil side. The tubes are 19 mm OD x 14.8 mm ID (3/4 in., 14 gage).

The limitation on the heat transfer capacity of this exchanger lie mainly oil properties in the shell. The steam entering the exchanger is attemperated as close to the saturation temperature as is practical 8.3°C (15°F) to minimize the maximum film temperature that the oil will encounter. This is important because the oil degrades rapidly with increasing temperature at the higher operating temperatures. The second limitation is the oil velocity in the shell. Shell side fluid velocities greater than approximately 1.2 m/s (4 ft/s) could cause tube vibration problems which could ultimately cause the exchanger to self destruct.

Figure 3-19 is a photograph of a comparable sized heat exchanger (Type BTM size 60-216) to illustrate the type of construction.

This exchanger is approximately 1.5 times the diameter of the condenser and one-half of the length. It is more difficult to increase the diameter of exchangers than to increase the length. This is the result of the work required to form large-diameter, high-pressure bonnets.

Condensate Receiver -- The condensate receiver is located between the subcooler and condenser. It provides a controlled water-steam interface between the steam in the condenser and the condensate in the subcooler. Without the controlled interface either steam would pass through the condenser to the subcooler possibly to the discharge valve or condensate could back up into the condenser reducing the effective surface area. The condensate, as it leaves the condenser under the most severe conditions has a pressure of

Figure 3-19. Photo of Comparable-Sized/Heat Exchanger

10335 kPa (1500 PSI) and 310°C (590°F). Carbon steel 214 has an allowable stress of 9900 PSI at this temperature. With this stress and at the pressure specified, the unit has a wall thickness of 1.8 inches (4.6 cm).

The maximum flow rate is 56,700 Kg/hr (125,000 lb/m) and with this rate, the tank should be large enough so that it would take one minute to empty. This establishes a size 60.96 cm (2 ft.) by 487.7 cm (16 ft.) long with hemispherical ends. Two connections using flanged mounting are necessary for the 5-inch (12.7 cm) lines plus four pipe thread fittings (2.54 cm) one inch for the level indicator and for the level transmitter fittings.

Subcooler -- The subcooler contributes approximately 17 percent of the energy to the main storage oil flow stream. In the overall charging system it reduces the charging steam flow rate for a given charge heat flux and reduces the thermal load on the cooling tower and deaerator. The cooling tower would have to dissipate the thermal energy contained in the high temperature condensate if a subcooler was not used.

The subcooler is an anomaly in the system in that it utilizes a high pressure shell with the low pressure oil inside of the tubes. This is a result of the lower heat rate and lower surface area requirement than that of the condenser. To pass all of the oil through the subcooler it was necessary to pass the oil through the tubes rather than through the shell. If the oil was directed through the shell, the velocity would have been higher than that permitted by vibration limitations. To run only part of the oil stream through the exchanger, would reduce the mean oil to water temperature difference which would necessitate using more surface area to obtain the same heat transfer.

The high pressure in the shell requires that the tube walls be thicker than for the condenser tubes or that a stronger material be used. The latter option was exercised by using tubes of 19mm OD x 14.8 mm ID (3/4", 14 gage)

304 stainless steel. This stainless steel has sufficiently high design strength allowable to meet the compressive pressure loads. To use carbon steel would have required going to 19 mm OD x 13.5 mm ID (3/4", 12 gage) tubes and increasing their number by 21% to obtain the same flow area for the oil.

The limitation to the maximum rate of heat transfer imposed by this heat exchanger is in the oil flow velocity in the tubes. Exceeding the design flow velocity by more than a few percent would produce severe erosion problems inside of the tubes.

DISCHARGING SIDE

Preheater -- The preheater is to the discharge process what the subcooler is to the charge side of thermal storage. It exchanges sensible heat between the lowest temperature oil and lowest temperature water in the system. The preheater contributes approximately 10% of the energy required to pre-heat and boil the feedwater. Similar to the subcooler the oil flow volume is large and the surface area and heat transferred are relatively small. This again forces the design to be one with the water in the shell and the low pressure oil inside of the tubes. The discharge water pressure is only 40% of the charge side pressure; thus, carbon steel tubes have sufficient strength for this exchanger. The basic construction is an all carbon steel exchanger TEMA Type BEM size 28-144 single pass heat exchanger.

Boiler -- The boiler is the most important element in the thermal storage discharge process. The device selected to perform this duty was a tube in shell kettle boiler TEMA Type BKM. Figure 3-20 is a photograph of a Size 28/46-192 boiler. The first number '28' is the tube bundle diameter in inches (0.71 meter) and the second number '46' is the large diameter of the shell, 46 inches (1.17 meters), where the steam separates from the boiling water pool. The last number is the length of the tubes in inches 192" (4.88 meters). The pilot plant boiler would be considerably larger, 40/54-480, but is the same type and has similar proportions. The design of the boiler is a two pass arrangement with the oil inside of the tubes and the boiling water in the shell.

Figure 3-20. Photo of Size 28/46-192 Boiler

The alternative would be boiling inside of tubes which can have instabilities and erratic performance when operating at other than design flow rates. The kettle boiler has no stability problems in handling oil and steam flow rates from the design rate all the way down to zero flow. It also is its own steam/water separator because it is designed with an appreciable vapor space in the shell.

There are two limitations in the operation of the boiler. The first is the design oil flow rate through the tubes at the maximum velocity without serious tube erosion problems. The second limitation is the maximum pressure for which the shell is designed is 4.1 MPa (600 psi) which corresponds to a saturation pressure of 254°C (489°F). The hot oil entering system may reach 303°C (578°F). Relief valves will be provided and the oil circulation control system will be designed to reduce the oil flow rate commensurate with the steam flow demand and the boiler pressure.

Superheater -- The superheater receives the steam from the boiler and heats it to match the turbine expansion line temperature at the secondary injection port, at the design flow rate conditions. This permits instantaneous switching from receiver steam to storage supplied steam to accommodate a continuous demand on partly cloudy days.

The construction of the superheater is a counter flow shell and tube TEMA Type BEM heat exchanger Size 18-360. The superheater like the desuperheater is long and slender to provide the necessary surface area with the smallest diameter high pressure bonnets. This is desirable since the material in the bonnets increases approximately with the cube of the diameter but not at all with the shell length. The minimum shell diameter is that which will contain a sufficient number of tubes to keep the tube inside velocity low enough to prevent tube erosion. The general rule of thumb used was to maintain the ρv^2 product less than 4,000 lbm/ft-s² (6000 kg/m-s²).

This heat exchanger has a type 304 stainless steel shell and tubes selected from corrosion resistance to the hot Hitec. The bonnets are carbon steel for lower cost. The steam temperature and pressure are much lower than that of the desuperheater thus alleviating the requirements for high tensile strength materials.

The limitations to operation of the superheater are the flow velocity of steam through the tubes and the relatively high pressure drop for the Hitec in the shell. The Hitec pressure drop results from many closely spaced baffles necessary to obtain sufficiently high heat transfer coefficient.

Attemperator No. 1 -- The steam temperature entering the desuperheater must be limited to maintain the Hitec corrosion rate and thermal decomposition rate at acceptable levels. Molten Hitec has been used at temperatures in excess of 540°C (1000°F) but corrosion rate data is sparse and indicates an increased rate at temperatures above 454°C (850°F). It was determined that 44°C (80°F) was a sufficiently high temperature differential between the charging steam and the molten Hitec to obtain acceptable heat transfer rates and also minimize thermal decomposition of the molten salt and corrosion of the metal at local hot spots in the heat exchanger.

A secondary use of this attemperator could be to balance the amount of heat input to the superheater storage relative to the input to the main storage. By the lowering of the inlet steam temperature through attemperation the heat input to the superheat storage can be reduced relative to the input into main storage. Note that the superheat storage input cannot be increased without exceeding temperature limitations and/or buying a larger heat exchanger which would extract more heat from the charging steam flow. (It would be helpful to refer to the T-h diagram in Figure 3-17.)

In this installation, a single attemperator would be mounted vertically in the steam line with a mixing length of approximately 3 meters (10 feet) following the attemperator spray nozzles. The steam would then enter one leg of a

pipe Tee and exit after a 90° bend. The vertical mounting permits large turn down ratios in steam flow rate due to gravity recycling of the droplets impinging on the pipe wall. The use of a Tee capped with a blind flange down stream keeps the mixing length short by allowing any droplets, that might not evaporate within 3 meters (10 feet), impinge on the blind flange, since the heavy droplets could not make the 90° bend. The blind flange would be inspected and replaced if significant erosion occurs over a period of years.

A single spray attenuator can cover a wide range in mass flow rates (turndown ratio) at this location because the design attenuator water flow rate is only 1.2% of the steam mass flow rate and the steam final temperature is 189°C (340°F) above the saturation pressure. The low percentage flow and high temperature difference promote rapid evaporation of the water droplets.

A typical attenuator that meets these requirements is a Schutte and Koerting Model 6940-1500 WC-6 6 inch (0.15 m) attenuator. It would have approximately 24 psi (165 kPa) pressure drop and a 41:1 turn down ratio and still maintain satisfactory outlet steam temperature control. Increasing the turndown ratio would reduce the spray water and steam velocity to a point where uniform mixing and evaporation would not occur resulting in loss of temperature control.

At the lower steam flow rate, it is unlikely that local severe overheating of the Hitec in the heat exchanger would occur under any circumstance due to relatively high conductivity of the metal and salt compared to the heat flux attainable with low velocity convective heat transfer.

Attenuator No. 2 -- A second level of attenuation of the charging steam is necessary before the steam enters the condenser. The thermal decomposition rate of high temperature heat transfer oils increases rapidly with increasing temperatures. To reduce the amount of superheat in the

steam entering the condenser, an attemperator is required. If the superheat was not removed the entrance of the condenser would be heated to temperatures in excess of 350°C (662°F) causing rapid thermal decomposition and possible fouling of the heat exchanger surface. Figure 3-17 shows the heat exchange and attemperator processes on a T-h plot. You will note that the steam entering the condenser has approximately 8°C (15°F) of superheat in it. This is the approximate minimum approach temperature with which satisfactory attemperator operation can be attained while still maintaining a reasonable turndown ratio.

As the steam temperature is reduced towards the saturation temperature there is a correspondingly smaller temperature difference to transfer heat from the steam to the water droplets. The turndown ratio for the attemperators becomes smaller because the attemperator must provide high turbulence in the discharge steam to compensate for the reduced temperature difference. To maintain a high turbulence level at low flow rates the pressure drop across the device would be excessive at the maximum flow rates. Excessive pressure drops would lower the condensation temperature thus lowering the overall heat transfer rate for the condenser.

To reduce the problem of high pressure drop and maintain a high turndown ratio this design uses two attemperators operating in parallel. At less than 50% of design flow, one attemperator would be valved off and all of the flow routed through a single attemperator. This doubles the turndown ratio attainable with approximately 25% of the maximum pressure loss of a single attemperator.

An attemperator that would provide satisfactory performance in this operation is the Schutte and Koerting Model 6940-1500 WCD 4" size attemperator mounted two in parallel vertically oriented. These would provide approximately a 30:1 turndown ratio and a maximum pressure drop of approximately 155 kPa (22.5 psi) at the maximum flow rate. The importance in

minimizing pressure drop can best be illustrated by noting that the condensing temperature drops 1°C per 136 kPa (1°F per 11 psi) at the operating pressure, with the result, the mean temperature difference across the condenser decreases by 4.6% per °C (2.6% per °F). With heat transfer rate being proportional to the product of temperature difference and surface area one sees that maintaining a high condensing pressure and temperature will provide the highest heat transfer rates and the lowest cost system.

As mentioned earlier, the attemperator would be mounted vertically and in parallel. Similar to attemperator no. 1, the attemperator would require approximately 3m (10 ft) of straight mixing length downstream of the attemperators. The steam would again enter one leg of pipe "Tee" and make a 90° bend into a horizontal run. The vertical branch of the pipe Tee being capped with a blind flange which serves as a readily inspected and replaceable impingement plate. The two streams would be brought together in a "Y" before entering the condenser. A "Y" connector would be required rather than a "Tee" to reduce the possibility of any fluid flow interaction between the two attemperators.

Fluid Flow Loops

Figure 3-21 is a schematic diagram of the thermal storage system showing the major components and fluid flow lines. In the following paragraphs, the system will be discussed one part at a time to show the independence of the charging and discharging sides of the storage and to show the relationship between the high and low temperature storage functions.

In consideration of the flow loops, refer to Figure 3-18, the T-h diagram for the discharge of thermal storage. Observe that as the feedwater passes through the thermal storage heat exchangers, 83% of the enthalpy increase is contributed by the main storage and 17% is supplied by the superheat

Figure 3-21. Thermal Storage Schematic

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3-57

storage. This indicates the relative size of the heat transfer equipment required in the superheat and main storage system. Since energy is removed from the thermal storage system in that percentage ratio, it must also be added to storage in that ratio plus small adjustments for heat losses turbine sealing and Hitec tracing steam requirements.

The thermal storage flow loops will be discussed in the order that the charging and discharging water/steam flow through the system, starting with the charging of Hitec storage.

Superheat Charging -- An enlarged section of Figure 3-21 is presented in Figure 3-22 and will be used as a reference in the following discussion. Steam enters the system at the top left corner of the schematic and condensate leaves at the bottom left corner. Steam enters the system and passes through attemperator no. 1 where its temperature is reduced to 499°C (930°F) by spraying 205°C (400°F) water into the steam. This is done to reduce the thermal decomposition rate of the Hitec and minimize the corrosion rate of the Hitec on the heat exchanger.

Hitec is pumped out of the cold Hitec storage tank through the heat exchanger through the flow control valve ACV-2 back into the bottom of the hot storage tank. Both storage tanks are located in a vault placed below grade. The pump and control valves are located in a pit along side of the storage vaults with several meters of dry soil between the pump pit and the storage vault for insulation.

A constant speed centrifugal pump provides the necessary head requirements. One of the system operational requirements is to handle wide ranges of steam input rates which means wide ranges in Hitec flow rates must also be provided to maintain a constant 454°C (850°F) charging temperature. An obvious suggestion would be use of a variable speed pump drive to match flow rate with demand. This is not a good solution

Figure 3-22. Thermal Storage Charging Schematic

for this design because a major portion of the pumping head requirements are due to changes in elevation in pumping from the bottom of the pit to the above grade heat exchanger, plus the suction head on the pump varies considerably depending upon whether the cold tank is empty or full. A variable speed positive displacement pump would solve the problem nicely but none can be found with the long life, low cost, and particle handling capability of a centrifugal pump.

To meet the variable flow rate requirements with a constant speed centrifugal pump two control valves are required. The first is the main control valve ACV-2 which controls the flow between 100% and 25% of the design flow rates. For flows less than 25% of the design flow rate, the bypass valve is opened allowing approximately 25 percent of the design flow rate to circulate back to the cold Hitec storage tank through a small restricted line. At low flow rates the capacity versus head curve of a centrifugal pump is very flat permitting the bypass valve to open or close with little adjustment in the position of the control valve ACV-2. With the bypass valve open, the flow of Hitec through the exchanger can be throttled all the way down to zero flow without damage to the pump. The main reason for bypassing the Hitec all the way back to the storage tank is to bring a large volume of salt into the recirculation loop should the pump be operated for long periods with no flow through the heat exchanger. Recirculating a small volume of fluid in a closed loop around a pump can cause overheating of the fluid and pump since all of the power input to the pump must be dissipated in the fluid.

A line was provided from the bottom of the hot Hitec storage tank to the inlet of the cold Hitec pump. This line permits recirculation of the hot salt through the exchanger during initial charging and filling of the storage system and following any prolonged system shutdown period. The line also permits direct transfer of salt from the hot storage tank to the cold storage tank via the pump bypass line.

A required support line (not shown in Figure 3-22) is the vacuum breaker line extending from the ullage space of the cold Hitec tank to the vacuum breaker located on top of the desuperheater. With the lines and heat exchanger full of molten salt whenever the pump is stopped syphoning in the lines due to the difference in elevation between the tanks and the exchanger will be more than enough to reduce the pressure in the exchanger to the vapor pressure of the Hitec which is near zero pressure absolute. This would remove all of the salt from it and collapse the exchanger from external pressure. Building the exchanger shell strong enough to withstand the vacuum would not solve the second problem of salt draining from the heat exchanger. Removal of the salt from the exchanger would reduce its thermal mass, causing rapid cool down and thereby increasing thermal stress fatigue in the exchanger. A second problem arises when the pump is again started causing a sudden inrush of salt into the exchanger. Initial flow rates if not carefully controlled could damage tubes in the exchanger.

Installation of a check valve in the heat exchanger supply line and keeping the control valve closed when the exchanger is not in use will keep at full of salt and the vacuum breaker will prevent the formation of subatmospheric pressure should the salt cool or one of the valves leaks.

The entire Hitec system will be kept under a nitrogen blanket to exclude oxygen and water vapor. Oxygen and water vapor contribute to slow decomposition of the molten salt resulting in an increase in the melting temperature, the formation of oxides and possibly hydroxides.

To minimize the possible corrosion effects of high temperature molten salt all components of the Hitec storage system will be constructed of stainless steel. The tank, line and heat exchangers will all be type 304 stainless steel and the valves will have stellite trim for wear and corrosion resistance. The pump which will be discussed next will be fabricated of type 316 stainless steel.

Pressure changes within the charging loop are the result of elevation differences, frictional losses and pressure drop across the desuperheater. The piping will be 4 inch schedule 40 stainless steel pipe (114.3 mm O.C. x 102.3 mm I.D.). The piping system will contain approximately 61m (200 ft.) of pipe, 11 elbows, 12 gate valves, 1 check valve, and 1 control valve for an equivalent length of piping of 135m (442 ft) with a total pressure loss of 71 kPa (10.3 psi). One half of the line losses occur before the heat exchanger.

Line losses occurring after the heat exchanger can be accommodated by recovery of head. At the design flow rate, the pressure drop across the exchanger is 160 kPa (23.1 psi). The total pressure head that must be supplied by the pump is 325 kPa (47.1 psi) or 17.8m (58 ft) of head. A similar analysis of the discharge side of the Hitec storage shows that approximately 20.3m (67 ft) of head is required. The difference lines mainly in the lower density of the much hotter salt than the discharge pump must handle.

Hitec Pump -- The pump selected for the molten salt loops in a single speed end suction centrifugal pump made by Dean Brothers Pumps, Inc. of Indianapolis, Indiana. See Figure 3-23. Since, the charge and discharge pumping requirements are nearly identical both pumps were designed to be identical for interchangeability.

The following design parameters will be slightly different from that indicated on the quotation sheet, but can easily be accommodated by the oversized motor and maximum rotor size with no price increase.

Hitec Pump Requirement --

Temperature	454°C	850°F
Head	22.3 m	67 ft
Specific gravity	1.75 to 1.86	
Capacity	13.31 lit/s	211 GPM

Figure 3-23. Hitec Pump

The pump curve Figure 3-24 for a Dean Pump model R434 pump size 3" x 4" x 8-1/2" shows that these flow and head conditions can easily be met with this pump driven at 1750 rpm. The calculated power requirements at the highest fluid density are 11.2 horsepower (8.33 kW). A larger motor 11.2 kW (15 hp) motor was specified to minimize the chance of overheating in severe environment. The specification sheet shows that the entire pump is constructed from Type 316 stainless steel for corrosion resistance. The pump housing and packing does not need cooling due to the low speed and low power input requirements. Cooling water must be provided for the bearing oil. Inspection of the 3500 rpm curves on Figure 3-24 shows that the identical pump can be driven with much larger motors to provide higher heads and capacities. Consequently, in this application the bearing and seal life expectancy should be very long. Estimated life of the packing is a minimum of 18 months of continuous service.

Any necessary maintenance such as seal replacement, bearing repair or rotor inspection can be performed without removing the pump volute from the line or moving the drive motor.

Main Storage Charging -- The main thermal storage system is a packed bed of rocks using oil as the heat transfer fluid. The temperature enthalpy plot, Figure 3-17 of the charging process shows that approximately 17% of the heat input to main storage is contributed by the subcooler and 83% by the condenser. Economic tradeoffs have indicated that it is more economical to recover the sensible heat from the condensate by putting it into the main storage rather than having a separate thermal storage tank pumps and flow loop for subcooling and preheating.

To charge the main thermal storage system, oil is drawn from the lower manifold pumped through the subcooler then through the condenser. The flow control valve ACV-7 is located downstream of the condenser. The hot oil is returned to the top of the thermal storage tank where it is evenly

Figure 3-24. Hitec Pump Performance Curve

distributed over the bed by the upper manifold. Temperature of the oil returned to the storage tank is maintained by controlling the oil flow through the heat exchangers in response to the oil temperature and the varying steam flow rate. The relative percentage of heat input in the subcooler and condenser remains constant, independent of oil or steam flow rates because only water is allowed into the subcooler. The relative amount of energy extractable from the steam and the water is determined by thermodynamic properties of the steam/water.

For heat rates less than 40% of design flow, the two speed pump would be switched to the lower speed which is $2/3$ of the rated speed. This reduces the pump power requirements and allows the control valve to operate over a range where it has good controllability. For flow rates less than 10% of the rated flow, the bypass valve would be opened to recirculate oil through the pump and heat exchangers. This flow loop is different from the superheater flow loop because the condenser operates at a constant temperature.

Recirculating the oil is required to prevent overheating the pump and is beneficial to the heat exchange process in that it maintains a significant heat transfer coefficient in the condenser. Without recirculation local hot spots could develop causing oil degradation and fouling.

At high recirculation rates the subcooler would become ineffective, but it only contributes 17% of the energy to the oil.

The piping used in the charge loop is carbon steel, Type A106 14 inch schedule 30 (356 mm O. D. x 337 mm I. D.) pipe. Pressure losses for the piping loop can be found in Section 6. Table 3-5 provides a summary of all of the pressure losses in the charge loop. An inline screen or filter will be placed in the line ahead of the pump to filter out any rock particles that may tend to wash out of the packed bed. Particle sizes need to be removed

down to approximately 60 microns to prevent deposits from forming in low velocity areas of the heat exchangers or pipes.

Table 3-5. Main Storage Charge Loop Pressure Losses

Item	kPa	(Psi)
Lines valves elbows, etc.	62	9
Filter	35	5
Subcooler	35	5
Condenser	69	10
Manifolds and Bed	<u>21</u>	<u>3</u>
Total	222	(32)
Total fluid head	32.4m	(106 ft)

The following simplified analysis was used to predict maximum screen sizes:

Velocity to keep particles in suspension in a horizontal pipe.

$$\frac{V^2}{gD_s} \times \frac{\rho_L}{\rho_s - \rho_L} = 0.0251 \left(\frac{V D_t \rho_m}{\mu_L} \right)^{\sqrt{0.775}} \quad (\text{Ref. 8})$$

where:

V = liquid velocity

g = acceleration of gravity

D_s = diameter of solid particle

ρ_L = liquid density

ρ_s = solid density

ρ_m = mean slurry density

D_t = pipe diameter

μ_L = liquid

$V = 0.3 \text{ m/s}$ $D_s = 2.57 \times 10^{-3} \text{ in} = 65.3 \text{ micron}$

$V = 0.15 \text{ m/s}$ $D_s = 1.10 \times 10^{-3} \text{ in} = 27.9 \text{ micron}$

$V = 0.03 \text{ m/s}$ $D_s = 1.53 \times 10^{-4} \text{ in} = 3.9 \text{ micron}$

Start-up procedures will require close monitoring of the filter as the bed is being conditioned. After a few hundred hours of operation no appreciable amount of fines will remain in the bed.

A typical strainer unit that will meet the operational requirements is a Winston, Mfg., Co., Duplex Model RP-55-Q500. It has two 0.51 m x 1.37 m (20 in x 54 in) baskets of stainless steel mesh with 60 micron range filtration. Temperature rating is for service to 316°C (600°F).

Main Storage Discharging -- The main storage discharge loop is analogous to the charge loop in that the oil is circulated through two heat exchangers in series with most of the heat transferred being associated with the change in phase of the water. Figure 3-25 is the schematic of the flow loops for the discharge cycles.

To discharge the main storage system hot oil is drawn off from the top of the packed bed storage tank, sent through a screen, through pump to the boiler. The boiler is technically a two pass tube kettle type reboiler. The cold oil leaving the reboiler is sent through the preheater to preheat the feedwater up to the saturation temperature. Referring back to Figure 3-18 the temperature -- enthalpy diagram for the discharge process, note that the preheater contributes approximately 10% of the enthalpy to the preheating and boiling process. Not using the preheater would require increasing the boiler surface area considerably because of the resulting small pinch point. An alternative would have been to increase the oil temperature

Figure 3-25. Thermal Storage Discharge Loops

which reduces the charge side temperature differences and increases the oil degradation rate. A second alternative would be to circulate more oil through the heat exchanger taking a smaller temperature drop in the oil. This would require more storage volume and more exchanger surface area on the charge side of storage.

Figure 3-25 shows parallel sets of pumps and control valves for the oil flow loop and feedwater one set of valves and one pump have a much lower capacity than the other to provide a low flow rate for sealing and tracing steam requirements. This will be discussed in the paragraph on sealing and tracing.

The oil flow loop utilizes an identical pump to the one used in the charge loop, all lines are the same sizes with approximately the same lengths of pipes and similar pressure drops across the heat exchangers. Table 3-6 is a summary of the pressure drops experienced in the main storage loop.

Table 3-6. Main Storage Discharge Loop Pressure Losses

Item	kPa	(Psi)
Lines, valves, elbows, etc.	61	8.9
Screen	13.8	2
Preheater	21	3
Boiler	110	16
Manifolds and Bed	<u>21</u>	<u>3</u>
Total	226	(32.9)
Total fluid head loss	32.9 m	(108 ft)

Discharge Oil Pump -- The pump selected to circulate the oil is a size 8 x 10 x 15 1/2 Type R484 manufactured by Dean Brothers Pumps, Inc., Indianapolis, Indiana. The pump is very similar to the molten salt pumps used in the superheat storage shown in Figure 3-23. The pump performance

curve is presented in Figure 3-26. The charge and discharge oil pumps will be identical to provide interchangeability of parts. As in the superheat storage, the discharge side of storage puts a more severe requirement upon the pump in terms of volume flow and head required. The design point conditions are for slightly greater flow than those on the pump quotation sheet in the appendix. The pump can accommodate the increased flow by increasing the rotor diameter slightly. Because the specific gravity and head requirements are slightly lower than the initial design requirements, the electric power input requirements increase less than 5% from 127 to approximately 132 horsepower (94.7 to 98.5 kw). Note that the pump curves show power requirements for pumping fluid of a specific gravity of one. To obtain the power requirements for pumping other fluids, multiply the power requirement read from the performance curve by the new specific gravity. For Caloria HT-43 at 300°C (572°F) the specific gravity is approximately 0.66.

The basic pump construction will be cast steel with a cast iron impeller. The packing will be a bellows seal with a graphite slip ring. No cooling of the casing or seal is required. Cooling of the bearing oil supply will be required with a water flow rate of approximately 4 lit/s (1 gpm) at 25°C (80°F) to maintain the bearing oil at acceptable temperatures. The pump was designed to operate with a maximum motor size of 300 horsepower (224 kw). When being driven at less than 50% of the maximum power input the bearings should provide very long service.

The motor used to drive the pump would be a totally enclosed fan cooled (TEFC), two speed, 150 horsepower (112 kw) motor with class H electric insulation. This will provide a very good margin for service in a hot environment and continuous duty.

Referring to Figure 3-25 even though oil is drawn off from the top of the tank the pump is located at grade level to provide a net positive suction head (NPSH) in excess of 12 m (40 ft).

Figure 3-26. Charge/Discharge Oil Pump Performance Curve

Operational strategy for flow control on the discharge will be the same as on the charge side. At less than 40% of flow the two speed pump motor will be switched to the lower speed. For very low steam flow rates the bypass valve would be opened and a small quantity of oil recirculated. The water temperature in the boiler cannot be allowed to build up to the maximum oil temperature. At the maximum oil temperature the boiler pressure would exceed twice the design pressure limit of the boiler, preheater, and superheater. Anytime the turbine valve is closed oil flow from storage must be stopped to avoid venting steam through the pressure relief valve. Calculations have shown that if the steam discharge and the oil flow from the storage tank are stopped simultaneously the boiler pressure will approach but not exceed the maximum design pressure limit 4100 kPa (600 psig).

Superheater Discharge -- The superheater discharge flow loop consists of the two underground storage tanks, a pump, a heat exchanger, two control valves, and the associated piping. The function of the superheater is to provide enough sensible heat to the steam discharge to the turbine secondary admission port to match the turbine expansion line temperature at the design flow rate. With temperature matching an instantaneous transfer can be made from primary to secondary admission part steam. This is important when clouds suddenly cover all or part of the heliostat field. The difference between the design secondary admission port temperature and the temperature under part load conditions is always less than 45°C (100°F) which is the maximum temperature difference permitted for instantaneous transfer of steam. Under reduced flow rate conditions it would be possible to discharge steam at higher than the design temperature of 391°C (735°F) at the expense of returning Hitec to the cold storage tank at temperatures above 299°C (570°F) thus reducing the amount of dischargeable heat proportionately.

Looking at the discharge side of storage as a whole, Figure 3-25, one sees that the preheater supplies sensible heat to the feedwater, the boiler

provides the latent heat and determines the system pressure, and the superheater provides the sensible heat for expansion line matching. The superheat provides 17% of the total enthalpy from the thermal storage system.

Like the charge side the Hitec supply lines are all 4 inch nominal schedule 40 type 304 stainless steel pipe (114 mm O.D. x 102 mm I.D.). The control valves, heat exchanger and storage tanks are also constructed of type 304 stainless steel. The pump which was fully described in section 5.1 is constructed of type 316 stainless steel and uses a dry lubricated Graphoil packing to minimize the possibility of any organic material coming in contact with the hot salt.

Table 3-7 provides a summary of the pressure losses in the Hitec fluid flow loop. Because a large portion of the total head required is the result of the heat exchanger being mounted above grade, the pump must supply a total pressure head that is nearly independent of flow. As on the charge side the centrifugal pump must run at a constant speed to provide the required head and the flow rate controlled by the control valves. Similarly a vacuum breaker must be provided on the superheater with a nitrogen line running to the cold Hitec tank to prevent the superheater from being collapsed by the hydrostatic line pressure when the pump is stopped.

Table 3-7. Superheater Discharge Loop Pressure Losses

Item	kPa	(Psi)
Lines, valves, elbows, etc. *	29	4.2
Elevation difference 9.1 m (30 ft)	157	22.8
Heat exchanger	172	25
Positive Pressure for Control	<u>14</u>	<u>2</u>
	372	54

* Only half of the lines losses need be considered. Reduction in hydrostatic head will provide sufficient pressure to overcome frictional losses in the return line.

The total head that the pump must supply is 21.7 m (71.1 ft).

Sealing and Tracing -- During hours when the turbine is not operating, sealing steam must be provided to the labyrinth seals on the turbine shaft to prevent air from getting into the steam cycle. Approximately 450 kg/hr (1000 lb/hr) of steam must be provided at a temperature of 121°C (250°F) and 138 kPa (20 psia). An additional 225 kg/hr (500 lb/hr) must be provided to the deaerator to maintain it at a pressure above atmospheric.

The Hitec lines are small in diameter and do not contain a large thermal mass thus they will cool down to less than 205°C (400°F) within approximately 10 to 12 hours. Although new Hitec has a melting temperature of 142°C (288°F) any thermal degradation tends to increase the melting point and solid particles will form as the mixture is cooled. A second reason for maintaining a tracing temperature of 205°C (400°F) is to insure that all parts of the system remain above the freezing temperature since the tracing will not provide total jacketing of the lines and exchangers. At 250°C (400°F) the heat loss from the Hitec lines and heat exchangers will have a heat loss rate of approximately 17 kw (58 000 Btu/hr). This represents 32 kg/hr (70 lb/hr) of steam. Rather than supplying two steam sources and separate heat exchangers all steam will be generated at 205°C (400°F) and the steam going to turbine seals throttled down to 138 kPa (20 psia).

At termination of a discharge cycle the boiler and superheater will contain a considerable amount of sensible heat that would be lost to the environment. To use this sensible heat and to avoid buying another heat exchanger, the boiler and subcooler will be used as a generator for tracing and sealing

steam. Figure 3-25 shows the controls valves, oil pump and lines necessary to implement the sealing and tracing steam system.

Control valve ACV-15 will regulate the sealing steam pressure and flow rate. Control valve ACV-13 will provide control of the feedwater to maintain the boiler liquid level. Oil drawn from the main storage tank will be pumped through the boiler and subcooler by a small oil pump in parallel to the main oil pump. Control of the oil flow will be maintained by control valve ACV-9. Thermal storage capacity has been provided to supply sealing and tracing steam for 20 hours before providing the 94.8 MWhr(t) necessary to generate 2 MWhr(t). At the end of a normal discharge cycle the main storage tank contains oil at a temperature of 249°C (480°F) which should provide sealing and tracing steam for several days before the oil temperature drops below 205°C (400°F) where it can no longer maintain boiler pressure necessary for trace heating.

The oil flow rate necessary to provide 713 kg/hr (1571 lb/hr) of steam is approximately 15,500 kg/hr (34,250 lb/hr) of oil assuming a 44°C (80°F) temperature change in the oil. The flow rate is approximately 2% of the normal discharge rate making the pressure drop in the lines and exchangers negligible at the low flow rate.

Advantages of this sealing and tracing steam generation system are that very little extra equipment is needed, the sensible heat remaining in the exchangers is used, and the steam lines are kept hot by the tracing steam.

OIL MAINTENANCE UNIT

Oil Maintenance Unit Requirements

When petroleum fluids are exposed to high temperatures some of the carbon-hydrogen bonds are broken and new materials are formed. This action, called thermal cracking, occurs even in the absence of oxygen. Where unsuitable materials are involved it can occur at such high rates that extended

service at temperatures even as low as 204°C (400°F) is not possible. Thermal cracking forms both light, relatively volatile low boiling (LB) products, and heavier less volatile high boiling (HB) products. The more volatile products lower the flash point of the oil and possibly increase the rate of further degradation. The heavier, more viscous products increase the resistance to fluid flow through the system and lead to the formation of coke-like deposits.

The most volatile of the degraded components will be evaporated into the ullage space and trapped in the ullage vent. All other degradation components, including both HB's and LB's will be removed in a vacuum distillation column.

The rate of formation of these components will be less than 3% per week. Degradation rates of 2.5% per week were reported by Siefert and Jackson⁹. Later data¹⁰ has suggested that the rate of degradation will be much less, about 8% per year, with negligible formation of high boilers. Because of the contradictions in these data and because the long term (30 year) characteristics of the oil are still unknown the pilot plant is being designed to handle the most severe of these conditions, 3% per week degradation. Based on these data the equipment was designed for a rate of degradation of 3% per week with half of the degradation as LB and half as HB. The acceptable steady state concentrations of each of the degradation products in the bulk fluid were taken as 10%. Monsanto recommends operating at no higher than 10% HB concentration with its heat transfer fluid, Therminol 66.

On the pilot scale a 3% degradation per week corresponds to 3800 liters per day of degradation products. To remove those 1900 liters per day of each of the degradation components, 18,900 liters per day must be processed in the distillation column. At least 4000 liters of this stream can be recovered. Up to 1900 liters per day of each of the degraded products will be pumped to storage for removal. The annual makeup requirements for the

worst possible case of 3% per week degradation is 1,290,000 liters. A more realistic number follows from the value of 8% degradation per year. The annual make up requirement in this second case is 65000 liters per year. Both of these estimates are based on replacing only the degraded components in the oil and recovering all of the good oil in the distillation column.

Further treatment of the oil is required to remove any dissolved oxygen. If the oil encounters oxygen at the high temperatures of the oil storage, rapid oxidation will occur. The oxidized materials form thickening or, eventually, insoluble carbon-like components which can deposit on heat transfer surfaces. To prevent this deposition, equipment will be included in the maintenance unit to remove dissolved oxygen from the oil. This will be most important during start-up when the oil will be able to pick up residual oxygen from the storage tanks and pipelines. At times it may be desirable to operate this O₂ scrubber without the fractioning column so a bypass valve is provided to pass the oil directly to the O₂ scrubber and then back to the oil tankage.

The entire oil maintenance unit, including storage tanks should be located within the oil retaining wall of the complex. Closed cell insulation should be used on the system to prevent accumulation of vapors in the event of a leak. A description of the oil maintenance unit is provided in Appendix H.

Ullage Maintenance Systems

Requirements -- The thermal storage fluids will oxidize if exposed to air at the temperatures encountered in the thermal storage systems. If oil is allowed to oxidize the resulting products thicken the oil and eventually form insoluble material that deposits on heater and other surfaces in the system. These carbon-like deposits interfere with heat transfer. Consequently, in any indirect heating system involving petroleum oils care must be taken to exclude oxygen from the oil.

The Hitec salt in the superheat storage system is also affected by exposure to oxygen at high temperature. The sodium nitrite component of the salt will oxidize according to the reaction,

This composition change will raise the freezing point of the salt and make it more difficult to keep the salt in the pipes from freezing when they are not used over extended periods. To prevent the oxidation of these materials an inert nitrogen atmosphere must be kept in the empty tank space above the fluid level. The ullage maintenance unit will provide the source of nitrogen gas to fill this space. The nitrogen pressure in the tanks will be kept slightly positive to prevent leakage of oxygen into the tanks. A safety relief valve will be provided to be sure the tank pressure does not exceed the design values.

Equipment Design and Specification -- Nitrogen will be supplied to the two storage systems from a common liquid nitrogen storage tank through an ambient air vaporizer. The gas will be added to or vented from the thermal storage tanks by automatic control valves as needed to maintain the desired pressure in the tank.

The nitrogen storage for the pilot plant consists of a 6.057 cubic meters liquid nitrogen storage tank affording over 3540 cubic meters gas storage. The liquid nitrogen is gasified through ambient air vaporizers before entering the control station. The two-stage pressure temperature control station maintains a constant line pressure for use by the tanks when needed. A schematic flow diagram of a standard tank piping arrangement is shown along with a typical equipment layout drawing (Figures 3-27 and 3-28).

The automatic control systems on the thermal storage tanks will use the nitrogen line pressure to maintain the set pressures in the tanks. The total system is diagrammed in Figure 3-29. The main storage tank pressure will be maintained between 3.4 and 9.0 kPa. When the pressure in the tank

Figure 3-27. Typical Liquid Tank Installation

LEGEND

- V1 Bottom Fill Valve
 V2 Top Fill Valve
 V3 Liquid Shutoff To Pressure Build-up Coil
 V4 Full Trycock
 V5 Vacuum Gauge Shutoff Valve
 V6 Vacuum Line Shutoff Valve (Special Tool Required)
 V7 Fill Line Drain Valve
 V8 Liquid-Level Gauge Vapor Phase Shutoff Valve
 V9 Liquid-Level Gauge Normalizing Valve
 V10 Liquid-Level Gauge Liquid Phase Shutoff Valve
 V11 Shutoff Valve - Pressure Build-Up Coil Circuit
 V12 Vapor Vent Valve
 V13 Liquid Feed Valve To Vaporizer
 V14 & V15 House Line Regulator Shutoff Valve
 V16 House Line Pressure Regulator Bypass Valve
 V17 Economizer Circuit Shutoff Valve
 V18 House Line Pressure Gauge Shutoff Valve
 LI-1 Liquid-Level Gauge
 PI-1 Tank Pressure Gauge
 PI-2 House Line Pressure Gauge
 PCV-1 Tank Pressure Buildup Regulator
 PCV-2 Economizer Circuit Pressure Regulator from Tank Vapor Space
 PCV-3 House Line Pressure Regulator from Vaporizer

- TCV-1 Automatic Low Temperature Cutoff Valve
 CV-1 Check Valve - Economizer Circuit
 R-1 Rupture Disc - Inner Tank
 R-2 Relief Disc - Outer Tank
 SV-1 Relief Valve - Inner Tank
 SV-2 Relief Valve - Fill Line
 SV-3 Relief Valve - Pressure Build-up Circuit
 SV-4 Relief Valve - Pressure Build-up Circuit
 SV-5 Relief Valve - House Line Circuit
 S-1 Strainer - Pressure Build-up Circuit

- SHUTOFF VALVE
 CHECK VALVE
 PRESSURE CONTROL VALVE
 SAFETY RELIEF VALVE
 DIAL INDICATOR
 RUPTURE DISC
 STRAINER

TE 1 Vaporizer and customer house line controls provided as integral part of tank assembly only on Model CLC-15 (1500 Gal). These items are remote & supplied separately on all other CLC tanks.

Figure 3-28. Schematic Flow Diagram Cryogenic Liquid Customer Station Model CLC-IV

Figure 3-29. Storage Equipment System.

drops close to the low limit an automatic control valve (ACV-16) will open to admit more nitrogen from the line into the tank. When the pressure in the tank rises toward the upper limit, as during the heating of the oil in the tank, a different automatic control valve (ACV-18) will open to allow the excess pressure to be released. The gases released through this valve will flow through a condenser to remove entrained oil vapors. The non-condensable nitrogen will be passed on to the atmosphere and the condensed oil vapors will be sent to the LB storage tank. An extra pressure relief valve will be on the tank to prevent pressure buildup in the event that the automatic control valve does not open.

The two Hitec storage tanks will have their ullage spaces connected with a pipe. This will allow the ullage pressure in both tanks to be controlled by a single control system. The pressure in the Hitec system will be controlled between 1.38 and 4.83 kPa. When the pressure drops toward the lower valve the automatic control valve (ACV-6) will open to admit nitrogen and raise the pressure. When the pressure rises toward the upper limit a pressure relief valve on the tank will open to release the excess pressure. The effluent gas will be clean nitrogen and may be vented to the atmosphere. A more complete description of the control apparatus is given in the subsection on control in Section 5.

Hitec Maintenance Unit

Requirements -- Hitec heat transfer salt is stable at temperatures up to about 850°F (454°C). In closed systems at temperatures between 454 and 538°C (850 and 1000°F) the salt undergoes a slow thermal breakdown of nitrite to nitrate according to the reaction:

To replace the sodium nitrite and keep the composition of the salt at its eutectic composition (53% KNO_3 , 40% NaNO_2 , 7% NaNO_3) make up salts must be added to the storage tanks. The purpose of the Hitec maintenance unit will be to melt these salts and introduce them to the Hitec system. The maintenance unit will be required to melt the salts to be added in an inert atmosphere and then pump the salts into the Hitec storage tanks where it is allowed to mix with the bulk fluid. The tank and pumping lines should be able to be drained after the salt has been added. The tank should be insulated. All pipes, pumps, and valves should be lagged and traced to prevent freeze ups during operation.

Equipment -- The melting tank should have a capacity of 2600 liters. This is capacity sufficient to correct a two-percentage point deficiency of sodium nitrite in one charge. The tank will be heated and thermostatically controlled. A mixer will be added to provide forced convection to speed the melting of the salt. The tank should be capable of heating to 335°C (635°F), the temperature required to melt pure potassium nitrate. The tank will be purged with nitrogen during melting to prevent oxidation of the nitrites.

The melted salt is then pumped to the "cold" Hitec tank. To empty the charging tank in one hour, the discharge pump will have to pump 48 liters/min. After the composition of the salt in the Hitec tank has been corrected, the piping of the Hitec maintenance tank should be drained and the tracing steam shut off until the equipment is needed again. A schematic of the unit is given in Figure 3-30.

Figure 3-30. Hitec Maintenance Unit

Oil Manifolds

Requirement -- Storage tank height to diameter ratio is determined by construction costs, minimum heat loss and packed bed heat transfer results. Optimization of these parameters dictate that the packed bed has an L/O L/O ratio on the order of 0.75. To obtain the maximum use of the storage material, rock plus oil, it is necessary that the mass flow rate of oil be uniform over the entire tank cross section. With $L/D < 1$ the pressure drop for flow in the vertical direction is less than for flow in the horizontal direction which results in maldistribution of flow propagating through the entire bed rather than being damped by sideways flow. Therefore, a manifold must be used to introduce the oil into the packed bed.

An ideal manifold would consist of large constant pressure chambers with a porous wall which would form the interface with the packed bed. The porous wall would have a high pressure drop to reduce any effects due to non-uniform bed porosity. This scheme, though ideal, poses engineering problems that make it impractical, a) the lower manifold would have to support the entire bed, b) the manifold would contain a large quantity of

expensive oil that, due to mixing, is not fully usable for thermal storage, c) to obtain a significant pressure drop, the porous wall would have to have very small holes which could become plugged with fine rock dust.

The manifold design that appears to make the best compromise is a grid of tubing with small holes (orifices) to distribute the oil uniformly over the top and bottom of the bed. To ensure that a minimum amount of bed material was carried into the manifold, the manifold hole size was selected to be approximately $1/4$ of the mean bed material size or 3.2mm for 12.7mm size gravel ($1/8$ in. for $1/2$ in. dia gravel). This ratio could be decreased with improved screening of the gravel which should be evaluated in detailed design. After determining the mass flow rate requirement for the storage tank and selecting the maximum orifice size, the number of orifices required is then a function of the pressure differential across the orifice.

The design goals set for the manifold are the following:

- 1) Maximum orifice size 3.2mm ($1/8$ inch).
- 2) Pressure differential per manifold approximately 6.9 kPa (1 psi)
- 3) Less than 10% variation in flow rate within bed.
- 4) Within the plane of the manifold, no point more than 0.3 in. (12 in.) from an orifice.
- 5) The manifold could be built outside and assembled inside of the tank.

The above goals are based upon engineering judgment and cannot be proven to be thermodynamically optimal nor have they proven to be cost optimal. The optimization would have to come from detailed fluid flow and cost trade-off studies.

Goal 1 is met by selecting the orifice size. Goal 2 is met by using the orifice flow equation:

$$W = CA \sqrt{2 \rho \Delta P} \quad (3-1)$$

where:

W = mass flow rate

C = orifice coefficient = 0.6

A = orifice area

ρ = fluid density

ΔP = pressure differential across the orifice

Since coefficient C is relatively independent of orifice diameter the orifice area per unit area of the tank can be calculated and then distributed over 'n' holes per unit tank area.

Goals 4 and 5 are met by laying out the manifold in such a manner that proper coverage is obtained and that it can be subdivided into small enough units that it can be factory made, shipped, and field assembled. Figure 3-31 is such a layout. Each of the 10 feeder lines can be assembled with its laterals, the smallest tubes. The 10 feeder modules can be shipped, inserted into the tank and welded to the main supply line to complete the assembly out of the tank.

The flow distribution, goal 3, is probably the most difficult to design for because it involves iterative calculations. No single calculating scheme can handle all possible multiple branching manifold arrangements. The usual technique in manifold design is to consider only the single closed ended tube with uniformly spaced holes or a continuous slot^{11, 12}. To solve the multi-branched manifold flow distribution the graphical determination of Reference 12 was used. For the laterals which are single

Figure 3-31. Pilot Plant Manifold Layout

closed ended tubes the method is directly applicable. For the feeder lines which terminate in laterals, the method must be modified since the discharge area is now the area of the holes in each lateral not the cross sectional area of each lateral. With this distinction noted, the laterals can be sized to obtain a sufficiently uniform flow rate along their length. The method breaks down when sizing the main supply line since there are only five discharge locations which supply unequal tank areas and which in no way can be construed as approximating a continuous slot. For the pressure distribution in the main supply line, the equations for frictional pressure drop, Equation (3-2), and changes in momentum were solved step by step to obtain the variation in pressure along its length.

$$P_2 - P_1 = f \left(\frac{L}{D} \right) \frac{u^2}{2} \quad (3-2)$$

$$P_2 - P_1 = \frac{\rho}{2} (U_2^2 - U_1^2) \quad (3-3)$$

Note that the pressure loss due to friction Equation (3-2) occurs all along the pipe and the pressure change in momentum, Equation (3-3) occurs at the discharge points, where there is a change in main stream velocity.

In a blowing manifold where the fluid velocity decelerates as it proceeds along a tube of constant cross section and with uniformly distributed orifices, the pressure rises due to the velocity decrease while at the same time being decreased by the frictional forces. In the sucking manifold, the two effects add such that they both oppose the attainment of a uniform flow. This tends to drive the design of sucking manifolds towards large sizes to minimize frictional and acceleration losses. In charging and discharging the storage system, the direction of oil flow must be reversed thus both the upper and lower manifold must perform as blowing and as sucking manifolds.

In the design of the lower manifold, consideration was made for the number of manifold holes that will be blocked by the bed material randomly packed

around the manifold. This calculation appears in the appendix. The net effect was that with a bed particle diameter to orifice diameter of 4:1, the lower manifold requires approximately 18% more orifices than the upper manifold to compensate for the number of orifices that are blocked totally or partially.

Another point of concern is the differential expansion between rock and steel. To reduce these effects slip joints were placed in all major manifold lines. A complete layout drawn for the pilot plant manifold is presented in Figure 3-32.

Insulation

The insulation on tankage, piping and equipment is provided (1) to reduce heat loss and (2) to reduce the possibility of injury to personnel from contact with hot surfaces. The latter reason sets a minimum insulation thickness. The required insulation thickness is determined by trading-off the cost of energy lost with the capital investment in insulation cost. A procedure for computing the optimum insulation thickness is detailed in Section 4.

The type of insulation selected should be compatible with the material in the equipment and the temperature. There are two types of insulation currently in use for high temperatures (up to 450°C) applications, closed cell and open cell.

Industrial experience has shown that at times, insulation soaked with organic fluid and exposed to air at elevated temperatures undergo auto oxidation with subsequent burning when the auto ignition temperature is reached. Open cell insulation gets easily soaked with flammable organic liquid and could result in spontaneous combustion. The closed cell insulation would absorb essentially no fluid beyond the outer layer of cells that were crushed during cutting.

Figure 3-32. Storage Tank Manifold Plan and Details

Closed cell insulation is recommended in areas where there is a possibility of it coming in contact with the organic liquid especially at elevated temperatures. Open cell insulation can be used on long runs of pipe that does not contain a fitting or a make or break joint that may leak, or where fluid could leak onto the insulation.

The only known acceptable closed cell insulation that is used at this time is FOAMGLAS made by the Pittsburg Corning Corporation. The acceptable open cell insulation that has a calcium silicate base (asbestos free) and currently in use is Kaylo-10 (Owens Corning), Thermos-12 (Johns-Manville), Careytemp-1500 (Philip-Carey).

FOAMGLAS insulation will be used on all equipments, piping and tankage containing or carrying caloria oil – the heat transfer and storage media for main storage and also on all piping and equipment in the Hitec loop. Hitec is the heat transfer and storage media for superheat storage.

Equipment and Piping -- Table 3-8 lists the recommended insulation thickness, for equipment and piping, based on the insulation trade-off analysis discussed in Section 4. Data in Section 4 was used in calculating the optimum insulation thicknesses. Since the insulation thicknesses are sold in discrete sizes, the closest available size to that given in the table will be used.

Main Storage Tank -- The optimum heat loss rate calculations are detailed in Section 4.

Table 3-9 and 3-10 shows the heat loss rate from the main storage tank for different insulation thicknesses. An insulation thickness of 0.229m (9") corresponds to the optimum heat loss rate of 133 KW or 108 W/M^2 from main storage tank. The FOAMGLAS thermal conductivity as a function of temperature is given in Table 3-11. Table 3-9 also gives the surface

Table 3-8. Recommended Insulation Thickness on Equipment

EQUIPMENT	O.D. (METERS)	INSULATION PARAMETER	INSULATION THICKNESS (M)	HEAT LOSS, KWt
HEAT EXCHANGERS:				
DESUPERHEATER	.457 (18.0 IN.)	1.91	.229 (9.0 IN.)	5.66
CONDENSER	1.07 (42.0 IN.)	0.20	.203 (8.0 IN.)	11.00
SUBCOOLER	.711 (28.0 IN.)	0.45	.198 (7.8 IN.)	3.32
PREHEATER	.711 (28.0 IN.)	0.45	.198 (7.8 IN.)	1.72
BOILER	1.02/1.37 (40/54 IN.)	0.12	.206 (8.1 IN.)	9.52
SUPERHEATER	.025 (1.0 IN.)	1.91	.229 (9.0 IN.)	3.42
PIPING:				
HITEC LINES	.114 (4.5 IN.)	30.60	.173 (6.8 IN.)	21.93
OIL LINES	.356 (14.0 IN.)	1.78	.178 (7.0 IN.)	37.30
CHARGE STEAM LINES	.219 (8.625 IN.)	6.5	.178 AVE. (7.0 IN.)	27.30
DISCHARGE STEAM LINES	.273 (10.75 IN.)	4.2	.184 AVE. (7.25 IN.)	
CONDENSATE LINES	.141 (5.56 IN.)	11.30	.142 (5.6 IN.)	5.60
FEEDWATER LINES	.114 (4.5 IN.)	17.26	.137 (5.4 IN.)	

temperature of the insulation. The calculation of the surface temperature requires an iterative procedure since surface conductance is a function of the insulation surface temperature.

Hitec Storage Tanks -- It was found advantageous from heat loss and operational point of view to bury the Hitec storage tanks. When above ground, the empty tank would cool down rapidly to ambient temperature within hours even with a 0.2 m (8") insulation thickness.

Table 3-9. Heat Loss From Main Storage Tank-Emittance 0.40

INPUT DATA FOR JOHN WIRT, BROWN MINNE. TANK CO.
BY PITTSBURGH CORNING CORPORATION

OUTPUT DATA
PROGRAM PP 2, LAST REVISION 10/10/73

ENGLISH UNITS

INSULATION MATERIAL - FOAMGLAS
NOMINAL PIPE SIZE = 720.00 INCHES ACTUAL DIAMETER = 720.000 INCHES
AMBIENT TEMPERATURE = 48.50 DEG F WIND VELOCITY = 9.0 MILES/HOUR EMITTANCE = 0.40

INSULATION THICKNESS				PIPE TEMP = 550.00 DEG F				PIPE TEMP = 575.00 DEG F				PIPE TEMP = 600.00 DEG F			
INCHES				SURFACE				SURFACE				SURFACE			
NOM	EQUIV	TEMP	BTU	HR	SOFT	BTU	HR	FT	BTU	HR	SOFT	BTU	HR	FT	BTU

3.0	3.01	90.65	-87.10	-16553.46	93.20	-93.64	-17797.20	95.82	-100.45	-19092.74	98.51	-107.57	-20444.50		
3.5	3.52	85.88	-75.14	-14300.72	89.14	-80.77	-15372.22	90.47	-86.64	-16490.08	92.86	-92.77	-17656.41		
4.0	4.07	82.16	-66.06	-12589.94	84.20	-71.00	-13532.47	86.29	-76.16	-14515.74	88.45	-81.54	-15541.61		
4.5	4.58	79.16	-58.93	-11247.23	81.02	-63.34	-12058.68	82.94	-67.94	-12546.46	84.90	-72.74	-13682.25		
5.0	5.03	76.70	-53.19	-10165.41	78.41	-57.17	-10925.47	80.17	-61.32	-11718.88	81.92	-65.64	-12545.57		
6.0	6.05	72.83	-44.31	-8528.83	74.36	-47.33	-9166.20	75.88	-51.30	-9830.84	77.45	-54.92	-10524.20		
7.0	7.07	70.63	-38.25	-7349.99	71.34	-41.10	-7898.72	72.62	-44.08	-8471.09	74.07	-47.19	-9068.17		
8.0	8.09	67.82	-33.53	-6459.92	69.00	-36.03	-6941.95	70.21	-38.64	-7444.73	71.45	-41.36	-7949.21		
9.0	9.11	66.05	-29.83	-5764.13	67.12	-32.06	-6194.06	68.22	-34.38	-6642.50	69.36	-36.80	-7110.28		
10.0	10.14	64.60	-26.87	-5005.19	65.58	-28.87	-5593.30	66.60	-30.96	-5978.11	67.64	-33.14	-6420.36		
12.0	12.20	62.36	-22.40	-4362.85	63.21	-24.07	-4688.00	64.03	-25.81	-5027.11	64.98	-27.63	-5580.84		
14.0	14.27	60.69	-19.19	-3753.47	61.44	-20.62	-4038.19	62.21	-22.11	-4330.19	63.00	-23.67	-4634.76		
16.0	16.35	59.40	-16.78	-3303.26	60.07	-18.03	-3549.27	60.76	-19.33	-3895.85	61.48	-20.69	-4073.19		
18.0	18.44	58.38	-14.90	-2943.13	58.92	-16.00	-3167.70	59.61	-17.16	-3396.63	60.25	-18.37	-3635.42		
20.0	20.55	57.54	-13.39	-2653.44	58.09	-14.38	-2861.72	58.67	-15.42	-3068.50	59.25	-16.51	-3284.18		

Table 3-10. Heat Loss From Main Storage Tank-Emittance 0.90

OUTPUT GENERATED FOR JOHN WIRT, BROWN MINNE. TANK CO.
BY PITTSBURGH CORNING CORPORATION

OUTPUT DATA
PROGRAM PP 2, LAST REVISION 10/10/73

ENGLISH UNITS

INSULATION MATERIAL - FOAMGLAS

NOMINAL PIPE SIZE = 720.00 INCHES ACTUAL DIAMETER = 720.000 INCHES

AMBIENT TEMPERATURE = 48.50 DEG F WIND VELOCITY = 9.0 MILES/HOUR EMITTANCE = 0.90

INSULATION THICKNESS			PIPE TEMP = 550.00 DEG F			PIPE TEMP = 575.00 DEG F			PIPE TEMP = 600.00 DEG F			PIPE TEMP = 625.00 DEG F		
INCHES			SURFACE			SURFACE			SURFACE			SURFACE		
NOM	EQUIV	TEMP	BTU HR SQFT	BTU HR FT	TEMP	BTU HR SQFT	BTU HR FT	TEMP	BTU HR SQFT	BTU HR FT	TEMP	BTU HR SQFT	BTU HR FT	TEMP
3.0	3.01	83.82	-87.98-16722.94	86.01	-94.57-17974.23	83.25	-101.44-19279.74	90.56	-108.60-20641.76					
3.5	3.52	79.70	-75.82-14429.85	81.64	-81.48-15508.63	83.63	-87.40-16634.01	85.68	-93.57-17808.11					
4.0	4.02	76.50	-66.60-12693.02	78.24	-71.57-13641.30	80.03	-76.76-14630.51	81.87	-82.13-15662.49					
4.5	4.53	73.93	-59.37-11831.75	75.51	-63.81-12177.87	77.14	-68.43-13040.47	78.82	-73.26-13981.21					
5.0	5.03	71.82	-53.56-10236.18	73.27	-57.56-11000.14	74.77	-61.73-11797.03	76.31	-64.08-11743.33					
6.0	6.05	68.55	-46.78-8931.07	69.80	-48.12-9721.07	71.10	-51.60-9983.61	72.48	-55.23-10594.96					
7.0	7.07	66.12	-38.46-7390.43	67.22	-41.83-7941.37	68.37	-44.82-8515.61	69.55	-47.43-9114.97					
8.0	8.09	64.24	-33.69-6492.21	65.24	-36.20-6975.99	66.26	-38.82-7480.57	67.32	-41.55-8008.54					
9.0	9.11	62.75	-29.97-5790.61	63.65	-32.20-6291.97	64.53	-34.53-6571.88	65.53	-36.96-7141.15					
10.0	10.14	61.53	-26.98-5227.35	62.35	-29.99-5616.66	63.20	-31.09-6022.67	64.08	-33.77-6446.21					
12.0	12.20	59.65	-22.48-4379.16	60.35	-24.16-4705.18	61.08	-25.90-5045.18	61.83	-27.72-5399.83					
14.0	14.27	58.26	-19.26-3770.79	58.88	-20.69-4051.43	59.52	-22.18-4344.11	60.18	-23.74-4649.39					
16.0	16.35	57.19	-16.93-3313.09	57.74	-18.03-3559.61	58.32	-19.39-3816.71	58.90	-20.75-4084.87					
18.0	18.44	56.34	-14.94-2956.24	56.84	-16.05-3176.17	57.36	-17.21-3405.53	57.89	-18.42-3644.76					
20.0	20.55	55.65	-13.42-2670.18	56.10	-14.42-2868.81	56.58	-15.46-3075.95	57.06	-16.55-3291.99					

Table 3-11. Foamglas Thermal Conductivity as a Function of Temperature

TEST GENERATED FOR JOHN WIRT, BROWN MINNE. TANK CO.
PITTSBURGH CORNING CORPORATION

TEMPERATURE DEG F	FOAMGLAS CONDUCTIVITY BTU-IN/HR/INCH/DEG F	KCAL/HR/M/DEG C	DEG CENTIGRADE
0.00	0.34	0.042	-17.78
50.00	0.37	0.046	10.00
100.00	0.40	0.049	37.78
150.00	0.43	0.053	65.56
200.00	0.46	0.057	93.33
250.00	0.50	0.062	121.11
300.00	0.54	0.067	148.89
350.00	0.58	0.072	176.67
400.00	0.63	0.078	204.44
450.00	0.67	0.085	232.22
500.00	0.75	0.092	260.00
550.00	0.81	0.101	287.78
600.00	0.88	0.109	315.56

The Hitec storage tanks shown in Figure 3-33 are buried underground in a pit of dimension 7.6 m (width) x 14.6 m (length) x 9.1 m (depth) for pilot plant. The pit is covered with a 0.6 m of insulation. The hot tank also losses heat to the cold tank through the insulated partition. The hot tank and cold tank exchange heat with the opposite surfaces of the partition mainly by radiation. An order of magnitude calculation of heat loss rates from Hitec storage is detailed in Appendix

Heat Loss Rate from Tanks, Lines and Equipment -- Time Constant -- For heat loss from a body with uniform surface temperature, the heat transfer equation is,

$$MC_P \frac{dt}{d\tau} = -h A (t - t_f) \quad (3-4)$$

where:

MC_P = the energy loss per degree decrease in temperature

h = the external heat transfer coefficient

A = external surface area

t = surface temperature

t_f = ambient air temperature

τ = time

Let $\theta = t - t_f$. Equation 3-4 can be solved to yield temperature as a function of time.

$$\theta = \theta_o \exp \left(\frac{-hA}{MC_r} \cdot \tau \right) \quad (3-5)$$

$$t = t_f + \theta_o \exp \left(\frac{-hA}{MC_p} \cdot \tau \right) \quad (3-6)$$

Figure 3-33. Molten Salt Storage Vault

Since the outside convective resistance is small compared to the conductive resistance of the insulation, it can be safely neglected and

$$h = \frac{k}{L_e}$$

where:

k = thermal conductivity of insulation

L_e = equivalent insulation thickness.

For cylindrical equipment, $L_e = r_o \ln \left(\frac{r_o}{r_i} \right)$.

The equations were derived for temperature decay of main storage tank, heat exchangers and pipings. Figure 3-34 shows the temperature decay of main storage tank. It takes about 2000 hr (~ 3 months) of holding time without charge or discharge for the temperature to decrease from 300°C to 150°C, with 0.23 m (9 in.) of insulation and with a -20°C ambient. A sample calculation for heat loss from a pipe is shown in Appendix.

ELECTRICAL

Electrical Requirements

Requirements for Thermal Storage -- The electrical requirements for power and distribution for both pilot plant and commercial plant include the following major components and categories.

- Charge and discharge pumps for oil and HITEC
- Motor starters and switchgear for oil and HITEC pumps.
- Oil and ullage maintenance pumps for oil and HITEC
- Bus distribution and power transformers

Figure 3-34. Temperature Decay of Oil and Rock Tark

- Control panels, panel boards and annunciators associated with local control.
- Instrumentation and control power
- Auxiliary grid power and uninterpretable power.
- Fire protection, lighting and miscellaneous.

Refer to the Electrical One-Line Diagrams in Figures 3-35 and 3-36.

The power requirements for thermal storage are obtained primarily from the turbine bus grid and will vary depending upon mode of operation of thermal storage as outlined in Table 3-12.

Table 3-12. Auxiliary Power Requirements Thermal Storage

Parameter	Pilot Plant	Commercial
<u>Total Auxiliary Power</u>		
Charge	337 kW (e)	2920 kW (e)
Discharge	207 kW (e)	1984 kW (e)
Hold	44 kW (e)	351 kW (e)
Charge and Discharge	401 kW (e)	3614 kW (e)
<u>Total Non-interruptible Power</u>		
Charge	30 kW (e)	269 kW (e)
Discharge	30 kW (e)	269 kW (e)
Hold	30 kW (e)	269 kW (e)
Charge and Discharge	30 kW (e)	269 kW (e)

An additional requirement is to provide uninterruptible power in the event of loss of auxiliary grid power, for fail-safe control for shutdown of the

Figure 3-36. Electrical One-Line Diagram

system. These power requirements will be supplied, controlled and monitored at the plant central control room. The primary requirement here is to maintain electronic equipment such as controller, auxiliaries, certain pumps, etc., to shut the system down to repair the particular problem.

In this mode, it is of particular importance to consider the Hitec system design for freeze protection of the salt. It has been shown that the time constant for cooling of the Hitec system to the normal 149°C freeze point is sufficiently longer than the time required to make appropriate system repairs in the event that bus power is lost. This means that no additional independent power source is required to operate the Hitec system other than the normal pipe tracing steam and electrical valve heating system for Hitec loops.

Equipment Design and Specifications -- For pilot plant thermal storage, electrical service will be provided by a single 1200A, 480V, 3~~φ~~ 3 wire, 60 Hz feeder line from central facilities. The power transformers will provide the capability to produce 220 VAC, 110 VAC, and 24 VDC power at the local Control Center for appropriate distribution to electrical components.

A 1200A-drawout power circuit breaker with ground fault relay will protect the 1200A bus.

Local Control Center -- Motor starters, high and low voltage switch-gear, manual control equipment, distribution and power transformers, and miscellaneous panel boards and monitoring devices will be housed in a local control center in the thermal storage area. The center will be of the two-sided outdoor protected aisle walk-through type and will also provide the interface terminal boxes for wiring power and instrumentation to central control.

For commercial plant, 2-2000A, and 1-600A 480V feeder line will provide power to thermal storage.

Motor Starters -- All motor starters will be full voltage non-reversing type with integral fused switch. All starters will be furnished with 120 volt control power transformers, hand-off automatic switches, overload relays, running pilot lights, auxiliary contacts and auxiliary control relays as required for automatic control interfacing.

Panels and Monitor Boards -- A 120/208-volt, 3- , 4-wire lighting panel board will be furnished for site lighting, convenience receptacles and miscellaneous 120 volt loads. A 30-KVA dry type transformer will be used to supply the 120/208-volt panel board.

Conduit and Wiring -- All wiring for thermal storage will be through a continuously grounded galvanized rigid steel raceway system. All power, control and communication conduit will be buried not less than 0.76 meter below grade.

All power, control and communications wire will be copper. Except where high ambient temperatures are encountered, all power conductors will be rated for 75°C and will have moisture and heat resistant, 600 volt thermoplastic insulation. Control and instrumentation conductors will consist of multi-conductor low voltage cables. Communication wiring will be shielded twisting pair cables.

Field wiring from transmitters and valves will be collected at distributed handholes and terminal cabinets and then routed back to the main terminal cabinet at the local Control Center.

Annunciator/Alarm Panel -- A special annunciator/alarm panel will be provided in local control for monitoring and alarming of specific thermal

storage variables. This is a dedicated panel for the purpose of monitoring and giving status of general plant conditions for safety, troubleshooting, and maintenance purposes.

The detailed design of the annunciator panel with hi/lo alarm and visual audible requirements is shown in Section VI, Component Selection.

Local Monitoring Electronics -- The local control room will contain certain analog indicators for monitoring thermal storage process variables. These will include standard off-the-shelf indicators which mount in a standard 19" EIA rack assembly and will provide hi/lo alarm setpoints as specified in Section 6, Component Selection.

The local monitoring electronics and annunciator panel for the commercial plant are assumed to be identical to the pilot plant requirements.

Electrical Site Plan -- The electrical site plan layout for the pilot plant is shown in Figure 3-37.

The 10 MW(e) pilot plant drawing shows the locations of various major electrical connections for input/output instrumentation in the thermal storage area and locations of pumps, fire protection, lighting, local control center, and electrical hand holes for instrumentation and power wiring connections.

Fire Protection -- As discussed earlier, four UV detectors will monitor the oil/rock tank Zone 1 area, and three UV detectors will monitor the heat exchanger, pump house, and piping areas. The fire protection equipment is shown adjacent to the local control center. See the following subsection, Auxiliary Systems, for fire protection design details.

Figure 3-37. Pilot Plant Electrical Site Layout

Oil/Rock Instrumentation -- The instrumentation associated with the oil/rock tank will terminate at the four junction boxes at the tank and routed to termination center TC-2. This will house the transmitters, data logger, and transmission equipment to send the signals to Central Control directly without terminating at local control. However, signaling associated with pressure and strain measurements will be routed to the local control center.

Process Instrumentation and Hand Holes -- The process instrumentation wiring will be routed to underground hand holes (HH) for distribution to local control and Central Control. This will allow flexibility in configuring race-way and wire-runs in addition to providing maintenance and troubleshooting of the system.

Hitec Instrumentation -- The thermo-couple signals associated with Hitec will be run to terminal center TC-2 for direct multi-plex transmission to central. All other signaling will be conditioned and routed to either local or central control.

Local Control Room -- The local control room layout shows the design and location of various equipment. This will house principally switchgear, motor starters, monitors and panels, terminal boxes, transformers, etc., and will serve as a demarcation point for interfacing the required central control wiring. The local control room does not provide process control or back-up capability for thermal storage. It is only for housing, maintenance, termination, and distribution of equipment.

Electrical One-Line Wiring Diagrams -- The electrical one-line diagrams for the pilot plant is shown in detail on Figure 3-38.

This diagram shows in detail the specific instrumentation associated with each piece of process equipment as specified in the P & ID drawings previously discussed. This also shows how the interfacing wiring is related to

Figure 3-38. Pilot Plant Electrical One-Line Diagram

the hand holes discussed in the electrical site plan layout. Included here are pressure, temperature, flow, level, and strain sensors and/or transmitters for signal conditioning.

Conditioning and Transmission -- Of interest is the wiring associated with the oil/rock tank for interfacing with the data logger and modem for transmission to central control.

The local control center shows paging, fire protection, instrumentation and control cabinets, and annunciator equipment as detailed in the electrical site plan layout of Figure 3-37 .

The upper portion of the one-line diagram illustrates the design of the power distribution system for motor starters, pumps, and transformers. For the pilot plant, this shows the 1200 amp feeder bus distributed to each of the appropriate starters and pump motors.

The block for "central instrumentation and control" represents the solar Pilot Plant Central Control room and shows the process instrumentation and data logger signals input for appropriate distribution to indicators, controllers, recorders, and data acquisition computer located at central.

Symbology and Abbreviations are again detailed in the Glossary Section of this document.

The 100 MW (e) Commercial Plant electrical one-line diagram is similar in distribution and design and is shown in Figure 3-36..

Auxiliary Systems

This section covers the requirements and design of the following auxiliary systems for both pilot plant and commercial plant. This includes:

- Fire protection
- Lightning protection
- Communication
- Area Lighting

Fire Protection System -- The fire protection system for the thermal storage area will contain two zones (areas) of protection/operation. Zone 1 is defined as the oil/rock tank storage area. Zone 2 consists of the piping and heat exchanger area. The layout of the fire protection system is shown in Figure 3-39 and the electrical site plan drawing.

The fire protection system consists of two basic elements (1) ultraviolet (UV) detectors for fast response and maximum area coverage and (2) light water type foam agent for application to either Zone 1 or Zone 2.

The "light water" foam system is a synthetic fluoro chemical which requires mixing with water, at the proper concentrate level to achieve maximum effectiveness. The system spreads a vapor-sealing water film on liquid hydrocarbon fuels. In addition, light water is biodegradeable and soluble in water for clean up.

The UV detectors will be mounted on 25 foot steel poles and at strategic locations to provide maximum coverage of the thermal storage area. The UV controllers will be mounted in the local control center and will provide the activating circuitry to initiate the light water foam spray system. The foam and charging system will be located near the local control center (away from the oil/rock tank area).

Figure 3-39. Thermal Storage Subsystem Fire Protection System Plan

In the event of a fire in the area, the UV detectors will sound an alarm and charge the foam "proportioning" stations (mixes water and agent in the proper proportion). The mixing proportion is nominally 3% foam concentrate to 97% water. Each zone has a capacity of 32 lit. /s spray for a maximum of 30 minutes of full spray coverage.

A 120, 000-liter underground water tank is located near the fire protection shed which houses the foam supply, proportioning valves and associated control valves. The water supply is used to supply water to both the foaming agent system and as standard water supply for extinguishing non-oil type fires. A 30 kW pump is required for the water tank.

Zone 1 (oil/rock tank) application will provide two automatic oscillating nozzles to obtain full surface coverage. Nominal maximum spray distance is 50 m.

Zone 2 (heat exchanger and piping) application will be provided by portable foam nozzles (4) at hose lines located in the area. Simultaneous controls for shut off valves in the oil systems will correspondingly be closed to control oil leakage in each zone.

Each hose rack (item 5 in Figure 3-39) consists of two hoses, one for foam-ing agent application and the other for standard water extinguishable fires with a low velocity fog spray nozzle to isolate small fires while protecting operating personnel from heat. The hoses for both foam and water are 30 m in length from each hose rack to provide overlapping coverage.

Lightning Protection 13, 14, 15- The protection system of the oil field tank farm from lightning strikes is implemented as described below.

The specific design of the protection system is a function of 1) the frequency and intensity of thunderstorms for the given location (isokeraunics) and 2) the typical ground soil resistance.

The isokeraunic level for thunderstorm activity for Barstow, California, is 5-10 indicating a relatively low activity and frequency level.

Steel enclosures are generally considered as self protecting against lightning if they are vapor tight and of sufficient wall thickness to withstand direct strikes without puncture. This is presumed to be the case for the oil/rock tank farm design and associated transfer piping.

However, additional secondary sources of protection are considered as acceptable standard design practices as discussed below.

A secondary source of lightning protection for the oil tank will be to ground the tank with Cadweld bare 500 MCM wire at three locations (nominally 60 foot intervals) around the tank. The Cadweld wire (nominal 20 mm) will be welded to the tank steel wall and grounded in the reinforced steel concrete wiring (rebars) in the foundation.

An additional but built-in source of lightning protection for the thermal storage area is provided by the SPP receiver tower itself. The height of the tower provides a 30-45° cone of influence where any direct strikes would "tend" to be grounded through the tower system as shown in Figure 3-40.

This results in protection of ground equipment up to a nominal radius of 65m from the base of the tower. This is sufficient to cover the thermal storage oil tank system.

Communications -- A local paging system consisting of an amplifier, microphone, and weatherproof horn type speakers will be provided. The amplifier

Figure 3-40. Lightning Protection – Receiver Tower Influence

will normally be fed from the central paging system with local preemption via a push-to-talk pushbutton.

Local intercom stations will be provided at the Motor Control Center and at the Terminal Cabinet for the Oil Storage Tank. These intercom stations will be connected to the plant intercom system.

Area Lighting -- Area lighting will be provided to flood the thermal storage area to an average maintained three-foot candle illumination level. Light sources will be 400-Watt metal halide lamps in floodlighting luminaries mounted on 25-foot steel poles. Luminaries will be controlled by an astromonic dial time switch located in the MCC. Ballasts will be high power factor type for 120-volt operation.

Refer to Figure 3-37 for location of the flood lighting for the thermal storage area.

COMMERCIAL PLANT CONCEPTUAL DESIGN

Storage Subsystem Site Plan

Figure 3-41 shows the four tower 100 MW(e) commercial plant general arrangement. The storage area is located in the central complex north of the main turbine and generator area. The dimensions are nominally 79 m (260 ft) north-south by 91 m (300 ft) east-west. Services would be transferred to and from the storage area on the south-center perimeter. Main steam from the four receivers will be delivered from the turbine building via a 16" schedule 160 type A335 P12 alloy steel line located approximately eight feet above grade. Condensate returning to the deaerator will be piped through an 8" schedule 80 type A106-Grade B pipe. Storage steam to the turbine will flow through a 20 inch schedule 30 (XS), type A106-Grade B pipe located also 8 ft above grade. The feedwater supply to storage is via an 8 inch, A106 Grade B standard weight pipe.

Figure 3-42 shows a preliminary thermal storage site plan. The general features of the pilot plant arrangement are recognizable. The basic plan is to modularize the heat exchangers and flow loops and expand the tankage based on pilot plant sizes and actual experience. For example, the pilot plant boiler and condenser heat exchangers are currently sized to be the largest modules that are economically road transportable. Maintaining this modularity concept for the commercial plant results in eight boilers and six condensers in parallel in their respective discharge and charge loops. Each module will have been thoroughly evaluated in the pilot plant test program and lower unit production costs would result in lower installed and bus bar costs for the modular approach. With tankage it is somewhat different. Here the salt storage tanks are scaled up versions of the similar pilot plant tanks. Below ground storage and tank designs will be thoroughly demonstrated in the pilot program.

Figure 3-41. 100 MW(e) Solar Plant Conceptual Site Arrangement

NUMBER	DESCRIPTION
1	OIL AND ROCK STORAGE TANKS
2	PREHEATER
3	BOILER
4	MAIN DISCHARGE PUMP
5	MAIN CHARGE PUMP
6	CONDENSER
7	SUBCOOLER
8	HOT HITEC STORAGE TANK
9	COLD HITEC STORAGE TANK
10	HITEC DISCHARGE PUMP
11	HITEC CHARGE PUMP
12	ULLAGE AND HITEC MAINTENANCE
13	DESUPERHEATER
14	SUPERHEATER
15	ELECTRICAL SWITCHGEAR AND LOCAL CONTROL STATION
16	REBOILER
17	DISTILLATION COLUMN
18	CONDENSER - LOW BOILERS
19	CONDENSER - HIGH BOILERS
20	OIL MAINTENANCE PUMPS
21	LOW BOILERS STORAGE TANK
22	HIGH BOILERS STORAGE TANK
23	MAKE-UP OIL STORAGE TANK

THERMAL STORAGE SUBSYSTEM 100 MW(e) PLANT		
DESIGNED BY GLT	SITE PLAN	CONTRACT NO. 575-2776
APPROVED BY GLT		DATE 1/1/77
APPROVED BY GEO. SCHWENK, MAYORSON & ASSOCIATES, INC. CONSULTING ENGINEERS 301 EAST HENRIETTA AVE. ANN ARBOR, MICHIGAN 48103	DESIGN NO. 1	

Figure 3-42. Preliminary Thermal Storage Site Plan

The maximum size of oil and rock tank proposed at this time is 34.76 meter diameter. Therefore, two such sizes will be used on the first commercial plant. Subsequent plants may contain larger size tankage.

The key in Figure 3-42 locates the basic equipments. Approximately 7250 m² are required to contain these equipments. A berm completely isolating the oil tankage from the remaining equipment is used to contain the entire oil, if a spillage occurs.

Low area drains will enable spilled oil to be returned to the makeup oil storage tank where it can be pumped into mobile trailer trucks for temporary storage. In the event that the spill involves hot oil a fire may ensue. The fire protection system provides automatic dispensing of light water foam on the tank and within the berm. The light water foam is biodegradeable and this will greatly simplify the post spill clean up process. Notice that the inorganic salt (HITEC) storage tanks are located on the opposite end of the storage field and are below ground. The hot oil and hot salts are not compatible and present a general safety hazard. However, with such an arrangement, the personnel and equipment safety is assured for all except the most devastating ground zero earthquakes, well beyond the design level. The heat exchangers are arranged and spaced to allow the tubes to be pulled for inspection and maintenance.

The power distribution and control cables from the plant will be routed below ground to the Local Control Station (Item 15).

Piping and Instrument Diagram (P&ID) -- Figure 3-43 is the preliminary P&ID for the Commercial Plant. This clearly shows the modularity concept envisioned for scaling the pilot plant.

Figure 3-43. Commercial Plant Piping and Instrument Diagram

Tankage Design

The superheater tanks (2) are 2X scale versions of those of the pilot plant. Figure 3-44 shows the commercial plant design. The major difference between the two designs is in the bottom shell to head. The commercial design uses a 1.22 meter knuckle and does not require an external compression ring. Design calculations are similar to those documented in Appendix G.

The main storage tank design is shown on Figure 3-45. This tank is 34.8 meters in diameter by 20.7 meters high. The design features 2.44 meter knuckles at the top and bottom of the six-course wall. Design calculations are similar to those documented in Appendix G. Two such tanks are used in the commercial plant.

Heat Exchangers

The heat exchanger designs are based on data supplied by Manning and Lewis. Refer to Section 3 for heat exchanger design discussions. The data sheets on each unit can be found in Appendix A.

Fluid Flow Loops

The design of the fluid loops was predicted on the pilot plant configuration. On the charging side a) main storage, one subcooler is coupled to two condensers in a pumping loop. Three such loops are required. b) superheater storage, one desuperheater in a pumping loop. Three such loops are required. On the discharging side a) main storage, one preheater is coupled to two boilers in a pumping loop. Four such loops are required. b) Superheat storage, one superheater in a pumping loop. Four such loops are required.

Figure 3-44. Superheater Tank Design

Figure 3-45. Main Storage Tank Design

DATA SHEET	
DESCRIPTION	OIL / ROCK TANK
NUMBER REQUIRED	1
CAPACITY	43' OF ROCK @ 75% COMPACTION ± 13' OF OIL
DESIGN PRESSURE	1.3 PSI + ROCK @ 32' ± 10 PCFT + OIL SFGR = 1.3 PSI
OPERATING PRESSURE	1.1 PSI
TEST PRESSURE	1.625 PSI + HYDROSTATIC HEAD
DESIGN TEMPERATURE	600°F WITH COOLDOWN TO -50°F
TEST TEMPERATURE	AMBIENT
JOINT EFFICIENCY	1.0 SHELL
CORROSION ALLOWANCE	NONE
CODE & STAMP	SEE NOTE # 2
CUSTOMER SPECIFICATION	EXHIBIT A
DESIGN DATA	
SHELL 2 BOT. W/ KNUCKLE	A 533 CLASS 2 GRADE A
TOP & TOP KNUCKLE	A 516-60
HEADS	NONE
NOZZLE	NECK A 105 FLANGE A 105
MANWAY	NECK A 516-60 FLANGE A 516-60 COVER A 516-60
REINFORCING PADS	A 533 CLASS 2 GRADE A
PIPING	NONE
COUPLINGS	NONE
STIFFENER RINGS	NONE
INTERNAL	NONE
BOLTING	BOLTS 193-B7 NUTS A 94-2H STUDS NONE
GASKETS	COMPRESSED ASBESTOS
STRUCTURAL	A 533 CLASS 2 GRADE A
ELECTRODES	60XX OR E 70XX A 516-60
MATERIALS	
STRESS RELIEF	REQUIRED PWHT PER ASME, SEC VIII DIV. 1
CLEANING	BROOM CLEAN AFTER ERECTION
SURFACE PREPARATION	NONE
CONSTRUCTION	
INTERNAL PAINTING	NONE
EXTERNAL PAINTING	NONE
LINING	NONE
INSULATION	REQUIRED 9" OF FOAMGLASS @ ON ROOF
LADDERS & PLATFORMS	SHELL & ANCHOR CHAIRS
CATHODIC PROTECTION	NONE
FOUNDATIONS	3000 PSI CONCRETE @ 4615-60 RE-BAR PER DRAWING
QUALITY ASSURANCE	
QA MANUAL	NOT APPLICABLE
MILL CERTIFICATIONS	ALL PRESSURE RETAINING MATERIAL
WELDERS	ASME SECTION 8 QUALIFIED
WELDING	ASME SECTION 8 APP D
NONDESTRUCTIVE TESTING	RADIATION SHELL & BOTTOM KNUCKLE PER A.P.I. STD. 650 APP D
SPECIAL TESTING	NONE
TESTING	SHELL HYDROTEST + 1.625 PSI
BOTTOM	VACUUM BOX PER A.P.I. STD. 650
ROOF	

NOTES: 1. FLANGE BOLT HOLES STRADDLE TANK VERTICAL & RADIAL CENTER LINES - UNLESS OTHERWISE SPECIFIED.

2. A.P.I. STD. 650 APP. D, FOR FABRICATION, ERECTION, TESTING & EXAMINATION. A.P.I. STD. 650 APP. D, DESIGN MODIFIED FOR THERMAL LOADS.

PROJECT ENGINEER APPROVAL & DATE CHECKED BY & DATE DRAWN BY & DATE	NO. 4-5-77	REVISION THIS DRAWING IS THE PROPERTY OF BROWN-MINNEAPOLIS TANK AND IS TO BE USED ONLY IN CONNECTION WITH WORK PERFORMED BY BROWN-MINNEAPOLIS TANK. THE DRAWING IS NOT TO BE COPIED IN WHOLE OR IN PART AND MUST BE RETURNED UPON REQUEST. PURCHASER'S NO.
	4-4-77	
	DESCRIPTION 114' Ø x 48' HIGH OIL / ROCK TANK FOR HONEYWELL	
	DRAWING NUMBER 114D441103 ORDER NUMBER SHEET 1	

Oil Maintenance Unit -- This unit consists of four foot distillation columns and associated equipment. The design is based on the same oil degradation rate as the pilot plant unit. See Appendix H for details.

Ullage Maintenance Unit -- This unit serves both the Hitec and main storage tanks. The commercial plant system is based on a 37,200 liter (9,300 gallon) liquid nitrogen storage tank affording 10,000 m³ gas storage with ambient air vaporizers and control station. The design is similar to the pilot plant unit. See Section 3 for details.

Hitec Maintenance Unit -- This unit is similar to the pilot plant unit except that the tank capacity is 16,275 liters. A description is supplied in Section 3.

Oil Manifolds -- Four oil manifolds sized to the 34.75 meter diameter tanks is required. The design is similar to the pilot plant configuration. See Section 3 for details.

Electrical

The electrical site plan layout and one-line diagrams are shown respectively in Figures 3-43 and 3-44.

The major difference is in the power requirements for electrical power and auxiliary power for operation of thermal storage. The commercial plant requires two 2000A and one 600A, 480V, 3-phase feeder line to local control for power distribution.

The auxiliary power requirements for commercial plant are summarized in Table 3-12, for various modes of thermal storage operation. Other design requirements remain similar to pilot plant but vary only in quantity or size.

Controls for Commercial Plant

The commercial plant is an expansion of the pilot plant with a greater number of units but essentially a similar control system. Hitec storage tanks are larger, the main oil tank has two units instead of one, there are 4 preheaters, 8 boilers, 4 superheaters, 3 desuperheaters, 2 attemperators, 6 condensers, 1 condensate receiver and 3 subcoolers.

The control loops (13 for the pilot plant) are identical to the pilot plant with the following additions. All 8 boilers will probably not be in service at one time since if the demand is less than full capacity, several boilers should be in standby. The central digital computer or some combination of computer plus an encoder could be used to determine the number of boilers in use at any one time. The encoder is a simple economic method of a buffer or storage for the number of boilers needed at any one time. Anytime the encoder is told by the computer to keep 6 boilers in operation, it keeps this reference until changed. In the event of an emergency the encoder can be operated manually.

Each of the boilers has an individual oil pump that supplies hot oil from storage to the preheaters and boilers. These would be shut down if the accompanying boiler is also down. Demand would be taken care of by running an even number of boilers at full capacity and then modulating the next two boilers. This overcomes the need, when demand is less than full capacity, for modulating all 8 boilers. Modulation of the feedwater to the boiler is exactly like the pilot plant system.

On the charge side, each of the desuperheaters has a separate Hitec charge pump. If receiver steam supply is not low, one or more of the desuperheaters can be shut down and modulating can be done with the third desuperheater. This would avoid running all three at partial output with reduced efficiency.

The three subcoolers and six condensers can be controlled in the same fashion as the other units. If incoming receiver steam is less than normal, units can be shut down with one condenser used for modulation. Again, this type of operation in which only one condenser is used for modulating and with the remaining units at full flow is more efficient.

It may be more efficient to have more than one condensate receiver between the subcoolers and condensers. Several smaller units in parallel may be more cost efficient than one unit.

The ullage and oil maintenance loop provide no problem and are merely an extension of the pilot plant system. All 13 control systems should be applicable to commercial system with only the few additions described previously.

SECTION 4

PERFORMANCE ANALYSIS/TRADEOFF STUDIES

TRADEOFF STUDIES

Main Storage Tank Configuration and Heat Loss Tradeoffs

The basic parameters affecting the tank height to diameter ratio H/D for a given system are the heat loss rate and the utilization factor. The cost factors determining the optimum tank H/D are the tankage cost, the storage medium cost, insulation cost and pumping cost. The major factors for optimizing the heat loss rate are the insulation and energy cost.

For a low heat loss rate, the insulation costs would increase while for high heat loss rate, the energy, tankage and material cost would increase. A low optimum heat loss rate would tend to shift the optimum H/D ratio towards minimizing the tank surface area, while a high optimum heat loss rate would tend to shift the optimum H/D ratio towards minimizing tankage cost. Thus, heat loss rate and H/D are interdependent. The optimum is determined by trial and error.

Table 4-1 shows the cost equations as functions of heat loss rate, P, (expressed in percent of stored heat loss per hour) and tank height to diameter ratio, β (= H/D). The development of the equations is shown below.

Storage Capacity and Tank Volume -- The dischargeable heat storage capacity, Q_D , is given by

$$Q_D = \frac{MW(e) \times t_{stor} \times f_{MS}}{\eta_{turb}}, [MWH(t)] \quad (4-1)$$

Table 4-1 Cost Equations

Cost Item	Equation	Constants
Tank Cost, C_T	$K \left\{ T_1 \left[\frac{5}{(5-P) [\phi(\beta)]} \right]^{2/3} \cdot \left[\frac{B+0.8}{\beta^{2/3}} \right] \cdot \left[T_2 \left[\frac{5 \cdot \beta^{1/2}}{(5-P) [\phi(\beta)]} \right]^{2/3} + X \right\}^a$	$T_1 = 159.8 \cdot V_D^{2/3}$ $T_2 = 1.15 \times 10^{-6} \cdot \rho \cdot V_D^{2/3}$ $M = V_D \cdot \hat{C}_M$ $I = \frac{6.82 \times 10^{-4} V_E^{4/3} k(t_s - t_a) \hat{C}_I}{Q_D}$ $E = 552.7 \cdot Q_D \cdot \hat{C}_E$ $v_D = \frac{Q_D \cdot 3413 \times 10^3}{\zeta C_p \cdot \Delta t}$ $Q_D = \frac{MW(e) \times Hrs \times fMS}{(\eta_{turb})}$ $X, a = \text{Constants in tank cost equation}$ $\hat{C}_T = KW^a$
Material Cost, C_M	$M \cdot \frac{5}{(5-P) [\phi(\beta)]}$	
Insulation Cost, C_I	$I \cdot \beta^{4/3} \cdot \frac{(B+0.25)^2}{P^2 (5-P) [\phi(\beta)]^{1/3}}$	
Energy Cost, C_E	$E \cdot \frac{P}{(5-P) [\phi(\beta)]}$	
Total Cost, C_{Tot}	$C_T + C_M + C_I + C_E$ $C_{Tot} = f(P, \beta)$ $\phi(\beta) = \text{Thermocline utilization factor as a function of } \beta$	

40703-V

4-2

where

MW(e) = net electrical output

t_{stor} = storage hours

f_{MS} = fraction heat stored in main storage

η_{turb} = turbine net thermal efficiency running from storage

and the ideal volume, V_D , of the storage media required is

$$V_D = \frac{Q_D \times 3413 \times 10^3}{(\rho C_p)_m \cdot \Delta t} \quad (4-2)$$

where

$(\rho C_p)_m$ = mean heat capacity of storage medium

$\Delta t = t_{\text{hot}} - t_{\text{cold}}$ = difference in hot and cold storage temperature, °F

If UF is the heat utilization factor and P is the percent heat loss rate per hour, then the required storage capacity, Q_{sto} , for a 20-hour hold is given by:

$$Q_{\text{sto}} = \frac{Q_D}{U_F} + Q_{\text{sto}} \times \frac{P}{100} \times 20 \quad (4-3)$$

UF is a function of tank H/D for given system parameters, i.e., $UF = \phi(\beta)$ where $\beta = H/D$, then:

$$Q_{sto} = \frac{Q_D}{\phi(\beta)} \cdot \frac{5}{5-P}$$

and

$$Q_{loss} = \frac{Q_D}{\phi(\beta)} \cdot \frac{P}{(5-P)}$$

(4-4)

The heat loss rate is:

$$q_{loss} = \frac{Q_{loss}}{20}, \text{ MW(t)} \quad (4-5)$$

The total volume, V, of storage media is:

$$V = \frac{V_D}{\phi(\beta)} \cdot \frac{5}{5-P}, (\text{ft}^3) \quad (4-6)$$

Tank Cost -- The tank cost is a function of the weight of material (W) used in fabrication and is of the form:

$$C_T = KW^a \quad (4-7)$$

The tank weight, W, can be approximately calculated from,

$$W \text{ (lb)} = 136 D (H + 0.8D) (t + x), \quad (\text{Ref. 16}) \quad (4-8)$$

where:

D = diameter, ft

H = height, ft

t = average shell thickness, inches

x = equivalent thickness to be added to account for manholes, internal supports, etc.

According to API code-650, the shell thickness, t , is calculated from,

$$t = \frac{2.6 (H-1) (D) (G)}{SE} \quad (\text{Ref. 17}) \quad (4-9)$$

where S is the allowable stress (corrected for high temperatures to meet the ASME Code, Sec. VIII, Div. 2), E is the joint efficiency factor, and G is the specific gravity.

Thus, for a given tank specification, tank weight is a function of H/D ratio. Rewriting, the Equation (4-8) in terms of β ,

$$W(\text{lbs}) = 136 D^2 (\beta + 0.8) \left(\frac{2.6 \beta D^2 G + X}{SE} \right) \quad (4-10a)$$

and

$$D = \left(\frac{4V}{\pi \beta} \right)^{1/3} \quad (4-10b)$$

V is total volume of tank given by Equation (4-6) and $\beta = H/D$.

The minimum tank weight can be obtained by differentiation of above equation with respect to β .

The tank cost equation becomes,

$$C_T = K \left[136 D^2 (\beta + 0.8) \left(\frac{2.6 \beta D^2 G}{2 SE} + X \right) \right]^a \quad (4-11a)$$

and substituting for V and D and defining,

$$\psi = \frac{5}{(5-P) [\phi(\beta)]}$$

we get

$$C_T = \left\{ K T_1 \psi^{2/3} \left| \frac{\beta + 0.8}{\beta^{2/3}} \right| \left[T_2 (\beta \psi^2)^{1/3} + X \right] \right\}^a \quad (4-11b)$$

where:

$$T_1 = 159.8 V_D^{2/3}$$

$$T_2 = 0.025 \cdot \frac{\rho \cdot V_D^{2/3}}{SE}$$

X = Thickness allowance, inches

Insulation Cost -- The surface area, A_s , for insulating the sides and top is:

$$A_s = \pi DL + \frac{\pi D^2}{4} = \pi D^2 (\beta + 0.25) \quad (4-12)$$

The insulation cost is:

$$C_I = \hat{C}_I \cdot A_s \cdot \chi_I \quad (4-13)$$

where:

C_I = unit insulation cost installed, \$/ft³

χ_I = insulation thickness, ft

The insulation thickness, χ_I , can be calculated from

$$\dot{q}_{\text{loss}} = \frac{k \cdot A_s}{\chi_I} \cdot (t_s - t_a) \quad (4-14)$$

where;

k = thermal conductivity of insulation, $\frac{\text{BTU}}{\text{hr-ft-}^\circ\text{F}}$

t_s = average storage temperature, $^\circ\text{F}$

t_a = ambient temperature, $^\circ\text{F}$

also $\dot{q}_{\text{loss}}$ is given by Equation (4-5),

Comparing Equations (4-5) and (4-14),

$$\chi_I = \frac{k \cdot \pi D^2 (\beta + 0.25) \cdot (t_s - t_a)}{Q_D \times 3413 \times 10^3} \cdot \frac{5-P}{P} \cdot \phi(\beta) \cdot 20 \quad (4-15)$$

Substituting for D and χ_I in Equation (4-13)

$$D = \left(\frac{4V}{\pi\beta} \right)^{1/3} = \left(\frac{4 \cdot V_D}{\pi\beta} \cdot \frac{5}{5-P} \right)^{1/3}$$

$$C_I = \frac{\hat{C}_I \cdot k \cdot \pi^2 D^4 (\beta + 0.25)^2 \cdot (t_s - t_a)}{Q_D \times 3413 \times 10^3} \cdot \frac{5-P}{P} \cdot \phi(\beta) \cdot 20$$

or

$$C_I = I \cdot \frac{(\beta + 0.25)^2}{\beta^{4/3} \cdot P [(5-P) \cdot \phi(\beta)]^{1/3}} \quad (4-16)$$

where

$$I = \frac{6.824 \times 10^{-4} V_D^{4/3} \cdot k (t_s - t_a) \hat{C}_I}{Q_D}$$

Energy Cost -- The cost of the annual energy loss is calculated as:

$$\text{Annual energy loss} = \frac{Q_{\text{loss}}}{20} \times 8760 \frac{\text{hrs}}{\text{yr}}, \text{ MWH(t)}$$

Equivalent annual electrical energy loss =

$$\frac{Q_{\text{loss}}}{20} \times 8760 \times \eta_{\text{turb}}, \text{ MWH(e)}$$

Cost of energy loss per year =

$$\hat{C}_e \cdot \frac{Q_{\text{loss}}}{20} \times 8760 \times \eta_{\text{turb}} [\$]$$

where

$\hat{C}_e$ = cost of electrical energy in mils/KWH(e)

Present worth of total energy loss in n years. =

$$\left(\frac{1}{\text{PWF}} \right) \cdot \hat{C}_e \cdot \frac{Q_{\text{loss}}}{20} \times 8760 \times \eta_{\text{turb}}$$

The present worth factor (PWF) at a rate of return of 20 percent for 30 years is 0.168.

Substituting for Q_{loss} , the cost of energy loss is

$$C_E = E \cdot \frac{P}{(5-P) [\phi(\beta)]} \quad (4-17)$$

where:

$$E = 2607 \times \frac{\hat{C}_e \cdot \eta_{\text{turb}}}{Q_D}$$

Material Cost -- The storage media cost is

$$C_M = \hat{C}_M \cdot V$$

where:

$$\hat{C}_M = \text{unit cost of storage media, } \$/\text{ft}^3$$

Substituting for V,

$$C_M = M \cdot \frac{5}{(5-P) [\phi(P)]} \quad (4-18)$$

where:

$$M = \hat{C}_M \cdot V_D$$

The other cost factors affecting the optimum solution are the cost of the concrete pad for tank which increases as square of the diameter, and the increase in thickness allowances for seismic forces, which increases as height. Besides, the unit cost of electricity is a function of heat loss rate since the net energy collected for a given capital investment varies with heat loss rate. However, these effects are relatively small and can safely be ignored.

The total cost equation is:

$$C_{TOT} = C_T + C_M + C_I + C_E$$

or

$$C_{TOT} = KW^a + \hat{C}_M \cdot V + \hat{C}_I \cdot A_s \cdot x_I + \hat{C}_e \cdot Q_L \quad (4-19)$$

or writing as a function of heat loss rate, $\bar{P}$, and height to diameter ratio, β , and defining:

$$\psi = \frac{5}{(5-P) [\phi(\beta)]}$$

$$C_{TOT} = K \left\{ T_1 \psi^{2/3} \left(\frac{\beta + 0.8}{\beta^{2/3}} \right) \left[T_2 \left(\frac{\beta}{\psi^2} \right)^{1/3} + X \right] \right\}^a \quad (4-20)$$

$$+ M \cdot \psi + E \cdot \psi + I \cdot \frac{(\beta + 0.25)^2}{1.71 \beta^{4/3} \cdot P} \cdot \psi^{1/3}$$

which gives,

$$C_{TOT} = f(P, \beta)$$

The equations are summarized in Table 4-1.

Result -- The trial and error solution of the Equation (4-20) results in a total minimum cost for

$$\beta = 0.7 \text{ and } P = 0.12\%/hr$$

Figures 4-1 and 4-2 show the cost versus H/D at optimum heat loss rate and cost versus percent heat loss rate at optimum H/D. Only the major cost factors affecting the optimum solution are shown on the graphs.

Figure 4-1. Main Storage Tank Tradeoff--Cost versus Height/
Diameter

Figure 4-2. Main Storage Tank Heat Loss Tradeoff

Main Storage Pinch Point Tradeoffs

For a given charge and discharge cycle conditions, the heat storage temperature varies between the condensing temperature of charge steam and boiling temperature of discharge steam as shown in Figure 4-3. The minimum cost of storage media will be for a maximum possible swing in storage temperatures. But as the storage temperatures approach the charge or discharge temperatures, i.e., as the "pinch point" decreases, the log mean temperature difference to the heat exchanger decreases resulting in an increase in surface area and cost of heat exchanger. The other cost factors affecting the "pinch point" tradeoffs are the tankage, insulation, oil

$$\text{Heat Storage Oil Temperatures} = T_{\text{hot, oil}} - T_{\text{cold, oil}}$$

Heat Exchanger Approach temperatures

$$\text{Condenser} = T_{\text{charge}} - T_{\text{hot, oil}}$$

$$\text{Boiler} = T_{\text{discharge}} - T_{\text{cold, oil}}$$

Figure 4-3. Pinch Point

replacement costs and hours of storage. With increase in pinch point, the material, tankage, and insulation cost increases while heat exchanger and oil replacement cost decreases.

The optimum pinch point is determined to be about 5.6°C (10°F) as shown in Figure 4-4. A detailed analysis showed an optimum pinch point of 6.6°C (12°F) and 5.6°C (10°F) for condenser and boiler, respectively. To determine the effect of pinch point on heat loss rate P and H/D ratio, the cost equations for tankage, material and insulation shown in Table 4-1, were used with P , β and pinch point as parameters. Pinch point does not affect P and β significantly.

Effect of Thermocline on Pinch Point -- The temperature of the heat transfer fluid out of the tank decreases towards the end of the discharge. For a complete utilization of the heat stored in the tank the final fluid temperature will be equal to the lowest storage temperature. Since the heat exchangers have to be designed to meet a certain heat rate condition even towards the end of the discharge, the heat exchangers will have to be oversized to increase the heat utilization factor.

With a decrease in final fluid temperature, the required bed height decreases. Consequently, we have a savings in material, tankage, and insulation but an increase in the cost of heat exchangers.

Figure 4-5 shows the cost versus fluid temperature out of the tank at the end of three-hour discharge. The optimum fluid temperature out is 300°C which is 3.4°C less than the hot storage temperature.

This effect when included in pinch point optimization increases the optimum pinch point by less than 0.3°C (0.5°F).

Figure 4-4. Thermal Storage Heat Exchanger Pinch Point Tradeoff

Figure 4-5. Thermal Storage Subsystem Tradeoff Studies for Final Fluid Temperature Out

Effect of Storage Hours -- For a given heat rate condition, the cost of heat exchangers becomes significant in the total system cost as the hours of storage are decreased. Therefore, with decrease in storage hours the pinch point increases to decrease the cost of heat exchangers. Figure 4-6 shows the pinch point tradeoffs with storage hours as parameters. For a 12-hour storage the optimum pinch point is 1°C while for a $1/2$ -hour storage the optimum pinch point is about 12°C .

A parametric study on thermocline performance (see page 4-32) has shown that the storage hours and storage temperatures affect the utilization factor for given system requirements. However, in this analysis, this effect is not included.

Optimization of Average Size of Rock for Oil/Rock System

The bed pressure drop increases as the average size of the rocks decreases resulting in an increase in pumping cost. However, with decrease in average size the surface area per unit bed volume increases which results in a sharper thermocline and hence a better utilization factor and a decrease in material cost.

The utilization factor as a function of average particle size was obtained utilizing the thermocline model described later in this section. Figure 4-7 is a plot of the total Δ - cost versus particle size. The Δ -material cost is based on a zero material cost for 0.013 m (0.5 in.) average size rocks. The Δ -pumping cost is calculated from bed pressure drop (ΔP).

Figure 4-6. Pinch Point Tradeoff with Storage Hours Parameter

Figure 4-7. Particle Size Tradeoff

Equations:

Pressure drop:

$$\Delta P = \frac{2 f_m G^2 L (1-\epsilon)^{3-n}}{D_p g_c \rho \phi_s^{3-n} \epsilon^3} \quad (\text{Ref. J. H. Perry, Chem. Eng. Handbook, p. 5-50.})$$

where:

 ΔP = pressure drop, lb_f/ft^2 L = depth of bed, ft g_c = dimensional constant = $32.17 \text{ lb-ft/lb}_f\text{-sec}^2$ D_p = average particle diameter, ft ϵ = voidage (fractional free volume) n = exponent, a function of modified Reynolds number N_{Re}
(Ref: Fig. 5-64, J.H. Perry, 4th Ed.) ϕ = shape factor of the solid G = fluid superficial mass velocity, lb/sec-ft^2 ρ = fluid density, lb/ft^3 f_m = friction factor, a function of N_{Re}

(Ref: Fig. 5-64, J.H. Perry, 4th Ed.)

$$N_{Re}' = \frac{D_p G}{\mu}$$

and

$$D_p = \frac{6(1-\epsilon)}{\phi_s S}$$

S is the specific surface, sq. ft/cu.ft.

Approximate equations for n and fm are:

$$n \approx 0.588 (N_{Re}')^{0.2304} \quad (N_{Re}' > 10)$$

$$n = 1 \text{ for } N_{Re}' \leq 10$$

and

$$f_m \approx 5000 (N_{Re}')^{-1.7}$$

The pumping cost is given by:

$$C_p = \frac{(\Delta P) \cdot G}{550} \cdot \frac{\pi D^2}{4} \times \frac{0.746}{\eta_{\text{pump}}} \times \frac{\tau \times \hat{C}_e}{(\text{PWF})}$$

where:

C_p = pumping cost, \$

D = tank diameter, ft

η_{pump} = pump efficiency

τ = number of operating hours per year

$\hat{C}_e$ = unit cost of electricity, \$/kWH(e)

PWF = present worth factor (0.168 at 20 percent return for 30 years)

Also, 550 and 0.746 are conversion factors from ft-lbf/s to hp and hp to KW, respectively

Δ -material cost is calculated from:

$$\Delta C_M = \left[\frac{V_D}{UF} - \left(\frac{V_{D_1}}{UF_1} \right) \right] \hat{C}_M \text{ (\$)}$$

V_D is the dischargeable volume [see Equation (4-2)]

UF is the utilization factor

V_{D_1} and UF_1 are V_D and UF for 1/2-inch size rocks

$\hat{C}_M$ is the unit material cost, \$/ft³

Number of Storage Stages (Table 4-2)

The hot storage temperature limit is determined by the charging steam condensation temperature while the cold storage temperature is determined by the feedwater and steam temperatures at discharge conditions. Thus, given the charge, discharge steam temperatures and feedwater temperature, the design minimum temperature of subcooled water out of storage is fixed.

Figure 4-8a shows a one-stage and a two-stage main storage. In the single-state unit where heat is stored in one main storage tank, the storage temperature of 303°C and 249°C are determined from the enthalpies of feedwater and discharge steam and using a 5.6°C pinch point in boiler and preheater. Thus, the minimum temperature of subcooled water out of storage cannot be less than 249°C, resulting in a charge efficiency of 86 percent, based on 171°C feedwater to receiver, whereas in a two-stage unit it is possible to cool the water down to 210°C, which gives a charge efficiency of 87 percent at an extra cost of a preheat storage tank. The hot oil temperature is chosen at 266°C because the degradation of oil is lowest and it is assumed that oil refining equipment is not required. The bar graph in Figure 4-8b shows a

Table 4-2. Number of Storage Stages Tradeoff

	One Storage Stage	Two Storage Stage
<u>Design Parameters</u>		
Temperatures, S1	303°C	303°C
S2	249°C	254°C
		266°C
Charge Temperature	Condensation: 309°C	Condensation: 309°C
	Subcool: 309°- 254°C	Subcool: 309°-216°C
Tank Cost, S1	0.372	0.363
S2	---	0.058
Insulation Cost, S1	0.074	0.072
S2	---	0.022
Material Cost, S1	0.356	0.325
S2	---	0.063
Condenser Cost	0.698	0.756
Boiler Cost		
Subcooler Cost		
Preheater Cost		
Cost for Controls and Pumps, etc.	0	0.06
<u>Capital Cost</u>	<u>1.500</u>	<u>1.719</u>
Excess Capital Investment	0	0.219
Cost of Energy Saved	0	0.133
Δ -Cost of Energy	1.0	1.64

Figure 4-8. Numbered Storage Stages Tradeoff

savings of about 0.219 in capital cost with a single stage storage and an annual energy of 372 MWh(e) of electricity is 1.64. However, increasing the hours of storage would tend to shift the optimum design towards a two-stage main storage system.

Equipment Insulation Tradeoff

The optimum insulation thickness on piping, heat exchangers and other equipment will be different from the standard insulation thickness recommended by manufacturers, due to a higher solar energy cost. Generalized equations and chart for any cylindrical shaped equipment (including tankage) have been developed.

The cost factors determining the optimum insulation thickness are the installed insulation cost and energy cost. The heat loss rate, $\dot{q}_L$, is calculated from,

$$\dot{q}_L = UA \Delta t \quad (4-21)$$

where:

$A = \pi DL$ is the surface area

$\Delta t = t_f - t_a$ = the total temperature difference between the medium and ambient.

The overall coefficient U is given by:

$$U = \left[\frac{1}{h_a} + \frac{1}{h_i} \right]^{-1} \quad (4-22)$$

where:

$1/h_a$ = outside resistance

$1/h_i$ = resistance due to insulation

For a cylinder:

$$h_i = \frac{2k}{D \log_e \left(\frac{D+2x}{D} \right)} \quad (4-23)$$

where:

D = tube diameter

X = insulation thickness

k = thermal conductivity of insulation

The heat loss becomes,

$$\dot{q}_L = \left[\frac{1}{h_a} + \frac{D \log_e [(D+2x)/D]}{2k} \right]^{-1} \cdot \pi D L \cdot \Delta t \quad (4-24)$$

Neglecting the outside resistance:

$$\dot{q}_L = \frac{2 \pi k l \cdot \Delta t}{\log_e (D+2x/D)} \cdot \frac{\text{Btu}}{\text{hr}} \quad (4-25)$$

The annual energy lost is $\dot{q}_L \times 8760$ (hrs/years).

If η is the thermal-to-electrical conversion efficiency and $\hat{C}_e$ is the unit cost of electricity in \$/kWh(e), then cost of thermal energy is $\eta \hat{C}_e$. The cost of annual energy lost through insulation is then,

$$C_E = \dot{q}_L \times \frac{8760}{3413} \times \eta C_e, [\text{\$}] \quad (4-26)$$

where 3413 is the Btu to kWh conversion factor.

If PWF is the present worth factor given by,

$$PWF = \frac{(1+r)^{n-1}}{\sum_0^n (1+r)^n} = \frac{r(1+r)^{n-1}}{(1+r)^n - 1} \quad (4-27)$$

where r is the rate of return and n is the expected life, then the present worth of energy lost in n years is:

$$C_E = \dot{q}_L \times \frac{8760}{3413} \times \eta C_e \times \frac{1}{PWF} \quad [\text{\$}] \quad (4-28)$$

The capital cost of the insulation is:

$$C_I = \pi D (D + X) L \cdot \hat{C}_i \quad (4-29)$$

where $\hat{C}_i$ is the unit cost of insulation in $\text{\$/ft}^3$. The total cost is:

$$C_T = C_E + C_I \quad (4-30)$$

Substituting for $\dot{q}_L$ in C_E , the total cost expression is:

$$C_T = \frac{2\pi kL\Delta t}{\log_e (1 + 2x/D)} \cdot \frac{8760}{3413} \times \eta \frac{\hat{C}_e}{PWF} + \pi D (D + X) L C_i \quad (4-31)$$

Differentiating C_T with respect to X and equating to zero we get,

$$\left(1 + \frac{2x_{\text{opt}}}{D}\right) \cdot \log_e (1 + 2x_{\text{opt}}/D) = \frac{4A}{D^2 C_I} \quad (4-32a)$$

where X_{opt} is the optimum insulation thickness

$$A = \frac{k \cdot \Delta t \cdot \eta \cdot \hat{C}_e}{\text{PWF}} \times \frac{8760}{3413} \quad (4-32b)$$

or rewriting

$$y \log_e y = I \quad (4-33a)$$

where:

$$y = 1 + \frac{2x_{\text{opt}}}{D} \quad (4-33b)$$

and

$$I = \frac{4A}{D^2 C_I} \quad (4-33c)$$

The equations are summarized in Table 4-3.

Figure 4-9 shows a plot of x/D versus I for values of I ranging from 10^{-6} to 10^2 .

For $D \gg X$, the above expression becomes

$$\log_e y = I \quad (4-34)$$

Table 4-3. Heat Loss Optimization Equation
(Ref. Figure 4-9)

$$\text{Piping: } y \log_e y = \frac{2}{D} \sqrt{\hat{I}'} = I$$

$$\text{Tankage: } \chi_{\text{opt}} = \sqrt{\hat{I}'} \quad \text{for } D \gg \chi$$

$$\hat{I}' = \frac{k \cdot \Delta t \cdot \eta \cdot \hat{C}_e}{\text{PWF} \times \hat{C}_i} \times \frac{8760}{3413}$$

$$I = \frac{4}{D^2} \cdot \hat{I}'$$

χ = Insulation thickness

D = Pipe/cylinder diameter

k = Thermal conductivity of insulation, Btu/hr-ft-F

Δt = Temperature difference with ambient, °F

η = Thermal to electrical conversion efficiency

$\hat{C}_e$ = Electrical energy cost, \$/kWh(e)

$\hat{C}_i$ = Insulation cost (installed), \$/ft³

$$\text{PWF} = \text{Present worth factor} = \frac{r(1+r)^{n-1}}{(1+r)^n - 1}$$

r = Rate of return on investment

n = Expected life of equipment/plant

8760 is number of hours/year and 3413 is conversion factor from Btu's to kWh.

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4-30

Figure 4-9. Chart for Determining Optimum Insulation Thickness for Cylindrical Equipment

or with $\log_e y \approx y-1$

$$X_{\text{opt}} = \sqrt{\frac{A}{\hat{C}_1}} \quad D \gg X \quad (4-35)$$

which is independent of shape and is proportional to ratio of unit costs of energy and insulation.

(Figure 4-9 shows a plot of $\frac{X}{D}$ versus I for I ranging from 10^{-6} to 10^2 .)

The typical values used in estimating the optimum thickness are:

$$k = 0.05 \text{ Btu/hr-ft-}^\circ\text{F (high temperature)}$$

$$\eta = 0.212$$

$$\text{PWF} = 0.168 \text{ (for a 20 percent return and an expected life of 30 years)}$$

then:

$$I = 6.478 \cdot \frac{\Delta t \cdot C_e}{D^2 \cdot C_i}$$

For a solar plant C_e is 60 mils/kWh (assumed) and a typical installed cost for insulation is \$13^e/ft³ which gives

$$I = 3 \times 10^{-3} \cdot \frac{\Delta t}{D^2}$$

For a tank 18.3 m (60 feet) in diameter and a Δt of 304°C (580°F),

$$I = 4.83 \times 10^{-4}$$

and from Equation (4-34)

$$X_{\text{opt}} = 0.66 \text{ ft} = 8 \text{ in.}$$

and from Equation (4-35)

$$X_{\text{opt}} = 7.9 \text{ in.}$$

and from Equation (4-33a)

$$X_{\text{opt}} = 7.812 \text{ in.}$$

Table 4-4 gives the calculated optimum insulation thickness for pilot plant equipment.

Table 4-4. Recommended Insulation Thickness on Equipment

Equipment	O. D. (meters)	Insulation Parameter	Insulation Thickness (m)	Heat Loss kW _o
<u>Heat Exchangers:</u>				
Desuperheater	0.457 (18.0 in.)	1.91	0.229 (9.0 in.)	5.66
Condenser	1.07 (42.0 in.)	0.20	0.203 (8.0 in.)	11.00
Subcooler	0.711 (28.0 in.)	0.45	0.198 (7.8 in.)	3.32
Preheater	0.711 (28.0 in.)	0.45	0.198 (7.8 in.)	1.72
Boiler	1.02/1.37 (40/54 in.)	0.12	0.206 (8.1 in.)	9.52
Superheater	0.925 (1.0 in.)	1.91	0.229 (9.0 in.)	3.42
<u>Piping:</u>				
Hottee Lines	0.114 (4.5 in.)	30.60	0.173 (6.8 in.)	21.93
Oil Lines	0.356 (14.0 in.)	1.78	0.178 (7.0 in.)	37.30
Charge Steam Lines	0.219 (8.625 in.)	6.5	0.178 ave. (7.0 in.)	27.30
Discharge Steam Lines	0.273 (10.75 in.)	4.2	0.184 ave. (7.25 in.)	
Condensate Lines	0.141 (5.56 in.)	11.30	0.142 (5.6 in.)	5.60
Feedwater Lines	0.114 (4.5 in.)	17.26	0.137 (5.4 in.)	

MAIN STORAGE THERMOCLINE PERFORMANCE ANALYSIS

The Thermocline Principle

Transferring heat to or from a fluid stream to beds of broken materials is one of the commonest of industrial processes. Such a transfer takes place in every fuel bed, in blast furnaces, in lime kilns, in foundry cupolas, in gas producers and in water-gas generators. In mass transfer operations too, this technique is very widely used and finds applications in such diverse fields as the recovery of valuable solvent vapors from gases, purifying air as with gas masks, dehydration of gases and liquids, decolorizing minerals and vegetable oils, the concentration of valuable solutes from liquid solutions and many others.

Consider the case of hot oil at T_0 entering a bed of cold rocks at T_1 relative to the oil. This operation would be referred to as charging of the bed. The uppermost layers of solid, in contact with hot oil, at first get heated rapidly and effectively, and what little heat is left in oil is substantially all removed by the layers of solid in the lower part of the bed. The oil from the bottom of the bed is practically at the temperature of the cold rocks at T_1 as in Figure 4-10. The temperature distribution in the solid is indicated in the sketch where relative diversity of horizontal lines is meant to indicate the relative heat content or hotness.

Most of the heat transfer takes place in a relatively narrow heat transfer zone in which the temperature changes rapidly, as shown. As fluid continues to flow, the heat transfer zone moves downward as a wave, at a rate related to the linear velocity of the fluid through the bed. At a later time, as in b, roughly half of the bed is charged, but the temperature of oil out of the bed is still at about T_1 . At C in the figure the lower portion of zone has just reached the bottom of the bed and temperature of oil has risen to a value T_C .

Figure 4-10. Thermocline Principle (Heat Transfer Zone)

The oil temperature now rises rapidly as the heat transfer zone passes through the bottom of the bed and at d has essentially reached the initial oil temperature T_o . The bed is now fully charged.

A similar phenomena happens during the discharge of the bed. Up to point C, it is possible to maintain a constant heat rate, by increasing the oil flow. But the sizing of the heat exchangers and pumps limits the oil flow rate to a certain maximum (generally 10% in excess of design). Therefore, from point C onwards the heat rate would begin to fall, unless the heat exchangers and associated equipment are oversized.

Point C is determined by trading-off the costs of heat exchangers and the storage media cost.

Mathematical Analysis

Analytical Model -- The problem of estimating the temperature changes in a fluid stream and in a fixed bed where heat transfer proceeds intermittently presents formidable mathematical difficulties which have not been completely solved, in a closed form solution, for the general case. However, for special cases the mathematical development of equations dates back to 1929. Subsequent to that a lot of analysis had been published and charts are now available for designing a fixed bed.

In its first development, analytical solutions for the case of unsteady state heat transfer in a non-reacting fluid flowing through a porous medium at a uniform initial temperature and with the assumption of constant fluid and solid properties were proposed (Refs. 18, 19, 20). Neglecting the transverse heat conduction and temperature gradients in the direction of flow in both fluid and solid and assuming the fluid velocity to be uniform across the cross section, a heat balance on an element of fluid of volume dV_g at any point of the bed yields,

$$\rho_f C_{pf} dV_f \left(\frac{\partial t_f}{\partial \tau} + u \frac{\partial t_f}{\partial z} \right) = U dA (T_s - T_f) \quad (4-36)$$

and on the solid element of volume dV_s ,

$$\rho_s C_{ps} dV_s \frac{\partial T_s}{\partial \tau} = -U dA (T_s - t_f) \quad (4-37)$$

Defining $f = dV_g/dV$ = fractional porosity of bed, and $A_b = dA/dV$ = surface area per unit volume of bed, the solution of the above equations with the boundary conditions,

$$\begin{array}{ll} \text{B.C. 1} & T_f = T_{o,f}, \text{ at } Z = 0, \text{ for all } \tau \\ \text{B.C. 2} & T_s = T_{o,s}, \text{ at } \tau = 0, \quad Z = 0 \end{array}$$

is given in terms of four dimensionless groups, θ_f , θ_s , aZ and $b\tau$ in Table 4-5. Figure 4-11 shows a typical plot of temperature distribution in bed at various times. The parameter 'a' is the reciprocal of the height of a transfer unit and aZ is the number of transfer units required to reach point C shown in Figure 4-10. The shape of the thermocline at point C depends on various parameters which are listed in Table 4-6. The curves generally have an S shape and their relative steepness or flatness depends on the heat transfer rate. If the heat transfer rate were infinitely rapid the curve would be flat, i.e., as the parameters $b\tau$ and aZ increase, the curve at point C tends to be relatively flat and the shaded area becomes smaller resulting in a higher utilization of the stored energy. The utilization factor is defined as the ratio of the energy extracted up to point C to the total energy stored between T_1 and T_o , corresponding to point D in Figure 4-10.

The analytical solutions presented in Table 4-5 have a limited applicability in that they can be used for a constant flow rate and a uniform initial temperature of the solid. Lawrence M. Grossman (Ref. 21) has developed a graphical solution to find the transient temperature history of the fluid and the solid catalyst as function of time and position after entrance of the fluid stream

Table 4-5. Equations for Calculating Temperature Changes in Fluid Stream and Bed

$$\text{Fluid: } \theta_f = \frac{t - t_o}{t_o - T_o} = 1 - e^{-b\tau} \int_0^{aZ} e^{-aZ} J_0(2i\sqrt{aZ b\tau}) d(aZ)$$

$$\text{Solid: } \theta_s = \frac{T - T_o}{T_o - t_o} = e^{-aZ} \int_0^{b\tau} e^{-b\tau} J_0(2i\sqrt{aZ b\tau}) d(\beta\tau)$$

t = Fluid temperature

T = Solid temperature

Subscript, o = Initial temperature

τ = Time

z = Bed height

J_0 = Bessel function of first kind

$a = UA_v/C_f G = 1/HTU$

$b = UA_v/C_s \rho_s = G/\rho_s (HTU)$

A_v = Surface Area per unit volume of bed

U = Overall Coefficient for heat transfer

HTU = Height of a transfer unit

Table 4-6. Parameters Affecting Thermocline Performance

- Discharge heat rate
- Fluid velocity
- Storage temperatures
- Bed height
- Number of Storage hours
- Fluid and solid properties
- Particle size

Figure 4-11. Typical Thermocline During Discharge

into the reactor. His work represents an advance over the previous method in that a variable heat source term is included in the solid bed, and any arbitrary initial solid temperature distribution may be assumed. For a system analysis, under any flow, or fluid temperature condition or any solid temperature distribution a computer simulation model is developed by using the finite difference approach.

Finite Difference Model (see Figure 4-12) - The heat balance Equations (4-7) and (4-37) can be changed into an equation of finite differences by splitting the height into intervals ΔZ . Then if G is the superficial mass velocity of the fluid, the time interval, $\Delta \tau$, is

$$\Delta \tau = \rho \Delta Z / G$$

and the mass of fluid introduced into the cell of diameter D and height ΔZ is,

$$\Delta m_f = G \cdot \pi D^2 \Delta Z \cdot \Delta \tau$$

Considering the n^{th} cell, if t_{fn-1} is the temperature of fluid entering the cell and t_{fn} is the temperature of fluid leaving the cell after a $\Delta \tau$ residence time and $t_s(n-1, \tau)$ and $t_s(n-1, \tau + \Delta \tau)$ are the corresponding solid temperatures, then the heat transfer and heat balance equations can be written as:

$$\dot{q} = G C_{pf} (t_{f,n} - t_{f,n-1}) = UA_v \Delta Z \left[\frac{t_s(n-1, \tau) + t_s(n-1, \tau + \Delta \tau)}{2} - \frac{t_{fn} + t_{f,n-1}}{2} \right] \quad (4-38)$$

Figure 4-12. Thermocline Finite Difference Model

Equations

$$t_s(n-1, \tau + \Delta\tau) = F_1 t_{fn-1} + F_2 t_s(n-1, \tau)$$

$$t_{f,n} = t_{f,n-1} - F_3 [t_s(n-1, \tau + \Delta\tau) - t_s(n-1, \tau)]$$

where,

$$F_1 = \frac{2b \cdot \Delta\tau}{2 + a\Delta Z + b \cdot \Delta\tau}$$

$$F_2 = \frac{2 + a\Delta Z - b \cdot \Delta\tau}{2 + a\Delta Z + b \cdot \Delta\tau}$$

$$F_3 = \frac{a \cdot \Delta Z}{b \cdot \Delta\tau}$$

$$a = \frac{Ua_v}{C_p C}$$

$$b = \frac{Ua_v}{(\rho C_p)_{m1}}$$

$$\Delta\tau = \frac{G \cdot \Delta Z}{\rho_f}$$

Where the last term on right hand side is the mean temperature difference for heat transfer, and heat balance on the cell gives,

$$Q = (\rho C_p)_m \cdot \Delta Z [t_s(n-1, \tau + \Delta\tau) - t_s(n-1, \tau)] = G C_{pf} (t_{f,n} - t_{f,n-1}) \Delta\tau \quad (4-39)$$

where:

$$\begin{aligned} G &= \text{superficial velocity, lb/hr-ft}^2 \\ C_{pf} &= \text{heat capacity of fluid, Btu/lb-F} \\ (\rho C_p)_m &= \rho_s C_{ps} (1-\epsilon) + \rho_f C_{pf} \cdot \epsilon = \text{mean heat capacity, Btu/ft}^3\text{-F} \\ \epsilon &= \text{porosity of bed} \\ a_v &= \text{surface area per unit volume of bed, ft}^{-1} \end{aligned}$$

a_v is calculated from,

$$a_v = \frac{6}{D_p(1-\epsilon)}$$

where D_p is the average particle size.

Equations (4-38) and (4-35) can be solved for $t_{f,n}$ and $t_s(n-1, \tau + \Delta\tau)$ in terms of the initial fluid and solid temperatures, thus,

$$t_s(n-1, \tau + \Delta\tau) = F_1 \cdot t_{f,n-1} + F_2 \cdot t_s(n-1, \tau) \quad (4-40)$$

$$t_{f,n} = t_{f,n-1} - F_3 [t_s(n-1, \tau + \Delta\tau) - t_s(n-1, \tau)] \quad (4-41)$$

where

$$F_1 = \frac{2b \cdot \Delta\tau}{2 + a \cdot \Delta Z + b \cdot \Delta\tau}$$

$$F_2 = \frac{2 + a \cdot \Delta Z - b \cdot \Delta\tau}{2 + a \cdot \Delta Z + b \cdot \Delta\tau}$$

$$F_3 = \frac{a \cdot \Delta Z}{b \cdot \Delta\tau}$$

$$a = \frac{Ua_v}{C_{pf} \cdot G}$$

$$b = \frac{Ua_v}{(\rho C_p)_m}$$

$$\Delta\tau = \frac{G \cdot \Delta Z}{\rho_f}$$

From the given initial solid temperature distribution, $t_s(Z, 0)$ and inlet temperature of fluid at any time, $t_f(0, \tau)$, the fluid and solid temperatures at any time and location can be progressively calculated using Equations (4-40) and (4-41). Equations (4-40) and (4-41) can be further modified to include heat conduction between the cells during the time interval $\Delta\tau$. Thus,

$$t_s(n-1, \tau + \Delta\tau) = t_s(n-1, \tau) + \frac{U_c \cdot \Delta\tau}{(\rho C_p)_m \cdot \Delta Z} [t_s(n, \tau) - 2t_s(n-1, \tau) + t_s(n-2, \tau)]$$

and for the first and last cell,

$$t_s(N, \tau + \Delta\tau) = t_s(m, \tau) + \frac{U_c \cdot \Delta\tau}{(\rho C_p)_m \cdot \Delta Z} [t_s(N-1, \tau) - t_s(N, \tau)]$$

A computer program was set up for evaluating thermocline performance.

Packed Bed Design

The design of a rock bed storage tank and the prediction of the height of tank between charge and discharge cycles requires first defining the fully charged state. This in turn requires knowledge of the normal mode of operation of the storage. Thus, with the initial temperature distribution of the solid

(charged state) and the final fluid temperature towards the end of discharge (point C in Figure 4-10) defined, the mathematical model can be exercised to determine the required bed height to charge or discharge a given amount of heat, and meet the system design requirements.

Final Fluid Temperature (Discharged State)

One of the design requirements is to discharge at a constant heat rate for 3 hours after 20 hours of hold and discharge to provide for sealing and tracing steam for the turbine and Hitec storage system respectively. Thus, when the oil temperature out of storage decreases, the flow rate would have to be increased to maintain a constant heat rate. This would mean oversizing the heat exchangers and pumps to accept the higher flows besides providing more surface area to compensate for the decrease in the log-mean temperature difference. However, by discharging the bed to exhaustion, the heat utilization factor (the unshaded area shown in Figure 4-11) increases, which would mean buying less material and tankage. The final fluid temperature at discharge can be set by trading off the material and heat exchanger costs, coupled with the flow limitations aforementioned.

Based on the tradeoff study, discussed earlier in this section, the optimum temperature was determined to be 300°C (572°F) which is 3°C (6°F) less than the hot storage temperature.

Initial Temperature Distribution (Charged State)

Similarly, towards the end of the charge, the fluid temperature rises resulting in a decrease in heat rate. However, the constraint of constant heat rate is not there, but a certain rationale and engineering judgment is required in determining the charging time which is governed by the receiver

operation and plant operational strategy. Besides the initial temperature distribution affects the bed height design. A more efficient operation would be to charge the tank completely. Calculations have shown that to charge the last 2 percent it takes about 0.5 hour, besides resulting in an energy waste since condensate cannot be cooled below the oil temperature. For the bed design, a charge time of 4.0 hours was selected. The temperature of the oil out of a bed height of 14.3 m (47 ft) was 290°C (554°F) and the heat rate at a constant flow rate corresponding to this temperature was found to be 25 percent of the design.

In other words, a bed height of 14.3 m is required to discharge for 3 hours at a constant heat rate with the final fluid temperature of 300°C which when charged back with the same amount of heat would result in a 290°C final fluid temperature out the bottom of tank at the end of four hours. A repeated cycle of charge for 4.0 hours and discharging same amount of heat charged at constant flows would not significantly smear the thermocline. Computer results are discussed later in this section.

Effect of Design Parameters on Thermocline

The relative steepness or flatness of the thermocline or the breakthrough curve depends on various parameters. Generally, the breakpoint (Point C in Figure 4-10), time decreases with decreased bed height, increased particle size, increased rate of flow of fluid through the bed.

Effect of Particle Size

The particle size has a very large influence on the resistance to flow and the relative steepness of the thermocline and hence the utilization factor or bed height.

Most things which increase resistance to flow may be expected to increase the coefficient of heat transfer. Besides with decrease in particle size or increase in packing density for a given particle size, the surface area per unit volume of bed (a_v) increases. Therefore, as particle size decreases, the width of the heat transfer zone decreases and the thermoclines would be narrower, resulting in an increase in utilization factor.

The increase in utilization factor with decrease in particle size would be at the expense of a higher pressure drop (Figure 4-13). An optimum particle size is determined by trading off the pumping cost with material cost as discussed earlier in this section.

Effect of Fluid Velocity

The relative velocity of the temperature layers in the bed and the growth of the heat transfer zone is profoundly affected by the fluid velocity. For example, consider the thermocline profiles in Figure 4-12 during discharge. The 276°C temperature layer, which is the midpoint temperature between 249°C and 303°C moves at the velocity of the fluid itself. Whereas, the 300°C and 252°C temperature layers move at a higher and lower velocities respectively, relative to the 276°C layer. For a constant fluid velocity, the velocity of any temperature layer would be constant relative to itself. It is this difference in the relative velocities of the different temperature layers which results in the smearing of thermocline and the growth of the heat transfer zone. Again, the velocity of any temperature layer depends on the particle surface per unit bed volume, the coefficient of heat transfer, heat capacity of solid, and the fluid velocity itself. Figures 4-14 through 4-16 show the effect of fluid velocity on thermoclines and utilization factor for the same particle size and same solid and fluid properties. An overlay of the 25 percent flow in dotted lines over a 100 percent flow to reach the same breakpoint of 300°C is also shown in Figure 4-14.

Figure 4-13. Effect of Particle Size

Figure 4-14. Discharge of Design Flow

Figure 4-15. Thermocline Profile--Discharge of 25% of Design Flow

Figure 4-16. Effect of Fluid Velocity on Utilization Factor

Effect of Solid and Fluid Properties

For given size particles and heat rate, solid particles and fluid with a lower thermal diffusivity may be expected to give a better utilization factor. Since, with low solid heat capacity, larger volumes of material will be required for a given storage capacity, and therefore, the surface area per unit of energy transferred or stored would increase, and so the effect on the thermocline performance is same as is with decrease in particle size. However, from economic reasons this feature is not desirable at all.

The Height of a Transfer Unit

All the parameters discussed have been expressed in the dimensionless parameters aZ and $b\tau$, described in the mathematical model. The parameter 'a' defined as

$$a = \frac{U a_v}{C_{p_f} \cdot g} = \text{HTU}$$

has the dimensions of $(\text{length})^{-1}$ and is the reciprocal of the height of a transfer unit and aZ is the number of transfer units.

Similarly, the parameter 'b' defined as,

$$b = \frac{U a_v}{(\rho C_p)_m} = \frac{G C_{p_f}}{(\rho C_p)_m} \cdot \frac{1}{\text{HTU}}$$

has the dimensions of $(\text{time})^{-1}$ and $b\tau$ is the dimensionless time.

From the discussion above it is apparent that as ' $b\tau$ ' and ' aZ ' increase simultaneously the thermoclines would be narrow and the utilization factor would increase. Incidentally, the ratio of $b\tau$ and aZ is the utilization factor and $aZ = f(b\tau, \theta)$. θ is the dimensionless temperature.

$$\frac{b\tau}{aZ} = \frac{G C_{p_f} \cdot \tau}{(\rho C_p)_m \cdot Z} \quad \frac{\text{heat rate x time of discharge}}{\text{heat stored}}$$

and

$$\lim_{\substack{b\tau \rightarrow \infty \\ aZ \rightarrow \infty}} \left(\frac{b\tau}{aZ} \right)_{\theta} = 1.0$$

$$b\tau \rightarrow \infty$$

$$aZ \rightarrow \infty$$

Charts of θ versus $b\tau$ with aZ as parameters are available and can be used in the design of the bed (Ref. 20).

Experimental Evaluation of 'a' and 'b'

Where uncertainty prevails in the evaluation or calculation of the height of a transfer unit, values of 'a' and 'b' can be obtained using the chart or the math model, directly from the experimental data by measuring the exit fluid temperature from a given bed with time, provided the bed is initially at a uniform temperature. If the properties are known then the heat transfer coefficient can be calculated. The method of using these charts is given in Reference 20.

Packed Bed Heat Transfer

One basic difficulty for a description of pressure drop and heat transfer in packed beds is the large variety and often the poor definition of geometries. For heat transfer past spheres Raithby (Ref. 22) correlated,

$$Nu = 2 + 0.236 Re^{0.606} Pr^{1/3}$$

For $Re \rightarrow 0$, this equation goes towards $Nu = 2$, which is the value for heat transfer by conduction in spherical shell. For irregular particles, the average diameter is defined as,

$$\bar{D}_P = \frac{6}{a_v}$$

a_v denotes the surface area per volume. For calculations of heat transfer coefficient the above equation was used.

In the absence of known effect of Pr , the heat transfer data may be put in the j_H form (Colburn j -factor) and the analog completed by equating j_D to j_H . j_D is the j -factor for mass transfer. For flow of air through fixed beds, the equation recommended is $j = 0.23 (Re)^{-0.3}$ (Ref. 7). For flow through fixed bed of pellets,

$$j = 2.4 \left(\frac{Re}{\epsilon} \right) \quad (\text{Ref. 23})$$

Symbols

$$Nu = \frac{h \bar{D}_P}{k}, \quad (\text{Nusselt number})$$

$$Pr = \frac{\mu C_P}{k}, \quad (\text{Prandtl number})$$

$$Re = \frac{\bar{D}_P G}{\mu}, \quad (\text{Reynolds number})$$

$$j = (St_{av}) (Pr)^{2/3}, \quad (St = \text{Stanton number})$$

or

$$j = \frac{h}{C_P G}$$

System Performance Under Design and Off-Design Conditions

The mathematical model was used to study the performance of thermocline during charge and discharge at various heat rates, various initial temperature distributions, and under various modes of charge and discharge.

Charge and Discharge Cycles

When cold fluid is introduced into the bottom of a hot bed, with a uniform temperature distribution throughout the bed, a thermocline is established first. And as the flow is continued, the thermocline moves up the tank, as was described before.

Consider a uniform temperature distribution of 303°C in the bed (13.73 m high x 18.3 diameter) described in Section 3. Curve 1 in Figure 4-17 which is a vertical line, corresponds to this case. The dotted lines show the temperature distribution in the bed, when discharged at a rate of 550 kW_t (1.7 percent of the design heat rate) for 20 hours with the cold fluid at 249°C . The other curves shown are bed temperature profiles as function of time, as labeled, during discharge at the design rate of 26.23 MW(t) initially with the cold fluid at 249°C and hot fluid withdrawn at 303°C . After about 2.5 hours of discharge the thermocline had moved to the top of the tank and the fluid temperature out of bed begins to drop. The curve at 4.4 hours shows the temperature distribution at complete exhaustion of bed. Figure 4-18 shows the system performance during the discharge cycle. Curves 1 and 2 are the fluid temperatures at the bed inlet and exit respectively with time. Curves 3 and 4 are the heat rate and flow rate respectively, with time. Curve 5 is the fraction of total heat discharged. The maximum flow rate was set at 110 percent of the design as shown in Curve 4. The figures show that a fully discharged bed can be discharged at a design rate for 3.2 hours, subsequent to which the heat rate decreases along the Curve 5 in Figure 4-18.

Figures 4-19 and 4-20 show the thermocline profiles and system performance respectively during the subsequent charging of the bed at constant flow rate.

Figure 4-17. Thermocline Profiles--Main Storage Discharge to Exhaustion

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Figure 4-18. System Performances--Main Storage Discharge

Figure 4-19. Thermocline Profiles During Charge at Constant Flow Rate

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Figure 4-20. System Performance--Main Storage Charge

Effect of Initial Temperature Distribution

The initial temperature distribution effects the thermocline performance. Curve 1 in Figure 4-21 shows the temperature distribution in the bed (13.7 m high x 18.3 m diameter). Curve 2 in dashed lines shows the thermocline after discharge of about 9 percent of the heat stored, at a rate of 500 kW(t) (~ 2 percent of design) for 20 hours to provide for sealing and tracing steam. Curve 3 is the thermocline profile after discharge at the design heat rate until the fluid temperature out of storage is 300°C, equal to the design temperature (the storage can provide a constant heat rate until fluid temperature out is 300°C). The amount of heat discharged until this point is about 82 percent of the total heat stored. Figure 4-22 shows thermoclines in the second discharge cycle; i. e., after subsequent charge and then discharge. Curve 1 results from the charging of bed in Figure 4-21 at constant flow rate until the charge rate at end of cycle equals 50 percent. The amount of heat stored at this point is 96 percent. Curve 2 is thermocline after discharge for sealing and tracing steam. Curve 3 is the thermocline after discharge at constant heat rate until exit fluid temperature is 300°C. Curve 4 in dotted line corresponds to Curve 3 of Figure 4-21. The percent of heat stored after second discharge is approximately 29 percent. That is only 90 percent of the heat inputted can be delivered in the second discharge, up to the design temperature of 300°C. Figure 4-23 shows the thermoclines after 24 cycles of charge and discharge; each time charging until 50 percent charge rate and discharging until 300°C. Curve 1 is the initial temperature distribution at the beginning of the 24th cycle; Curve 2 is the thermocline after 20 hours of sealing and tracing steam discharge and Curve 3 is the thermocline after discharge at design rate until fluid temperature out is 300°C. The percent heat stored at the end of 24th discharge cycle is about 28 percent, showing there is not much smearing of the thermocline.

Figure 4-24 shows the thermoclines for discharge until 300°C from a fully charged state, same as in Figure 4-21. Figure 4-23 shows the thermoclines

Figure 4-21. Thermoclines for Discharge from Fully Charged State

Figure 4-22. Thermocline after Second Charge and Discharge Cycle

Figure 4-23. Thermoclines after 24 Charge and Discharge Cycles

Figure 4-24. Thermoclines for Discharge from Fully Charged State

during the second discharge cycle. Curve 1 is the initial temperature distribution, which results from charging the bed in Figure 4-24 at constant flow rate until the charge rate at end of charge cycle is 25 percent of the design. Curve 2 is after 20 hours of sealing steam discharge and Curve 3 is after discharge at design rate until 300°C. Curve 4 in dotted lines is the same as Curve 3 of Figure 4-24. Comparison of Curves 3 and 4 in Figure 4-25 with Figure 4-22 shows that the smearing of the thermocline is much smaller. The curves would coincide when the bed is completely charged. Figure 4-26 shows the thermoclines after 24 cycles of charge and discharge each time charging until heat rate is 25 percent of design and discharging until 300°C fluid exit temperature. Figure 4-27 shows system performance.

Partial Charge/Discharge Cycles

Figure 4-28 shows a partial charge and discharge cycle, typical of cloudy days or winter months. Starting from a full charge tank and discharging for 1.5 hours at design rate, the thermocline profile would be as shown in Curve 1 of Figure 4-29. If we now partially charge for 0.5 hour and then discharge for 0.5 hour, the thermocline would smear to that shown in Curve 2. If the operation of charge for 0.5 hour and discharge for 0.5 hour is continued, the thermocline continues to smear. Figure 4-29 shows the thermoclines for 1 to 10 cycles and at the end of 40 cycles. Figures 4-30 through 4-32 show the thermoclines for 1 to 10 cycles and at the end of 40 cycles, respectively.

As is evident from Figure 4-32, there is no significant change in the profile after about 30 cycles, which for all practical purposes can be considered as a limit. However, the number of cycles it takes to reach this limiting condition depends on length of the charge and discharge cycles. For example, if the charge and discharge cycles were for 1.0 hour duration, then the limiting profile would be reached in approximately 15 cycles.

Figure 4-25. Thermoclines after Second Charge and Discharge Cycle

Figure 4-26. Thermoclines after 24 Charge and Discharge Cycles

Figure 4-27. System Performance

Figure 4-28. Partial Charge and Discharge Cycles

Figure 4-29. Thermoclines: Partial Charge and Discharge Cycles

Figure 4-30. Thermoclines: Partial Charge and Discharge Cycles for 1 to 10 Cycles

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Figure 4-31. Thermoclines: Partial Charge and Discharge Cycles for 10-20 Cycles

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Figure 4-32. Thermoclines: Partial Charge and Discharge Cycles for 30-40 Cycles.

The dischargeable capacity at design rates would decrease with number of cycles. As shown in Figure 4-27 discharge time during the first cycle up to 300°C is 1.5 hours, which is the design case. But after 10 cycles the discharge time decreases to 1.0 hour and in the limit, tapers off to about 30 minutes of discharge time.

Cyclic Charge/Discharge (Constant Heat Rate)

Figure 4-33 shows the thermocline at the end of 1, 3, and 85 charge and discharge cycles, with a constant and equal design heat rate on both charge and discharge cycles. With a flow rate maximum of about 10 percent above design the final fluid temperatures out of storage at the end of charge and discharge will be fixed at 253°C and 300°C, respectively. Curves 1, and 1' are initial and final temperature distributions for the first discharge cycle. Curve 2 is the thermocline after subsequent charge at constant heat rate until fluid temperature out corresponds to 253°C. Thermocline at 2' is the subsequent discharge until fluid temperature is 300°C and so on. Curves 85, 85' are the thermoclines after 85 charge and discharge cycle of only constant heat input/output (I/O) rate. The shaded area is the limiting dischargeable capacity.

Figure 4-34 shows the fluid temperatures out of storage at 1, 3, and 85 cycles versus the cycle discharge time. The heat I/O capacity at the end of the 85th cycle is only 15 percent of the total storage capacity. Figure 4-35 shows that this limit is reached after about 20 cycles and there is not much smearing of the thermoclines after 20 cycles. The discharge or I/O time corresponding to the limiting capacity is about 42 minutes.

This, thus establishes the need for a decreasing charge rate so that the thermocline can be either completely driven out of the tank during charge or at least returned to its design profile. However, the bed can be designed

Figure 4-33. Thermoclines for up to 85 Cycles in a Charge/Discharge at a Constant Input/Output Heat Rate with a Fluid Temperature Limit on a Charge (252°C) and Discharge (300°C)

Figure 4-34. Fluid Temperatures: Charge and Discharge Cycles at Constant Rate

Figure 4-35 Charge and Discharge Cycle at Constant Heat Rates

to meet the constant heat rate requirement, to do so the bed would have about five times the present capacity, or the heat exchangers and pump sized to handle the end condition heat rates.

Effect of Introducing Hot Oil at the Bottom of Tank

During a charge or discharge, the oil returning from the heat exchangers could be hotter or colder than the design temperatures or at times the failure of valves in the system could lead to introducing hot oil at the bottom or cold oil at the top.

A case typical of the above, but exaggerated, is shown in Figure 4-36. Curve 1 in Figure 4-36 shows a constant fluid inlet temperature at bottom of tank of 249°C for 1.5 hour and then an input of 303°C fluid for 0.5 hour and followed by 249°C input temperature. Curve 2 in Figure 4-36 shows the fluid temperature leaving storage as a function of time. Figure 4-36 and 4-35c show flow rate and heat rate as functions of time. Figure 4-37 shows the temperature distributions in the bed at various times. The curve labeled 90 min is the thermocline profile after discharging for 1.5 hours at design rate. The curve labeled 120 min is the temperature distribution after introducing hot oil at 303°C for 0.5 hour. After 120 min the flow of cold oil at 249°C is restored; the curve labeled 150 min is the thermocline after further 0.5 hour of 249°C oil and discharge time of 2.5 hours. The curves show a blip of hot fluid at the bottom while the actual thermocline has moved to a height of about 7.5 m. As cold oil flow continues, the blip moves up the tank and after 180 min the temperature of the oil from the top of the tank has dropped to 300°C as shown in Figure 4-37, showing the fluid layers at the top of the tank would move irrespective of the conditions at the bottom. In fact, the curves at 90, 120 and 180 minutes near the top of the tank would correspond to the curves at the respective times, during a regular discharge cycle at design rate. As the oil flow is continued, the blip moves up the tank and the outlet fluid temperature drops, as shown in Figure 4-36a, and as the

Figure 4-36. Effect of Introducing Hot Oil at Bottom of Tank

Figure 4-37 Thermocline Profile : Effect of Introducing Hot Oil for 1/2 hour at Bottom of Tank

blip is driven out of the tank the fluid temperature rises and then falls. If the blip is not completely driven out of the bed and the bed is charged with hot oil introduced at the top the blip would move down the tank and exit fluid temperature would increase when the blip is near the bottom and then decreases. Figure 4-38 shows the composite picture.

However, the hot fluid layers below the cold layers are not stable and the bed would turn over due to natural convection. This phenomenon is hard to model and is not included in the finite difference model. Figure 4-39 shows the effect of introducing hot oil after continuing for 1.5 hours after discharging approximately 9 percent of the stored energy.

An interesting point to note is that the blips that appear all contain the same amount of energy, and in this case equal to 0.5 hour of charge. As the blip moves up the bed its width increases and consequently its amplitude must decrease. This is due to the convective smearing of the thermocline. This graphically demonstrates a convective transport of a thermal pulse through a packed bed and offers a means of measuring the growth of the heat transfer zone.

Figure 4-38 Thermocouple Profiles: Effect of Introducing Hot Oil at Bottom of Tank

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Figure 4-39. Bed Temperature Profiles

THERMAL STORAGE OFF-DESIGN OPERATING PERFORMANCE

Under normal operating conditions, the thermal storage must be able to provide thermal energy under conditions in which the demand is less or the ratio between receiver steam and storage steam is changed. Conditions under which the performance should be achieved are listed in Tables 4-7 through 4-11.

Discharge

Table 4-7. Pilot Plant - Turbine Operating from Storage Only - No Charging

Parameters	Design Discharge only 100% of Flow		Off Design Discharge only			
			50% of Flow		25% of Flow	
	Steam OUT	FW IN	Steam OUT	FW IN	Steam OUT	FW IN
Flow, kg/hr	49,024	49,024	24,512	24,512	12,256	12,256
Pressure, MPa	3.62	3.96	3.62	3.96	3.62	3.96
Temperature, °C	391	205	391	172	391	141
Enthalpy, kJ/kg	3,200	879	3,200	728	3,200	593
Gross Heat Rate [kWhr(θ)/kWhr(e)]	3.512	---	4.255	---	6.347	---
Gross Thermal Efficiency	0.285	---	0.235	---	0.158	---
Gross Electric Output kW(e)	9,000	---	3,955	---	1,348	

Table 4-8 Pilot Plant - Turbine Operating from both Receiver
and Storage - No Charging
R/S = 1:3 Flow Ratio

Parameters	Receiver	Storage	
		Steam OUT	FW IN
Flow, kg/hr	12,610	37,830	37,830
Pressure, MPa	10.10	3.62	3.96
Temperature, °C	510	391	207
Enthalpy, kJ/kg	3398	3200	891

Gross Heat Rate, kWhr(te)/kWr(e) 3.298
 Gross Thermal Efficiency 0.303
 Gross Electrical Output, kW(e) 10,020

Table 4-9 Pilot Plant - Turbine Operating from both Receiver
and Storage - No Charging
R/S = 1:1 Flow Ratio

Parameters	Receiver	Storage	
		Steam OUT	FW IN
Flow, kg/hr	23,587	23,587	23,587
Pressure, MPa	10.10	3.62	3.96
Temperature, °C	510	391	203
Enthalpy, kJ/kg	3398	3200	872

Gross Heat Rate, kWhr(te)/kWhr(e) 3.175
 Gross Thermal Efficiency 0.315
 Gross Electrical Output, kW(e) 10,019

Note: R/S = Receiver/Storage

Table 4-10. Pilot Plant - Turbine Operating from both Receiver and Storage - No Charging
R/S = 3:1 Flow Ratio

Parameters	Receiver	Storage	
		Steam OUT	FW IN
Flow, kg/hr	33,203	11,068	11,068
Pressure, MPa	10.1	3.62	3.96
Temperature, °C	510	391	199
Enthalpy, kJ/kg	3398	3200	859

Gross Heat Rate, kWhr(te)/kWhr(e) 3.067

Gross Thermal Efficiency 0.326

Gross Electrical Output, kW(e) 10,010

Table 4-11. Pilot Plant - Turbine Operating from Receiver and Storage - No Charging

Parameters	Receiver	Storage	
		Steam OUT	FW IN
Flow, kg/hr	12,973	12,973	12,973
Pressure, MPa	10.1	3.62	3.96
Temperature, °C	510	391	175
Enthalpy, kJ/kg	3,308	3,200	749

Gross Heat Rate, kWhr(te)/kWhr(e) 3.663

Gross Thermal Efficiency 0.273

Gross Electrical Output, kW(e) 5,021

These conditions were simulated on the total power plant simulation. There seems to be no problem with any of the operating conditions since the system comes up to the required energy level in around 30 seconds after the demand signal is received.

Off-Design Charging Storage Mode

A few of the off-design conditions in the charging mode are listed (Table 4-12). These conditions represent the extreme since the charging mode is reflected in the conditions of charging with only the Hitec storage or with just the main oil storage.

Table 4-12. Off-Design Charging Storage Mode

Parameter	Design	Off Design	
	Simultaneous Charging Both Tanks	Main Oil Storage Only	Hitec Storage Only
Pressure, kPa (psia)	10100 (1465)	> 9300(1350)	< 9300(1350)
Temp., °C (°F)	510 (950)	< 454 (850)	> 454 (850)
Flow kg/hr(lb/hr)	50356 (110782)	Low range	Low range
Charge Rate MW		Variable	Variable
Gross	37.7	↓	↓
Net	31.6		
Efficiency	83.8%		

In the limited studies for the charging cycle the off-design conditions as listed above can be achieved. It may be noted in the off design conditions that with the main oil storage only the temperature ranges are lower than normal and pressures are in the range where condensation cannot take place.

SECTION 5

OPERATION, INSTRUMENTATION AND CONTROL

STORAGE OPERATION

Initial Startup

The starting point for this operation is with main storage filled with oil/rock with oil cold flow and ullage pressure testing complete. The superheater storage has been pressure tested but no salt has been put into the system.

Superheater Storage Startup -- Figure 5-1 shows the startup tracing steam supply to the superheater. Since steam is not yet available from storage a source from the receiver is used. The hot Hitec tank is filled with the salt mixture and the cold Hitec tank filled sufficiently to provide make-up for the lines and heat exchangers. Vertical thermo-flo, longitudinal finned tube tank heaters are mounted in each tank. The receiver supplied steam is then admitted to the tank heaters, lines and pumps. The valves are electrically traced. After 48 hours of receiver-supplied low-grade steam the system is warmed to 149°C (300°F) and the salt is completely melted. Steam is now permitted to flow through the Desuperheater Station and the salt charging pump is started. Salt is circulated through the heat exchangers and is placed into the hot tank. Salt from the cold tank is admitted to the system to bring the entire salt volume to the operating temperature.

Main Storage Startup -- The oil has been admitted to the main tank via the oil maintenance unit. This startup operation is concurrent with the superheater. A portion of the stored ambient temperature oil is circulated through the oil maintenance unit to be heated to 149°C (300°F). The heated oil is then admitted to the condenser where the oil is further heated to

Figure 5-1. Seal and Trace Steam

approximately 260°C (500°F). This process continues until the entire volume of oil has been preheated via the oil maintenance unit. The preheating eliminates the thermal shock that would be present without it.

Normal Operations (Refer to Figure 5-2)

Charging -- During normal operations the storage motor operated valve (B & V-P & ID M1003) will be open to maintain a hot condition. The condensate return control valve located near the deaerator will be opened to initiate a charging flow. Three different logic states are implemented.

- State (a) Steam pressure greater than 9300 kPa (1350 psia) and temperature greater than 454°C (850°F).
- State (b) Steam pressure greater than 9300 kPa (1350 psia) and temperature less than 454°C (850°F) with steam flow in the low range.
- State (c) Steam pressure less than 9300 kPa (1350° psia) and temperature greater than 454°C (850°F) with steam flow in the low range.

For State (a) both SH and MS pumps will start and heat will be extracted from the steam for both storage stages.

For State (b) only the MS oil pump will be started since the steam temperature is too low for effective heat exchange with the salt. For low flow into the condenser the excess surface area will allow the pinch point to decrease to 2°C (3-4°F). The saturation temperature at 9300 kPa (1350 psia) is 306°C (582°F) and with a 2°C (4°F) pinch point the oil at low flow can be supplied into the tank at 303°C (578°F).

Figure 5-2. Thermal Storage System

For State (c) only the SH salt pump will be started since the steam pressure will result in saturation temperatures below that required. However, for low steam flows the salt flow can be adjusted to produce the required outlet temperature due to the excess area brought about by the reduced flows. The steam exiting the attemperators will be bypassed around the condenser and subcooler.

Using the above charging conditions the Honeywell storage subsystem can handle a wide variety of operating scenarios from trickle to full charge. The variable pressure receive startup in the morning will allow steam to be used in storage. Likewise, because of abnormal conditions the SH and MS energy content may be out of balance for a demand full discharge. Consequently, storage can work the variable pressure startup into its charging strategy.

Discharging -- To produce 7MW(e) net for 3 hours from storage requires that the MS produce 83 percent and SH produce 17 percent of the energy. If this is not maintained then a 3-hour dispatch can not be met. During standby the boiler water level will be stabilized and the pressure allowed to rise to $\Delta 100$ kPa (600 psia). Discharge will be initiated when the storage admission valve at the turbine is opened. The MS and SH pumps will be started and the valve opened. A drop in boiler pressure generates steam and causes the liquid level to fall. The oil control valve modulates in response to the demand plus boiler conditions and the SH control valve responds to the superheater outlet temperature. The energy and rate conditions are monitored on the storage display panel.

Hold -- During a hold period the storage subsystem will be required to supply tracing steam to the superheater piping and pumps and may, if the turbine is on turning gear, provide sealing steam to the turbine.

Sealing Steam -- (Refer to Figure 5-2). The pressure in the sealing steam header is used to control the position of ACV-15, the sealing steam control valve. An auxiliary pump (AMDP) in the MS oil flow loop provides flow of hot oil through the main boiler. The rate is controlled by valve ACV-9 in that loop. The feedwater makeup is provided by ACV-13 based on standard 3 element control.

Tracing Steam -- The tracing steam is generated and supplied in the same manner to ensure that the salt lines and pumps are maintained above 204°C (400°F).

Abnormal/Emergency Operations

Charging -- For a long service life it is imperative that the salt film temperature be kept below 465°C - 482°C (870 - 900°F). The function of attemperator No. 1 is to maintain the steam temperature below 499°C (930°F) to ensure not exceeding the salt temperatures stated above. If the steam temperature out of the attemperator is greater than 499°C (930°F) and the spray valve is full open then signals are sent to GV-1 (blowdown the steam) and steam charging motor operated valve to close. The same situation holds for attemperators 2 a and b with the oil but the steam would be bypassed through GV-24.

Discharging -- A loss of superheat is a serious abnormal condition. The superheat temperature is continuously monitored and annunciated. The corrective action for a decreasing superheat condition is to first increase superheater salt flow then and/or decrease overall demand. The loss of the high pressure feedwater heater during an active discharge would preclude any charging operations and reduce the discharge duration.

Hold -- If sealing and tracing steam is required for an extended period of time it can be obtained at the expense of a storage discharge time.

Shutdown

Charging -- Normal shutdown would consist of closing the main motor operated charge valve to storage followed by an open contact signal to the Hitec and oil pump motors. The pressure in the condenser will fall to 9300 kPa (1350 psia) corresponding to the saturation of the oil and heat exchanger shell. If the shutdown were to be a scheduled long term the Hitec would be drained from the exchangers and lines and returned to the available tank. Emergency operations for shutdown is covered under abnormal operations.

Discharging -- Normal shutdown during a discharge would consist of closing the turbine admission valve followed by an open contact signal to the Hitec and oil pump motors. Sealing and/or tracing steam would subsequently be initiated. The hot oil remaining in the boiler tubes would cause the water on the shell side and the heat exchange metal to heat up. The boiler shell is designed for 4100 kPa (600 psia).

The amount of heat input by the oil setting in the tubes will cause the boiler pressure to rise to approximately 4100 kPa (600 psia) 252°C (486°F). A relief valve will vent several pounds of steam to the condenser.

INSTRUMENTATION AND DATA ACQUISITION

This section on Instrumentation and Data Acquisition is organized to reflect the implementation of both the Solar Pilot Plant and Commercial Plant. The implementation for each plant varies due to the basic differences in objectives for each.

By relative comparison of size, the Pilot Plant has been engineering instrumented more extensively due to the requirements to (1) acquire data to determine the actual operating performance of the system. (2) analyze a sufficient body of engineering data to determine the feasibility of a cost-effective commercial plant, and (3) determine how and to what degree the commercial plant should be automated.

General Requirements and Philosophy

Basic Objectives -- The prime objectives for instrumenting thermal storage in both pilot and commercial plants are:

- (a) Proper design of storage to charge, hold, and discharge sufficient energy when demanded by master control.
- (b) To determine and monitor energy balances throughout the system.
- (c) To determine thermal losses incurred as a function of operating conditions.
- (d) Monitor and safely control the process variables over a full range of operating conditions.

The above objectives give rise to a specific thermal storage instrumentation philosophy as a guideline for implementation. These are as follows:

Energy Balances

- System -- Instrument so that the energy balances, heat losses, and specific heat rates around all components can be either measured or calculated.

- Hitec and Oil/Rock Tanks -- Instrument to monitor net energy into and out of the system at prescribed time intervals; along with energy balances between Hitec and Oil/Rock.

Dynamics

- Instrument so that internal system dynamics can be properly monitored and controlled.
- Instrument to sufficiently determine the dynamics of the thermocline in Oil/Rock tank and the heat energy stored in Hitec.
- Instrument to determine extent of thermal dynamics (ratcheting) of Oil/Rock tank.

System Implementation

- Instrument to provide system flexibility to maximize ease of central control interface and integration (automatic, manual, etc.)

Equipment and Safety

- Instrument to provide personnel safety where necessary.
- Instrument so that proper alarming and maintenance functions can be accomplished by maintenance personnel with ease of troubleshooting, repair, etc.

Analog Versus Digital Tradeoff -- The master plant control and data acquisition computers, of which thermal storage shares, has the overall flexibility built-in to provide the following capabilities for both control and data acquisition.

Regarding the storage subsystem portion of the pilot plant, the primary mode of monitoring and controlling the processes will be analog. The primary reasons for this are as follows:

- (1) The number of control loops is sufficiently small to make analog control more competitive than direct digital control.
- (2) The basic process is analog in nature which tends to make implementation of proportional/integral feedback less complex.
- (3) Power plant operating personnel are more familiar with analog control than digital. Hence, time to train operations personnel will be minimized.
- (4) Analog control more readily accommodates man-in-the-loop capability because of manual set-point control.
- (5) Speed and response of control loops are typically slow for thermal storage.

Regarding data acquisition and mode sequencing, the primary configuration will be digital. The reasons for this are as follows:

- (1) Accumulation of significant data is required for evaluation.
- (2) Start up and shut down procedures and system status can more effectively be handled digitally (with manual intervention capability).

- (3) The data acquisition computer can be flexibly configured for input/output of real-time data.
- (4) The digital computer can readily accommodate program changes regarding computation, measurement, and control.

As a result of this unique configuration where the capabilities of both analog and digital are used, the system has become known as an analog/digital hybrid.

With this configuration flexibility, the pilot plant can be operated fully automatic, partially automatic, or manually, in any of the operating modes. The system also provides back-up capability for control. To have this overall system flexibility is the key to complete determination of how the commercial plant should be automated.

A convincing argument for totally digital control can be made. First, digital control has the distinct advantage of optimizing system performance. It can handle many problems simultaneously (including system non-linearities and discontinuities with on-line compensation). Additional digital control generally provides smoother start-up and shut down than analog. For systems with long time constants a digital system is advantageous because they can be programmed into the software. Analog requires manual inputs by the operator.

System Measurement Requirements -- The ability to determine thermal storage subsystem input, storage, and output energy capacity and rates shall be measurable within 3 percent at design conditions. This means typical measurement accuracies of about 1 percent (1σ) can be expected. This represents the overall system accuracy requirement for the combined instrumentation, control, and data acquisition. Appropriate instrumentation must therefore be specified to reflect the accuracy required for measurement of pressure, temperature, mass flows, and fluid levels. The thermal

energy is all transported, neglecting heat loss terms, across system boundaries by water or steam flow; thus steady-state energy balances are made by summing fluid enthalpy fluxes. Refer to the following section on Instrument Error Analysis and Section 6, Supporting Data.

As an example, the accuracy specified means that the instrumentation and data acquisition system must be able to measure heat $(Q = \sum_{L=1}^n (m_i) (h_i))$

throughout the system within the 1σ value. This means that the accumulation of the independent measurement errors of pressure, temperature and flow around all heat exchanger loops must be less than the required heat rate determination error of 3 percent.

Instrument Error Analysis -- Measurement error analysis begins with consideration of the inaccuracies of the primary sensors (pressure, temperature, level). Additional major errors are introduced in (1) transmitters, (2) data acquisition system itself, and (3) steam quality determination.

The errors associated with each specific instrument for use in both pilot and commercial plants are shown in Table 5-1. In order to precisely determine the effect that instrumentation error has on enthalpy determination it is only required that the estimated system instrumentation errors be plotted on steam charts and compared with the requirements set forth above. The steam charts plot lines of constant pressure and temperature as functions of specific volume and enthalpy. Hence, a direct comparison of actual versus required accuracies can be made.

In similar fashion, the entire heat balance of the thermal storage system can be determined for charge and discharge cycles along with the error associated with instrumentation measurement.

Table 5-1. Instrumentation Errors
Pilot and Commercial Plants

Instrument	Range	Output Signal	Error
Pressure Transducer	0-1500PSI	4-20 ma	Max ± 0.2 of span (TYP. $\pm .1\%$)
Differential Pressure		4-20 ma	Max. $\pm 0.35\%$ of span (TYP. $\pm$.25%)
Orifice Plates			+ 0.5% of F.S.
Thermocouples AnsI Type K - Premium Grade	0-2300°F	Millivolts	$\pm 0.38\%$ of reading
Temperature Transmitters		4-20 ma	$\pm 0.1\%$ of F.S.
Level Sensors		4-20 ma	$\pm 0.5\%$ of F.S.
Data Acquisition System	$\pm 4-20$ ma		$\pm 0.39\%$ of F.S.
Data Logger Fluke		Serial Data	0.6% of F.S.
Controllers			$\pm 0.5\%$ of S. P. $\pm 0.1\%$ comp.
Proportioning Valves			+ 0.5% span

Local Control Center -- In addition to the overall plant requirement for a co-ordinated Master Control Center for all subsystems, a basic need exists for an on-site thermal storage control center to meet the following requirements:

- (1) Housing of motor starters, switchgear, high and low voltage control circuits, etc.
- (2) Maintenance, repair and troubleshooting purposes
- (3) Interface wiring between thermal storage and central control

- (4) Local fire control and protection for thermal storage
- (5) Thermal storage power and signal distribution
- (6) Auxiliary alarm, status, and monitoring panels to assist maintenance personnel

Note: The local control center is not configured to control or over-ride the processes which master control performs.

Therefore, the equipment required to implement the local control configuration should reflect what is deemed necessary from a general maintenance, safety, economic and convenience standpoint.

Quantitative Requirements - Pilot Plant versus Commercial. This functionally defines the differences in quantitative instrumentation hardware requirements for the commercial versus the pilot plant. As discussed earlier, the performance data gathered in the pilot plant program will significantly assist in determining how and to what degree the commercial plant will be automated and monitored. The instrumentation and data acquisition philosophy for the commercial plant will be to instrument in the following manner:

- (1) To instrument those parameters which pilot plant dictates are required for "sufficient" control and monitoring
- (2) To achieve this in a manner to minimize cost levels for instrumentation

This approach is consistent with the overall storage design philosophy in that the commercial plant will be conceptually identical to the pilot plant but vary only in storage capacity and equipment quantity.

Pilot Versus Commercial --

- For commercial, boiler and condensate receiver level controls are increased
- Main storage thermocouples reduced to monitor thermocline in vicinity of upper and lower manifolds
- General process instrumentation and monitoring devices will increase
- Data acquisition, software, and through-put will remain similar or decrease because gathering performance data will be less extensive
- Major control loops will remain similar
- Instrumentation along transfer piping will decrease significantly
- Hitec storage instrumentation will remain or decrease
- Wiring runs will increase
- Data acquisition hardware will remain or increase slightly
- Interfacing requirements both at local and central will remain or increase slightly
- Field multiplexing equipment will remain similar.
- Analog and digital I/O will increase.

System Design Configuration

The basic instrumentation and data acquisition system configuration for the pilot plant thermal storage system is shown in Figure 5-3. This figure illustrates the general flow of process data for transmission, distribution, conditioning, gathering and storing required information. It has been broken down into three discrete sections: process instrumentation, local control, and central control. In addition, it shows the inter-relationships of the various devices along with the command and control scheme for integrating the thermal storage system with master control.

The basic implementation philosophy is that wherever possible the analog low level signals to be transmitted for either data acquisition or control will be converted to high level 4-20 ma outputs prior to transmission. This is to ensure the best signal integrity.

The basic philosophy for wire-routing and terminations is to route directly to central those signals which would be used primarily for data acquisition.

Conversely, because of the general layout and proximity of the thermal storage local control station to the process, all process signals will be routed and terminated at the local control station. This allows the local alarming maintenance, monitoring, troubleshooting, etc. and provides flexibility in the overall configuration to have pin in/pin out capability at local.

Additionally, the system design reflects the philosophy of minimizing individual long cable runs from the thermal storage area to central by providing on-site multiplexing for heavily instrumented equipment. This minimizes the necessity to run low-level analog signals large distances and cuts down on relatively expensive cable and raceway costs.

Figure 5-3. System Configuration

The heavily instrumented main storage oil/rock tank and Hitec tanks are configured such that signal conditioning and reference junction compensation will be accomplished at the site. The data will be multi-plexed, digitized and transmitted over a twisted pair RS-232-C interface directly to the data acquisition computer for computation, spooling off-line, and storing for later reduction. A data logger which is RS-232-C compatible will provide this capability so that a standard modem can be used with direct computer input. The logger can also be programmed at any desired sampling rate either manually or by remote computer.

The basic purpose of the oil/rock tank instrumentation is to study thermocline profiles, thermal ratcheting, and skin strain effects, and determine energy storage capabilities of the oil/rock tank.

For Hitec, the principal purpose is to determine energy storage and long-term thermal dynamic effects on the tanks.

The process instrumentation and control loop design includes analog and direct digital control (DDC) process hardware and proportional and on/off solenoid operated valves to monitor, control and sequence the process for start-up, shutdown and on design/off design conditions. These signals will be routed to local control for access prior to transmitting to central control.

Central control will physically house the controllers and data acquisition system to support the thermal storage requirements.

The basic control philosophy is set point control for the thermal storage control loops, with man-in-the-loop capabilities. In addition, the controllers and central computer will provide DDC set point capability which allows the computer to control the processes with resident software. This will require 20-30 percent on-line computer memory capability for computation and control.

The master plant computer provides the coordinated demand and mode signals either to the controllers and/or the computer to initiate thermal storage activity.

Mode status information of thermal storage is sent to central computer to keep the plant informed as to thermal storage operation.

Figure 5-4 represents a more detailed block diagram showing the process input/output requirements for analog and digital interfacing. They are summarized below:

(1) Analog outputs (4-20 ma) Includes all 4-20 ma process variables and main storage pressure and strain	121
(2) Analog outputs (millivolt level)	524
(3) Analog inputs (4-20 ma) Includes the control signals for controlling 13 automatic proportional control valves	13
(4) Digital outputs (On/Off) Includes proportional and On/Off valve status and various Hi/ Lo process alarms	145
(5) Digital inputs (On/Off) Includes control relay inputs to operate On/Off valves	145

Process Instrumentation Design

The system configuration has been divided into the following three sections:

(1) Process Instrumentation

All sensors, transducers, transmitters which are monitoring the storage processes. These are physically on the process floor.

Figure 5-4. Detailed System Block Diagram

(2) Local Control

Indicators, annunciators, terminations and alarms, etc., located in the local control room.

(3) Central Control

Data acquisition, control, indicators, computer peripheral and interfacing equipment located at central control.

In general, the succeeding discussions on process instrumentation, local control, and central control apply both to pilot plant and commercial plant design, but vary only in quantities.

The process instrumentation consists of, and is broken down as follows:

(1) Oil/Rock Main Storage Tank Instrumentation

Thermo-couple, strain, level and pressure required to monitor and study tank performance. This is all analog data.

(2) Hitec Tank Instrumentation

Bulk temperature thermo-couples and level instrumentation for both hot and cold tanks to monitor and study Hitec performance. This is all analog data.

(3) Process Monitoring Instrumentation

Includes all pressure, temperature, flow and level instrumentation to monitor process variables and status of valves, etc.

Figure 5-4 showed a detailed design layout of the signals required (types and quantity) to fully instrument thermal storage for data transmission, status, wiring, and interfacing between local and central control. This also illustrates the "flow" of analog and digital signals along with the special data logger and multiplex equipment configured for the oil/rock and Hitec tanks.

Main Storage Tank Instrumentation -- Main storage tank instrumentation design varies between pilot and commercial plants. The pilot plant design is required to fully study the thermocline and associated dynamics of the tank as an aid in design of the commercial plant. The commercial plant instrumentation is primarily for determination of Hi/Lo energy storage in the system and will be instrumented accordingly. The storage instrumentation is compared in Table 5-2.

Main Storage Tank Instrumentation (Pilot Plant) -- The main storage oil/rock tank instrumentation consists of imbedded temperature rakes, surface strain gages, manifold pressure instrumentation and heat loss thermocouples. The instrumentation is shown in Figure 5-5.

Thermocline Instrumentation -- The thermocline temperature profile instrumentation requires a series of temperature rake assemblies positioned at 0.6 m (2 ft) vertical intervals in the rock bed and inserted at the time the main storage tank is filled with rocks. The high, middle, and low positions will require a total of 61 thermocouples while the intermediate locations (18) will require 13 thermocouples each. Figure 5-6 shows the design distribution of thermocouples in the tank.

The accuracy and resolution to which the main storage thermocline movement is measurable is a function of the density and location at which thermocouples are instrumented in the tank.

The thermocouple instrumentation has been selected to measure temperature at 2 foot (.61 meter) vertical intervals. This means temperature can be measured within "0.61 meter resolution" in the vertical direction. This results in an average uncertainty of $\pm .3$ meters of where the thermocline is physically located during charging or discharging, or about ± 2 percent. The resultant effect is that stored energy at any given time is measurable within 2 percent of actual. From this standpoint, a 0.6 meter interval

Table 5-2. Storage Instrumentation

<u>Main Storage</u>	<u>Comment</u>
● Imbedded thermocline thermocouples rakes	417 required for PP for thermocline dynamics - 400 total for CP energy level determination
● Manifold Pressures	Pilot Plant - 4 required Commercial Plant - none required
● Skin tank strain (hi and mid location)	Pilot Plant - 16 required Commercial Plant - none required
● Knuckle strain	Pilot Plant - 16 required Commercial Plant - 16 required
● Skin tank temperature	Pilot Plant - 12 required Commercial Plant - none required
● Ullage temperature	Pilot Plant - 3 required Commercial Plant - none required
● Ground temperature	Pilot Plant - 40 required Commercial Plant - none required
● Tank Base temperature	Pilot Plant - 12 required Commercial Plant - none required

Figure 5-6. Thermocline Thermocouple Distribution
Oil/Rock Tank

seems a reasonable tradeoff between density and cost considerations for monitoring thermocline movement.

Regarding distribution of thermocouples at each level, it seems reasonable that to gather meaningful temperature data, any one given thermocouple at a level should be vertically in-line with its counterpart at all the other levels. The basic reason for this is that it will better assist in determining thermocline location and the rate of change of temperatures from bottom to top. This will be used to determine energy stored.

The thermocouples at any one level provide the means to average temperatures at that level since profiles will not be constant.

Tank Skin Temperatures -- To obtain tank skin temperature profiles and heat loss data, 4 T/C's each at the high, mid, and low positions will be attached to the outer tank skin to record temperatures. They will be placed 90 degrees apart.

Temperature Profiles (Heat Loss to Ground) -- To obtain data on "Heat Loss to Ground" temperature gradients, four single leg rakes each with 10 thermocouples spaced at 2.6 m intervals will be inserted 6.1 m below the tank in a vertical position in the ground.

Temperature Profiles (Base of Tank) -- To monitor tank skin temperature below the lower manifold, 12 thermocouples will be attached to the base of the tank.

Temperature Profiles (Ullage Space) -- To monitor ullage space temperature, three thermocouples at 120 degrees around the tank dome will be inserted into the ullage space through the dome.

Strain Profile (Tank Skin) -- At the high, mid and low positions of the tank, four strain gages will be attached at 90 degrees intervals around the tank circumference. These will be used to monitor long-term stress and creep characteristics of the tank as related to temperature cycling (ratcheting). This is required because the coefficients of expansion between the steel tank and rock are dissimilar giving rise to tank skin stresses from heating and cooling effects.

Manifold Pressures -- Pressure sensing devices will be inserted in both the upper and lower manifolds at points of estimated high and low pressures. These will be used to determine whether proper distribution of oil into the rock bed is occurring as predicted. The data will be used to assist in commercial plant manifold design.

Proper distribution and insertion of oil into and out of the storage tank is partly a function of the ΔP drop across the manifold. Pressure instrumentation in the manifold will assist in determining whether manifold holes are plugged and whether the maldistribution of oil gives rise to degradation in the thermocline.

Regarding the lower manifold, an 18 percent blocking allowance has been designed into the manifold for the purpose of taking into account the holes which are covered by random distribution of the rocks in the tank. Pressure instrumentation in the lower manifold will additionally assist in determining blocking factor characteristics.

Tank Knuckle Strain Profile -- A series of strain gages (16) will be instrumented at 90 degrees intervals (four each) at the base (knuckle) of the tank to determine plastic deformation of the circumferential knuckle and verify design of the support structure.

Main Storage Electronics -- The main storage conditioning electronics associated with the instrumentation will be housed in a heated NEMA-4 enclosure approximately 20 feet from the tank.

The thermocouple signals will be conditioned and multiplexed via an onsite data logger in serial form through an RS-232C interface and transmitted directly to the data acquisition system in central control. This will allow 2-two wire twisted pairs with data transmission speed of up to 300 baud.

Main Storage Instrumentation (Commercial Plant) -- As stated earlier, the main storage oil/rock instrumentation configuration for the commercial plant will vary from that of the pilot plant.

The principal objective, for thermocouples in the oil/rock bed, is not to study thermocline dynamics, but is for the determination and anticipation of Hi/Lo level energy storage in the system. Operationally, this is to alert personnel of main storage energy status by measuring the level and movement of the thermocline as thermal storage charges and discharges. This anticipatory scheme notifies operations personnel as to the availability of energy from storage so that appropriate measures can be taken to schedule the demand to the turbine and grid.

Figure 5-7 shows the instrumentation design for the commercial main storage tank. Note that the tank is nominally 34.75 m in diameter and 14.6 m high. Also note that the following instrumentation which was in the pilot plant has been eliminated:

- (1) Heat loss to ground thermocouples
- (2) Circumferential strain gages at high, mid and low levels
- (3) Skin temperature thermocouples

- (4) Ullage dome temperatures
- (5) Manifold pressures

Figure 5-7. Commercial Main Storage Tank Instrumentation Design

The need for thermocouple assemblies for energy level anticipation are based on the fact that as the thermocline moves up and down the tank based on charge and discharge demand, the thermocouples will sense the temperature discontinuities as the thermocline passes through the coplanar temperature rake assemblies. This will be proportional (but non-linear since the thermocline profile changes as a function at energy level) to the energy level in the tank. See thermocline simulation curves of Section 5, supporting data.

Nominal values of 80 percent and 20 percent of full charge are selected as the levels required which will provide about 36 minutes of lead time for predicting either a fully charged or fully discharged tank. The exact instrumented level will be determined from pilot plant data.

Each of the two major levels will consist of 20 thermocouples as a tentative selection. This represents a density of one per 47 m^2 (500 ft^2).

Intermediate thermocouples will be inserted at nominally 0.6 m-1.0 m intervals each with 20 thermocouples. They will be positioned vertically in-line with each of the counterpart thermocouple at the other levels. A total of 10 levels will be instrumented for a total of 200 thermocouples per tank.

Hitec Tank Instrumentation -- Instrumentation for both the Hitec tanks (hot and cold) consists of; (1) measurement of bulk temperature at a level from 0-100 percent full, and (2) liquid level sensing at extremely high temperatures. See Figure 5-8, Hitec Instrumentation, and Table 5-6.

The principal purpose for this instrumentation is to determine the amount and availability of thermal energy stored in the tank at any given time. In addition, it is desired to determine the effects of thermal cycling (ratcheting) on the tank skin and ambient temperature gradients (losses) inside the tank enclosures.

Bulk Temperature Measurements -- During normal operational modes for thermal charging and discharging, the Hitec tank level will vary from 0-100 percent full.

It is required that the average salt temperature be determined to determine the energy content of the Hitec storage tank. A temperature rake assembly nominally 14 feet in length shall be inserted vertically in each of the tanks at a convenient position.

Figure 5-8. Hitec Tank Instrumentation

To determine net thermal energy stored in the tank, the data acquisition system will sample the thermocouples, determine temperature gradient and average the thermocouples which are submerged in the Hitec solution.

Table 5-3 summarizes the instrumentation design requirements for Hitec tanks taken directly from the referenced P & ID. Note that the requirements are unchanged for pilot and commercial implementation.

Table 5-3. Hitec Tank Instrumentation Summary

<u>Sensor</u>	<u>Pilot/Commercial</u>
Bulk Temp Rakes	2 req'd 4.2 m long 10 T/C's each
Skin Temp	4 T/C's
Room Temp	4 T/C's
Wall Temp	6 T/C's
Pump Room Temp	2 T/C's
Level Sensor	2 req'd

Skin, Room Ambient and Wall Temperatures -- To determine heat loss effects through the tank skin and the degree of heat transfer in ambient Hitec room, various thermocouples will be instrumented both monitoring room ambient air and room wall temperatures.

Figure 5-9 shows the layout for T/C instrumentation in the Hitec tank area.

Figure 5-9. T/C Instrumentation Hitec Tank Area

Hitec Pump Room -- For the principal purpose of maintenance and personnel safety, the pump room will be instrumented with thermocouples to monitor ambient conditions (2 required).

Hitec Level Sensing -- Each Hitec storage tank will contain liquid level sensing instrumentation which is capable of measuring the salt solution level for the entire vertical length of each tank (approximately 4.2 meters (14 ft)).

Due to the extremely high operating temperatures of the salt, a non-contacting gamma ray device which is mounted outside of the tank and thermally isolated from metal heat transfer will be instrumented. This device (Figure 5-10) measures the absorption of gamma energy as a function of salt level in the tank.

Figure 5-10. Hitec Liquid Level Sensor

Hitec Storage Electronics -- The thermocouple instrumentation signaling will be transmitted directly to the same data logger used for main storage so that economies of cold junction compensation and multiplexing can be used. All other instrumentation will be conditioned to 4-20 ma and transmitted to central control.

Process Monitoring Instrumentation -- This section includes pressure, temperature, flow and level instrumentation required to meet objectives outlined earlier in this section.

All instrumentation required will be implemented with standard off-the-shelf equipment for both commercial and pilot plant to meet accuracy requirements as stated earlier.

This includes pressure sensors and transmitters, temperature transmitters (including elements and wells), flow elements and transmitters, level sensors and transmitters and associated indicators and controllers as shown in the P & ID drawings under Hitec Tank Instrumentation Process and summarized in Table 5-4.

Table 5 4. Process Instrumentation Summary

Instruments	Quantities	
	Pilot	Commercial
<u>Sensors</u>		
-Pressure	27	74
-Temperature	31	50
-Flow	17	47
-Level	5	15
<u>Transmitters</u>		
-Pressure	27	74
-Temperature	31	50
-Flow	15	47
-Level	5	15
<u>Indicators (Central)</u>		
-Pressure	10	20
-Temperature	16	40
-Flow	8	29
-Level	5	15
<u>Indicators (Local)</u>		
-Pressure	5	10
-Temperature	4	8
-Flow	0	0
-Level	5	10

Table 5-5. SPP Thermal Storage Process
Alarm Summary

Refer to P & ID Drawing in Section 3

Identified Alarm PID Symbol	Description
1) TT-1	Overtemp Steam into Desuperheater
2) TT-4	Overtemp Salt out of Desuperheater
3) TT-5	Overtemp Steam out of Aitemp 2
4) TT-15	Overtemp Oil Out of Condenser
5) LI-4	Hi/Lo Level
6) TT-10	Low Temp (Hot Hitec)
7) TT-11	Low Temp (Cold Hitec)
8) PT-10	Hi/Lo Alarm - Hitec Pressure
9) LI-1	Lo Level (Hot Hitec) - No Charge
10) LI-2	Lo Level (Cold Hitec) - Overcharge
11) PT-11	Hi/Lo - Main Storage Pressure
12) N ₂ Ullage	Lo Level
13) Pumps (7)	Overtemp/Hi current
14) Oil Maintenance	Hi/Low Oil Level
15) PT-9	Lo Press - Output to Turbine
16) TT-9	Lo Temp - Output to Turbine
17) LI-5	Hi/Lo Level - Boiler
18) PT-23	Lot Press - FW Input
19) TT-2	Lo Temp - Hitec Pump Bearing
20) TT-21	Overtemp - Output Condenser
21) Special Main Storage Instr.	Hi Temp/Ground Loss

Process Alarms -- Table 5-5 summarizes the major alarming requirements for thermal storage. The alarms are identified by the specific process variable instrumentation symbol which appears on the referenced P & ID's.

These alarms are classified as major system alarms and are sent back to central control for monitoring purposes.

Local Control Design Interface

The local control room is a natural demarcation point for many interfaces. The room is conveniently located so that the routing of wiring can be accomplished economically while providing maximum capability for maintenance and troubleshooting of the system.

The local control room layout is shown in Figure 5-11.

Figure 5-11. Local Control Room

The local control room will house the following "standard" types of hardware and associated interfaces.

- 1) High and low voltage switchgear and motor starters.
- 2) Manual motor and starter control.
- 3) Motor control center and associated panels, switchboards, and transformers.
- 4) Power distribution transformers and equipment.
- 5) Control and alarm panels with terminal boxes for input/output wiring of process signal.
- 6) Computer control relays and interlock circuitry.

Termination Interfaces -- All processing interfacing signals (analog, digital and control) from either the central control room or the process itself will terminate at a junction box. This will also include power wiring to required sensors. (This excludes the special test instrumentation for Main Storage and Hitec Instrumentation.

Alarms and Annunciators -- To provide for personnel safety, the local control room will contain an alarm and annunciator panel which will visually/ audibly display monitored status or alert maintenance to critical alarm functions. This will also be used for troubleshooting, checking and maintenance of the thermal storage system at a local level. The annunciator panel is shown in Figure 5-12.

Local Control Indicators -- The local station will also contain local analog indicators displaying those major process variables which would be of direct

Figure 5-12. Annunciator Panel Local Control Station

concern to any personnel working or operating in the thermal storage area, and as a convenience tool for maintenance. This is meant to be a scaled-down version of the monitored variables which will exist at central control.

The indicators will also contain where required, hi/lo alarm monitoring which will be used to activate portions of the annunciator panel for critical parameters. These are specified in the Component Selection & Specification section.

Power Distribution -- Power requirements for the thermal storage system dictate the availability of the following power sources for operation:

- 1) 440 VAC 60 Hz (3 ϕ)
- 2) 220 VAC 60 Hz (1 ϕ)
- 3) 110 VAC 60 Hz (1 ϕ)
- 4) 24 VDC (Instrument Power)

Local Control Configuration Diagram -- Figure 5-13 shows a preliminary layout of the interface requirements for the local control station.

The detailed requirements which reflect the P & ID one-line interface drawings of Section 3 are shown in Appendix B for both the indicators and annunciator panels.

Master Control Interface

The master control thermal storage subsystem interface schematic is shown in Figure 5-14.

Colocated in the central control room and integrated with the master controller are:

- 1) Dedicated thermal storage controllers
- 2) The plant data acquisition and control computer
- 3) The associated peripheral storage, displays, etc., and interface wiring to the master monitor and status panels.

The master data acquisition and control computers will act as the primary interface for all control and data acquisition functions, and as such will be the "traffic director" for thermal storage operation and other subsystems. It will also provide updates to the thermal storage controllers and has the flexibility to be linked to other subsystem computers or interfaces if required.

For control, the basic design of the system centers around flexibility of either man-in-the-loop or computer set-point update with on-line resident software.

40703-V

Figure 5-13. Local Control Interface

Figure 5-14. Master Control Room Interface

The basic control operation and interface between thermal storage and the master plant computer is as follows.

- 1) Coordinated master plant control demand signals will be sent to thermal storage commanding start-up or shutdown for any of the charge, discharge, or concurrent operating modes. This is accomplished by inputting the mode command signals (manual or automatic) into either (1) the thermal storage memory portion of the computer or (2) the master controllers.
- 2) The computer will then initiate the proper mode sequence to operator valve and pump commands for start up or shutdown based on the desired mode (charge, discharge, or combination).
- 3) The computer will receive mode status as to current state of thermal storage (i. e., is there sufficient stored charge to operate turbine, etc.). If so, the computer will sequence and operate the appropriate valves and pumps depending on requested mode. The logic will reside in the computer.
- 4) The computer will update the controllers to their required operating conditions for the given mode. (This is also stored on-line in the computer.) The computer will be linked to the controllers to provide DDC set point and gain adjustment so that either master control or T. S. control can automatically manipulate the control parameters.
- 5) Analog control of the thermal storage system will be accomplished principally by the stand-alone controllers assigned to control each loop.

The analog controllers provide manual override (desired for pilot plant) so that there is a man-in-the-loop maintaining set-point control. This will override the computer control automatic updating signals.

- 6) The controllers will provide visual readout of set points and PV and can be operated manually or by the computer for updating.
- 7) Mode status to master will be acknowledged when the thermal storage system has completed the assigned tasks or is in a steady state mode and is ready for a new command.
- 8) Approximately 30 percent of the dedicated thermal storage core memory will be used for on-line purposes relating to:
 - Mode command and status
 - T. S. S. acknowledgement
 - Updating controllers
 - Valve and pump commands and status
 - Energy calculations and display
 - Clock timers
 - Critical parameter data
 - Resident control algorithms

Data Acquisition -- For data acquisition, the computer hardware system for thermal storage is a non-dedicated system since it is a part of the plant computer system, sharing input/output, priority as efficiently as possible. The computer I/O is configured as a sensor based system which will sample thermal storage instrumented variables and, depending on priority,

either compute or directly store raw data on disc for subsequent spooling to magnetic tape for data reduction off-line.

The data acquisition system will provide the following functions and flexibility:

- 1) Storage of application programs.
- 2) Acquire all desired analog process data for manipulation, calculation, store and spool off-line.
- 3) Provide variable rate sampling of process data.
- 4) Digital I/O for:
 - a) On/Off status of valves, switches, etc.
 - b) On/Off control of valves
- 5) Input/output access via CRT and disk.
- 6) Alarm status information.
- 7) Provide an estimated 20 to 30 percent on-line control and data reduction for those processes requiring on-line manipulation.
- 8) Interface for the master controller.
- 9) Clock timer for time of day and control.

The required computer hardware, peripheral, and input/output requirements are detailed in Section on Component Selection. In summary form, 16K of dedicated core memory in the master plant computer is required.

In addition, the capability to provide 1 megabyte of disk storage per day with off-line data reduction is required. (See Supporting Data Section) Programming will be assembly language with option Fortran compiling capability.

The overall input/output requirements are detailed in System Design Configuration of Figure 5-4.

Non-dedicated hardcopy line printing and CRT I/O is required with the following capacities:

- 1) CRT - 2,000 chars/day
- 2) Printing - 100 lines/minute average

Graphics Display -- A graphics display panel showing a graphic layout of the thermal storage area has been designed for the following reasons: 1) to show the current energy flow and storage status of the system at a glance, 2) to show the current mode of operation regarding coordinated demand control at the receiver (input) and turbine power requirements (output and 3) general display of storage throughout.

This is illustrated in Figure 5-15. The display will visually show,

- 1) Thermal Storage Mode of Operation as demanded by master control.
- 2) Net energy rate charging.
- 3) Net energy rate discharging.
- 4) Totalized stored energy.
- 5) Energy balance between Hitec and main storage.

The panel will be mounted at the operator's control station in central control.

Figure 5-15. Graphics Display Panel

Component Selection and Specification

The purpose of this section defines the salient requirements for each category of instrumentation for thermal storage and lists the selected specific components or subsystems which will meet those requirements.

The categories of instrumentation are as follows:

- 1) Absolute pressure sensors and transmitters
- 2) Thermocouples and transmitters
- 3) Flow orifices and P transmitters
- 4) Level sensors and transmitters
- 5) Data loggers and multiplexers
- 6) Data acquisition computer and peripheral
- 7) Recorders
- 8) Indicators
- 9) Strain gages

General Requirements -- The general requirements apply to all process sensors, transmitters, indicators, and recorders except as specified otherwise.

- 1) All field-mounted sensors, transmitters and indicators shall be capable of operating within an ambient temperature range of -5°C to 50°C .
- 2) All electronic indicating and controlling equipment normally panel mounted shall be capable of operating throughout the range of 16°C to 49°C .

- 3) All transmitters shall have a 4-20 ma output capability with accuracy of $\pm 0.1\%$ FS or better.
- 4) All sensors shall have a nominal full scale accuracy of $\pm 0.5\%$ or better.
- 5) All indicators shall have an accuracy requirement of $\pm 2\%$ full scale.
- 6) All equipment shall operate from 24 VDC power.
- 7) All sensor and transmitter assemblies shall be UL listed intrinsically safe and explosion proof per CSA standards.

Absolute Pressure Sensors and Transmitters -- Pressure sensors (elements) are inserted at various locations in the thermal storage system, particularly in the piping and transfer lines. The lines are operating in a high-temperature environment at the process connection point. This is the location where the pressure sensing diaphragm comes in direct contact with the fluid in the line.

In the case of oil, process temperatures are nominally 260 - 316°C where normal commercially available sensors operate in ambient temperatures up to about 94°C. Since normal heat conduction occurs through the process connections the diaphragms and eventually the entire transducer will internally heat up to above normal rated conditions of the sensor.

In the case of Hitec salt, normal operating temperatures approach 427 - 482°C with salt freezing at about 142°C, well above the normal operating conditions of the pressure sensors (assuming conduction occurs).

For both oil and salt pressure instrumentation, it is therefore required to thermally insulate the sensing device from heat conduction while still rendering them useful for process pressure measurement.

The solution to these problems are to provide adaptable diaphragm protection seals which will protect each sensor from temperature, and internal corrosion or clogging (particularly in the salt lines). The diaphragms must be readily adaptable to interface the sensor and field replaceable.

With the above stated problems in mind, the pressure transducing equipment should be selected as follows:

- 1) The pressure sensor and transmitter shall be configured as an integral assembly.
- 2) The sensor shall be of the piezo-resistive strain gage type to provide long term stability and accuracy.
- 3) The wiring shall consist of a two-wire arrangement which is capable of handling both power and signal.
- 4) The sensor shall be capable of handling overload to twice the maximum rated value.
- 5) The process connection shall be 1/2 inch NPT female capable of a compression fitting to withstand up to 10.3 MPa.
- 6) All zero and span adjustments shall be electrical (not mechanical)
- 7) Diaphragm protection seals for pressure sensor shall be supplied with each pressure sensor selected.

It is also significant to note that with diaphragm pressure seals instrumented, calibration of each sensor must be accomplished with the utmost of care and accuracy.

Thermocouples and Transmitters

- 1) All thermocouples shall be ANSI Type J premium grade with accuracies of $\pm .38\%$ of reading.
- 2) Temperature measurement shall be 0 - 760°C
- 3) For measurement of process temperature, each thermocouple assembly shall be configurable with temperature wells, element protection for insertion and an integral transmitter.
- 4) The temperature element shall be readily field replaced.
- 5) Element insertion length and protection shall be variable from 5 up to 61 cm depending on pipe size.
- 6) Each hot junction shall be of the remote insulated type (welded junction within sheath).
- 7) Each process temperature transmitter shall contain reference junction compensation.
- 8) Process connections for insertion shall be no greater than 1 1/4 inch NPT.
- 9) Thermocouple calibration curves shall be directly traceable to the National Bureau of Standards.
- 10) All temperature elements shall provide protective covers of 316SS.
- 11) All process fittings shall be of the compression type to avoid leakage.

Flow Transducers -- The flow transducers may be configured as either ΔP , venturi or vortex shedding type.

- 1) Flow orifices (if used) shall be calibrated for an overall accuracy of ± 1.0 percent of full scale over the specified range.
- 2) Either individual or a combination of orifices shall be used to attain total flow turndown ratios of 10:1 within the above specified accuracy.
- 3) Calibration shall be based on design conditions of viscosity and pressure head for each line.
- 4) The ΔP transmitters (if orifices are used) shall be of the diffused silicon strain gage type for long term stability and accuracy.
- 5) The ΔP transmitters shall have accuracies within ± 0.35 percent of span.
- 6) Process connections shall be either 1/4 inch NPT or 1/2 inch NPT female.
- 7) The orifice and transmitter shall be an integral unit if possible to minimize installation.
- 8) The orifice assembly shall be configured with complete flange assembly and hardware to readily field install the unit.
- 9) Optimal: Optimal vortex shedding type flow devices may be substituted for the orifice type to obtain the required turndown ratios to meet the accuracy requirements.
- 10) The sensor shall be compatible with process pipe diameters ranging from 2 inches up to 48 inches I. D.
- 11) Diaphragm protection seals for interfacing the process connection with the sensor shall be specified for each of the ΔP connections.

Level Sensors and Transmitters -- The level sensor and transmitter instrumentation applies to the following process equipment only.

- 1) Boiler level control
- 2) Condensate receiver level control
- 3) Main Storage tank level monitor
- 4) Hitec Storage tank level monitor

General Requirements

- 1) All level sensors and transmitters shall be integral in design and shall provide the capability for local readout.
- 2) All transmitters shall be accurate to within ± 1 percent FS of input sensor signal.
- 3) All sensors shall be accurate to within ± 0.5 percent of FS reading.

Boiler Level

- 1) The sensor shall be capable of measuring boiler level height variation of nominally 2 feet.
- 2) The sensor will be positioned at the 107 cm position and sense ± 3 meter deviation with high/lo alarm capability.
- 3) The sensor shall be capable of operating in a temperature range of $-18 - 316^{\circ}\text{C}$.
- 4) Accuracy requirements shall be ± 0.5 percent of full scale with zero and span adjustment for 4 - 20 ma output
- 5) The measurement fluid is saturated water.

Condensate Receiver Level

- 1) The sensor shall measure a 2 foot vertical span within ± 0.5 percent.
- 2) The sensor shall have zero and span adjustment with 4 - 20 ma output.
- 3) The sensor shall operate within a temperature range of -18 to 316°C
- 4) The measured liquid is water.

Main Storage Level Monitor

- 1) The level sensing equipment shall be of the immersible type to read up to nominal . 61 meter of vertical oil level span.
- 2) The equipment shall operate in the temperature range of -18 to 316°C.
- 3) Transmitter output shall be 4 - 20 ma with adjustable span to calibrate full scale 20 ma output to the specific desired high oil level.

Hitec Storage Level Monitor

- 1) The level sensing equipment shall be capable of operating up to a nominal 454 to 482°C temperature of product temperature.
- 2) The equipment shall be of the gamma ray type mounted outboard to the tanks.
- 3) The equipment shall have accuracy within ± 0.5 percent with adjustable zero and span to measure a level range from 0 to 4.3 meters.
- 4) The equipment shall provide a 4 - 20 ma output over the desired level.
- 5) The measured material is Hitec.

- 6) The transmitter receiver assemblies shall be thermally isolated from the tank to minimize heat loss and to prevent sensor damage due to heat transfer.

Data Logger and Multiplexer -- The data logger and multiplexer system will be used to process, multiplex and transmit to Central an array of thermocouple signals from both the main storage and Hitec tanks.

- 1) The logger shall be capable of inputting up to 1000 low level millivolt type J thermocouple signals.
- 2) The system shall have integral cold junction thermocouple compensation.
- 3) The system shall have plug-in interface capability (25 pair- Amp connector) for an RS-232C connection to a data acquisition computer.
- 4) Transmission shall be serial data at up to 300 baud over two twisted wire pairs.
- 5) The system shall be programmable such that a computer can sample from 1 minute up to 24-hour intervals, through an asynchronous line interrupt command.
- 6) The logger shall have local hardcopy printout capability with a clock to display hours, days, minutes and seconds.
- 7) Overall system accuracy shall be $\pm .6$ percent.
- 8) Overall system resolution shall be $\pm .1$ percent.
- 9) The unit shall be capable of programming Hi/Lo alarms remotely.
- 10) The unit shall be rack-mountable.
- 11) The unit shall be able to operate over the temperature range of 16 to 49°C.

Data Acquisition System -- The computer system shall be located at Central Control along with associated peripheral equipment. The system and peripherals will be an integrated part of the master control computer and are therefore not stand alone items. The computer will provide two major functions:

- a) Acquire process data for data analysis and reduction.
 - b) Provide the interface for mode commands from Central and perform thermal storage sequencing operations.
- 1) The computer shall contain 16K of core memory.
 - 2) The computer I/O shall be sensor-based capable of handling 4 - 20 ma analog inputs and outputs along with digital input/outputs.
 - 3) The operating system shall have the following capabilities:
 - a) Multidimensional tasking
 - b) Communication processor
 - c) Assembly language with optional FORTRAN compiler.
 - d) Disk sort and communication support.
 - 4) The system shall include asynchronous line capability with RS-232-C modem compatibility.
 - 5) The peripheral equipment shall include a CRT display, printer, 1 megabyte disk cartridge and tape drive.

Main Storage Strain Gage Selection -- As stated earlier, strain gages are required on the oil/rock tank skin at the hi, mid, and low level locations. The principal purpose of these is to measure long term tank stress dynamics due to thermal cycling (ratcheting) and creep characteristics.

An additional instrumentation design consideration is to determine plastic deformation characteristics of the knuckle arrangement at the base of the tank. This will test the integrity of the knuckle and tank supporting structure design for the commercial plant.

All gages must be configured to operate in a 316°C surface temperature environment. The hi and mid locations will be instrumented with a standard type one dimensional gage with dummy for temperature compensation.

The knuckle arrangement will consist of a series of four rosette-type gages each at each of 90 degree positions around the tank. These will also have temperature dummy gages in the Wheatstone bridge loop for compensation. The layout is shown in Figure 5-16.

Figure 5-16. Main Storage Knuckle Strain Gages

Anticipated strains will range from 68.9 MPa up to 344 MPa. The transmitters for 4 - 20 ma output will be located in the same NEMA-4 cabinet housing the data logger. See P&ID Drawing.

Recorders -- Analog recorders shall be located at Central Control for the principal purpose of recording critical process parameters (see General Requirements).

Indicators -- See General Requirements.

Test Equipment Specification

Special Test Instrumentation -- Certain instrumentation has been designed specifically for the pilot plant. The objectives are to study the real operating conditions and effects on the hardware as a basis for design of commercial plant equipment. This type of instrumentation has been classified as Special Test Equipment Instrumentation and is summarized in Table 5-6 and compared with Commercial Plant Requirements.

Table 5-9 shows that the major part of the special test instrumentation is associated with the oil/rock tank. The objectives are as follows:

- 1) Evaluate the dynamics of the thermocline principle of energy storage in a real operational environment. See Supporting Data for Thermocline modeling.
- 2) Ascertain the operating capabilities/limitations of the main storage tank under a large range of dynamic operating conditions.

For these reasons, some 417 thermocouples (pilot) will be strategically located into the rock field. These sensors will measure temperatures at nominally 2-foot vertical intervals in selected horizontal plane location.

Table 5-6. Special Test Instrumentation Comparison

<u>Main Storage</u>	<u>Comments</u>
● Imbedded Thermocline thermocouples rakes	417 required for PP for thermocline dynamics - 400 total for CP energy level determination
● Manifold Pressures	Pilot Plant - 4 required Commercial Plant - none required
● Skin tank strain (hi and mid location)	Pilot Plant - 16 required Commercial Plant - none required
● Knuckle strain	Pilot Plant - 16 required Commercial Plant - 16 required
● Skin tank temperature	Pilot Plant - 12 required Commercial Plant - none required
● Ullage temperature	Pilot Plant - 3 required Commercial Plant - none required
● Ground temperature	Pilot Plant - 40 required Commercial Plant - none required
● Tank base	Pilot Plant - 12 required Commercial Plant - none required
<u>Hitect Tank</u>	
Skin temperature	Pilot Plant and Commercial Plant - 4 required
Room ambient	Pilot Plant and Commercial Plant - 4 required
Wall temperature	Pilot Plant and Commercial Plant - 6 required
Pump room temperature	Pilot Plant and Commercial Plant - 2 required
Bulk temperature	Pilot Plant - 24 required Commercial Plant - 24 required

The test instrumentation will be periodically sampled by the data acquisition computer and particularly to evaluate the thermocline curves under dynamic operating conditions.

Process Instrumentation -- The pilot plant has been instrumented so that significant amounts of steady state and dynamic data will be available for reduction and analysis. This is primarily due to desirability to gain a superior understanding of the use of storage in the many modes of operational environment.

Since the pilot versus commercial plant design philosophy is ultimately to design a commercial plant as a scaled-up version of the pilot plant, the process instrumentation requirements vary accordingly.

Test Plan -- The 2-year pilot plant test plan is to acquire data to determine thermal storage system computer and performance evaluation.

The test plan is designed to evaluate the following:

- 1) Heat energy balances
- 2) Thermal ratcheting and cycling of the oil/rock and Hitec tanks and long term creep analysis (stresses)
- 3) Heat rate
- 4) Thermocline profiles
- 5) Heat exchanger designs

CONTROLS

Master Control Interface

The master control block diagram is shown on Figure 5-17. The master control represents the highest level in the control loop. The master control through pressure, temperature, flow, and level transmitters is aware of the overall plant status and can establish demand signals to the subsystems to implement the necessary control. Turbine and generator control, under master control, is used to regulate turbine speed prior to synchronization and regulates generator load after synchronization. "Storage in" demand regulates the surplus solar generated steam to charge the Hitect and oil/rock storage.

"Storage out" demand controls the generation of steam through the preheater, boiler and superheater to augment or replace direct solar generated steam.

The master control monitors the status of the storage energy state and the dispatcher makes decisions based on this information.

If steam is generated in excess of turbine requirements, master control can direct the solar generated steam to storage. In the event the turbine demand is greater than the solar generated steam, additional steam can be generated from storage through the master control. This demand integrates through a bias signal that initiates the steam flow from storage to the low pressure turbine inlet. Steam flow from storage is increased until the demand load is met. Normally, feed forward signals (anticipation) from the integrated throttle pressure error and demand error signal are used to anticipate changes for storing energy or storage out to effect smooth, stable control,

Figure 5-17. Master Control Block Diagram Interface

Storage Control System Design

The basic control system schematic is shown on Figure 5-18. A computer dynamic simulation was mechanized (see discussion in Appendix D) and used as an aid in determining control loops. The thermal storage subsystem has two energy storage modes and two stages. Each must receive and/or discharge the proper amount of thermal energy in definite proportions. The requirements are given below:

<u>Mode</u>	<u>Main Storage</u>	<u>SH Shortage</u>	<u>Net Energy Delivered MWH (t)</u>
Storage in	84%	16%	107
Storage out	83%	17%	95

There are other requirements on the storage system that must be considered. Hitec temperatures should not exceed 465.6°C (870°F) because higher temperatures cause decomposition of the molten salt. If the temperature of the Hitec falls below 143°C (288°F) massive freezing of the salt will occur.

Oil temperatures must be limited to around 600°F bulk temperature. Actually the oil tends to cling to the heating tubes so that a thin film is formed of slowly moving oil. The film temperature of the oil is around 360°C (680°F) and with the 80° gradient, a 315.6°C (600°F) bulk temperature is allowed. On the lower end, the caloria has a pour point of -9°C (15°F).

Since the oil storage is maintained at a temperature above the flash point of 204°C (400°F) there must be some system of ullage control. Nitrogen is introduced to the top of the tanks and the pressure is maintained for safe high temperature operation. Provisions have been made for relieving the excess pressure as well as a quick release should the pressure build up rapidly.

Figure 5-18. Storage Control Schematic

The succeeding paragraphs describe the various control loops as shown on Figure 5-19.

Attemperator Control (Figure 5-19) -- Attemperators reduce temperature through the introduction of water. The water cools the steam through evaporation. The water is atomized in the venturi section for thorough mixing with the steam. The water pressure is 10% greater than the steam pressure. A pressure drop of 13.78 kPa (2 psi) to 68.9 kPa (10 psi) occurs.

The object is to transfer a maximum of heat to the Hitec storage without exceeding an allowable maximum temperature of the Hitec. This is set at 455°C (850°F) at the set point which is compared with the actual Hitec temperature. This error signal (note + and -) has a proportional plus integral action which has the effect of anticipation or lead on it. The attemperator No. 1 outlet temperature is compared with a set point temperature. Any error signal from the Hitec comparison is added to the set point.

Figure 5-19. Attemperator Storage Control

Hitec Storage Control (Charge (Figure 5-20) -- Master control calls for heat transfer to Hitec storage. The oil storage inlet and outlet temperatures are compared, so that the heat put into Hitec storage and that into oil storage is balanced. A solenoid operated bypass valve allows the Hitec to return to storage if not enough heat is being transferred to it. In effect this modulates the Hitec flow rate through the desuperheater.

Figure 5-20. Hitec Storage Control (Charge)

Hitec Charge Control Bypass (Figure 5-21) -- Master control will set the desired temperature for the Hitec into storage. If the Hitec is less than nominal 410°C (770°F) as it comes out of the desuperheater the ACV-2 valve is modulated. Should it be necessary to reduce flow through the desuperheater and increase Hitec temperature, the operator controls a bypass return valve. This control bypasses some of the flow back to Hitec cold storage which in turn reduces flow through the desuperheater and increases Hitec temperature.

Figure 5-21. Hitec Charge Control Bypass

Oil Charge Loop (Figure 5-22) -- Master control has selected a storage mode of control and calls for heat transfer to the oil and then to storage. Oil inlet and oil outlet temperatures are compared and constitute the "delta" error. The oil charge is controlled in the same proportions (84% oil and 16% Hitec) as determined from master demand. The usual proportional plus integral control is used.

Figure 5-22. Oil Charge Loop

A manual operated, solenoid controlled bypass valve is used in conjunction with the automatically controlled valve. Should it be necessary to reduce flow through the subcooler and condenser and increase the oil temperature, the operator controls a bypass valve.

Condensate Level (Figure 5-23) -- The object is to remove all of the heat from the steam until it changes to water. This controls the level of the water in the condensate receiving unit.

Figure 5 23. Condensate Level

Hitec Storage Tank Pressure Control (Figure 5-24) -- The space above the Hitec in the Hitec storage tank is pressurized with nitrogen to avoid accumulation of gases. At pressures under 3.44 kPa (0.5 psi) the nitrogen is vented to the tank. At pressures over 8.96 kPa (1.3 psi) the excess pressure is vented to a condensate chamber. Master control can override the set pressures.

Figure 5-24. Hitec Storage Tank Pressure Control

Oil Storage Tank Pressure Control (Figure 5-25) -- The space above the oil is pressurized with nitrogen to avoid the accumulation of gases that could ignite. At pressures under 3.44 kPa (0.5 psi) the nitrogen is introduced to the ullage space in the tank. At pressures over 8.96 kPa (1.3 psi) the excess pressure is vented to a chamber that separates the oil vapors and returns them to the oil cleaner tank. Master control can override the set pressures.

Figure 5-25. Oil Storage Tank Pressure Control

Hitec Discharge Control (Figure 5-26) -- The temperature of the Hitec into the superheater is compared with the temperature out. If there isn't enough difference it indicates not enough heat is being extracted, so the Hitec is modulated. To further reduce flow, the operator can now open a solenoid operated valve which shunts the Hitec back to Hitec hot storage tank. This reduces the flow through the superheater resulting in an increase in heat transfer. The discharge cycle is based on the same ratio of heat stored in the Hitec and the oil. Since Hitec has been charged with 17 percent of the heat in, this same ratio will be used on the discharge.

Figure 5-26. Hitec Discharge Control

Oil Discharge to Preheater and Boiler (Figure 5-27) -- Since the oil received 83 percent of the heat into storage, a similar ratio will be used on discharge. The oil inlet temperatures and boiler oil flow are an indication of the heat discharged into the preheater and boiler. The usual proportional plus integral control is used on the control signal. The temperature of the oil is monitored as it enters the boiler and again when it leaves the preheater. If the difference in temperature is small, it indicates that not enough heat is being absorbed. The operator opens the bypass valve and recirculates the oil and also closes the valve in the return line to the tank.

Figure 5-27. Oil Discharge to Preheater and Boiler

Feedwater Regulator Valve (Figure 5-28) -- The flow of feedwater is regulated by the steam flow out of the superheater, the water level in the boiler and the actual feedwater flow. The three element controller has the usual proportional plus integral control.

Figure 5-28. Preheater Regulator Valve

Oil Maintenance Control (Figure 5-29)-- Oil **must** be replenished or refined as the temperatures tend to break down the composition. Vapors that may mix with the inert nitrogen atmosphere in the oil tank ullage are controlled through ACV-18 to the oil maintenance unit. Here the "low boilers" are condensed and then reprocessed with the oil to remove all impurities. Reprocessed oil is controlled by flow rate and enters the oil tank. Control of flow rate for processing is through ACV-11.

Figure 5-29. Oil Maintenance Control

Heat for Hitec Lines (Figure 5-30) -- It is necessary to provide auxiliary tracing heat to the Hitec lines, tanks and pumps in the event long down times are necessary. Steam from the receiver or from the sealing and tracing system can be used to heat these units. This control reduces the pressure to a safe 1723 kPa (250 psi) before introducing it to the various units. Two valves, ACV-20 and ACV-21, are necessary since there are two sources for this steam.

Figure 5-30. Heat for Hitec Lines

Control Valves -- Control valves have been carefully selected on the basis of pressure drop, fluid temperature, pressure and line size. All of the applications control rate of flow and therefore introduce a pressure drop into the flow systems. Valves have been selected for the proper pressure drop associated with the necessary valve flow coefficient (C_v). A flow coefficient of 10 means that when the valve is open it passes 10 gpm (0.38 m/min.) of water with 6.89 kPa (1 psi) pressure drop. This flow capacity is a function of port area, plug design and body design.

All of the control valves are of a single or double seated gate valve construction since they are all controlled by pneumatic actuators. Some of the selected valves have a cast steel body since the fluid and temperature range are not severe. The other valves have a 316 stainless steel body in order to withstand the higher temperatures. Flanges on the body of the valve have been specified on the basis of the pressures in the line, the fluid controlled and the temperature range. Trim, plug, and cage are usually of a 17-4 PH stainless or in a few cases No. 6 solid stellite faced. The bonnet with the actuator and mount is either cast steel or stainless steel dependent on the temperature range. Where temperatures are very high an extrusion column has been specified as well as cooling fins on the trim.

Shredded teflon or teflon asbestos was selected for most of the valve packings. The single ported valves are used because the flow tends to be in one direction only so that the flow tends to open the valves. Plug valves are of the skirted V type with an equal percentage flow characteristic so that a wide range of control can be maintained. At temperatures above 400°F the valves have cooling fins to protect the valve packing. The stainless steels selected for the valves are in keeping with the recommendations of the Hitec manufacturer. Another feature of the cage valve selected is that the trim (internal) can be removed and replaced without taking the valve out of service. This procedure can take 12 to 13 hours versus 1 hour for only the trim removal and replacement.

Control Actuator and Transducer -- An electro-pneumatic transducer converts the current signal from a controller (4 to 20 ma) into a pneumatic output pressure over a 3-15 psig range. Although they are designed for valve mounting, these transducers can also be mounted at the panel or on the pipe. Either a single stage or a two-stage model will be used dependent on the volume of the actuator. Normally a two-stage transducer is used for actuators that require a volume more than 50 cu. in. These units meet all Underwriters Lab specifications and are furnished with redundant diodes to suppress possible stored energy in the coils so as to maintain safe operation under faulty conditions. The range and zero adjustment can easily be made at the unit.

The size of the pneumatic actuator is selected on the basis of travel and the necessary pounds of force for operating the valve. All of the actuators have a positioner so that the actuator position is linear with the control output. Actuators will also have several configurations depending on whether the air-to-open or air-to-close feature is needed. In some applications, the valve will close in the event power is lost while in others, the reverse is true. Where fail-safe operation is not necessary or where a large amount of thrust is needed, a springless actuator can be used. The actuators are of (1) the direct type in which air pressure pushes the stem down or (2) reverse acting type in which the stem moves up.

Analog Controller

The controllers sum the feedbacks such as pressure, temperature, and flow to provide proportional reset, rate and integral control of various gate valves. Output of the controller is a current in the range of 4 to 20 milliamperes that is used to drive a positioner. The positioner which is attached to the side of the valve converts the electrical input to a pneumatic pressure output. Pneumatic actuators on the valve, position the valve in proportion to the input signal.

The various control signals such as pressure, temperature and flow are either summed, multiplied, integrated, or differentiated to get rate or form a set point. In proportional control there is a continuous linear relation between the variable input and the position of the control element. All of the outputs are valve position even though the position of the valve controls flow rate. Gain must be determined so that the relationship between input and output is established. If other feedback signals are used, the proportional band of control will be limited to some percentage of the full travel in order to permit some range of control for the other signals. If proportional is used as the only signal, a droop occurs in the system. A load condition and at the other load conditions has some error. This error is called offset or droop and can be compensated for by other means.

With a reset, manual or automatic set point, the final position can be controlled without droop. This reset or set point can be changed from the storage control console or can be changed automatically from the master control. In some of the control loops the set point is some predetermined temperature that is compared to the actual temperature and is then used as an error signal to the control. For other control loops, the inlet and outlet temperature may be compared to give a delta temperature change that is then compared to the set point. For still other control circuits, the master control may set the set point to some value that represents the start or warm-up in the morning. Later as the system is in full operation, the set point is then to set to some other value. With proportional plus reset a control without offset error (droop) is possible under all load conditions but reset by itself does not contribute to the stability of the control loop.

Reset rate (integral) control is usually expressed in repeats per minute. Proportional error moves the valve position in direct proportion to the error. At the same time, the reset (integral) begins to move the valve at a rate proportional to that error. In control theory this could be called the integration rate but in process control the reset time or integral time is the

time it takes to double the initial position of the proportional response. Quite commonly the reset action is called "repeats per minute" or RPM. This term refers to the number of times per minute that the reset action is repeating the valve change produced by proportional control alone. The integral action can be seen, in that, the valve position is proportional to the integral of the error which has existed since time zero.

The reset or integral action is also called anticipation since it tends to decrease the system response time. If a proportional and an integral signal are combined, the resulting transfer function is called a lead network since it provides lead or anticipation to the signal. The anticipation feature of integral control can also be seen by comparing it to straight proportional control. If an error exists, proportional control will open the valve in direct proportion to the error. The integral or reset action calls for larger valve opening, thereby providing greater flow in anticipation of the large error. In a sense it is a form of overcontrol so as to speed up the response.

A derivative or rate signal is a control action based on the rate of change of error. This additional correction exists only while the error is changing and disappears when the error stops changing.

All of the control variables such as temperature, pressure, flow, levels or other control inputs are available at the storage control console. These signals are summed in the analog controller and used to control the valves in the different control loops. These control loops are described in the control section in greater detail.

SECTION 6

SUPPORTING DATA

- A. Tankage and Foundation Design Summary
 - 1. Hitec Tanks
 - 2. Main Oil/Rock Tanks
- B. Heat Loss from Hitec Storage
- C. Heat Exchanger Design Calculations
- D. Materials
 - 1. Caloria HT-43
 - 2. Heat Transfer Salts
 - 3. Granite Rock
- E. Equipment Lists
 - 1. Major
 - 2. Valve Lists
 - a. Automatic
 - b. Manual
 - 3. Piping
- F. Thermal Storage Subsystem Switching Times

DESIGN REPORT
FOR
OIL/ROCK TANK

18.3m Diameter x 14.6m High

BMT Contract No. 441101

Honeywell, Inc. No. 426699-AA

(See Appendix G)

DESIGN SUMMARY
FOR
HITEC TANK

6.10m Diameter x 5.49m Shell ht.
BMT Contract No. 441102
Honeywell, Inc. No. 426699-AA

(See Appendix G)

HEAT LOSS FROM HITEC STORAGE

Pilot Plant

Storage Pit Dimensions

7.6W x 14.6L x 9.1D (25'W x 48'L x 30'D)

Hot Storage Tank Temperature 454C (850F)

Cold Storage Tank Temperature 300C (570F)

Soil Thermal Conductivities (*)

<u>Soil Type</u>	<u>W/m²C</u>	<u>Btu/hr ft²F</u>
Soil, dry	0.13	0.08
Soil, dry plus stones	0.5	0.3
Sand, dry	0.33	0.19
Gravel	0.38	0.22
Earth plus 42 % water	1.0	0.6

To obtain an order of magnitude estimate of the heat losses each half of the pit, the hot tank and cold tank areas, was approximated by a right cylinder of equal inside area. A closed form solution for heat loss from a cylinder buried in a semi-infinite media (the earth) is presented in Reference 4.

$$q = \frac{2\pi}{\ln(4L/D)} kL (T_1 - T_s)$$

where; D = diameter

L = length

k = soil thermal conductivity

T₁ = cylinder surface temperature

T_s = earth surface temperature

ln = natural logarithm

(*) Mark's Handbook 7th Edition

(4) Handbook of Heat Transfer Rohsenow, WM and Hartnett, J. P.

Assuming that the inside wall of the pit is the same as the tank temperature and that the soil conductivity is $0.5 \text{ W/M}^{\circ}\text{C}$ ($0.3 \text{ BTU/hr ft}^{\circ}\text{F}$),

$$Q_{\text{LOSS}} (\text{Hot}) = \frac{2\pi}{\ln(4(9.1)/9.51)} 0.5 (9.51) (454-0)$$

$$Q_{\text{LOSS}} (\text{Hot tank}) = 10.1 \text{ kW} \quad (34500 \text{ Btu/hr})$$

$$Q_{\text{LOSS}} (\text{Cold tank}) = 6.7 \text{ kW} \quad (23000 \text{ Btu/hr})$$

The above solution assumes no loss through the cover of the pit. Here it is assumed that $\approx 0.6 \text{ m}$ (2ft) of insulation will be used having a k value of $0.087 \text{ W/M}^{\circ}\text{C}$ ($0.05 \text{ Btu/hr ft}^{\circ}\text{F}$).

$$Q_{\text{LOSS}} (\text{Cover}) = kA (T - T_s)/X$$

$$Q_{\text{LOSS}} (\text{Hot tank}) = 0.081 \text{ W/M}^{\circ}\text{C} (55.7 \text{ m}^2) (454 - 0)^{\circ}\text{C}/.6 \text{ m}$$

$$Q_{\text{LOSS}} (\text{Hot tank cover}) = 3.7 \text{ kW} \quad (12600 \text{ Btu/hr})$$

$$Q_{\text{LOSS}} (\text{Cold tank cover}) = 2.4 \text{ kW} \quad (8200 \text{ Btu/hr})$$

The hot tank also loses heat to the cold tank through the insulated partition. The hot tank and cold tank exchange heat with the opposite surfaces of the partition mainly by radiation. Assuming tank and partition emittances are equal to 0.9, the iterative solution results in a heat transfer rate of 4.5 kW (15400 Btu/hr).

The net losses from the hot tank and cold tank are obtained by summing the energy losses through the walls and the cover.

$$Q_L \left(\text{Hot} \right) = 0.75 Q_L (\text{Soil}) = Q_L (\text{Cover}) + Q_L (\text{Cold tank})$$

The hot and cold tanks have one wall in common hence they lose only 0.75 of the energy to the soil as a single cylinder would, which was the result of the first calculation.

$$\begin{aligned} Q_L \text{ Hot} &= 0.75 (10.1 \text{ kW}) + 3.7 \text{ kW} + 4.5 \text{ kW} \\ &= 15.8 \text{ kW} \quad (53800 \text{ Btu/hr}) \end{aligned}$$

$$\begin{aligned} Q_L \text{ (Cold)} &= 0.75 (6.7 \text{ kW}) + 2.4 \text{ kW} - 4.5 \text{ kW} \\ &= 2.9 \text{ kW} \quad (10,000 \text{ Btu/hr}) \end{aligned}$$

The point of the analysis is to determine how cold the storage tank could get if the hot storage tank was kept at 454°C (850°F). Since all of the heat transfer rates are linear functions of temperature the calculation is relatively straight forward. (The radiant transfer coefficient accounts less than 5% of the total temperature difference between the hot and cold tanks). The equilibrium temperature of the cold tank would be 246°C (475°F). This is above the freezing point and consequently the hot tank will supply sufficient heat to maintain the cold tank at about 246°C (475°F).

No consideration has been given to the thermal response time of the system when the heat capacity of the soil is considered.

A comparative heat loss calculation was made to compare heat loss for insulated tank above grade with the below grade tanks.

Area of tanks 152 m² each

Q_L (hot tank) = 15.8 kW

Insulation K value = 0.0865 W/m²°C

Equivalent Thickness $X = kA (T - T_a)/Q$

$$X \text{ (hot tank)} = 0.0865 \text{ W/m}^{\circ}\text{C} (152 \text{ m}^2) (454 - 0)^{\circ}\text{C}/15800 \text{ W}$$

$$X = 0.3778 \text{ m (1.25 ft)}$$

$$X \text{ (cold tank)} = 0.0865 \text{ W/m}^{\circ}\text{C} 152 \text{ m}^2 (300 - 0)^{\circ}\text{C}/2900 \text{ W}$$

$$X = 1.36 \text{ m (4.46 ft)}$$

Surface Temperature of Pipe Insulation

To find the surface temperature of pipe insulation for a given pipe temperature.

Method of Solution: The transfer of heat between an insulated pipe and its surroundings is controlled by the thermal conductance of the insulation and the ability of the insulation surface to transfer heat to the local environment. The heat transferred within the cylindrical insulation is governed by the equation

$$Q/L = 2\pi k (T_1 - T_2)/\ln(R_2/R_1)$$

where Q is the energy flow per hour or the power, L is the length, k is the thermal conductivity, and $R_1, T_1; R_2, T_2$ the radius and temperature at the inside and outside surface of the cylindrical insulation. For this problem the total temperature difference from the source of the energy to the energy sink is given, i. e., the absolute value of the expression (pipe temperature - ambient temperature).

The surface conductance and hence the flux are not known as the surface conductance is a function of the insulation surface temperature.

The surface conductance is given by the ratio of the flux through the surface to the temperature difference between the surface and the environment.

The contribution to the heat flow per unit area through the insulation surface due to radiation is calculated by using the Stephan-Boltzmann equation

$Q(\text{rad}) = \epsilon \sigma (T_3^4 - T_2^4)$ where σ is Stephan-Boltzmann constant with a value of 0.1714×10^{-8} Btu /hr. sq. ft. deg. R^4 ; ϵ is the emittance of the surface, T_2 is the surface temperature in degrees Rankine and T_3 is the ambient temperature in degrees Rankine.

The contribution to the energy flux through the insulation surface due to convective transfer from the surface to the ambient temperature is given by Malloy.²⁴ Thus for horizontal cylinders

$$Q(\text{conv}) = 1.016 \cdot (1/d)^{0.2} \cdot (0.5(T_2 + T_3))^{-0.181} \cdot (T_2 - T_3)^{1.266} \cdot ((V + 68.9)/68.9)^{0.5}$$

where d is the cylinder diameter in inches and V is the air velocity in ft/min. The total energy flux is given by the sum of the radiation and convective contributions, thus $Q = Q(\text{rad}) + Q(\text{conv})$.

The calculation of the surface temperature requires an iterative procedure as it is not possible to write an explicit equation of T_2 , the surface temperature in terms of the input parameters. The initial iteration is started by assuming the surface temperature is the average of the pipe and ambient temperature. One calculates the thermal conductivity k from the conductivity polynomial, the thermal resistance of the insulation from k and the known insulation geometry, the surface conductance from the ratio of the surface flux due to radiation and convection to the temperature difference between the surface and ambient. One now has an estimate of the total thermal resistance between the pipe and the ambient. Using this resistance, the surface conductance and the surface flux, one can find the surface temperature. Using this new surface temperature the process is repeated until the surface temperature changes less than a predetermined amount, usually 0.1 degree F.

Heat Loss Rate from Tanks Lines and ExchangersTemperature as a Function of Time - Sample Calculation

Assumed ambient conditions

Temperature -29°C (-20°F)

Wind 143 m/s (32 mph)

Air properties at 1.013×10^5 Pa, -29°C (1 atm, -20°F) (Ref. 25)density ρ = 1.447 kg/m³ (0.09031 lbm/ft³)viscosity μ = 15.78×10^{-6} Nt-s/m² (0.03817 lbm/ft-hr)conductivity k = 0.01949 W/m-°C (0.01127 Btu/hr-ft-°F)

$$Re = \frac{\rho \bar{u} D}{\mu} = \frac{1.447 \text{ kg/m}^3 (14.3 \text{ m/s}) D}{15.78 \times 10^{-6} \text{ Nt-s/m}^2 \frac{1 \text{ kg m/s}^2}{\text{Nt}}}$$

$$Re_d = 1.311 \times 10^6 x D \text{ (meters)}$$

for Re_d 40,000 to 4000,000 (Ref. 26)

$$Nu_d = 0.43 + 0.0239 (Re_d)^{0.805}$$

For Re greater than 4×10^5 , it was assumed that the equation was a good approximation.

Heat loss from a body with uniform surface temperature, the heat transfer equation is:

$$\rho C_p V \frac{dt}{d} = hA (t - t_f) \quad (6-1)$$

where $\rho C_p V$ = the energy loss per degree decrease in temperature

h = the external heat transfer coefficient

A = external surface area

t = surface temperature

t_f = ambient air temperature

τ = time

Letting $\theta = t - t_f$ equation (1) can be solved to yield temperature as a function of time.

$$\theta = \theta_o \exp \left[\frac{-hA}{C_p V} \times \tau \right] \quad (6-2)$$

$$t = t_f + \theta_o \exp \left[- \frac{hA}{C_p V} \times \tau \right] \quad (6-3)$$

Example:

Pipe 4" nominal schedule 40

Contents Hitec $C_p = 0.321 \text{ W-hr/kg}^\circ\text{C}$ (0.373 Btu/lb $^\circ\text{F}$)

Temperature 292°C (558 $^\circ\text{F}$)

Insulation Thickness 15 cm (6 in)

Conductivity $k = 0.069 \text{ W/m}^\circ\text{C}$ (0.04 Btu/hr-ft- $^\circ\text{F}$)

Ambient Conditions as listed previously

Pipe O. D. 4.500 in 4.026 in I. D., Wt 16Kg/m (10.79 lb/ft)

Volume $8.21 \times 10^{-3} \text{ m}^3/\text{m}$ (.0884 ft 3 /ft)

Energy Content $C_p V = 6.659 \text{ W-hr/m}^\circ\text{C}$ (3.845 Btu/ft- $^\circ\text{F}$)

Heat transfer coefficient "h" is the sum of the corrective "h_o" and the thermal resistance k/L_e of the insulation. When evaluating the equivalent transfer coefficient based upon outside surface area, the equivalent thickness L_e is given by $L_e = r_o \ln (r_o/r_i)$ where r_o and r_i are the outside and inside radii respectively.

$$L_e = 0.2096 \text{ m} \times \ln \frac{0.2096}{0.05715} = 0.2723 \text{ m} \text{ (10.72 inches)}$$

Convective Coefficient

$$Re = 1.311 \times 10^6 \times \frac{16.5 \text{ in}}{39.37 \text{ in/m}} = 5.494 \times 10^5$$

$$Nu_d = 0.43 + 0.0239 (5.494 \times 10^5)^{0.805}$$

$$Nu_D = 998.2$$

$$h_o = \frac{Nu}{D} k = \frac{998.2 \times 0.01949 \text{ W/m}^\circ\text{C}}{0.4191 \text{ m}}$$

$$h_o = 46.42 \text{ W/m}^2 \text{ }^\circ\text{C} \quad (8.181 \text{ Btu/hr-ft}^2 \text{ }^\circ\text{F})$$

Adding convective and conductive coefficients

$$\frac{1}{h} = \frac{1}{h_o} + \frac{1}{k/L_e} = \frac{1}{46.42 \text{ W/m}^2 \text{ }^\circ\text{C}} + \frac{1}{.069 \text{ W/m}^\circ\text{C}/.272 \text{ m}}$$

$$\frac{1}{h} = \frac{1}{46.42} + \frac{1}{.254}$$

$$h = 0.252 \text{ W/m}^2 \text{ }^\circ\text{C}$$

Since the outside convective coefficient is very large compared to the conductive resistance of the insulation, it can be neglected in all further calculations.

Outside area of pipe per unit length

$$A = 1 \text{ m} \times \pi \times 0.272 = 0.8545 \text{ m}^2/\text{m} \quad (4.320 \text{ ft}^2/\text{ft})$$

$$\frac{hA}{C_p V} = \frac{0.252 \text{ W/m}^2 \text{ }^\circ\text{C} \times 0.8545 \text{ m}^2/\text{m}}{6.659 \text{ W-hr/m}^\circ\text{C}} = 3.23 \times 10^{-2} \text{ m}^{-1}$$

To find the temperature of the pipe as a function of time substitute into Equation (6-3).

$$t = -29^\circ\text{C} + 321 \exp \left[-3.23 \times 10^{-2} \times \tau \right] \quad (6-4)$$

or Equation (6-3) can be rearranged to determine τ as a function of t surface.

$$\tau = \frac{-1}{3.23 \times 10^{-2}} \ln \left(\frac{t - t_f}{321} \right) \quad (6-5)$$

The time required for the pipe to reach 200°C starting from 292°C is

$$= -30.95 \ln \left(\frac{200 - 29}{321} \right) = 10.45 \text{ hours}$$

HEAT EXCHANGER DESIGN CALCULATIONS

All heat exchanger designs were done by computer analysis provided by Manning and Lewis Engineering Co., Union, N. J. Estimates of fluid temperatures, pressures, flow rates and heat transfer rates were provided to Manning and Lewis who selected the best exchanger configurations. They then used computer analysis routines provided by the Heat Transfer Research Institute to size the heat exchangers. The computer analysis routine determines fluid velocities, heat transfer coefficients, surface areas pressure drops, shell size and baffle spacing. These data are then checked by their thermal analysis engineers and the designs are checked for vibration problems and a stress analysis is done to determine shell and bonnet sizes, weights and penetrations. Cost estimates are the provided based upon size, weight, materials and difficulty of construction.

As part of the preliminary design process and ongoing systems studies new mass flux and temperature requirements and better oil property data was obtained. These data were then used to adjust the Manning and Lewis designed heat exchangers based upon the following relations.

Heat transfer inside of tubes can be estimated by the Dittus Boelter equation:

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \quad (6-6)$$

and,

$$h = Nu k / D \quad (6-7)$$

where:

Nu = Nusselt number

Re = Reynolds number ($\rho u D / \mu$)

Pr = Prandtl number ($\mu C_p / k$)

h = heat transfer coefficient

ρ = fluid density

u = fluid velocity

D = characteristic diameter

μ = viscosity

C_p = specific heat

k = fluid thermal conductivity

Since the computer analysis includes entrance effects and equation (1) does not only the power law relations were used to adjust the inside heat transfer coefficients using the equations

$$\frac{h_2}{h_1} = \left(\frac{Re_2}{Re_1} \right)^{0.8} \left(\frac{Pr_2}{Pr_1} \right)^{0.4} \quad (6-8)$$

where subscripts 1 and 2 designate initial and final conditions, respectively.

For the outside heat transfer coefficient equation (6-9) was used

$$Nu = 0.35 (a/b)^{0.2} Re^{0.6} Pr^{0.36} (Pr/Pr_w)^{0.2} \quad (6-9)$$

This equation was taken from reference (27).

As was previously done only the power law relations were used because Equation (6-5) does not account for baffle leakage and flow parallel to tubes at the ends of the baffles, etc. The resulting relation gives

$$\frac{h_{2,0}}{h_{1,0}} = \left(\frac{Re_{2,0}}{Re_{1,0}} \right)^{0.6} \frac{Pr_{2,0}^{0.36}}{Pr_{1,0}} \quad (6-10)$$

where subscripts 1 and 2 indicate initial and final states respectively.

Wherever possible surface areas were changed in such a manner to maintain fluid velocities constant to avoid changing the heat transfer coefficient or the pressure drop per unit length.

New weights were calculated by calculating weights of tubes and shells and weights of bonnets were estimated based upon required thickness of metal and diameter.

Cost estimates were adjusted on a cost per unit exchanger surface area with minimal consideration given for excessive weight changes relative to surface area changes.

The results of Manning and Lewis Engineering Company's design with Honeywell's adjustments to size and coefficients appear on the heat exchanger specification sheets located in Appendix B. The specification sheets are standard formats provided by the tubular Exchanger Manufacturer's Association. Both performance specification and design data appear on the form and it provides the normal complete set of specifications that are obtained with a heat exchanger.

MATERIALS

CALORIA HT 43* Heat Transfer Oil (Table 6-1)

CALORIA HT 43 is a heat-transfer fluid that provides excellent performance in a wide variety of applications. CALORIA HT 43 is a petroleum-base heat-transfer fluid formulated from a highly stable parafinic base stock fortified with a high-temperature oxidation inhibitor. CALORIA HT 43 heat-transfer fluid is manufactured from petroleum stocks produced by a special refining method. Since thermally unstable components are separated and removed by this treatment, the resulting product has exceptional resistance to thermal decomposition.

Oxidation Stability -- Base stocks used in the manufacture of CALORIA HT 43 are selected for good oxidation stability, a characteristic that is further improved by selected refining techniques and the addition of an oxidation inhibitor. With these advantages, CALORIA HT 43 is especially resistant to the formation of oxidation sludges that may otherwise insulate the coil against efficient heat transfer and may also cause obstructions to fluid flow.

Table 6-1 Properties of Caloria HT 43

Gravity ° API	33.2							
Color ASTM	L1.0							
Viscosity Index	115							
Flash Point °C	204°C							
Pour Point	-9°C							
Rotary Bomb Oxidation Life, 150°C	115 min							
Phenol, mass %	.002							
Saturates, mass % (ASTM D2007)	91.0							
Conradson Carbon, mass %	.003							
Aniline Point	100.8°C							
Temperature °C	0	50	100	150	200	250	300	315
Viscosity m ² /s x 10 ⁶	400	23.6	5.76	2.50	1.50	1.00	.721	.648
Specific Heat kj/kg°C	-	1.81	1.96	2.10	2.26	2.40	2.56	2.60
Thermal Conductivity W/m ² °K	125	.118	.111	.104	.0467	.0895	.0828	.0813
Density kg/m ³	873.0	834.6	799.3	764.1	730.0	694.3	655.2	646.2

Maximum and minimum operating temperatures are 303°C and 249°C, respectively.

* Data obtained from Exxon Corporation

Low Volatility -- Another essential high-temperature property is low volatility - low vapor pressure and high flash point. The low vapor pressure of CALORIA HT 43 helps to eliminate vapor lock in circulating pumps; and reduces the possibility of cavitation, which is destructive to centrifugal pump blades. The low vapor pressure of CALORIA HT 43 throughout the normal operating range also prevents the buildup of excessive temperature drop of 44°C (80°F) across the fluid film adjacent to the heater surface, this permits a maximum bulk temperature of 316°C (600°F).

Safety -- With its low volatility and high flash point, CALORIA HT 43 offers a reasonable degree of safety. When used as recommended the danger of fire or explosion is minimized. Like petroleum products in general, however, the fluid will burn if subjected to the proper combinations of high temperature, oxygen, and source of ignition.

CALORIA HT 43 presents no special toxicity hazards and can be handled with the simple precautions ordinarily observed with lubricating oils.

The low volatility and high flash point of CALORIA HT 43 are due to its excellent distillation characteristics. The characteristic high flash point of this heat-transfer fluid permits higher expansion tank temperatures than common with many other fluids.

Low-Temperature Performance -- The effectiveness of a heat-transfer fluid depends upon its low-temperature performance as well as its high-temperature performance. With a typical pour point of -9°C (15°F), CALORIA HT 43 has good pumpability in cold-weather start-ups, thereby diminishing the likelihood of hot spots - dangerously high fluid temperatures at the heater. The oil's low-temperature fluidity is a function of its high viscosity index - typically 115. This exceptionally high value gives CALORIA HT 43 greater resistance to changes in viscosity with varying temperatures.

Heating Efficiency -- CALORIA HT 43 has the ability not only to resist heat, but to transfer it efficiently. Its viscosity characteristics are such that it provides a high rate of circulation under a wide range of operating temperatures. Other properties enable CALORIA HT 43 to transmit full heating loads rapidly. High specific heat gives CALORIA HT 43 the capacity to supply or remove the large amount of heat that efficient operation requires. High thermal conductivity enables it to transfer heat efficiently. These properties contribute not only to fuel economy, but to more even heat distribution and longer equipment life.

Compatibility -- CALORIA HT 43 is compatible with other petroleum heat-transfer fluids and, if necessary, can be added to them as make-up. This is not recommended, however, for fluids that are in poor condition. The mixing of a new petroleum oil with one that has deteriorated may cause the precipitation of sludges particularly at elevated temperatures - and will accelerate degradation of fresh oil. Adding of other petroleum fluids to CALORIA HT 43 is also feasible, though it can be expected that performance will be modified in proportion of the amount of added material.

Thermal Expansion -- All petroleum oils expand upon heating, and it is desirable to be able to predict the volume expansion of the oil to permit proper design of the expansion tank.

Application - Closed System -- CALORIA HT 43 heat-transfer fluid is recommended for service in closed, inert-gas blanketed systems, involving a maximum film temperature at the heater surface of 360°C (680°F).

Figure 6-1 Thermal Stability of Heat Transfer Fluids at Constant Temperature
(Ref. 28)

Heat Transfer Salts

Honeywell used the following references to obtain data on heat transfer salts. No attempt has been made to reproduce these excellent reports for this document.

1. Survey of Technology for Storage of Thermal Energy in Heat Transfer Salt, by M. D. Silverman and J. R. Engel, Oak Ridge National Laboratory ORNL/TM-5602.
2. Hitec Heat Transfer Salt, Properties, Uses, Storage and Handling - a Dupont Publication.
3. Fused Salt Heat Transfer, ORNL-2433.
4. Molten Salt for Heat Transfer, H. P. Voznick and V. W. Uhl, Atlantic Research Corp. and Drexel Institute of Technology, Chemical Engineering, May 27, 1963.
5. Heat Transfer Agents for High Temperature Systems, Joel R. Fried, General Electric Co., Chemical Engineering, May 28, 1973.
6. High Temperature Properties and Decomposition of Inorganic Salts Part 3: Nitrates and Nitrites by Kurt H. Stern, NRL, Washington, D. C.
7. The Design and Operating Features of Houdry Fired Bed Catalytic Cracking Units - AIChE paper presented by R. H. Newton and H. G. Shimp in St. Louis, Mo, November 1944.

Table 6-2. Properties of Hitec Heat Transfer Salt

Freezing Point	142°C
Electrical Resistivity	1.7 - cm
Thermal Conductivity	36.3 w
Coefficient of Linear Expansion	$5.13 \times 10^{-5} \text{ }^{\circ}\text{C}^{-1}$
Coefficient of Cubical Expansion	$3.63 \times 10^{-4} \text{ }^{\circ}\text{C}^{-1}$
Specific Heat of Solid	1.34 kJ/kg°C
Specific Heat of Liquid	1.56 kJ/kg°C
Latent Heat of Fusion	83.7 kJ/kg

Temperature °C	150	200	250	300	350	400	450	500
Viscosity nt-s/m ² x 10 ³	16.3	7.47	4.71	3.20	2.35	1.76	1.41	1.13
Density kg/m ³	1974.	1940.	1901.	1867.	1830.	1790.	1757.	1719.

Table 6-3. Properties of Granite

Density	2,670 kgm/M ³
Specific Heat	.84 kJoules/Kg°C
Thermal Conductivity	2.22 W/m - °C 200°C
Linear Expansion Coefficient	$8 \pm 3 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$

*Mean values from various locations

EQUIPMENT LISTS

Major Equipment List - Pilot Plant EquipmentStorage

<u>Quantity</u>	<u>Item</u>	<u>Size</u>
1	Rock/Oil Tank	Diameter 18.29 m Height 14.63 m
2	Oil Distribution Manifdd	Piping 1.5 inch Schedule 40 48, 3 mm OD Spacing 610 mm
2	Salt Storage Tanks	Diameter 6.10 meters Height 4.88 meters
2	Heaters in Salt Tanks	Height 1.66 meters Heat Transfer Area 24.62 m ²

Charge System

1	Attemperator No. 1	Orifice Diameter .15 m
1	Desuperheater Heat Exchanger	Shell I. D. 0.46m Overall length 13.1 m Weight 30,750 kg
2	Attemperators No. 2a & 2b	Orifice Diameter - 10m
1	Condensate Receiver	Diameter 69.6 cm Length 4.874 m
1	Subcooler Heat Exchanger	Shell I. D. .71 m Overall Length 7.8 m Weight 9570 kg
1	Main Charge Pump, MCP	Power 98 kw
1	Hitec Charge Pump, HCP	Power 7.6 kw

Discharge System

1	Preheater Heat Exchanger	Shell I. D. 0.71 m Overall Length 6 m Weight 5625 kg
1	Boiler Heat Exchange	Shell I. D. 1.02/1.37 m Overall length 14.2 m Weight 29,000 kg
1	Superheater Heat Exchanger	Shell I. D. 0.46m Overall length 10.1 m Weight 4810 kg
1	Main Discharge Pump, MDP	Power 98 kw
1	Hitec Discharge Pump, HDP	Power 7.6 kw

Major Equipment List - Commercial Plant EquipmentStorage

<u>Quantity</u>	<u>Item</u>	<u>Size</u>
2	Oil/Rock Tank	Diameter 34.75 m Height 14.63 m
2	Oil Distribution Manifold	Piping 1.5 inch Schedule 40 (48.3 mm OD) Spacing 610 mm
2	Salt Storage Tanks	Diameter 12.19 m Height 9.75 m
4	Heaters in salt tanks	Height 1.68 m Heat Transfer Area 295 ft ²

Charge System

1	Attemperator No. 1	Orifice Diameter 410 mm
3	Desuperheater Heat Exchangers	Shell I. D. 0.61 m Length 14.33 m Weight 10400 kg
2	Attemperators No. 2a & 2b	Orifice Diameter 305 mm
6	Condenser Heat Exchangers	Shell I. D. 1.07 m Length 14.33 m Weight 33600 kg
1	Condensate Receiver	Diameter Length
3	Subcooler Heat Exchanger	Shell I. D. 0.99 m Length 8.08 m Weight 26100 kg
3	Main Charge Pump, MCP	Power 22.4 kw
3	Hitec Charge Pump, HCP	Power 200 kw

Discharge System

4	Preheater Heat Exchanger	Shell I. D. 0.99 m Length 5.64 m Weight 10200 kg
8	Boiler Heat Exchanger	Shell I. D. 1.02/1.37 m Length 14.22 m Weight 29500 kg
4	Superheater Heat Exchanger	Shell I. D. 0.64 m Length 12.24 m Weight 9100 kg
8	Main Discharge Pump, MDP	Power 100 kw
4	Hitec Discharge Pump, HDP	Power 22.4 kw

VALVE LISTS

Automatic Valves and Actuators

With the exception of the ullage valves used for nitrogen control, all valves are of a gate valve construction using 316 stainless steels. The high temperature and pressures associated with the Hitec storage system requires a material that can withstand the corrosive action. In most valves selected, the cage and plug are of a 17-4 PH stainless or of solid stellite or stellite faced. The trim is easily removed so that if replacement is necessary, the task can be done in about 1 hour in comparison to 12 hours for a normal valve. For the high temperature ranges, the bonnets are also of stainless as well as the extension column. Shredded teflon asbestos has been specified for the packing.

Actuators have been sized to provide the necessary force using the available pneumatic supply. Controllers that convert the electrical control signal to pneumatic pressure changes are located on the actuator extension housing. Actuators have been selected to provide air to open and air to close dependent on the type of control needed. In the event of a loss of air, the valve will be spring loaded to close or open, as the case may be, to provide fail safe operation. Actuators have been selected on the basis of operating force and required valve travel.

Modulating valves for automatic control

A list of the valves used only in the storage subsystem is listed below.

Attemperator Temperature Control

Called ACV-1 and ACV-4 on print

Double seated valve (3.826" ID line)

4 inch (stellite faced)

Tracing Steam Control

Called ACV-15 (7.625" ID line)

8 inch valve (used a C_v 500)

85910012-024-008-04-15-02 (Honeywell or equivalent)

8 inch extension

Hitec Valve On The Charge Side

Called ACV-2

4 inch valve - 4 inch line (C_v = 100)

85910009-011-09-15-01 (Honeywell or equivalent)

316 stainless

Ullage on the Hitec Tank

Called ACV-6 and ACV-17 on print

1/2 inch line C_v = .63

1/2 inch valve

8514001-001-067002-01-103 (Honeywell or equivalent)

Electro-pneumatic Positioner

870020-012011013 (Honeywell or equivalent) (11 required)

Hitec Discharge Side

Called ACV-17 and ACV-18

4.026" ID line 4 inch valve

85910009-011-09-15-01 $C_v = 100$ (Honeywell or Equivalent)

Oil Ullage Control

Called ACV-16 and ACV-18 on print

1/2 inch line, 1/2 inch valve $C_v = 0.63$

85140001-001-067002-01-103 (Honeywell or Equivalent)

Oil (Discharge)

Called ACV-12 on print

13.25" lines

85910014-020-002-03-15-01 (Honeywell or Equivalent)

Flow Return to Oil Tank

Called ACV-9 and ACV-10 on print

13.25" lines 12 inch valves

85910014-020-002-03-15-01 (Honeywell or Equivalent)

Boiler Liquid Level

Called ACV-13

4 inch lines 4 inch valve

84910009-024-03-15-01 (Honeywell or Equivalent)

Boiler Auxiliary Valve

Called ACV-14 on print

4 inch lines 4 inch valve

84910009-024-03-15-01 (Honeywell or Equivalent)

Pressure Sealing Header

Called ACV-15 8 inch valve

85910012-023-002-06-15-01 (Honeywell or Equivalent)

KEY TO VALVE TYPE NUMBERS**GATE VALVE
CLASS 150**

Pressure-Temperature Rating
Carbon Steel, ASTM A216 Grade WCB
285 psi @ -20F to 100F

OS&Y Bolted Bonnet
Flexible Wedge Disc

No. 46, Threaded
No. 47, Flanged
No. 47½, Butt-Welding

**Weights
and
Dimensions**

Valve N.P.S.	Weight—Pounds			Dimensions—Inches				
	46	47	47½	A			B	C
				46	47	47½		
2	40	46	45	6.25	7.0	8.50	15.75	8.0
2½	60	70	60	7.00	7.5	9.50	16.50	8.0
3	63	76	62	7.38	8.0	11.12	18.88	9.0
4	85	110	95	8.00	9.0	12.00	23.00	10.0
5	—	155	140	—	10.0	15.00	27.88	12.0
6	—	175	165	—	10.5	15.88	31.00	12.0
8	—	310	260	—	11.5	16.50	38.75	14.0
10	—	455	410	—	13.0	18.00	46.75	16.0
12	—	650	580	—	14.0	19.75	55.00	18.0

Valve N.P.S.	Weight—Pounds		Dimensions—Inches			
	47	47½	A		B	C
			47	47½		
14	1070	905	15.0	22.5	62.75	24.0
16	1385	1190	16.0	24.0	72.50	24.0
18	1735	1510	17.0	26.0	81.00	30.0
20	2125	1855	18.0	28.0	89.00	30.0
24	3120	2500	20.0	32.0	104.00	36.0
30	4250	3245	24.0	24.0	127.62	36.0

**GATE VALVE
CLASS 400**

OS&Y Bolted Bonnet
Solid Wedge Disc

No. 61, Flanged
No. 61½, Butt-Welding

Pressure-Temperature Rating
Carbon Steel, ASTM A216 Grade WCB
985 psi @ -20F to 100F

**Weights
and
Dimensions**

Valve N.P.S.	Weight—Pounds		Dimensions—Inches			
	61	61½	A		B	C
			61	61½		
4	270	220	16.0	16.0	30.75	12.0
5	390	330	16.0	18.0	35.00	14.0
6	530	460	19.5	19.0	40.25	16.0
8	940	830	23.5	22.5	50.00	20.0
10	1200	1030	26.5	26.5	59.75	24.0
12	1680	1420	30.0	30.0	67.75	24.0
14	3325	2900	32.5	32.5	80.75	36.0
16	4125	3575	35.5	35.5	92.00	36.0

Table 6-4. Listing of Manual Valves by Pipeline

Line Designation	Normal Pipe Size (inches)	Gate Valves			Globe Valves			Check Valves
		Remote	Manual	type	Automatic	Manual	type	
Stem & H ₂ O Charge								
DSS	8	1	2	87			7187	
ATS	8	1	1	83			7181	
CSS	8	1	1	83			7181	
CSR	5	1	2	83			7181	
SCS	5	1	2	83			7181	
SCR	5	2	1	83			7181	
Stm & H ₂ O Discharge								
FWS	4	1	3	61	1	1	161	
AFW	1		2	61	1	1	161	
PBS	4		2	61			171	
SAS	8		2	76			171	
SHS	10	1	1	76			171	
Sealing	1.5	1	2	76			171	
Tracing	1	2		76	1	1	171	
Oil								
MCS	14	1	5	47	1	1	143	1
MCL	14		2	47			143	
MCB	14		1	47			143	
MCS-MDS	14	1		47			143	
MDS	14	2	3	47			143	2
MDB	14		1	47			143	
OPH	14		2	47			143	
MDR	14	1	5	47	2	2	143	
Hitec								
HCS	4	2	8	47	1	1	143	
HDS	4	1	2	47			143	
HDL	4		2	47			143	
HDR	4	1	4	47	1	1	143	
Ullage	.5	1	8	47	1	1	143	
Attemperators	1	1	7	47	2	2	143	

GATE VALVE CLASS 600

OS&Y Bolted Bonnet
Solid Wedge Disc

No. 76, Flanged
No. 76½, Butt-Welding

Pressure-Temperature Rating
Carbon Steel, ASTM A216 Grade WCB
1480 psi @ -20F to 100F

Weights and Dimensions

Valve N.P.S.	Weight—Pounds		Dimensions—Inches		
	76	76½	A	B	C
			76 & 76½		
2	90	80	11.5	18.25	8.0
2½	140	120	13.0	22.25	9.0
3	180	140	14.0	25.75	10.0
3½	310	—	15.0	32.00	14.0
4	350	270	17.0	31.50	14.0
5	520	430	20.0	36.75	16.0
6	730	640	22.0	42.75	20.0
8	1220	1080	26.0	52.25	24.0
10	1790	1580	31.0	65.50	24.0
12	2570	2160	33.0	71.00	30.0
14	3455	2960	35.0	80.75	36.0
16	4375	3675	39.0	92.00	36.0
18	6020	4460	43.0	93.25	36.0
20	7015	5755	47.0	106.50	42.0
24	9360	8020	55.0	112.25	42.0

GATE VALVE CLASS 900

OS&Y Bolted Bonnet
Solid Wedge Disc

No. 83, Flanged
No. 83½, Butt-Welding

Pressure-Temperature Rating
Carbon Steel, ASTM A216 Grade WCB
2220 psi @ -20F to 100F

Weights and Dimensions

Valve N.P.S.	Weight—Pounds		Dimensions—Inches		
	83	83½	A	B	C
			83 & 83½		
3	260	220	15.0	27.25	12.0
4	430	360	18.0	31.50	14.0
5	660	560	22.0	36.75	16.0
6	900	750	24.0	42.75	20.0
8	1560	1300	29.0	52.50	24.0
10	2470	2140	33.0	66.25	30.0
12	3580	2770	38.0	74.50	30.0
14	4925	4170	40.5	80.00	36.0
16	5850	4950	44.5	89.00	36.0

GATE VALVE CLASS 1500

OS&Y Bolted Bonnet
Solid Wedge Disc

No. 87, Flanged
No. 87½, Butt-Welding

Pressure-Temperature Rating
Carbon Steel, ASTM A216 Grade WCB
3705 psi @ -20F to 100F

Weights and Dimensions

Valve N.P.S.	Weight—Pounds		Dimensions—Inches		
	87	87½	A	B	C
			87 & 87½		
1	80	65	10.00	16.00	8.0
1½	90	75	11.00	16.50	8.0
1½	130	105	12.00	20.00	9.0
2	180	155	14.50	22.12	10.0
2½	280	225	16.50	26.38	12.0
3	370	300	18.50	28.00	14.0
4	610	520	21.50	33.00	16.0
5	1020	830	26.50	38.75	20.0
6	1410	1250	27.75	47.00	24.0
8	2600	1910	32.75	55.00	27.0
10	4910	3690	39.00	71.75	36.0
12	7150	4650	44.50	80.75	36.0
14	8580	6420	49.50	83.62	36.0

GLOBE AND ANGLE VALVES CLASS 150

OS&Y Bolted Bonnet

Globe Valves
No. 142, Threaded
No. 143, Flanged
No. 143½, Butt-Welding
Angle Valve
No. 145, Flanged

Pressure-Temperature Rating
Carbon Steel, ASTM A216 Grade WCB
285 psi @ -20F to 100F

Weights and Dimensions

Valve N.P.S.	Weight—Pounds			Dimensions—Inches				
	143	143½	145	A	A/2	B		C
				143 & 143½	145	143 & 143½	145	
2"	47	34	38	8.0	4.00	13.75	12.50	8.0
2½	66	53	57	8.5	4.25	14.50	13.00	8.0
3	91	75	81	9.5	4.75	16.50	15.00	9.0
4	143	122	110	11.5	5.75	19.75	17.75	10.0
5	190	150	170	14.0	7.00	23.00	20.75	10.0
6	250	230	215	16.0	8.00	24.50	21.75	12.0
8	420	390	360	19.5	9.75	26.50	24.00	16.0
10	570	480	570	24.5	11.25	31.65	31.75	24.0
12	1431	1310	750	27.5	13.75	42.00	55.12	36.0
14	1525	1360	—	31.0	—	49.00	—	36.0
	142	—	—	142	—	142	—	142
2"	41	—	—	10.5	—	17.25	—	9.0

*2" valve does not have disc stem guide

GLOBE AND ANGLE VALVES CLASS 400

OS&Y Bolted Bonnet

Globe Valves
No. 161, Flanged
No. 161½, Butt-Welding
Angle Valve
No. 163, Flanged

Pressure-Temperature Rating
Carbon Steel, ASTM A216 Grade WCB
985 psi @ -20F to 100F

GLOBE AND ANGLE VALVES CLASS 600

OS&Y Bolted Bonnet
Globe Valves
No. 171, Flanged
No. 171½, Butt-Welding
Angle Valves
No. 173, Flanged
No. 173½, Butt-Welding

Pressure-Temperature Rating
Carbon Steel, ASTM A216 Grade WCB
1480 psi @ -20F to 100F

GLOBE VALVE CLASS 1500

OS&Y Bolted Bonnet

No. 189, Flanged
No. 189½, Butt-Welding

Pressure-Temperature Rating
Carbon Steel, ASTM A216 Grade WCB
3705 psi @ -20F to 100F

Weights and Dimensions

Valve N.P.S.	Weight—Pounds			Dimensions—Inches				
	161	161½	163	A	A/2	B		C
				161 & 161½	163	161 & 161½	163	
4	250	230	235	16.0	8.00	25.25	25.25	14.0
5	350	320	340	18.0	9.00	28.50	28.50	18.0
6	500	470	385	19.5	9.75	31.25	31.25	20.0
8	820	900	685	23.5	11.75	38.75	38.25	27.0

Weights and Dimensions

Valve N.P.S.	Weight—Pounds				Dimensions—Inches				
	171	171½	173	173½	A	A/2	B		C
					171 & 171½	173 & 173½	171 & 171½	173 & 173½	
2	90	78	—	—	11.5	—	19.00	—	10.0
2½	110	100	120	110	13.0	8.5	21.25	21.25	12.0
3	160	130	180	130	14.0	7.0	23.50	23.50	12.0
4	320	230	315	170	17.0	8.5	27.50	27.50	18.0
5	480	450	500	370	20.0	10.0	30.75	30.75	20.0
6	640	560	630	490	22.0	11.0	35.00	35.00	24.0
8	800	670	—	—	26.0	—	43.25	—	30.0

Weights and Dimensions

Valve N.P.S.	Weight—Pounds		Dimensions—Inches		
	189	189½	A	B	C
			189 & 189½		
2	215	160	14.5	25.12	14.0
2½	320	265	16.5	28.12	18.0
3	460	425	18.5	33.50	24.0

List of Piping by Loops

The following tables list the piping and associated hardware in each of the flow loops within the thermal storage system. The abbreviated line designations (e. g. MCL) refer to the piping and instrument diagram in Section 3.

CALCULATIONS

LINE DESIGNATION: Condenser Charge Loop - Oil Suction Line & Discharge
- MCS-MCR

<u>FLOW:</u>	<u>4360</u>	<u>G.P.M.</u>	<u>Corrosion Allowance</u>	<u>0.065 inches</u>
<u>PRESSURE:</u>	<u>50</u>	<u>P.S.I.G</u>	<u>Allowable Stress</u>	<u>12,350 psi</u>
<u>TEMPERATURE:</u>	<u>600</u>	<u>°F</u>	<u>P/S</u>	<u>0.00405</u>
<u>LINE SIZE:</u>	<u>14</u>	<u>INCHES</u>	<u>Y = 0.4</u>	
<u>SCHEDULE:</u>	<u>40</u>	<u>A 106 Gr. A</u>	<u>P_{max} - 800 psig</u>	

LENGTH OF STRAIGHT PIPE 250 FT.

Equivalent
Length Pipe

<u>NO. OF ELBOWS</u>	<u>15</u>	<u>x</u>	<u>25</u>	<u>FT.</u>	<u>375</u>	<u>FT.</u>
<u>NO. OF GATE VALVES</u>	<u>8</u>	<u>x</u>	<u>8</u>	<u>FT.</u>	<u>64</u>	<u>FT.</u>
<u>NO. OF GLOBE VALVES</u>		<u>x</u>		<u>FT.</u>		<u>FT.</u>
<u>NO. OF CHECK VALVES</u>	<u>2</u>	<u>x</u>	<u>75</u>	<u>FT.</u>	<u>150</u>	<u>FT.</u>
<u>NO. OF TEES</u>		<u>x</u>		<u>FT.</u>		<u>FT.</u>
<u>NO. OF STRAINERS</u>		<u>x</u>		<u>FT.</u>		<u>FT.</u>
<u>NO. OF CONTROL VALVES</u>	<u>1</u>	<u>x</u>	<u>400</u>	<u>FT.</u>	<u>400</u>	<u>FT.</u>

OTHER

TOTAL 1239 FT.
=====

<u>TOTAL</u>	<u>1164</u>	<u>FT.</u>	<u>0.618</u>	<u>ΔP</u>	<u>7.19</u>	<u>TOTAL PSI DROP</u>
				<u>100 FT.</u>		

COMMENTS:

Refer to Section 2 for line listings on P & ID's

6-35
CALCULATIONS

LINE DESIGNATION: Desuperheater Charge Hitec HCL-HCS

<u>FLOW:</u>	<u>210</u>	G.P.M.	Corrosion Allowance <u>0.065 inches</u>
<u>PRESSURE:</u>	<u>50</u>	P.S.I.G	Allowable Stress <u>5000 psi</u>
<u>TEMPERATURE:</u>	<u>900</u>	^o F	P/S <u>0.0100</u>
<u>LINE SIZE:</u>	<u>4</u>	INCHES	Y = 0.5
<u>SCHEDULE:</u>	<u>40</u>	A 106 Gr. A 304 Stainless	P _{max} = 326 psig

<u>LENGTH OF STRAIGHT PIPE</u>			<u>Equivalent Length Pipe</u>	<u>200</u> FT.
<u>NO. OF ELBOWS</u>	<u>11</u>	x	<u>7</u> FT.	<u>77</u> FT.
<u>NO. OF GATE VALVES</u>	<u>12</u>	x	<u>2.5</u> FT.	<u>30</u> FT.
<u>NO. OF GLOBE VALVES</u>		x	FT.	FT.
<u>NO. OF CHECK VALVES</u>	<u>1</u>	x	<u>35</u> FT.	<u>35</u> FT.
<u>NO. OF TEES</u>		x	FT.	FT.
<u>NO. OF STRAINERS</u>		x	FT.	FT.
<u>NO. OF CONTROL VALVES</u>	<u>1</u>	x	<u>100</u> FT.	<u>100</u> FT.
<u>OTHER</u>				
			TOTAL	<u>442</u> ===== FT.

TOTAL	<u>407</u>	FT.	<u>1.84</u>	ΔP	<u>7.48</u>	TOTAL PSI DROP
				100 FT.		

COMMENTS:

CALCULATIONSLINE DESIGNATION: Charge Oil MC1-MCS

<u>FLOW :</u>	<u>5001</u>	<u>G.P.M.</u>	<u>Corrosion Allowance</u>	<u>0.065 inches</u>
<u>PRESSURE:</u>	<u>50</u>	<u>P.S.I.G</u>	<u>Allowable Stress</u>	<u>12,350 psi</u>
<u>TEMPERATURE:</u>	<u>600</u>	<u>°F</u>	<u>P/S</u>	<u>0.00405</u>
<u>LINE SIZE:</u>	<u>14</u>	<u>INCHES</u>	<u>Y = 0.4</u>	
<u>SCHEDULE:</u>	<u>40</u>	<u>A106 Gr. A</u>	<u>P_{max} = 800 psig</u>	

LENGTH OF STRAIGHT PIPE

			<u>Equivalent</u>		<u>FT.</u>
			<u>Length Pipe</u>		
<u>NO. OF ELBOWS</u>	<u>11</u>	<u>x</u>	<u>25</u>	<u>FT.</u>	<u>275</u> <u>FT.</u>
<u>NO. OF GATE VALVES</u>	<u>13</u>	<u>x</u>	<u>8</u>	<u>FT.</u>	<u>104</u> <u>FT.</u>
<u>NO. OF GLOBE VALVES</u>		<u>x</u>		<u>FT.</u>	<u>FT.</u>
<u>NO. OF CHECK VALVES</u>		<u>x</u>		<u>FT.</u>	<u>FT.</u>
<u>NO. OF TEES</u>		<u>x</u>		<u>FT.</u>	<u>FT.</u>
<u>NO. OF STRAINERS</u>		<u>x</u>		<u>FT.</u>	<u>FT.</u>
<u>NO. OF CONTROL VALVES</u>	<u>1</u>	<u>x</u>	<u>400</u>	<u>FT.</u>	<u>400</u> <u>FT.</u>
<u>OTHER</u>					
			<u>TOTAL</u>		<u>979</u> <u>FT.</u>

<u>TOTAL</u>	<u>979</u>	<u>FT.</u>	<u>x</u>	<u>0.904</u>	<u>ΔP</u>	<u>=</u>	<u>8.85</u>	<u>TOTAL PSI DROP</u>
								<u>100 FT.</u>

COMMENTS:

CALCULATIONSLINE DESIGNATION: Superheater Discharge - Hitec HDS-HDR

<u>FLOW:</u>	<u>211</u>	<u>G.P.M.</u>	<u>Corrosion Allowance</u>	<u>0.065 inches</u>
<u>PRESSURE:</u>	<u>50</u>	<u>P.S.I.G</u>	<u>Allowable Stress</u>	<u>5000 psi</u>
<u>TEMPERATURE:</u>	<u>900</u>	<u>°F</u>	<u>P/S</u>	<u>0.0100</u>
<u>LINE SIZE:</u>	<u>4</u>	<u>INCHES</u>	<u>Y = 0.5</u>	
<u>SCHEDULE:</u>	<u>40</u>	<u>304 Stainless</u>		

LENGTH OF STRAIGHT PIPE

			<u>Equivalent</u>		<u>130</u>	<u>FT.</u>
			<u>Length Pipe</u>			
<u>NO. OF ELBOWS</u>	<u>10</u>	<u>x</u>	<u>7</u>	<u>FT.</u>	<u>70</u>	<u>FT.</u>
<u>NO. OF GATE VALVES</u>	<u>12</u>	<u>x</u>	<u>2.5</u>	<u>FT.</u>	<u>30</u>	<u>FT.</u>
<u>NO. OF GLOBE VALVES</u>		<u>x</u>		<u>FT.</u>		<u>FT.</u>
<u>NO. OF CHECK VALVES</u>	<u>1</u>	<u>x</u>	<u>35</u>	<u>FT.</u>	<u>35</u>	<u>FT.</u>
<u>NO. OF TEES</u>	<u>1</u>	<u>x</u>	<u>23</u>	<u>FT.</u>	<u>23</u>	<u>FT.</u>
<u>NO. OF STRAINERS</u>		<u>x</u>		<u>FT.</u>		<u>FT.</u>
<u>NO. OF CONTROL VALVES</u>	<u>1</u>	<u>x</u>	<u>100</u>	<u>FT.</u>	<u>100</u>	<u>FT.</u>
<u>OTHER</u>						
			<u>TOTAL</u>		<u>388</u>	<u>FT.</u>

TOTAL 388 FT. X 2.18 ΔP = 8.46 TOTAL PSI DROP
100 FT.

COMMENTS:

6-38
CALCULATIONS

LINE DESIGNATION: Feedwater From Plant - Discharge Cycle FWS-PBS

O

<u>FLOW:</u>	<u>240</u>	<u>G.P.M.</u>	<u>Corrosion Allowance</u>	<u>0.065 inches</u>
<u>PRESSURE:</u>	<u>590</u>	<u>P.S.I.G</u>	<u>Allowable Stress</u>	<u>12000 psig</u>
<u>TEMPERATURE:</u>	<u>336</u>	<u>°F</u>	<u>P/S</u>	<u>0.0479</u>
<u>LINE SIZE:</u>	<u>4</u>	<u>INCHES</u>	<u>Y = 0.4</u>	
<u>SCHEDULE:</u>	<u>80</u>	<u>A106 GrA</u>		<u>P_{max} - 1278</u>

<u>LENGTH OF STRAIGHT PIPE</u>			<u>Equivalent Length Pipe</u>		<u>120</u> FT.
<u>NO. OF ELBOWS</u>	<u>9</u>	x	<u>7</u>	FT.	<u>63</u> FT.
<u>NO. OF GATE VALVES</u>	<u>7</u>	x	<u>3</u>	FT.	<u>21</u> FT.
<u>NO. OF GLOBE VALVES</u>		x		FT.	FT.
<u>NO. OF CHECK VALVES</u>		x		FT.	FT.
<u>NO. OF TEES</u>		x		FT.	FT.
<u>NO. OF STRAINERS</u>		x		FT.	FT.
<u>NO. OF CONTROL VALVES</u>	<u>1</u>	x	<u>100</u>	FT.	<u>100</u> FT.
<u>OTHER</u>					
TOTAL					<u>304</u> FT.

TOTAL 304 FT. X 2.34 ΔP 7.11 **TOTAL PSI DROP**
100 FT.

COMMENTS:

6-39
CALCULATIONS

LINE DESIGNATION: Condenser - Water Discharge Subcooler CRS
SCS
SCR

<u>FLOW:</u>	<u>325</u>	G.P.M.	Corrosion Allowance	<u>0.065 inches</u>
<u>PRESSURE:</u>	<u>1390</u>	P.S.I.G	Allowable Stress	<u>15,000 psi</u>
<u>TEMPERATURE:</u>	<u>583</u>	°F	P/S	<u>0.0926</u>
<u>LINE SIZE:</u>	<u>5</u>	INCHES	Y = 0.4	
<u>SCHEDULE:</u>	<u>80</u>	Gr P12 A335		Pmax = 1794 psig

<u>LENGTH OF STRAIGHT PIPE</u>				<u>150</u> FT.
			<u>Equivalent Length Pipe</u>	
<u>NO. OF ELBOWS</u>	<u>12</u>	x	<u>9</u> FT.	<u>108</u> FT.
<u>NO. OF GATE VALVES</u>	<u>6</u>	x	<u>3</u> FT.	<u>18</u> FT.
<u>NO. OF GLOBE VALVES</u>		x	FT.	FT.
<u>NO. OF CHECK VALVES</u>		x	FT.	FT.
<u>NO. OF TEES</u>		x	FT.	FT.
<u>NO. OF STRAINERS</u>		x	FT.	FT.
<u>NO. OF CONTROL VALVES</u>		x	FT.	FT.
<u>OTHER</u>				
TOTAL				<u>==276==</u> FT.

TOTAL 276 FT. X 2.08 ΔP = 5.74 TOTAL PSI DROP
100 FT.

COMMENTS:

CALCULATIONSLINE DESIGNATION: SAS Steam

FLOW: 105,400 lb/hr Corrosion Allowance 0.065 inches
PRESSURE: 545 P.S.I.G Allowable Stress 12,000 psi
TEMPERATURE: 478 °F P/S 0.0454
LINE SIZE: 8 INCHES Y = 0.4
SCHEDULE: 80 A106 - GrA Pmax = 1074 psig

<u>LENGTH OF STRAIGHT PIPE</u>		<u>Equivalent Length Pipe</u>		<u>90</u> FT.
<u>NO. OF ELBOWS</u>	<u>8</u> x	<u>15</u> FT.	<u>120</u> FT.	
<u>NO. OF GATE VALVES</u>	<u>2</u> x	<u>5</u> FT.	<u>10</u> FT.	
<u>NO. OF GLOBE VALVES</u>	<u> </u> x	<u> </u> FT.	<u> </u> FT.	
<u>NO. OF CHECK VALVES</u>	<u> </u> x	<u> </u> FT.	<u> </u> FT.	
<u>NO. OF TEES</u>	<u> </u> x	<u> </u> FT.	<u> </u> FT.	
<u>NO. OF STRAINERS</u>	<u> </u> x	<u> </u> FT.	<u> </u> FT.	
<u>NO. OF CONTROL VALVES</u>	<u> </u> x	<u> </u> FT.	<u> </u> FT.	
<u>OTHER</u>				

TOTAL 220 FT.

TOTAL 220 FT. X 1.0 ΔP = 2.20 TOTAL PSI DROP
 100 FT.

COMMENTS: Velocity = 4200 ft/min

CALCULATIONSLINE DESIGNATION: SHS Steam to Turbine

<u>FLOW :</u>	<u>105,400</u>	<u>lb/hr</u>	<u>Corrosion Allowance</u>	<u>0.065 inches</u>
<u>PRESSURE:</u>	<u>510</u>	<u>P.S.I.G</u>	<u>Allowable Stress</u>	<u>10,700 psi</u>
<u>TEMPERATURE:</u>	<u>730</u>	<u>°F</u>	<u>P/S</u>	<u>0.0476</u>
<u>LINE SIZE:</u>	<u>10</u>	<u>INCHES</u>	<u>Y = 0.4</u>	
<u>SCHEDULE:</u>	<u>80</u>	<u>A106 - GrA</u>		<u>Pmax = 935 psig</u>

LENGTH OF STRAIGHT PIPE

			<u>Equivalent</u>		<u>85</u>	<u>FT.</u>
			<u>Length Pipe</u>			
<u>NO. OF ELBOWS</u>	<u>5</u>	<u>x</u>	<u>18</u>	<u>FT.</u>	<u>90</u>	<u>FT.</u>
<u>NO. OF GATE VALVES</u>	<u>2</u>	<u>x</u>	<u>6</u>	<u>FT.</u>	<u>12</u>	<u>FT.</u>
<u>NO. OF GLOBE VALVES</u>		<u>x</u>		<u>FT.</u>		<u>FT.</u>
<u>NO. OF CHECK VALVES</u>		<u>x</u>		<u>FT.</u>		<u>FT.</u>
<u>NO. OF TEES</u>		<u>x</u>		<u>FT.</u>		<u>FT.</u>
<u>NO. OF STRAINERS</u>		<u>x</u>		<u>FT.</u>		<u>FT.</u>
<u>NO. OF CONTROL VALVES</u>		<u>x</u>		<u>FT.</u>		<u>FT.</u>
<u>OTHER</u>						

TOTAL ==187== **FT.**

TOTAL	<u>187</u>	FT.	<u>0.8</u>	ΔP	<u>1.5</u>	TOTAL PSI DROP
				100 FT.		

COMMENTS: Velocity = 4200 ft/min

6-42
CALCULATIONS

LINE DESIGNATION: Steam Supply RSS, DSS, ATS, CSS, CSR, SCS, SCR

<u>FLOW:</u>	<u>160,000</u>	lb/hr	Corrosion Allowance	<u>0.065 inches</u>
<u>PRESSURE:</u>	<u>1,445</u>	P.S.I.G	Allowable Stress	<u>11,000 psi</u>
<u>TEMPERATURE:</u>	<u>930</u>	°F	P/S	<u>0.1314</u>
<u>LINE SIZE:</u>	<u>8</u>	INCHES	Y = 0.5	
<u>SCHEDULE:</u>	<u>A335 Gr P12 Cr Mo</u>			Pmax = 1780 psig

<u>LENGTH OF STRAIGHT PIPE</u>			<u>Equivalent Length Pipe</u>		<u>300</u> FT.
<u>NO. OF ELBOWS</u>	<u>20</u>	x	<u>15</u>	FT.	<u>300</u> FT.
<u>NO. OF GATE VALVES</u>	<u>14</u>	x	<u>5</u>	FT.	<u>70</u> FT.
<u>NO. OF GLOBE VALVES</u>		x		FT.	<u> </u> FT.
<u>NO. OF CHECK VALVES</u>		x		FT.	<u> </u> FT.
<u>NO. OF TEES</u>		x		FT.	<u> </u> FT.
<u>NO. OF STRAINERS</u>		x		FT.	<u> </u> FT.
<u>NO. OF CONTROL VALVES</u>		x		FT.	<u> </u> FT.
<u>OTHER</u>					
TOTAL					<u>670</u> ===== FT.

TOTAL	<u>670</u>	FT.	<u>2.5</u>	ΔP	<u>16.75</u>	TOTAL PSI DROP
				100 FT.		

COMMENTS: Velocity = 4800 ft/minute

Certain assumptions were made for this study and are listed below:

- Any excess steam pressure can be vented and will not present a problem in terms of time delays.
- A 20 second operating time for valve opening or closing was used.
- Computer studies have shown that the preheater, boiler and superheater can come up to within 38°C , 100°F of operating temperature in about 20 seconds. If this steam is then introduced to the turbine at a temperature 38°C , 100°F below normal that the "shock" is well within turbine limits.
- If demand changes, the turbine manufacturer has indicated that the turbine can be increased at a rate of 5% per minute to accommodate the demand. The turbine can also withstand a 10% instantaneous load change if the need should arise.

The switching modes are identified by two numbers which show the mode presently in operation and the mode to which the system will not switch.

Mode 1-2

This is a switch from running turbine with receiver steam to a running turbine and charging storage with excess receiver steam.

The operations involved are the start of the Hitec pump and the main oil pump. Both control valves to storage are also opened to allow flow of Hitec and oil to storage. Valves to allow steam to pass through the desuperheater, condenser and other units are also opened.

Estimated switch time - 30 seconds.

THERMAL STORAGE SUBSYSTEM SWITCHING TIMES

The plant dynamic simulation was exercised and the time lags associated with storage have been identified. The various modes considered are shown in Table 6-5.

Table 6-5. Switching Modes

	Mode 1	2	3	4	5	6
Steam System "On"	x	x	x	x		x
Steam to turbine (From steam generator)	x	x	x	x		
Steam to turbine (From storage)			x	x	x	
Thermal Storage (charge)		x		x		
Thermal Storage			x	x	x	
Thermal Storage (Hold)	x					

Mode 1-3

This is a change from running turbine with receiver steam only to a running turbine with receiver steam and storage steam.

The Hitec discharge pump and the preheater-boiler discharge pump are started. At the same time the valves from both storage systems and feed-water are opened.

Estimated switch time - 20 seconds.

Mode 1-4

A change from running turbine with receiver steam to a running turbine with receiver and storage steam. At the same time the storage is charged with receiver steam.

Hitec charge and discharge pumps are started as well as the main oil charge and discharge pumps. All charge and discharge control valves are opened.

Estimated time for charge - 30 seconds

Max. time for discharge - 40 seconds

Since these can occur simultaneously the maximum switching time is taken as 40 seconds. If there is a change in turbine load or more than 10%, the allowable ramp input should be not greater than 5% per minute.

Mode 1-5

Change from a running turbine with receiver steam to a running turbine with storage steam and shutting down the receiver.

Start all Hitec and main oil discharge pumps and open control valves. Close the control valves to switch from receiver steam to storage steam.

Switching time - 40 seconds if the load remains the same otherwise the same ramp limits apply.

Mode 1-6

This requires a change from a running turbine with receiver steam to shutting down the turbine and charging storage.

Start storage pumps and open all storage valves.

Switching time - 30 seconds for charging storage.

20 minutes to shut down turbine from full load.

Mode 2-3

A running turbine with receiver and storage steam is switched to a running turbine with receiver and storage steam and storage is charged.

Start storage pumps and open valves to storage.

Time - 20 seconds and same turbine ramp changes as before.

Mode 2-4

A change from running turbine with receiver steam and charging storage to a mode of a running turbine with receiver and storage steam while still charging storage.

Start discharge pumps and open valves.

Time - 40 seconds.

Mode 2-5

A running turbine with receiver steam and charging storage is changed to a running turbine with storage steam and receiver steam shut down.

Start storage discharge pumps and open valves. Stop the storage charge pumps, close valves and shut down receiver.

Time - 40 seconds to begin running the turbine on storage steam.

20 seconds for storage shut down. Receiver shut down unknown.

Mode 2-6

A change from a running turbine with receiver steam and charging storage and shut down of the turbine.

Time - From full power 15 MW, it should take 20 minutes to shut down the turbine.

Mode 3-4

A running turbine with receiver and storage steam is changed to a running turbine with receiver and storage steam plus charging storage.

Open charge valves and start charge pumps.

Time - 20 seconds

Mode 3-5

A change from running the turbine with receiver steam to a mode of running turbine with storage steam and shutting down the receiver.

Start storage discharge pumps and open storage discharge valves. Shut down receiver.

Time - 40 seconds for no change in turbine demand. If turbine demand changes, ramp limits apply.

Mode 3-6

A running turbine with receiver steam and storage steam is changed to a mode with charging storage and turbine shutdown.

Open storage charge valves and start storage charge pumps. Close discharge valves and stop storage discharge pumps. Ramp down the turbine at .75 kw per minute.

Mode 3-6 (continued)

Time - the time would depend on the turbine load at the time of switching.
Maximum time of 20 minutes.

Mode 4-5

A condition of running turbine with receiver steam, storage steam and charging storage to a condition of running turbine with just storage steam and shutting down the receiver.

Shutdown receiver and its pumps and valves. Shutdown storage charge valves and pumps.

Time - 30 seconds if demand load remains constant.

Mode 4-6

A running turbine with receiver steam, storage steam and charging storage to a condition of just charging storage.

Close valves to turbine - close storage valves - shutdown pumps.

Time - If we use .75 MW/minute ramp it would take 20 minutes to shut down the turbine from full load.

Mode 5-6

A condition of running turbine with storage steam to starting receiver steam and charging storage. Turbine is stopped.

Time - If we use .75 MW/minute it would take 20 minutes to shut down the turbine.

Mode 6-5

A condition of receiver charging storage to a turbine running with storage steam and stopping the receiver steam.

Time - The turbine is the deciding factor and with a .75 MW/minute ramp a 20 minute time is needed.

Mode 6-4

The receiver is charging storage and storage is running the turbine and charging storage. "Ramp up" the turbine.

Time - The turbine takes 20 minutes at the allowable rate of .75 MW per minute to reach full rated power.

Mode 6-3

A condition in which the receiver is charging storage is changed to a running turbine with receiver and storage steam. Storage charging is stopped.

Time - 20 minutes for the turbine at a rate of .75 MW/minute ramp.

Mode 6-2

A condition in which the receiver is charging storage to a running turbine with receiver steam and charging storage.

Time - 20 minutes at the allowable rate to full rated power.

Model 6-1

The receiver steam is charging storage. A new condition has the running turbine using the receiver steam.

Time - 20 minutes based on the allowable ramp of .75 MW per minute.

Mode 5-4

A change from a running turbine using storage to a running turbine with storage and receiver steam.

Time - Assume the steam is normal in the receiver and use a 20 second switching time to open valves.

Mode 5-3

A charge from a running turbine using storage to a running turbine with receiver steam and storage steam.

Time - Assume the steam is up in the receiver and use a 20 second switching time to open valves.

Mode 5-2

A change from a running turbine using storage steam to a running turbine using receiver steam and charging storage.

Time - If receiver is up, the 20 second time for opening valves is used.

Mode 5-1

The turbine is running on storage steam and is switched to a turbine running on receiver steam.

Time - Assume the steam is up in the receiver and the switching time is governed by the 20 seconds it takes to open valves.

Mode 4-3

The turbine is running from receiver and storage steam and is then switched to a turbine running a storage steam and charging storage.

Close valves and start charge pumps.

Time - 20 seconds.

Mode 4-2

The turbine is running from receiver and storage steam and is changed to a running turbine with receiver steam and charging storage.

Close valves and start charge pumps.

Time - 20 seconds.

Mode 4-1

The turbine is running with receiver and storage steam and is then switched to a running turbine with receiver steam and the storage in hold.

Time - 20 seconds.

Mode 3-2

A turbine that is running on receiver and storage steam is switched to a running turbine with receiver steam and charging storage.

Time - 20 seconds.

Mode 3-1

The turbine is running on receiver and storage steam and is switched to a turbine with just receiver steam.

Shutdown storage

Time - 20 seconds

Mode 2-1

A turbine is running on receiver steam and storage is being charged. The new mode is a running turbine with just receiver steam.

Shutdown valves and pumps on storage side.

Time - 20 seconds

Conclusions

- If the turbine load is not changed any switching time should not exceed 40 seconds if only the discharge side is involved.
- Normally 20 seconds is sufficient for any change on the charge side.
- If the turbine load is changed, the time depends on the ramp of .75 kw per minutes. This applies to turbine changes of greater than 10%.

SECTION 7
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APPENDIX A

LIST OF DATA AND IMPORTANT ITEMS

This Appendix contains tabulations or paragraph location of data as requested.

A tabulation, where possible, of the attached data list has been made. Discussion within the body of the report required to answer the list are located by page(s) and paragraph(s). On items where different definitions or interpretations apply, the desired definition is specified to provide uniformity. Other areas in the report where no specific definition has been provided, assumptions used have been made. In addition, safety factors or design margins are noted for all critical elements.

A. DESIGN CHARACTERISTICS

		Value or Paragraph Location	
		<u>Pilot Plant</u>	<u>Comm'l. Plant</u>
1	Storage materials (including specific heat, viscosity and density over the operating temperature range.	Table A-1	Table A-1
2	Quantity of storage materials per stage (kg and m ³).	Table A-2	Table A-2
3	Tankage type, size and quantity for each stage	Table A-2	Table A-2
4	Tankage volume per stage (m ³)	Table A-2	Table A-2

		Value or Paragraph Location	
		<u>Pilot Plant</u>	<u>Comm'l. Plant</u>
5	Design capacity for each stage (MW_{H_t})	Table A-2	Table A-2
6	Maximum and minimum charging rates for each stage (MW_t)	Table A-2	Table A-2
7	Maximum and minimum discharging rates for each stage (MW_t)	Table A-2	Table A-2
8	Thermal storage material temperatures when charged and discharged for each stage ($^{\circ}C.$)	Table A-2	Table A-2
9	Pinch points for charging and discharging for each stage ($^{\circ}C.$)	Table A-4	Table A-6
10	Number of heat exchangers (m)	Table A-4	Table A-6
11	Dimensions of each heat exchanger (m)	Table A-4	Table A-6
12	Weight of each heat exchanger (kg)	Table A-4	Table A-6
13	Number of tubes for each heat exchanger	Table A-4	Table A-6
14	Tube ID and OD for each heat exchanger (mm)	Table A-4	Table A-6

		Value or Paragraph Location	
		<u>Pilot Plant</u>	<u>Comm'l. Plant</u>
15	Tube length for each heat exchanger (m)	Table A-4	Table A-6
16	Total exterior and interior surface area for each heat exchanger (m ²).	Table A-4	Table A-6
17	Effectiveness, number of transfer units, and capacity rates (MW _t /°C) for each heat exchanger.	Table A-4	Table A-6
18	LMTD for each heat exchanger (°C.)	Table A-4	Table A-6
19	Maximum and minimum heat exchanged for each heat exchanger (°C.)	Table A-4	Table A-6
20	Storage fluid inlet and exit temperatures for each heat exchanger (kg/hr.)	Table A-4	Table A-6
21	Maximum and minimum storage fluid flow rates for each heat exchanger (kg/hr)	Table A-4	Table A-6
22	Maximum and minimum storage fluid flow rates for each heat exchanger (KPa)	Table A-4	Table A-6

		Value or Paragraph Location	
		<u>Pilot Plant</u>	<u>Comm'l. Plant</u>
23	Maximum and minimum storage fluid velocity for each heat exchanger (m/sec)	Table A-4	Table A-6
24	Steam/water inlet and exit temperatures for each heat exchanger (°C.)	Table A-4	Table A-6
25	Steam/water enthalpy in and out of each heat exchanger (°C.)	Table A-4	Table A-6
26	Maximum and minimum steam/water flow rates for each heat exchanger (kg/hr)	Table A-4	Table A-6
27	Maximum and minimum steam/water pressure loss for each heat exchanger (kPa)	Table A-4	Table A-6
28	Conditions of charging steam from receiver (kPa and °C.) for rated and derated steam (if applicable)	Table A-2	Table A-2
29	Conditions of steam discharging from storage (kPa and °C.)	Table A-2	Table A-2
30	Feedwater temperature to thermal storage steam generator at maximum and minimum flow rates (if different) (°C.)	Table A-2	Table A-2

		Value or Paragraph Location	
		<u>Pilot Plant</u>	<u>Comm'l. Plant</u>
31	Number of extraction stages used for feedwater heating	Table A-2	Table A-2
32	Number of degrees of superheat (°C.)	Table A-2	Table A-2
33	Maximum and minimum flow of charging steam from receiver to thermal storage (kg/hr at rated and derated conditions if applicable)	Table A-2	Table A-2
34	Maximum and minimum flow of discharging steam from thermal storage (kg/hr)	Table A-2	Table A-2

B. DESIGN DISCUSSION HIGHLIGHTS

- 1 A description of the design, including the design rationale and functional role, cost/performance analyses/tradeoff studies, analytic tools used, applicable safety codes, allowable stresses and safety factors, safety precautions, reliability, manufacturing and maintenance for the following elements.

	<u>Pages or Paragraph(s)</u>
1.1 Fluid maintenance unit	Appendix H, Table 3-1, Table 3-2, Section 3 Pg 3-77
1.2 Tankage	Appendix G
1.3 Heat exchangers	Table 3-1, 3-2, Section 3 Pg. 3-41

	Pages or	<u>Paragraph(s)</u>
1.4 Control system	Section 5,	Pg 5-60
1.5 Ullage unit	Section 3,	Pg 3-79
1.6 Fluid flow loop	Section 3,	Pg 3-56
2 Discuss rationale for thermal storage material selection, including:		
	Pages or	<u>Paragraph(s)</u>
2.1 Material properties	Table A-1,	Section 4,
	Section 6,	
2.2 Material stability, compatibility, and fouling, including weight loss, and viscosity versus time		Section 4
2.3 Cost tradeoff studies	Section 4	
2.4 Annual fluid makeup requirements, including method of estimating.	Appendix H	
2.5 Safety	Section 2	
2.6 Analytical methods used to determine the storage material quantities (See Table A-2)		
3 Discuss insulation/heat loss tradeoffs, including type, thickness, fire susceptibility, net heat loss, for tankage and piping. Paragraph ---- (See Table A-2)		
4 Discuss pressure drop and heat transfer correlations for dual- media storage units (if applicable) and heat exchangers, including fouling/scaling assumptions. Paragraph ---- (See Table A-2)		

- 5 Indicate variations in temperature, pressure, and flow rates that the thermal storage system can tolerate from the receiver, and can provide to the EPGS. Paragraph ---- Table A-2
- 6 Estimates of the time required for switching from:

On the Thermal Storage Subsystem (Volume V), in place of B. 6, include estimates of the time required for switching between the following operating modes: Section 5, Page 60

Mode	SGS "On"	EGS Turbine		TSS		
		Steam From SGS	Steam From TSS	Charge	Discharge	Hold
1	X	X				X
2	X	X		X		
3	X	X	X		X	
4	X	X	X	X	X	
5			X		X	
6	X			X		

Also indicate which subsystem or storage system component drives the time lags.

In Section B, Item 5, also discuss the following items: (a) Any limitations in thermocline storage charging rates when the storage tank approaches a fully charged state and the fluid ΔT begins to drop; (b) Any limitations in storage discharge rates as the maximum storage fluid temperature begins to drop due to heat losses or thermocline degradation. Any impact on the balance of plant, such as steam conditions out of the charging and discharging heat exchangers, should also be discussed.

- 7 Indicate variations in feedwater temperature, pressure and flow rate from the EPGS that can be tolerated. Paragraph ---- Table A-2
- 8 Describe the thermal storage subsystem control commands supplied by master control. Paragraph ---- Section 5, Figure 5-4
Page 5-60
- 9 Describe information supplied to master control by the thermal storage subsystem. Paragraph ---- Section 5 Figure 5-3,
Figure 5-4
- 10 Describe the control functions carried out within the thermal storage subsystem, as well as the role of master control for this subsystem. Paragraph ---- Section 5. Page 5-60, Page 5-10
- 11 Discuss subsystem efficiency (energy in ^{Page 5-16} versus energy out), including a list of all parasitic losses attributable to the thermal storage subsystem. Paragraph --- Figure A-2, Appendix A
- 12 Include stair step charts for both the pilot and commercial plant thermal storage systems, beginning with the maximum energy stored, extraction capability, daily heat loss to surroundings, and energy required for three and/or six hours of turbine operation. Paragraph ---- Figure A-2, Appendix A
- 13 Provide plant schematics and describe all operating modes of thermal storage, including the initial charging process and startup and shutdown modes. Paragraph ----Section 5, Page 5-1 to 5-7
Appendix A, Page A-7
- 14 Provide temperature enthalpy diagrams for charging and discharging. Paragraph ----Section 3, Page 3-41

Table A-1. Thermal Storage Materials

	Main Storage (Stage 1)		Superheat Storage (Stage 1.)
	Caloria HT-43 *	Rocks	Hitec
Composition	Petroleum based aliphatic oil Flash pt. 204°C	Granite in the size range 12.7 mm	Eutectic of 53% KNO ₃ , 7% NaNO ₃ and 40% NaNO ₂ of wt. F. Pt. 142°C
Min. Operating Temperature		-	149°C
Max. Operating Temperature	316°C (bulk) 360°C (film)	-	455°C (bulk) 500°C (film)
Specific heat, Wh/kg-°K Equation =	0.689 (mean) (250°C→300°C) 0.231+8.33x10 ⁻⁴ T (°K)	0.227 -	0.433 -
Density, kg/m ³ Equation =	67.5 (mean) (250°C→300°C) 1150-0.865 T°K	2643	1862 (299°C) 1745 (455°C) 2291-0.75 T (°K)
Viscosity, kg/m-s n·s/m ²	7.4 x 10 ⁻⁴ at 250°C 5.7 x 10 ⁻⁴ at 303°C	-	1.802x10 ⁻² at 149°C 4.307x10 ⁻³ at 260°C 3.001x10 ⁻³ at 316°C 1.802x10 ⁻³ at 427°C 1.505x10 ⁻³ at 482°C

* Note: Property data for Caloria HT-43 is based on the literature data supplied by the Exxon Company.

Table A-2. Design Characteristics

		Units	Pilot Plant	Commercial Plant
Quantity of Storage Material	Stage 2	kg m ³	Hitec 254,000 145. (at 455°C)	Hitec 1,928,000 1105 (at 455°C)
	Stage 1	kg	Oil/Rock 9.55 x 10 ⁵	Oil/Rock 6.8 x 10 ⁶
	Oil	m ³	1060 (at 15°C)	7580 (at 15°C)
	Rocks	kg	7.2 x 10 ⁶	51.5 x 10 ⁶
		m ³	2730	19,534
Tankage	Stage 2 Type		Buried cylindrical tank with domed bottom and top	Same
	Size		6.1 m Dia. 4.87 m Ht.	12.2 m. Dia. 9.74 m. Ht.
	Qty.		2	2
	Volume	m ³		
	Stage 1 Type		Above ground cylindrical tank with domed cover	Same
	Size		18.29 m Dia. 14.63 m. Ht. (wall)	34.76 m. 14.63 m. Ht. (wall)
	Qty.		1	2
Storage Capacity	Stage 2	MWh (t)	17.1	130
	Stage 1	MWh (t)	116	830
Thermal Storage Temperatures	Stage 2	°C	454 (charged)	451 (charged)
		°C	299 (discharged)	299 (discharged)
	Stage 1	°C	303.3 (charged)	303.3 (charged)
		°C	248.9 (discharged)	248.9 (discharged)

Table A-2. Design Characteristics (Continued)

		Units	Pilot Plant	Commercial Plant
Charge Rates	Stage 2			
	Max.	MW(e)	6.004	41.187
	Min.	MW(e)	0	0
	Stage 1			
	Max.	MW(e)	25.596	175.598
	Min.	MW(e)	0	0
Discharge Rates	Stage 2			
	Max.	MW(t)	5.420	45.358
	Min.	MW(t)	0	0
	Stage 1			
	Max.	MW(t)	26.227	219.493
	Min.	MW(t)	0	0
Charging Steam Conditions	Receiver	kPa	10100	10100
		°C	510	510
Discharging Steam Conditions	Storage Exit	kPa	3620	3620
		°C	390	390
Feedwater Temperature to Thermal Storage	100% Flow	°C	205.0	190.5
	50% Flow	°C	171.7	
	25% Flow	°C	140.5	
No. of Extraction Stages for FW Heating		#	3	3
Degrees of Superheat		°C	144	144
Charging Steam Flow	Receiver	kg/h	50,250 (Max.)	344,730
			0 (Min.)	0
Discharging Steam Flow	Storage	kg/h	49,024 (Max.)	410,273
			0 (Min.)	0

Table A-2. Design Characteristics (Continued)

Analytical Methods used to Determine Storage Material Quantities	Stage 2	Calculated from:
		<ul style="list-style-type: none"> • Dischargeable capacity • Heat Losses Ref: Sec. 4 (Tankage Equations)
	Stage 1	Calculated from:
		<ul style="list-style-type: none"> • Dischargeable capacity • Heat Losses • Utilization factor • Sealing and tracing requirements Ref: Sec. IV-... (Tankage Equations)
Insulation/ Heat Loss	Stage 1 & 2 Tradeoffs	Sec. 4
	Type	Sec. 3
	Equipment	Sec. 3
Pressure Drop/Heat Transfer Correlations		Sec. 4
Variations in Steam Temperature Pressure and Flow Rates	From Receiver	Max: P = 10,350 kPa T = 520°C Flow = 50,250 kg/hr (+10%) @ design
		Min: P = 9000 kPa T = 303°C Flow = 0
	to EPGS	Max: P = 4140 kPa T = 450°C Flow = 49,024 kg/hr (+10%)

Table A-2. Design Characteristics (Continued)

Variations in FW Temperature, Pressure and Flow	From EPGS	Min: P = Any
		T = Any
		Flow = Any
		Max: P = 4140 kPa
		T = 300°C
		Flow = 40924 kg/hr (+10%)
		Min: P = Any
		T = Any
		Flow = Any

A-14

STORAGE STATE POINTS
AND HEAT EXCHANGER
PERFORMANCE
DATA FOR
PILOT AND COMMERICAL PLANTS

40703-V

Table A-3. Pilot Plant Pressure, Temperature, Enthalpy States

Fluid State Points		P kPa	T °C	h kJ/kg	$\dot{m}$ kg/hr	LMTD °C	Q MW(t)
<u>Steam/Water Flow</u>							
Attemperator	A1	10200	205	878	582		
	A2	10200	205	878	4513		
<u>Charge</u>							
	1	10100	510	3400	50250		
	2	10040	499	3371	50831		
Desuperheater	3	10020	355.3	2946	50831	50.21	6.004
	4	9900	318.6	2777	55344		
Condenser	5	9850	309.9	1402	55344	21.82	21.151
	6	9845	309.9	1402	55344		
Subcooler	7	9810	255.6	1113	55344	21.94	4.445
<u>Discharge</u>							
	10	3790	205	876	49024		
Preheater	11	3720	246.1	1067	49024	20.98	2.601
Boiler	12	3685	245.6	2802	49024	24.70	23.626
	13	3655	245.6	2802	49024		
Superheater	14	3620	390.6	3200	49024	55.28	5.420
	15	3275	387.9	3200	49024		
<u>Storage Media</u>							
<u>Charge</u>				Cp kJ/kg°C			
Hitec	H1	- - -	299	1.56	88975		
Hitec	H2	- - -	454	1.56	88975		
Oil	M1	- - -	249	2.48	682835		
Oil	M2	- - -	258	2.48	682835		
Oil	M3	- - -	303	2.48	682835		
<u>Discharge</u>							
Hitec	H3	- - -	448	1.56	83910		
Hitec	H4	- - -	299	1.56	83910		
Oil	M4	- - -	300	2.48	745300		
Oil	M5	- - -	253.9	2.48	745300		
Oil	M6	- - -	249	2.48	745300		

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Table A-4a. Pilot Plant Heat Exchanger Parameters

	Units	1 Desuperheater	2a Condenser	2b Subcooler	3a Preheater	3b Boiler	4 Superheater
Pinch Points Storage Media Entering	°C (°F)	56.4 (101.6)	51.6 (92.8)	6.7 (12)	43.9 (79)	8.4 (15.2)	53.4 (96.1)
Storage Media Leaving	°C (°F)	44.4 (80)	6.6 (11.8)	51.6 (92.8)	7.9 (14.2)	54.5 (98.1)	57.2 (103)
Number of Exchangers	-	1	1	1	1	1	1
Dimensions of Shell							
Inside Diameter	M (in.)	0.46 (18)	1.07 (42)	0.71 (28)	0.71 (28)	1.02/ 1.37 (40/54)	0.46 (18)
Length Overall	M (in.)	13.1 (516)	11.3 (454)	7.8 (308)	6.0 (236)	14.2 (560)	10.1 (396)
Weight Dry	Kg (lb)	5715 (12600)	30750 (67800)	9570 (21,100)	5625 (12400)	29000 (64,000)	4810 (10600)
Number of Tubes	-	215	1424	600	750	1400	278
Tube ID	mm (in.)	15.7 (.620)	14.8 (.584)	14.8 (.584)	14.8 (.584)	14.8 (.584)	15.7 (.620)
Tube O.D.	mm (in.)	19 (3/4)	19 (3/4)	19 (3/4)	19 (3/4)	19 (3/4)	19 (3/4)
Tube Length	m (in.)	12.2 (480)	12.2 (480)	6.4 (252)	3.7 (144)	12.2 (480)	9.1 (360)
Exterior Tube Surface	m ² (A ²)	154.6 (1664)	1011.0 (10882)	218.7 (2354)	161.7 (1740)	1020.6 (10,986)	150.3 (1618)
Interior Tube Surface	m ² (ft ²)	127.8 (1376)	787.2 (8474)	170.3 (1833)	122.9 (1324)	794.7 (8554)	124.3 (1338)
Effectiveness	-	0.778	0.873	0.891	0.839	0.845	0.736
Capacity Rate Shell Side	MW/ °C (Btu/ hr-°F)	0.0386 (73166)	0.4701 (891193)	0.0818 (155074)	0.0633 (120,073)		0.0364 (69002)
Tube Side	MW/ °C (Btu/ hr-°F)	0.0410 (79277)		0.4701 (891,193)	0.5131 (972,721)	0.5131 (972,721)	0.0374 (70,825)
LMTD	°C (°F)	50.2 (90.37)	21.8 (39.28)	21.9 (39.50)	21.0 (37.76)	24.1 (43.41)	55.3 (99.51)
Heat Exchange Ratio							
Maximum	MW (M-Btu/ hr)	6.004 (20,485)	21.15 (72,171)	4.445 (15,166)	2.601 (8,873)	23.63 (80,617)	5.420 (18,493)
Minimum	MW	0	0	0	0	0	0
Storage Fluid Temp							
Inlet	°C (°F)	299 (570)	258 (497)	249 (480)	253.9 (489.1)	300 (572)	448 (838)
Exit	°C (°F)	454 (850)	303 (578)	258 (497)	249 (480)	233.9 (489.1)	200 (570)
Storage Fluid Flow							
Maximum	Kg/hr (lbm/ hr)	88975 (196156)	682838 (1505,400)	682838 (1505,400)	745298 (1,643,100)	745298 (1,643,100)	83911 (184,991)
Minimum	Kg/hr	0	0	0	0	0	0
Storage Fluid Pressure							
Maximum	kPa (psia)	460 (67)	340 (50)	390 (56)	280 (40)	410 (59)	440 (64)
Minimum	kPa (psia)	100 (14.7)	100 (14.7)	100 (14.7)	100 (14.7)	100 (14.7)	100 (14.7)

Table A-4b. Pilot Plant Heat Exchanger Parameters

	Units	1 Desuperheater	2a Condenser	2b Subcooler	3a Preheater	3b Boiler	4 Superheater
Storage Fluid Velocity							
Maximum	m/s (ft/s)	0.6 (2.1)	1.3 (4.4)	2.6 (8.6)	2.3 (7.4)	2.6 (8.6)	0.5 (1.5)
Minimum	m/s	0	0	0	0	0	0
Steam/Water Temperature							
Inlet	°C (°F)	499 (930)	318.6 (605.4)	309.9 (589.8)	205 (401)	245.5 (473.9)	245.5 (473.9)
Outlet	°C (°F)	355.3 (671.6)	309.9 (589.8)	256 (492)	246.1 (474.9)	245.5 (473.9)	391 (735)
Steam/Water Enthalpy							
Inlet	kJ/kg Btu/lb in	3371 (1449.4)	2777 (1194.1)	1402 (602.6)	876 (376.5)	1067 (458.6)	2802 (1204.5)
Outlet	kJ/kg (Btu/lb in)	2946 (1266.6)	1402 (602.6)	1113 (478.3)	1067 (458.6)	2802 (1204.5)	3200 (1375.6)
Steam/Water Flowrate							
Maximum	kg/hr (lbm/hr)	50831 (112064)	55344 (122013)	55344 (122013)	49024 (108080)	49024 (108080)	49024 (108080)
Minimum	kg/hr	0	0	0	0	0	0
Steam/Water Pressure Loss							
Maximum	kPa (psi)	28 (4)	7 (1)	34 (5)	69 (10)	34 (5)	34 (5)
Minimum	kPa	0	0	0	0	0	0
NTU	-	3.18	2.06	2.48	2.17	1.91	2.70

Table A-5. Commercial Plant Pressure, Temperature Enthalpy States

Fluid State Points		P kPa	T °C	h kJ/kg	$\dot{m}$ kg/hr	LMTD °C	Q MW(t)
<u>Steam/Water Flow</u>							
Attemperator	A1	10200	205	878	3989		
Attemperator	A2	10200	205	878	30964		
Charge	1	10100	510	3400	344730		
	2	10040	499	3371	348720		
Desuperheater						50.21	41.187
	3	10020	355.3	2948	348720		
	4	9900	318.6	2777	379684		
Condenser						21.82	145.105
	5	9850	309.9	1402	379684		
	6	9845	309.9	1402	379684		
Subcooler						21.94	30.493
	7	9810	255.6	1113	379684		
Discharge	10	3790	205	876	410273		
Preheater						20.98	21.767
	11	3720	246.1	1067	410273		
Boiler						24.70	197.729
	12	3685	245.6	2802	410273		
	13	3655	245.6	2802	410273		
Superheater						55.28	45.358
	14	3620	390.6	3200	410273		
	15	3275	387.9	3200	410273		
<u>Storage Media</u>				C_p			
Charge				kJ/kg°C			
Hitec	H1	- - -	299	1.56	610358		
Hitec	H2	- - -	454	1.56	610358		
Oil	M1	- - -	249	2.48	4684500		
Oil	M2	- - -	258	2.48	4684500		
Oil	M3	- - -	303	2.48	4684500		
Discharge							
Hitec	H3	- - -	448	1.56	702230		
Hitec	H4	- - -	299	1.56	702230		
Oil	M4	- - -	300	2.48	6237300		
	M5	- - -	253.9	2.48	6237300		

Table A-6a. Commercial Plant Heat Exchanger Parameters

	Units	1 Desuperheater	2A Condenser	2B Subcooler	3A Prcheater	3B Boiler	4 Superheater
Pinch Points							
Storage Media Entering	°C (°F)	56.4 (101.6)	51.6 (92.8)	6.7 (12)	43.9 (79)	8.4 (15.2)	53.4 (96.1)
Storage Media Leaving	°C (°F)	44.4 (80)	6.6 (11.8)	51.6 (92.8)	7.9 (14.2)	54.5 (98.1)	57.2 (103)
Number of Ex Exchangers	-	3	6	3	4	8	4
Dimensions of Shell							
Inside Diameter	m	0.61	1.07	0.99	0.99	1.02/ 1.37	0.64
	(in.)	(24)	(42)	(39)	(39)	(40/54)	(25)
Length Overall	m	13.41	14.33	8.08	5.64	14.22	12.24
	(in.)	(528)	(564)	(318)	(222)	(560)	(482)
Weight Dry	kg (lb)	10400 (23000)	33600 (74000)	26100 (57500)	10200 (22500)	29500 (65000)	9100 (20,000)
Number of Tubes	-	482	1680	1460	1460	1460	502
Tube ID	mm (in.)	15.7 (.620)	14.8 (.584)	14.8 (.584)	14.8 (.584)	14.8 (.584)	15.7 (.620)
Tube OD	mm (in.)	19 (3/4)	19 (3/4)	19 (3/4)	19 (3/4)	19 (3/4)	19 (3/4)
Tube Length	m (in.)	12.19 (480)	12.19 (480)	6.10 (240)	3.66 (144)	12.19 (480)	10.97 (432)
Exterior Tube Surface	m ² (ft ²)	382.2 (4114)	1220.8 (13140)	529.6 (5700)	310.8 (3345)	1060.9 (11419)	328.1 (3532)
Interior Tube Surface	m ² (ft ²)	316.0 (3401)	950.6 (10232)	412.3 (4438)	242.0 (2605)	826.1 (8892)	271.3 (2920)
Effectiveness	-	0.778	0.873	0.891	0.839	0.845	0.736
NTU	-	3.384	2.063	2.475	1.931	1.896	2.691
Capacity Rate Shell Side	MW/ °C (Btu/ hr-°F)	0.0883 (167,304)	0.5376 (1,019,000)	0.1871 (354,620)	0.1343 254660		0.0762 (144,364)
Tube Side	MW/ °C (Btu/ hr-°F)	0.0956 (181290)		1.0751 2,038,000	1.0736 2,0351,000	0.5368 (1,017,600)	0.0782 (148180)
LMTD	°C (°F)	50.2 (90.37)	21.8 (39.28)	21.9 (39.50)	21.0 (37.76)	24.7 (44.46)	55.3 (99.51)
Heat Exchange Rate							
Maximum	MW (M-Btu/ hr)	13.720 (46.845)	24.184 (82.520)	10.164 (34.682)	5.441 (18.565)	24.716 (84.333)	11.339 (38.690)
Minimum	MW	0	0	0	0	0	0
Storage Fluid Temp							
Inlet	°C (°F)	299 (570)	258 (497)	240 (480)	253.9 (489.1)	300 (572)	448 (838)
Exit	°C (°F)	454 (850)	303 (578)	258 (497)	249 (480)	253.9 (489.1)	299 (570)
Storage Fluid Flow							
Maximum	kg/hr (lbm/hr)	203453 (448,500)	780750 (1,721,300)	780750 (1,721,300)	1,559,300 (3,437,700)	779,660 (1,718,900)	175,557 387038
Minimum	kg/hr	0	0	0	0	0	0

Table A-6b. Commercial Plant Heat Exchanger Parameters

	Units	1 Desuperheater	2A Condenser	2B Subcooler	3A Preheater	3B Boiler	4 Superheater
Storage Fluid Pressure							
Maximum	kPa (psia)	680 (100)	680 (100)	680 (100)	680 (100)	680 (100)	680 (100)
Minimum	kPa	0	0	0	0	0	0
Storage Fluid Velocity							
Maximum	m/s (ft/s)	0.55 (1.8)	1.22 (4.0)	2.47 (8.1)	2.44 (8.0)	2.62 (8.6)	0.61 (2)
Minimum	m/s	0	0	0	0	0	0
Steam/Water Temperature							
Inlet	°C (°F)	499 (930)	318.6 (605.4)	309.9 (589.8)	205 (401)	245.5 (473.9)	245.5 (473.9)
Outlet	°C (°F)	355.3 (671.6)	309.9 (589.8)	256 (492)	246.1 (474.9)	245.5 (473.9)	391 (735)
Steam/Water Enthalpy							
Inlet	kJ/kg (Btu/lbm)	3371 (1449.4)	2777 (1194.1)	1402 (602.6)	876 (376.5)	1067 (458.6)	2802 (1204.5)
Outlet	kJ/kg (Btu/lbm)	2946 (1266.6)	1402 (602.6)	1113 (478.3)	1067 (458.6)	2802 (1204.5)	3200 (1375.6)
Steam/Water Flowrate							
Maximum	kg/hr (lbm/hr)	116340 (256270)	63281 (139,510)	126560 (279,020)	102570 (226,120)	51,284 (113,050)	102570 (226,120)
Minimum	kg/hr	0	0	0	0	0	0
Steam/Water Pressure Loss							
Maximum	kPa (psi)	28 (4)	7 (1)	34 (5)	69 (10)	34 (5)	34 (5)
Minimum	kPa	0	0	0	0	0	0

Figure A-1. Key to Energy Balance State Point Locations

FIG. A-2 STAIRSTEP ENERGY CHART

APPENDIX B
EQUIPMENT DESIGN DATA SHEETS

The following pages list the preliminary design data sheets for the primary equipment for the pilot plant and selected equipment for the commercial plant.

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TANKAGE
SYSTEMS
DATA SHEETS

40703-V . .

18. 3-Meter Diameter by 14. 6-Meter Oil and Rock Tank

DATA SHEET		
DESIGN DATA	DESCRIPTION	OIL/ROCK TANK
	NUMBER REQUIRED	(1)
	CAPACITY	45' OF ROCK @ 72% COMP & 44' OF OIL
	DESIGN PRESSURE	1.5 PSI ROCK (0.4224 TORR) + OIL 5.0 PSI
	OPERATING PRESSURE	1.5 PSI
	TEST PRESSURE	1.625 PSI + HYDROSTATIC HEAD
	DESIGN TEMPERATURE	60°F WITH COOLDOWN TO 70°F
	TEST TEMPERATURE	AMBIENT
	JOINT EFFICIENCY	1.0 SHELL
	CORROSION ALLOWANCE	NONE
DESIGN DATA	CODE & STAMP	SEE NOTE #2
	CUSTOMER SPECIFICATION	EXHIBIT A
MATERIALS	SHELL & BOTTOM/KNUCK	A533 CLASS 2 GRADE A
	TOP 1' & TOP KNUCK	A516-60
	HEADS	N.A.
	NOZZLE	NECK A106 FLANGE A105
	MANWAY	NECK A516-60 FLANGE A516-60 COVER A516-60
	REINFORCING PADS	A533 CLASS 2 GRADE A A516-60
	PIPING	N.A.
	COUPLINGS	A105
	STIFFENER RINGS	N.A.
	INTERNAL	N.A.
	BOLTING	BOLTS A193-B7 NUTS A191-2H STUDS
	GASKETS	COMPRESSED ASBESTOS
	STRUCTURAL	N.A.
	ELECTRODES	E 7018-D1 A533 CLASS 2 GRADE A E 70XX OR E 70XX A516-60
	CONSTRUCTION	STRESS RELIEF
CLEANING		BROOM CLEAN AFTER ERECTION
SURFACE PREPARATION		N.A.
INTERNAL PAINTING		N.A.
EXTERNAL PAINTING		N.A.
LINING		N.A.
INSULATION		REQUIRED, 9" OF FOAMGLASS (R) ON ROOF, SHELL & ANCHOR CHAIRS
LADDERS & PLATFORMS		N.A.
QUALITY ASSURANCE	CATHODIC PROTECTION	N.A.
	FOUNDATIONS	3000 PSI CONCRETE & A615-60 REBAR PER DRAWING
	Q.A. MANUAL	N.A.
	MILL CERTIFICATIONS	ALL PRESSURE RETAINING MATERIAL
	WELDERS	ASME SECTION IX QUALIFIED
	WELDING	PER API-650 APP. D
	NONDESTRUCTIVE TESTING	RADIO GRAPH SHELL & BOTTOM KNUCKLE PER API-650 APP. D
	SPECIAL TESTING	N.A.
TESTING	SHELL	HYDRO-TEST + 1.625 PSI
	BOTTOM	VACUUM BOX PER API-650
	ROOF	" " " "

NOTES: 1. FLANGE BOLT HOLES STRADDLE TANK VERTICAL & RADIAL CENTER LINES - UNLESS OTHERWISE SPECIFIED.

2. API-650 APP. D, FOR FABRICATION, ERECTION, TESTING, & EXAMINATION. API-650 APP. D, DESIGN MODIFIED FOR THERMAL LOADS.

6.1 - Meters Diameter by 5.5 Meters High Hitec Tank

DATA SHEET	
DESCRIPTION	
NUMBER REQUIRED	20.0 x 10 HIGH HITEC TANK
CAPACITY	TWO TONS
DESIGN PRESSURE	FLUENT HEAD, 1-130 PSIG @ 900°F
OPERATING PRESSURE	
TEST PRESSURE	HYDROSTATIC HEAD + 0.125 PSIG
DESIGN TEMPERATURE	300°F
TEST TEMPERATURE	AS SHOWN
JOINT EFFICIENCY	100% ON SHELL & BOTTOM HEAD
COMPOSITION ALLOWANCE	YES ON WELDED SURFACES
CODE & STAMP	ALL STD. NO. STAMP
CUSTOMER SPECIFICATION: EXHIBIT A	
MATERIALS	
SHELL	A 240-304
TOP, BOTTOM	NONE
HEADS	A 240-304
NOZZLE	NECK A 193-B FLANGE A 193-F 304
MANWAY	NECK A 240-304 FLANGE A 240-304 COVER A 240-304
REINFORCING PADS	A 240-304
PIPING	NONE
COUPLINGS	NONE
STIFFENER RINGS	A 240-304
INTERNAL	NONE
BOLTING	BOLTS A 193-B NUTS A 193-B STUDS NONE
GASKETS	COMP. A 193-B
STRUCTURAL	A 240-304
ELECTRODES	E 308
CONSTRUCTION	
STRESS RELIEF	N.A.
CLEANING	N.A.
SURFACE PREPARATION	N.A.
INTERNAL PAINTING	N.A.
EXTERNAL PAINTING	N.A.
LINING	N.A.
INSULATION	N.A.
LADDERS & PLATFORMS	N.A.
CATHODIC PROTECTION	N.A.
FOUNDATIONS	N.A.
QUALITY ASSURANCE	
Q A MANUAL	NOT APPLICABLE
MILL CERTIFICATIONS	READ ON ALL PRESSURE RETAINING PARTS
WELDERS	AS ME. SECTION 11 QUALIFIED
WELDING	PER A 193-B
NONDESTRUCTIVE TESTING	RADIOGRAPH SHELL & BOTTOM HEAD PER AP 110 920
SPECIAL TESTING	NONE
SHELL	HYDROTEST + 0.125 PSIG
BOTTOM	
ROOF	0.125 PSIG W/ SCALP 5005

NOTES: 1. FLANGE BOLT HOLES STRADDLE TANK VERTICAL & RADIAL CENTER LINES -- UNLESS OTHERWISE SPECIFIED.

OIL/ROCK TANK
MANIFOLD DESIGN REQUIREMENT
(PILOT PLANT)

Size	18.29m (60 ft) diameter
Tank Coverage	No point in the plane of the manifold be more than 0.3m (1 ft) from a manifold orifice.
Flow Rate	2560 Kg/hr-m ² (525 lb/hr - ft ²) at 250°C (480°F) of Caloria Ht-43 or equivalent heat transfer oil.
Pressure Drop	6.8kPa (1 psi) across each manifold maximum
Flow Distribution	Uniform to within 10% across the bed.
Orifice Size	3.2mm for 12.7mm gravel (1/8" for 1/2" dia gravel)
Orifice Location	Uniformly distributed in two rows 45° either side of the bottom centerline of each manifold line.
Number of Orifices	Number determined to attain maximum pressure drop listed above at the rated flow rate, plus 18% more for blockage allowance for bottom manifold.
Materials	Carbon steel pipe of sufficient strength to prevent crushing due to rock loading.
Construction	Welded joints with sub-units shop assembled and final welding done within the storage tank.

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Support	Lower manifold supported to prevent stressing tank wall due to packing or settling of bed. Upper manifold supported from tank rim or cover.
Size	34.7m (114') diameter
Flow Rate	3200 Kg/hr-m ² (650 lb/hr ft ²) at 250°C (480°F) of Caloria HT-43 or equivalent heat transfer oil.

All other requirements the same as for the Pilot Plant Manifold.

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PILOT PLANT
ULLAGE MAINTENANCE
DATA SHEETS

40703-V

PILOT PLANT DESIGN REQUIREMENTS
ULLAGE SYSTEMS

Nitrogen Source

Liquid Storage Capacity	6.05 m ³
Maximum Supply Rate (gaseous)	34.0 m ³ /hr
Line Pressure Control	two-stage pressure controlling manifold

Oil Tank Ullage

Control Pressure Range	3.4 to 9.0kPa
Maximum Supply Rate (gaseous)	28.3 m ³ /day
Maximum Daily Usage (gaseous)	85.0 m ³ /day
Effluent Treatment	A condenser is required to remove hydrocarbon vapors.

Hitec Tank Ullage

Control Pressure Range	1.38 to 4.82kPa
Maximum Supply Rate (gaseous)	5.66 m ³ /hr
Maximum Daily Usage (gaseous)	22.6 m ³ /day

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**PILOT PLANT
FLUID MAINTENANCE UNITS**

40703-V

PILOT PLANT DESIGN REQUIREMENTS
HITEC MAINTENANCE UNIT

Function	To melt salts and add them to Hitec storage as needed to restore the composition of the Hitec salt.
Tank Capacity	2.65 m ³
Heaters	Calrod electrical heaters
Mixer	To provide convection to speed melting.
Pump	45.4 l/m
Heat Required to heat Salt from Ambient to 200°C	1.8 GJ

PILOT PLANT DESIGN REQUIREMENTS
OIL MAINTENANCE UNIT

Function	To remove degraded components from the oil and return the good oil to the system.
Oil Type	Caloria HT-43 by Exxon
Maximum Degradation Rate	3% (weight) per week at 315°C
Rated Process Capacity	32 m ³ /day
Maximum Degraded Component Concentration	10% (weight)
Maximum Make Up Requirement	3.81 m ³ /day
Additives	Replacement of Caloria's oxidation inhibitors and other additives which may be lost in the distillation process.
Effluents	All volatiles must be condensed and discharged as liquids.

B-12

HEAT EXCHANGER

40703-V

General Fabrication and Performance Information

FIGURE G-5.1

HEAT EXCHANGER SPECIFICATION SHEET

1			JOB NO.
2	CUSTOMER	REFERENCE NO.	
3	ADDRESS	PROPOSAL NO.	
4	PLANT LOCATION	COMMERCIAL	DATE
5	SERVICE OF UNIT	DESUPERHEATER (1 of 3)	ITEM NO. 1
6	SIZE	24 - 480 TYPE BEM	CONNECTED IN
7	SQ. FT. SURF./UNIT (GROSS) (EFF.)	4114	SQ. FT. SURF./SHELL (GROSS) (EFF.) 4114
8	PERFORMANCE OF ONE UNIT		
9		SHELL SIDE	TUBE SIDE
10	FLUID CIRCULATED	H ₂ O	Super heated Steam
11	TOTAL FLUID ENTERING	448,600 lbm/hr	256,265 lbm/hr
12	VAPOR		
13	LIQUID	448,600	
14	STEAM		256,265
15	NON-CONDENSABLES		
16	FLUID VAPORIZED OR CONDENSED		
17	STEAM CONDENSED		
18	GRAVITY	1.81	
19	VISCOSITY	3.307 / 1.654 cP	
20	MOLECULAR WEIGHT		
21	SPECIFIC HEAT	0.323 BTU/LB.°F	BTU/LB.°F
22	THERMAL CONDUCTIVITY	0.360 BTU/HR-FT.°F	BTU/HR-FT.°F
23	LATENT HEAT		BTU/LB
24	TEMPERATURE IN	570 °F	930 °F
25	TEMPERATURE OUT	850 °F	671.6 °F
26	OPERATING PRESSURE	7.5 PSIG	1450 PSIG
27	NO. PASSES PER SHELL	ONE	ONE
28	VELOCITY	1.8 FT/SEC	45 FT/SEC
29	PRESSURE DROP	15 PSI	4 PSI
30	FOULING RESISTANCE (MIN.)	.0005	.0005
31	HEAT EXCHANGED-BTU/HR	46.845 x 10 ⁶	MTD CORRECTED °F 90.37
32	TRANSFER RATE—SERVICE	137.6	CLEAN 162
33	CONSTRUCTION OF ONE SHELL		
34	DESIGN PRESSURE	100 PSI	1500 PSI
35	TEST PRESSURE		PSI
36	DESIGN TEMPERATURE	900 °F	1000 °F
37	TUBES	304 SS NO. 482 O.D. 3/4 BWG 16	LENGTH 40 ft PITCH 15/16 Δ
38	SHELL	304 SS I.D. 24 O.D.	SHELL COVER (INTEG) (REMOVE)
39	CHANNEL OR BONNET	304 SS	CHANNEL COVER
40	TUBESHEET—STATIONARY	304 SS	TUBESHEET—FLOATING
41	BAFFLES—CROSS	304 SS TYPE	FLOATING HEAD COVER
42	BAFFLES—LONG	TYPE	IMPINGEMENT PROTECTION
43	TUBE SUPPORTS		
44	TUBE TO TUBESHEET JOINT		
45	GASKETS		
46	CONNECTIONS—SHELL SIDE	IN 10" OUT 10" RATING 300 #	
47	CHANNEL SIDE	IN 16" OUT 16" RATING	
48	CORROSION ALLOWANCE—SHELL SIDE	TUBE SIDE	
49	CODE REQUIREMENTS	ASME VIII DIV 1	TEMA CLASS C
50	REMARKS	WEIGHT 23,000 #	
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General Fabrication and Performance Information

FIGURE G-5.1

HEAT EXCHANGER SPECIFICATION SHEET

1			JOB NO.
2	CUSTOMER	REFERENCE NO.	
3	ADDRESS	PROPOSAL NO.	
4	PLANT LOCATION	COMMERCIAL	DATE
5	SERVICE OF UNIT	Condenser (1 of 6)	ITEM NO. 2a
6	SIZE	42-480	TYPE BEM (HORIZ.) (VERT.)
7	SQ. FT. SURF./UNIT (GROSS) (EFF.)	13140	SQ. FT. SURF./SHELL (GROSS) (EFF.) 13140
8	PERFORMANCE OF ONE UNIT		
9		SHELL SIDE	TUBE SIDE
10	FLUID CIRCULATED	OIL	CONDENSING STEAM
11	TOTAL FLUID ENTERING	16/hr	1,721,270
12	VAPOR		139,510
13	LIQUID	1,721,270	
14	STEAM		
15	NON-CONDENSABLES		
16	FLUID VAPORIZED OR CONDENSED		
17	STEAM CONDENSED		139,510
18	GRAVITY	0.694	
19	VISCOSITY	CP 0.14 / 0.57	
20	MOLECULAR WEIGHT		
21	SPECIFIC HEAT	0.592	BTU/LB.°F
22	THERMAL CONDUCTIVITY	0.067	BTU/HR-FT.°F
23	LATENT HEAT		BTU/LB
24	TEMPERATURE IN	497	°F
25	TEMPERATURE OUT	578	°F
26	OPERATING PRESSURE	75	PSIG
27	NO. PASSES PER SHELL	ONE	
28	VELOCITY	4.4	FT/SEC
29	PRESSURE DROP	10	PSI
30	FOULING RESISTANCE (MIN.)	0.001	
31	HEAT EXCHANGED-BTU/HR	86,320 x 10 ⁶	MTD CORRECTED °F 39.28
32	TRANSFER RATE—SERVICE	160	CLEAN 217
33	CONSTRUCTION OF ONE SHELL		
34	DESIGN PRESSURE	100	PSI
35	TEST PRESSURE		PSI
36	DESIGN TEMPERATURE	650	°F
37	TUBES	A 214 CS	NO. 1680 O.D. 3/4 BWG 14 LENGTH 40 ft PITCH 15/16 Δ
38	SHELL	CS	I.D. 42 O.D.
39	CHANNEL OR BONNET	CS	SHELL COVER (INTEG) (REMOV)
40	TUBESHEET—STATIONARY	CS	CHANNEL COVER
41	BAFFLES—CROSS	TYPE	TUBESHEET-FLOATING
42	BAFFLES—LONG	TYPE	FLUATIN G HEAD COVER
43	TUDE SUPPORTS		IMPINGEMENT PROTECTION
44	TUBE TO TUBESHEET JOINT		
45	GASKETS		
46	CONNECTIONS—SHELL SIDE	IN 18" OUT 18"	RATING 150
47	CHANNEL SIDE	IN 12" OUT 8"	RATING 1500
48	CORROSION ALLOWANCE—SHELL SIDE	1/16	TUBE SIDE
49	CODE REQUIREMENTS	ASME VIII, DIV 1	TEMA CLASS C
50	REMARKS	WEIGHT 74000 #	
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General Fabrication and Performance Information

FIGURE G-5.1

HEAT EXCHANGER SPECIFICATION SHEET

1			JOB NO.	
2	CUSTOMER		REFERENCE NO.	
3	ADDRESS		PROPOSAL NO.	
4	PLANT LOCATION <u>COMMERCIAL</u>		DATE	
5	SERVICE OF UNIT <u>SUBCOOLER (1 of 3)</u>		ITEM NO. <u>26</u>	
6	SIZE <u>39-240</u>	TYPE <u>BEM</u>	(HORIZ.) (VERT.)	CONNECTED IN
7	SQ. FT. SURF./UNIT (GROSS) (EFF.) <u>5700</u>	SHELLS/UNIT	SQ. FT. SURF./SHELL (GROSS) (EFF.) <u>5700</u>	
8	PERFORMANCE OF ONE UNIT			
9		SHELL SIDE	TUBE SIDE	
10	FLUID CIRCULATED	<u>WATER</u>	<u>OIL</u>	
11	TOTAL FLUID ENTERING	<u>279,020</u>	<u>3,442,530</u>	
12	VAPOR			
13	LIQUID	<u>279,020</u>	<u>3,442,530</u>	
14	STEAM			
15	NON-CONDENSABLES			
16	FLUID VAPORIZED OR CONDENSED			
17	STEAM CONDENSED			
18	GRAVITY		<u>0.71</u>	
19	VISCOSITY <u>cp</u>		<u>0.74 / 0.67</u>	
20	MOLECULAR WEIGHT			
21	SPECIFIC HEAT	BTU/LB.°F	<u>0.592</u>	BTU/LB.°F
22	THERMAL CONDUCTIVITY	BTU/HR-FT.°F	<u>0.063</u>	BTU/HR-FT.°F
23	LATENT HEAT	BTU/LB		BTU/LB
24	TEMPERATURE IN	°F	<u>589.8</u>	°F
25	TEMPERATURE OUT	°F	<u>492</u>	°F
26	OPERATING PRESSURE	PSIG	<u>1428</u>	PSIG
27	NO. PASSES PER SHELL		<u>ONE</u>	
28	VELOCITY	FT/SEC	<u>1.0</u>	FT/SEC
29	PRESSURE DROP	PSI	<u>5.0</u>	PSI
30	FOULING RESISTANCE (MIN.)			
31	HEAT EXCHANGED-BTU/HR	<u>34.65 x 10⁶</u>	MTD CORRECTED-°F	<u>39.50</u>
32	TRANSFER RATE—SERVICE	<u>154</u>	CLEAN	<u>238</u>
33	CONSTRUCTION OF ONE SHELL			
34	DESIGN PRESSURE	<u>1500</u>	PSI	<u>100</u>
35	TEST PRESSURE		PSI	
36	DESIGN TEMPERATURE	<u>650</u>	°F	<u>600</u>
37	TUBES <u>304 SS</u>	NO. <u>1460</u>	O.D. <u>3/4</u>	BWG <u>14</u>
38	SHELL <u>CS</u>	I.D. <u>39</u>	O.D.	
39	CHANNEL OR BONNET <u>CS</u>			
40	TUBESHEET—STATIONARY <u>CS</u>			
41	BAFFLES—CROSS <u>CS</u>	TYPE <u>H, CUT</u>		
42	BAFFLES—LONG	TYPE		
43	TUBE SUPPORTS			
44	TUBE TO TUBESHEET JOINT			
45	GASKETS			
46	CONNECTIONS—SHELL SIDE	IN <u>8</u>	OUT <u>8</u>	RATING <u>1500</u>
47	CHANNEL SIDE	IN <u>24</u>	OUT <u>24</u>	RATING <u>150</u>
48	CORROSION ALLOWANCE—SHELL SIDE		TUBE SIDE	
49	CODE REQUIREMENTS <u>ASME VIII, DIV 1</u>		TEMA CLASS <u>C</u>	
50	REMARKS <u>WEIGHT 52,500 #</u>			
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General Fabrication and Performance Information

FIGURE G-5.1

HEAT EXCHANGER SPECIFICATION SHEET

1			JOB NO.	
2	CUSTOMER		REFERENCE NO.	
3	ADDRESS		PROPOSAL NO.	
4	PLANT LOCATION		DATE	
5	SERVICE OF UNIT		ITEM NO.	
6	SIZE	TYPE	(HORIZ) (VERT)	CONNECTED IN
7	SQ. FT. SURF./UNIT (GROSS) (EFF.)	SHELLS/UNIT	SQ. FT. SURF./SHELL (GROSS) (EFF.)	
8	PERFORMANCE OF ONE UNIT			
9	SHELL SIDE		TUBE SIDE	
10	FLUID CIRCULATED			
11	TOTAL FLUID ENTERING			
12	VAPOR			
13	LIQUID			
14	STEAM			
15	NON-CONDENSABLES			
16	FLUID VAPORIZED OR CONDENSED			
17	STEAM CONDENSED			
18	GRAVITY			
19	VISCOSITY			
20	MOLECULAR WEIGHT			
21	SPECIFIC HEAT		BTU/LB.° F	BTU/LB.° F
22	THERMAL CONDUCTIVITY		BTU/HR-FT.° F	BTU/HR-FT.° F
23	LATENT HEAT		BTU/LB	BTU/LB
24	TEMPERATURE IN		° F	° F
25	TEMPERATURE OUT		° F	° F
26	OPERATING PRESSURE		PSIG	PSIG
27	NO. PASSES PER SHELL			
28	VELOCITY		FT/SEC	FT/SEC
29	PRESSURE DROP		PSI	PSI
30	FOULING RESISTANCE (MIN.)			
31	HEAT EXCHANGED-BTU/HR		MTD CORRECTED-° F	
32	TRANSFER RATE—SERVICE		CLEAN	
33	CONSTRUCTION OF ONE SHELL			
34	DESIGN PRESSURE		PSI	PSI
35	TEST PRESSURE		PSI	PSI
36	DESIGN TEMPERATURE		° F	° F
37	TUBES	NO. 1460 O.D. 3/4 BWG 14	LENGTH 12 ft	PITCH 15/16 Δ
38	SHELL	C.S. I.D. 39 O.D.	SHELL COVER	(INTEG) (REMOVA)
39	CHANNEL OR BONNET	C.S.	CHANNEL COVER	
40	TUBESHEET—STATIONARY	C.S.	TUBESHEET—FLOATING	
41	BAFFLES—CROSS	C.S. TYPE V. CUT	FLOATING HEAD COVER	
42	BAFFLES—LONG	TYPE	IMPINGEMENT PROTECTION	
43	TUBE SUPPORTS			
44	TUBE TO TUBESHEET JOINT			
45	GASKETS			
46	CONNECTIONS—SHELL SIDE	IN 8	OUT 8	RATING 400
47	CHANNEL SIDE	IN 24	OUT 24	RATING 150
48	CORROSION ALLOWANCE—SHELL SIDE	1/16	TUBE SIDE 1/16	
49	CODE REQUIREMENTS	ASME VIII, DIV 1	TEMA CLASS	C
50	REMARKS WEIGHT 22500 #			
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General Fabrication and Performance Information

FIGURE G-5.1

HEAT EXCHANGER SPECIFICATION SHEET

1			JOB NO.
2	CUSTOMER	REFERENCE NO.	
3	ADDRESS	PROPOSAL NO.	
4	PLANT LOCATION	COMMERCIAL	DATE
5	SERVICE OF UNIT	BOILER (1 of 8)	ITEM NO. 36
6	SIZE 40/54 - 480	TYPE BKM	(HORIZ.) (VERT.) CONNECTED IN
7	SQ. FT. SURF./UNIT (GROSS) (EFF.) 11 4/9	SHELLS/UNIT 1	SQ. FT. SURF./SHELL (GROSS) (EFF.) 11 4/9
8	PERFORMANCE OF ONE UNIT		
9		SHELL SIDE	TUBE SIDE
10	FLUID CIRCULATED	BOILING WATER	OIL
11	TOTAL FLUID ENTERING	113 062	1,718,830
12	VAPOR		
13	LIQUID		1,718,830
14	STEAM		
15	NON-CONDENSABLES		
16	FLUID VAPORIZED OR CONDENSED	113 062	
17	STEAM CONDENSED		
18	GRAVITY		0.63
19	VISCOSITY CP		0.36 / 0.61
20	MOLECULAR WEIGHT		
21	SPECIFIC HEAT		BTU/LB. ° F 0.592
22	THERMAL CONDUCTIVITY		BTU/HR-FT. ° F 0.067
23	LATENT HEAT		BTU/LB
24	TEMPERATURE IN	473.9 ° F	572 ° F
25	TEMPERATURE OUT	473.9 ° F	489.1 ° F
26	OPERATING PRESSURE	520.3 PSIG	50 PSIG
27	NO. PASSES PER SHELL	ONE	TWO
28	VELOCITY		FT/SEC 8.6
29	PRESSURE DROP		PSI 17
30	FOULING RESISTANCE (MIN.)	0.001	0.001
31	HEAT EXCHANGED-BTU/HR	84,333 x 10 ⁶	MTD CORRECTED ° F 44.16
32	TRANSFER RATE—SERVICE	16.9	CLEAN 275
33	CONSTRUCTION OF ONE SHELL		
34	DESIGN PRESSURE	600 PSI	100 PSI
35	TEST PRESSURE		
36	DESIGN TEMPERATURE	650 ° F	650 ° F
37	TUBES A 214 CS	NO. 1460 O.D. 3/4 BWG	14 LENGTH 40 ft PITCH 15/16 Δ
38	SHELL CS	I.D. 40/54 O.D.	SHELL COVER (INTG) (REMOV)
39	CHANNEL OR BONNET CS		CHANNEL COVER
40	TUBESHEET—STATIONARY CS		TUBESHEET—FLOATING
41	BAFFLES—CROSS — TYPE		FLOATING HEAD COVER
42	BAFFLES—LONG — TYPE		IMPINGEMENT PROTECTION
43	TUBE SUPPORTS CS	FULL	
44	TUBE TO TUBESHEET JOINT		
45	GASKETS		
46	CONNECTIONS—SHELL SIDE IN 6	OUT 12	RATING 400
47	CHANNEL SIDE IN 15	OUT 15	RATING 150
48	CORROSION ALLOWANCE—SHELL SIDE	TUBE SIDE	
49	CODE REQUIREMENTS ASME EBC, DIV 1	TEMA CLASS C	
50	REMARKS WEIGHT 65,000 #		
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General Fabrication and Performance Information

FIGURE G-5.1

HEAT EXCHANGER SPECIFICATION SHEET

1					JOB NO.
2	CUSTOMER				REFERENCE NO.
3	ADDRESS				PROPOSAL NO.
4	PLANT LOCATION <u>COMMERCIAL</u>				DATE
5	SERVICE OF UNIT <u>SUPER HEATER (1 of 4)</u>				ITEM NO. <u>4</u>
6	SIZE <u>25-432</u>	TYPE <u>BEM</u>	(HORIZ.) (VERT.)	CONNECTED IN <u>PARALLEL</u>	
7	SQ. FT. SURF./UNIT (GROSS) (EFF.) <u>3532</u>	SHELLS/UNIT <u>ONE</u>	SQ. FT. SURF./SHELL (GROSS) (EFF.) <u>3532</u>		
8	PERFORMANCE OF ONE UNIT				
9	SHELL SIDE		TUBE SIDE		
10	FLUID CIRCULATED <u>Hitec</u>		<u>Steam</u>		
11	TOTAL FLUID ENTERING <u>382,400</u>		<u>226,124</u>		
12	VAPOR				
13	LIQUID <u>382,400</u>				
14	STEAM		<u>226,124</u>		
15	NON-CONDENSABLES				
16	FLUID VAPORIZED OR CONDENSED				
17	STEAM CONDENSED				
18	GRAVITY <u>1.81</u>				
19	VISCOSITY <u>CP</u> <u>1.65 / 3.1</u>				
20	MOLECULAR WEIGHT				
21	SPECIFIC HEAT <u>0.323</u>		BTU/LB.°F	BTU/LB.°F	
22	THERMAL CONDUCTIVITY <u>0.35</u>		BTU/HR-FT.°F	BTU/HR-FT.°F	
23	LATENT HEAT		BTU/LB	BTU/LB	
24	TEMPERATURE IN <u>838</u>		°F	<u>473.9</u> °F	
25	TEMPERATURE OUT <u>570</u>		°F	<u>733</u> °F	
26	OPERATING PRESSURE <u>50</u>		PSIG	<u>550</u> PSIG	
27	NO. PASSES PER SHELL <u>ONE</u>		<u>ONE</u>		
28	VELOCITY <u>2</u>		FT/SEC	<u>51.7</u> FT/SEC	
29	PRESSURE DROP <u>20</u>		PSI	<u>6</u> PSI	
30	FOULING RESISTANCE (MIN.) <u>0.0005</u>		<u>0.0005</u>		
31	HEAT EXCHANGED-BTU/HR <u>38.69 x 10⁶</u>		MTD CORRECTED °F <u>99.51</u>		
32	TRANSFER RATE—SERVICE <u>110</u>		CLEAN	<u>125</u>	
33	CONSTRUCTION OF ONE SHELL				
34	DESIGN PRESSURE <u>100</u>		PSI	<u>600</u> PSI	
35	TEST PRESSURE		PSI	PSI	
36	DESIGN TEMPERATURE <u>900</u>		°F	<u>800</u> °F	
37	TUBES <u>304 SS</u>	NO. <u>502</u>	O.D. <u>3/4</u>	BWG <u>16</u>	LENGTH <u>36 ft</u> PITCH <u>15/16</u> Δ
38	SHELL <u>304 SS</u>	I.D. <u>25</u>	O.D.	SHELL COVER (INTEG) (REMOV)	
39	CHANNEL OR BONNET <u>CS</u>	CHANNEL COVER			
40	TUBESHEET—STATIONARY		TUBESHEET-FLOATING		
41	BAFFLES—CROSS <u>SS</u>	TYPE <u>H. CUT</u>	FLOATING HEAD COVER		
42	BAFFLES—LONG	TYPE	IMPINGEMENT PROTECTION		
43	TUBE SUPPORTS				
44	TUBE TO TUBESHEET JOINT				
45	GASKETS				
46	CONNECTIONS—SHELL SIDE	IN <u>8</u>	OUT <u>8</u>	RATING <u>300 #</u>	
47	CHANNEL SIDE	IN <u>16</u>	OUT <u>16</u>	RATING <u>600 #</u>	
48	CORROSION ALLOWANCE—SHELL SIDE		TUBE SIDE		
49	CODE REQUIREMENTS <u>ASME VIII, DIV 1</u>		TEMA CLASS <u>C</u>		
50	REMARKS <u>WEIGH 20,000 #</u>				
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General Fabrication and Performance Information

FIGURE G-5.1

HEAT EXCHANGER SPECIFICATION SHEET

1					JOB NO.
2	CUSTOMER				REFERENCE NO.
3	ADDRESS				PROPOSAL NO.
4	PLANT LOCATION <i>PILOT</i>				DATE
5	SERVICE OF UNIT <i>DESUPERHEATER</i>				ITEM NO. <i>1</i>
6	SIZE <i>18-480</i>	TYPE <i>BEN</i>	(HORIZ.) (VERT.)	CONNECTED IN	
7	SQ. FT. SURF./UNIT (GROSS) (EFF.) <i>1664</i>	SHELLS/UNIT <i>ONE</i>	SQ. FT. SURF./SHELL (GROSS) (EFF.) <i>1664</i>		
8	PERFORMANCE OF ONE UNIT				
9	SHELL SIDE		TUBE SIDE		
10	FLUID CIRCULATED <i>HITEC</i>		<i>SUPERHEATED STEAM</i>		
11	TOTAL FLUID ENTERING <i>196,156</i>		<i>112,064</i>		
12	VAPOR				
13	LIQUID <i>196,156</i>				
14	STEAM		<i>112,064</i>		
15	NON-CONDENSABLES				
16	FLUID VAPORIZED OR CONDENSED				
17	STEAM CONDENSED				
18	GRAVITY <i>1.81</i>				
19	VISCOSITY <i>CP</i> <i>3.31 / 1.65</i>				
20	MOLECULAR WEIGHT				
21	SPECIFIC HEAT <i>0.373</i>		BTU/LB.°F	BTU/LB.°F	
22	THERMAL CONDUCTIVITY <i>0.35</i>		BTU/HR-FT.°F	BTU/HR-FT.°F	
23	LATENT HEAT		BTU/LB	BTU/LB	
24	TEMPERATURE IN <i>570</i>		°F	<i>930</i> °F	
25	TEMPERATURE OUT <i>830</i>		°F	<i>671.6</i> °F	
26	OPERATING PRESSURE <i>25</i>		PSIG	<i>1450</i> PSIG	
27	NO. PASSES PER SHELL <i>ONE</i>			<i>ONE</i>	
28	VELOCITY <i>2</i>		FT/SEC	<i>45</i> FT/SEC	
29	PRESSURE DROP <i>23</i>		PSI	<i>4</i> PSI	
30	FOULING RESISTANCE (MIN.) <i>0.0005</i>			<i>0.0005</i>	
31	HEAT EXCHANGED-BTU/HR <i>20.455 x 10⁶</i>		MTD CORRECTED °F	<i>90.37</i>	
32	TRANSFER RATE—SERVICE <i>140</i>		CLEAN	<i>165</i>	
33	CONSTRUCTION OF ONE SHELL				
34	DESIGN PRESSURE		PSI	<i>1500</i> PSI	
35	TEST PRESSURE		PSI		
36	DESIGN TEMPERATURE <i>900</i>		°F	<i>1000</i> °F	
37	TUBES <i>304 SS</i>	NO. <i>215</i>	O.D. <i>3/4</i>	BWG <i>16</i>	LENGTH <i>40</i> FT
38	SHELL <i>304 SS</i>	I.D. <i>18</i>	O.D.	SHELL COVER (INTEG) (REMOV)	
39	CHANNEL OR BONNET <i>304 SS</i>	CHANNEL COVER			
40	TUBESHEET—STATIONARY <i>304 SS</i>	TUBESHEET—FLOATING			
41	BAFFLES—CROSS <i>304 SS</i>	TYPE <i>H CUT</i>	FLOATING HEAD COVER		
42	BAFFLES—LONG	TYPE	IMPINGEMENT PROTECTION <i>None</i>		
43	TUBE SUPPORTS				
44	TUBE TO TUBESHEET JOINT <i>Grooved and Rolled</i>				
45	GASKETS				
46	CONNECTIONS—SHELL SIDE	IN <i>6</i>	OUT <i>6</i>	RATING <i>300 #</i>	
47	CHANNEL SIDE	IN <i>12</i>	OUT <i>12</i>	RATING <i>1500 #</i>	
48	CORROSION ALLOWANCE—SHELL SIDE		TUBE SIDE		
49	CODE REQUIREMENTS <i>ASME VIII DIV 1</i>		TEMA CLASS <i>C</i>		
50	REMARKS <i>WEIGHT 12600 #</i>				
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General Fabrication and Performance Information

FIGURE G-5.1

HEAT EXCHANGER SPECIFICATION SHEET

1			JOB NO.	
2	CUSTOMER		REFERENCE NO.	
3	ADDRESS		PROPOSAL NO.	
4	PLANT LOCATION <i>PILLOT</i>		DATE	
5	SERVICE OF UNIT <i>CONDENSER</i>		ITEM NO. <i>2A</i>	
6	SIZE <i>42-480</i>	TYPE <i>BEM</i>	(HORIZ.) (VERT.)	CONNECTED IN
7	SQ. FT. SURF./UNIT (GROSS) (EFF.) <i>10882</i>	SHELLS/UNIT <i>ONE</i>	SQ. FT. SURF./SHELL (GROSS) (EFF.) <i>10882</i>	
8	PERFORMANCE OF ONE UNIT			
9	SHELL SIDE		TUBE SIDE	
10	FLUID CIRCULATED <i>OIL</i>		<i>CONDENSING STEAM</i>	
11	TOTAL FLUID ENTERING <i>1,505,000</i>		<i>122,013</i>	
12	VAPOR			
13	LIQUID <i>1,505,000</i>			
14	STEAM			
15	NON-CONDENSABLES			
16	FLUID VAPORIZED OR CONDENSED			
17	STEAM CONDENSED		<i>122,013</i>	
18	GRAVITY <i>0.694</i>			
19	VISCOSITY <i>2.74 / 0.55</i>			
20	MOLECULAR WEIGHT			
21	SPECIFIC HEAT <i>0.592</i>		BTU/LB. ° F	
22	THERMAL CONDUCTIVITY <i>0.067</i>		BTU/HR-FT. ° F	
23	LATENT HEAT		BTU/LB	
24	TEMPERATURE IN <i>497</i>		° F	
25	TEMPERATURE OUT <i>575</i>		° F	
26	OPERATING PRESSURE <i>75</i>		PSIG	
27	NO. PASSES PER SHELL <i>ONE</i>			
28	VELOCITY <i>4.4</i>		FT/SEC	
29	PRESSURE DROP <i>10</i>		PSI	
30	FOULING RESISTANCE (MIN.) <i>0.001</i>		<i>0.0005</i>	
31	HEAT EXCHANGED-BTU/HR <i>72.171 x 10⁶</i>		MTD CORRECTED ° F <i>39.28</i>	
32	TRANSFER RATE—SERVICE <i>168.9</i>		CLEAN <i>2.34</i>	
33	CONSTRUCTION OF ONE SHELL			
34	DESIGN PRESSURE <i>100</i>		PSI	
35	TEST PRESSURE		PSI	
36	DESIGN TEMPERATURE <i>650</i>		° F	
37	TUBES <i>A 214 CS</i> NO. <i>1424</i> O.D. <i>3/4</i> BWG <i>14</i> LENGTH <i>40 ft</i> PITCH <i>15/16</i> <i>△</i>			
38	SHELL <i>CS</i> I.D. <i>42</i> O.D.		SHELL COVER (INTEG) (REMOVE)	
39	CHANNEL OR BONNET <i>CS</i>		CHANNEL COVER	
40	TUBESHEET—STATIONARY		TUBESHEET—FLOATING	
41	Baffles—CROSS <i>CS</i> TYPE <i>VENT. DB</i>		FLOATING HEAD COVER	
42	BAFFLES—LONG TYPE		IMPINGEMENT PROTECTION	
43	TUBE SUPPORTS			
44	TUBE TO TUBESHEET JOINT			
45	GASKETS			
46	CONNECTIONS—SHELL SIDE	IN <i>18</i>	OUT <i>18</i>	RATING <i>150 #</i>
47	CHANNEL SIDE	IN <i>12</i>	OUT <i>8</i>	RATING <i>1500 #</i>
48	CORROSION ALLOWANCE—SHELL SIDE <i>1/16</i>		TUBE SIDE <i>1/16</i>	
49	CODE REQUIREMENTS <i>ASME VIII, DIV 1</i>		TEMA CLASS <i>C</i>	
50	REMARKS <i>WEIGHT 62800 #</i>			
51				
52				
53				
54				

General Fabrication and Performance Information

FIGURE G-5.1

HEAT EXCHANGER SPECIFICATION SHEET

1					JOB NO.
2	CUSTOMER				REFERENCE NO.
3	ADDRESS				PROPOSAL NO.
4	PLANT LOCATION <i>PILOT</i>				DATE
5	SERVICE OF UNIT <i>SUBCOOLER</i>				ITEM NO. <i>2B</i>
6	SIZE <i>28-252</i>	TYPE <i>BEM</i>	(HORIZ.) (VERT.)	CONNECTED IN	
7	SQ. FT. SURF./UNIT (GROSS) (EFF.) <i>2220</i>	SHELLS/UNIT <i>ONE</i>	SQ. FT. SURF./SHELL (GROSS) (EFF.) <i>2220</i>		
8	PERFORMANCE OF ONE UNIT				
9	SHELL SIDE		TUBE SIDE		
10	FLUID CIRCULATED <i>WATER</i>		<i>DI</i>		
11	TOTAL FLUID ENTERING <i>122.013</i>		<i>1505.000</i>		
12	VAPOR				
13	LIQUID <i>122.013</i>		<i>1505.000</i>		
14	STEAM				
15	NON-CONDENSABLES				
16	FLUID VAPORIZED OR CONDENSED				
17	STEAM CONDENSED				
18	GRAVITY		<i>0.71</i>		
19	VISCOSITY		<i>0.74 / 0.67</i>		
20	MOLECULAR WEIGHT				
21	SPECIFIC HEAT		BTU/LB.°F	<i>0.592</i>	BTU/LB.°F
22	THERMAL CONDUCTIVITY		BTU/HR-FT.°F	<i>0.063</i>	BTU/HR-FT.°F
23	LATENT HEAT		BTU/LB		BTU/LB
24	TEMPERATURE IN <i>589.5</i>		°F	<i>480</i>	°F
25	TEMPERATURE OUT <i>492</i>		°F	<i>497</i>	°F
26	OPERATING PRESSURE <i>14.28</i>		PSIG	<i>25</i>	PSIG
27	NO. PASSES PER SHELL <i>ONE</i>		<i>ONE</i>		
28	VELOCITY <i>2</i>		FT/SEC	<i>8.5</i>	FT/SEC
29	PRESSURE DROP <i>5</i>		PSI	<i>5</i>	PSI
30	FOULING RESISTANCE (MIN.) <i>0.001</i>		<i>0.001</i>		
31	HEAT EXCHANGED-BTU/HR <i>15.166 x 10⁶</i>		MTD CORRECTED-°F		<i>39.50</i>
32	TRANSFER RATE—SERVICE <i>173</i>		CLEAN		<i>287</i>
33	CONSTRUCTION OF ONE SHELL				
34	DESIGN PRESSURE <i>1500</i>		PSI	<i>100</i>	PSI
35	TEST PRESSURE		PSI		PSI
36	DESIGN TEMPERATURE <i>650</i>		°F	<i>600</i>	°F
37	TUBES <i>A249-304SS</i>	NO. <i>600</i>	O.D. <i>3/4</i>	BWG <i>14</i>	LENGTH <i>21 ft</i>
38	SHELL <i>CS</i>	I.D. <i>28</i>	O.D.	SHELL COVER (INTEG) (REMOV)	
39	CHANNEL OR DONNET <i>CS</i>	CHANNEL COVER			
40	TUBESHEET—STATIONARY <i>CS</i>	TUBESHEET—FLOATING			
41	BAFFLES—CROSS <i>CS</i>	TYPE <i>H CUT</i>	FLOATING HEAD COVER		
42	BAFFLES—LONG	TYPE	IMPINGEMENT PROTECTION		
43	TUBE SUPPORTS				
44	TUBE TO TUBESHEET JOINT				
45	GASKETS				
46	CONNECTIONS—SHELL SIDE	IN <i>6</i>	OUT <i>6</i>	RATING <i>1500#</i>	
47	CHANNEL SIDE	IN <i>18</i>	OUT <i>18</i>	RATING <i>150#</i>	
48	CORROSION ALLOWANCE—SHELL SIDE		TUBE SIDE		
49	CODE REQUIREMENTS <i>ASME VIII DIV 1</i>		TEMA CLASS <i>C</i>		
50	REMARKS <i>WEIGHT 21,100#</i>				
51					
52					
53					
54					

General Fabrication and Performance Information

FIGURE G-5.1

HEAT EXCHANGER SPECIFICATION SHEET

1			JOB NO.
2	CUSTOMER	REFERENCE NO.	
3	ADDRESS	PROPOSAL NO.	
4	PLANT LOCATION	DATE	
5	SERVICE OF UNIT	ITEM NO.	3A
6	SIZE 28-144	TYPE BEM	CONNECTED IN
7	SQ. FT. SURF./UNIT (GROSS) 1740	SHELLS/UNIT ONE	SQ. FT. SURF./SHELL (GROSS) 1740
8	PERFORMANCE OF ONE UNIT		
9		SHELL SIDE	TUBE SIDE
10	FLUID CIRCULATED	WATER	OIL
11	TOTAL FLUID ENTERING	108,050	1,643,000
12	VAPOR		
13	LIQUID	108,080	1,643,000
14	STEAM		
15	NON-CONDENSABLES		
16	FLUID VAPORIZED OR CONDENSED		
17	STEAM CONDENSED		
18	GRAVITY		0.71
19	VISCOSITY CP		0.67 / 0.12
20	MOLECULAR WEIGHT		
21	SPECIFIC HEAT	BTU/LB.°F	0.592 BTU/LB.°F
22	THERMAL CONDUCTIVITY	BTU/HR-FT.°F	0.065 BTU/HR-FT.°F
23	LATENT HEAT	BTU/LB	
24	TEMPERATURE IN	401 °F	488.1 °F
25	TEMPERATURE OUT	474.9 °F	480 °F
26	OPERATING PRESSURE	550 PSIG	85 PSIG
27	NO. PASSES PER SHELL	ONE	ONE
28	VELOCITY	2 FT/SEC	2.4 FT/SEC
29	PRESSURE DROP	10 PSI	3 PSI
30	FOULING RESISTANCE (MIN.)	0.001	0.001
31	HEAT EXCHANGED-BTU/HR	8.873 x 10 ⁶	MTD CORRECTED °F 31.26
32	TRANSFER RATE--SERVICE	150	CLEAN 228
33	CONSTRUCTION OF ONE SHELL		
34	DESIGN PRESSURE	650 PSI	100 PSI
35	TEST PRESSURE		PSI
36	DESIGN TEMPERATURE	500 °F	550 °F
37	TUBES A214 CS	NO. 150 O.D. 3/4 BWG	14 LENGTH 15 ft PITCH 15/16 Δ
38	SHELL CS	I.D. 28 O.D.	SHELL COVER (INTEG) (REMOV)
39	CHANNEL OR BONNET CS		CHANNEL COVER
40	TUBESHEET--STATIONARY CS		TUBESHEET-FLOATING
41	BAFFLES--CROSS CS	TYPE V CUT	FLOATING HEAD COVER
42	BAFFLES--LONG	TYPE	IMPINGEMENT PROTECTION
43	TUBE SUPPORTS		
44	TUBE TO TUBESHEET JOINT		
45	GASKETS		
46	CONNECTIONS-SHELL SIDE	IN 6 OUT 6	RATING ASA 400#
47	CHANNEL SIDE	IN 18 OUT 18	RATING ASA 150#
48	CORROSION ALLOWANCE--SHELL SIDE	1/16	TUBE SIDE 1/16
49	CODE REQUIREMENTS ASME VIII, DIV 1		TEMA CLASS C
50	REMARKS	WEIGHT 12400 #	
51			
52			
53			
54			

General Fabrication and Performance Information

FIGURE G-5.1

HEAT EXCHANGER SPECIFICATION SHEET

1			JOB NO.
2	CUSTOMER	REFERENCE NO.	
3	ADDRESS	PROPOSAL NO.	
4	PLANT LOCATION	DATE	
5	SERVICE OF UNIT	ITEM NO.	
6	SIZE	TYPE	CONNECTED IN
7	SQ. FT. SURF./UNIT	SHELLS/UNIT	SQ. FT. SURF./SHELL
8	PERFORMANCE OF ONE UNIT		
9		SHELL SIDE	TUBE SIDE
10	FLUID CIRCULATED	Boiling Water	Oil
11	TOTAL FLUID ENTERING	108,050	1,643,000
12	VAPOR		
13	LIQUID		1,643,000
14	STEAM		
15	NON-CONDENSABLES		
16	FLUID VAPORIZED OR CONDENSED	108,050	
17	STEAM CONDENSED		
18	GRAVITY		0.63
19	VISCOSITY	CP	0.56 / 0.67
20	MOLECULAR WEIGHT		
21	SPECIFIC HEAT	BTU/LB.°F	0.592 BTU/LB.°F
22	THERMAL CONDUCTIVITY	BTU/HR-FT.°F	0.067 BTU/HR-FT.°F
23	LATENT HEAT	BTU/LB	
24	TEMPERATURE IN	473.2 °F	572 °F
25	TEMPERATURE OUT	473.9 °F	482.1 °F
26	OPERATING PRESSURE	539.5 PSIA	75 PSIG
27	NO. PASSES PER SHELL	ONE	TWO
28	VELOCITY	— FT/SEC	8.5 FT/SEC
29	PRESSURE DROP	— PSI	16.5 PSI
30	FOULING RESISTANCE (MIN.)	0.001	0.001
31	HEAT EXCHANGED-BTU/HR	80,617 x 10 ⁶	MTD CORRECTED-°F 44.16
32	TRANSFER RATE—SERVICE	169	CLEAN 275
33	CONSTRUCTION OF ONE SHELL		
34	DESIGN PRESSURE	600 PSI	100 PSI
35	TEST PRESSURE	— PSI	— PSI
36	DESIGN TEMPERATURE	650 °F	650 °F
37	TUBES	A214 CS NO. 1400 O.D. 3/4 BWG 14 LENGTH 40 ft PITCH 15/16 Δ	
38	SHELL	CS I.D. 40/54 O.D.	SHELL COVER (INTEG) (REMOV)
39	CHANNEL OR BONNET	CS	CHANNEL COVER
40	TUBESHEET—STATIONARY	CS	TUBESHEET-FLOATING
41	BAFFLES—CROSS	— TYPE	FLOATING HEAD COVER
42	BAFFLES—LONG	— TYPE	IMPINGEMENT PROTECTION NONE
43	TUBE SUPPORTS	Full	
44	TUBE TO TUBESHEET JOINT	Grooved and Rolled	
45	GASKETS		
46	CONNECTIONS-SHELL SIDE	IN 6 OUT 12	RATING 400 #
47	CHANNEL SIDE	IN 18 OUT 18	RATING 150 #
48	CORROSION ALLOWANCE—SHELL SIDE	1/16	TUBE SIDE 1/16
49	CODE REQUIREMENTS	ASME VIII DIV 1	TEMA CLASS C
50	REMARKS	C-4000 #	
51			
52			
53			
54			

General Fabrication and Performance Information

FIGURE G-5.1

HEAT EXCHANGER SPECIFICATION SHEET

1					JOB NO.
2	CUSTOMER				REFERENCE NO.
3	ADDRESS				PROPOSAL NO.
4	PLANT LOCATION <i>PILOT</i>				DATE
5	SERVICE OF UNIT <i>SUPER HEATER</i>				ITEM NO. <i>4</i>
6	SIZE <i>18-360</i>	TYPE <i>BEM</i>	(HORIZ.) (VERT.)	CONNECTED IN	
7	SQ. FT. SURF./UNIT (GROSS) (EFF.) <i>1618</i>	SHELLS/UNIT <i>ONE</i>	SQ. FT. SURF./SHELL (GROSS) (EFF.) <i>1618</i>		
8	PERFORMANCE OF ONE UNIT				
9	SHELL SIDE		TUBE SIDE		
10	FLUID CIRCULATED	<i>HLI EC</i>	<i>SUPERHEATED STEAM</i>		
11	TOTAL FLUID ENTERING	<i>184,991</i>	<i>108,050</i>		
12	VAPOR				
13	LIQUID	<i>184,991</i>			
14	STEAM		<i>108,050</i>		
15	NON-CONDENSABLES				
16	FLUID VAPORIZED OR CONDENSED				
17	STEAM CONDENSED				
18	GRAVITY	<i>1.81</i>			
19	VISCOSITY <i>CP</i>	<i>1.65 / 3.10</i>			
20	MOLECULAR WEIGHT				
21	SPECIFIC HEAT	<i>0.323</i>	BTU/LB.°F	BTU/LB.°F	
22	THERMAL CONDUCTIVITY	<i>0.35</i>	BTU/HR-FT.°F	BTU/HR-FT.°F	
23	LATENT HEAT		BTU/LB	BTU/LB	
24	TEMPERATURE IN	<i>538</i>	°F	<i>473.7</i>	°F
25	TEMPERATURE OUT	<i>570</i>	°F	<i>235</i>	°F
26	OPERATING PRESSURE	<i>25</i>	PSIG	<i>530</i>	PSIG
27	NO. PASSES PER SHELL	<i>ONE</i>		<i>ONE</i>	
28	VELOCITY	<i>1.5</i>	FT/SEC	<i>54.7</i>	FT/SEC
29	PRESSURE DROP	<i>20</i>	PSI	<i>5</i>	PSI
30	FOULING RESISTANCE (MIN.)	<i>0.0005</i>		<i>0.0005</i>	
31	HEAT EXCHANGED-BTU/HR	<i>18,4925 X 10⁶</i>	MTD CORRECTED °F	<i>99.51</i>	
32	TRANSFER RATE--SERVICE	<i>115</i>	CLEAN	<i>132</i>	
33	CONSTRUCTION OF ONE SHELL				
34	DESIGN PRESSURE	<i>100</i>	PSI	<i>600</i>	PSI
35	TEST PRESSURE		PSI		PSI
36	DESIGN TEMPERATURE	<i>900</i>	°F	<i>800</i>	°F
37	TUBES <i>304 SS</i>	NO. <i>278</i>	O.D. <i>3/4</i> BWG <i>16</i>	LENGTH <i>30 ft</i>	PITCH <i>15/16</i> Δ
38	SHELL <i>304 SS</i>	I.D. <i>18</i> O.D.	SHELL COVER (INTEG) (REMOV)		
39	CHANNEL OR BONNET <i>CS</i>	CHANNEL COVER			
40	TUBESHEET--STATIONARY <i>304 SS</i>	TUBESHEET-FLOATING			
41	BAFFLES--CROSS <i>304 SS</i> TYPE <i>H. CUT</i>	FLOATING HEAD COVER			
42	BAFFLES--LONG TYPE	IMPINGEMENT PROTECTION			
43	TUBE SUPPORTS				
44	TUBE TO TUBESHEET JOINT <i>Grooved & Rolled</i>				
45	GASKETS				
46	CONNECTIONS--SHELL SIDE	IN <i>6</i>	OUT <i>6</i>	RATING <i>300 #</i>	
47	CHANNEL SIDE	IN <i>12</i>	OUT <i>12</i>	RATING <i>600 #</i>	
48	CORROSION ALLOWANCE--SHELL SIDE	TUBE SIDE			
49	CODE REQUIREMENTS <i>ASME VIII, DIV 1</i>	TEMA CLASS <i>C</i>			
50	REMARKS <i>WEIGHT 10500 #</i>				
51					
52					
53					
54					

ATTEMPERATOR REQUIREMENTS

ATTEMPT No. 1

Design Condition	P	T	h	Pilot Plant m	Commercial
	<u>kPa</u>	<u>°C</u>	<u>kJ/kg</u>	<u>kg/h</u>	<u>kg/h</u>
STEAM INLET	10,100	510	3398.8	59,600	342,900
WATER	10,140	172	731.3	609	3,490
STEAM DISCHARGE	10,000	499	3371.7	60,200	346,390
<u>Range of Operation</u>					
Mass Flow Range Inlet St	31,715 - 63,500 kg/h <u>20-1 turn down</u>				
TEMP RANGE	499 to 524 °C				
Pressure	9300 - 10,340 kPa				

ATTEMP'S Nos. 2a & 2b

<u>Design Conditions</u>					
STEAM INLET	10,000	383.6	3047.7	60,200	346,390
WATER	10,140	172	731.3	9,630	55,340
STEAM DISCHARGE	9,960	316	2588.6	69,830	401,730
<u>Range of Operation</u>					
Steam Mass Flow Rate	3175 - 63,500 kg/hr <u>20-1 turn down</u>				
Inlet Temp Range	304 to 454°C				
Pressure	9300 to 10,340 kPa				

40703-V

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STRUCTURES AND FOUNDATIONS

DATA SHEETS

40703-V

DESIGN DATA REQUIREMENTS SHEET

FOUNDATION DESIGN - OIL/ROCK TANK

● Soil Bearing Capacity	10,000 PSF	10 ft below grade
● Tank Weight (excluding bottom)	2.12 K/ft	
● Product Head (Press)	5.99 K/ft ²	
● Product on Knuckle (Press)	12.35 K/ft ²	
● Earthquake Load	$\pm$ 33.3 K/ft	
● Uplift Due to Pressure	2.81 K/ft	
● Soil Density	100 lb/ft ³	
● Concrete Density	140 lb/ft ³	
● Concrete Strength	3000 Psi	
● Reinforcement (A615-60)	Fy = 60000 KSI	
● Vertical Acceleration	$\pm$.25 g's	

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STORAGE MATERIALS

DATA SHEETS

DESIGN DATA REQUIREMENTS SHEET
HEAT TRANSFER FLUID PROPERTIES

Use	Hitec Tank (Hot and Cold)
Freezing Point	288°F (142°C)
Viscosity	17mPa-s at 149°C 1.5mPa-s at 438°C
Electrical Resistivity	1.7/cm
Latent Heat of Fusion	20 callg
Specific Heat	0.32 callg. C
Nominal Operating Range	142°C - 409°C
Heat Transfer Coefficient	-800 BTU/hr. ft ² F at 289°C -2900 BTU/hr. ft ² F at 442°C
Recommended Material	Dupont *Hitec Salt or Equivalent

DESIGN DATA REQUIREMENTS SHEET
HEAT TRANSFER FLUID PROPERTIES

Use	Oil/Rock Tank
Bulk Temperature	600°F (285°C) Maximum
Film Temperature	680°F (325°C) Maximum
Pour Point	15°F (-9°C)
Flash Point (COC)	420°F (216°C)
Auto-ignition Temp	759°F (404°C)
Vapor Press	0.689 kPa at 184°C 1.378 kPa at 209°C 2.067 kPa at 234°C 5.856 kPa at 272°C 7.579 kPa at 284°C
Recommended Material	Exxon CALORIA HT-43 or Equivalent

SYSTEM VALVES AND PUMPS

DATA SHEET

VALVES - STEAM AND WATER
CHARGE SYSTEM

<u>Line</u> <u>Designation</u>	<u>Gates</u> <u>1"-14"</u> <u>Number</u>	<u>Globes</u> <u>1"-24"</u> <u>Number</u>	<u>Design</u> <u>Class</u>	<u>Trim</u>
DSS	07	7187	1500 WCB	XU
ATS	83	7181	900 WC9	XU
CSS	83	7181	900 WCB	XU
CRS	83	7181	900 NCB	XU
SCS	83	7181	900 WCB	XU
SCR	83	7181	900 WCB	XU

GATE VALVES - Cast steel bolted bonnet outside screw and
yolk flanged
Numbers - Crane Company

GLOBE VALVES - Pressure seal bonnet
Butt-Welded
Numbers - Crane Company

VALVES - STEAM AND WATER
DISCHARGE SYSTEM

<u>Line</u> <u>Designation</u>	<u>Gates</u> <u>2"-24"</u> <u>Number</u>	<u>Globes</u> <u>2"-8"</u> <u>Number</u>	<u>Design</u> <u>Class</u>	<u>Trim</u>
SHS	76	171	600 WCB	XU
SAS	76	171	600 WCB	XU
PBS	61 (4"-16")	161 (4"-8")	400 WCB	XU
FWS	61 (4"x16")	161 (4"-8")	400 WCB	XU

GATE VALVES - Cast steel bolted bonnet outside screw and
yolk flanged
Numbers - Crane Company

GLOBE VALVES - Cast steel bolted bonnet
Outside screw and yolk flanged
Numbers - Crane Company

VALVES - OIL
CHARGE AND DISCHARGE SYSTEM

<u>Line</u>	<u>Gates</u>	<u>Globes</u>	<u>Design</u>	
<u>Designation</u>	<u>2"-14"</u>	<u>1"-14"</u>	<u>Class</u>	<u>Trim</u>
	<u>Number</u>	<u>Number</u>		
MCL	47	143	150	XU
MCS	47	143	150	XU
MCB	47	143	150	XU
MDS	47	143	150	XU
MDR	47	143	150	XU
MDB	47	143	150	XU

GATE VALVES - Cast steel bolted bonnet outside screw and
yolk flanged
Numbers - Crane Company

GLOBE VALVES - Cast steel bolted bonnet outside screw and
yolk flanged
Numbers - Crane Company

VALVES - HITEC
CHARGE AND DISCHARGE SYSTEM

<u>Line</u> <u>Designation</u>	<u>Gates</u> <u>2"-12"</u> <u>Number</u>	<u>Globes</u> <u>2"-14"</u> <u>Number</u>	<u>Design</u> <u>Class</u>	<u>Trim</u>
HCS	47	143	150	A
HCL	47	143	150	A
HCB	47	143	150	A
HDS	47	143	150	A
HDB	47	143	150	A
HDR	47	143	150	A

GATE VALVES - Cast steel bolted bonnet outside screw and
yolk flanged
Numbers - Crane Company

GLOBE VALVES - Cast steel bolted bonnet outside screw and
yolk flanged
Numbers - Crane Company

PILOT PLANT PUMP SPECIFICATION

1) Superheater Pumps (two required)

Type	Centrifugal constant speed
Flow rate	13.3 lit/s (211 GPM)
Head	22.5 m (73.8 ft)
Fluid	molten salt (53%KNO ₃ , 40%NaNO ₂ , 7%NaNO ₃) Trade name Hitec or Partherm 290
Specific Gravity	2.0 maximum, normal operating range 1.75 to 1.86
Viscosity	1.4×10^{-3} to 3.5×10^{-3} Nt s/m ²
Vapor Pressure	Zero
Temperature (max.)	454°C (850°F)
NPSH (available)	1.2 m (4 ft)
Packing	Oil less, should not require cooling.
Motor	Single speed TEFC Class H insulation
Materials	304 ss or 316 ss or equivalent corrosion resistance to salt.
Assembly	Pump, motor, baseplate, coupling assembled as unit. Must be able to remove impeller without removing pump from line or moving the motor

2) Main Storage Oil Pumps (two required)

Type	Centrifugal (two speed)
Flow	316 lit/s (5000 GPM)
Head	36.6 m (120 ft)
Fluid	Mineral oil Exxon CALORIA HT-43 or equivalent
Specific Gravity	Maximum 0.86, operating 0.66 to 0.7
Vapor Pressure	100 kPa (14.7 Psia)
NPSH (available)	7.6 m (25 ft)

Operating Temp	303°C (578°F)
Viscosity	Max. $10^{-4} \text{m}^2/\text{s}$ (100 cSt) Operating $7 \times 10^{-7} \text{m}^2/\text{s}$ (0.7 cst)
Packing	Should not contain copper Should not require cooling
Motor	Two speed, TEFC, Class H insulation
Assembly	Pump, motor, baseplate, coupling assembled as a unit, must be able to remove impeller without removing pump from line or moving the motor.

COMMERCIAL PLANT T/S PUMP REQUIREMENTS

	Max. * Temp °F	M lbm/hr	V GPM	lbm/ft ³	Head feet	Head psi	No of Pumps ---	Capacity GPM	NPSH feet
HITEC									
Charge Loop	350	949,300	1015	116.6	65	53	3	340	20
Discharge Loop	350	1,395,000	1590	109.4	65	50	4	400	20
OIL (HT-43)									
Charge Loop	578	8,527,000	24500	43.4	200	60	3	8200	25
Discharge Loop	578	13,070,000	40000	41.1	210	60	8	5000	30
TRACE HEATING									
Water Pump	300	4750	10	59.4	666	275	1	10	10
Oil Pump	578	80,000	14500	41.1	105	30	1	250	30

*Note: The density used in calculating heat was that for design point conditions - not for the density at maximum temperature.

PROCESS INSTRUMENTATION

DATA SHEETS

Storage Control Component Specifications

Specifications for the components in the automatic storage control sub-systems are given below.

Control Valves

- Materials - Valve bodies should be made of cast steel for temperatures up to 399°C. Above that temperature a 316 stainless should be used.
Trim plug and cage should be 17-4 PH or no. 6 solid stellite for the higher temperatures or 316 for temperatures up to 399° (750°F).
- Packings - Shredded teflon, teflon asbestos, or graphite asbestos should be used on the valves depending on the temperature range.
- Bonnets - Cast steel may be used for temperatures up to 282°C (450°F). At higher ranges, extension columns should be used. Stainless steel is also an acceptable material.
End connections should be flanged and all trim and plugs should be removable to facilitate overhaul.

Electro-pneumatic valve positioner

Performance

- Linearity 1% of span
Deadband 0.1% of span
Hysteresis 1% of span

Mounting

The positioner should be able to be mounted on the side of the actuator.

Span & Zero Adjustments

Should be easily adjusted by adjusting screws.

Stroke

Should work with any actuator 1.27 to 10.16 cm stroke.

Supply Pressure

64.7 Psia = 446 kPa

34.7 Psia = 239 kPa

Handling Capacity

7 scfm with 34.7 Psia pressure = 239 kPa

3304 cm³/sec

Input

4 to 20 milliamperes

Actuator

Operates on a small air signal from a controller and converts this signal into a mechanical force.

Air supply

64.7 Psia = 446 kPa

Air connections 0.64 cm

Travels

Depends on the valve selected

Construction

Steel or cast iron

Diaphragm

Nerprene with fabric insert

Spring ranges

17.7 - 29.7 Psia = 122 - 205 kPa

20.7 to 44.7 Psia = 143 to 308 kPa

Bonnet

(Radiation fin for temperature over 282°C (450°F)).

Analog Control Circuit

The control circuit sums the feedback signals from the various sensors and provides the proportional integral, and summing of these signals. The output is to a valve positioner that converts the electrical to a pneumatic signal for the actuator.

Input

1-5 VDC, 4-20 MA DC

Feedback Signal

1-5 VDC (950-1550 ohms source)

Output

4-20 MA into 790 ohms

Power DC

24 VDC nominal

Accuracy

+1% span

Normal Operating Conditions

16 - 49°C (60° to 120° F)

23 to 26 VDC

10 - 90% R. H. (humidity)

Operating Features

Integral, proportional, summing, derivative, gain adjust and limit switches.

GENERAL REQUIREMENTS

General Environment

All sensors and transmitters shall be capable of operating satisfactorily within the range of typical environment conditions established for Barstow, California.

Ambient Temperature Operation

All sensors and transmitters shall operate rated within the temperature range of -5°C to $+50^{\circ}\text{C}$. All electronic indicating and controlling equipment shall be capable of operating throughout the temperature range of 16°C to 49°C .

Accuracy (Sensors)

Sensors or transducers shall have a nominal full scale accuracy of $\pm 0.5\%$ or better.

Repeatability (Sensors)

Sensors or transducers shall have a repeatability within $\pm 1\%$ of indicated value.

Accuracy (Transmitters)

Transmitters shall have either a 4-20 ma or 1-5 VDC output capability with typical accuracy of $\pm 0.5\%$.

Repeatability (Transmitters)

Transmitters shall have repeatability within $\pm 1\%$ of indicated value, typical.

Indicators

Indicators shall have an accuracy requirement of $\pm 2\%$ full scale.

Power

All electronic equipment shall operate from 24 VDC power.

DESIGN DATA REQUIREMENTS SHEET

PROCESS INSTRUMENTATION

<u>Sensors</u>	<u>Pilot</u>		<u>Commercial</u>	
	Qty.		Qty.	
-Pressure	27		74	
-Temperature	31		50	
-Flow	17		47	
-Level	5		15	
<u>Transmitters</u>				
-Pressure	27		74	
-Temperature	31		50	
-Flow	15		47	
-Level	5		15	
<u>Indicators (Local Control)</u>		<u>Hi/Lo Alarms</u>		<u>Hi/Lo Alarm</u>
-Pressure	5	5/2	10	5/5
-Temperature	4	4/2	8	8/8
-Flow	0	0/0	0	0/0
-Level	5	5/5	10	5/5
<u>Indicators (Central Control)</u>				
-Pressure	10	10/5	20	10/10
-Temperature	16	10/10	40	25/25
-Flow	8	5/5	29	10/10
-Level	5	5/5	15	15/15
<u>Recorders (Central Control)</u>				
-Trend (12 channel)	2		2	
-3 channel	3		3	

PRESSURE TRANSMITTERS

Symbol	Design Pr	Max. Pr	Line Size	Mat'l in Line	Temp Amb
PT-1	1465 PSIA	1800 PSIA	7.625	Steam	930° max.
PT-2	"	"	"	"	"
PT-3	1405 PSIA	"	"	"	"
PT-4	50 PSIA	100 PSIA	4.026	Salt	
PT-5	50 PSIA	"	"	"	850°F
PT-6	50 PSIA	"	"	"	835°F
PT-7	550 PSIA	"	"	"	570°F
PT-8	"	"	"	"	"
PT-9	525 PSIA	"	9.75	Steam	735°F
PT-10	.2 PSIG	.5 PSIG		N ₂	850°F
PT-11	1.1 PSIG	1.5 PSIG		N ₂	580°F
PT-12	1425 PSIA	1800 PSIA	7.625	Steam	600°F
PT-13	1400 PSIA	" PSIA	4.813	H ₂ O	590°F
PT-14	50 PSIA	90 PSIA	13.25	Oil	930°F
PT-15	50 PSIA	"	13.25	Oil	930°F
PT-16	50 PSIA	"	13.25	Oil	
PT-17	50 PSIA	"	"	Oil	
PT-18	575 PSIA	650 PSIA	3.826	H ₂ O	350°F
PT-19	575 PSIA	"	3.826	"	490°F
PT-20	575 PSIA	"	4.026	Oil	490°F
PT-21	525 PSIA	650 PSIA	7.625	Steam	735°F
PT-22	Oil Manifold Press-		"		
	Upper	0-1000 PSIA		Oil	850°F
PT-23	" " "	"		Oil	850°F
PT-24	" " "	"		"	850°F
	Lower	"		"	850°F
PT-25	" " "	"		"	850°F
	Lower	"			850°F
PT-26	575 PSIA	"	7.625	FW Press-	
				Discharge	
PT-27	50 PSIA	100 PSIA	3.826	Oil	

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TEMPERATURE TRANSMITTERS, ELEMENTS, WELLS

<u>Symbol</u>	<u>Design Temp.</u>	<u>T max</u>	<u>Line Size</u>	<u>Mat'l in Line</u>
TT-1			Pipe Mt.	
TE-1	900°F	1000°F		Steam
TW-1				
(Prit. Tubes)				
TT-2			Pipe Mt.	
TE-2	900°F	1030°F		Steam
TW-2				
TT-3			Pipe Mt.	
TE-3	558°F	1000°F		Salt
TW-3				
TT-4			Pipe Mt.	
TE-4	850°F	1000°F		Salt
TT-5			Pipe Mt.	
TE-5	600°F	1000°F		Steam
TW-5				
TT-6			Pipe Mt.	
TE-6	838°F	1000°F		Salt
TW-6				
TT-7			Pipe Mt.	
TE-7	570°F	1000°F		Salt
TW-7				
TT-8			Pipe Mt.	
TE-8	490°F	1000°F		Steam
TW-8				
TT-9			Pipe Mt.	
TE-9	735°F	1000°F		Steam
TW-9				

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TEMPERATURE TRANSMITTERS, ELEMENTS, WELLS (Continued)

<u>Symbol</u>	<u>Design Temp.</u>	<u>T max</u>	<u>Line Size</u>	<u>Mat'l in Line</u>
TT-10 TE-10 TW-10	850°F	1000°F	Pipe Mt.	Salt
TT-11 TE-11 TW-11	850°F	1000°F	Pipe Mt.	Salt
TT-12 TE-12 TW-12	600°F	1000°F	Pipe Mt.	Steam
TT-13 TE-13 TW-13	590°F	1000°F	Pipe Mt.	H ₂ O
TT-14 TE-14 TW-14	476°F	650°F	Pipe Mt.	Oil
TT-15 TE-15 TW-15	578°F	650°F	Pipe Mt.	Oil
TT-16 TE-16 TW-16	570°F	650°F	Pipe Mt.	Oil
TT-17 TE-17 TW-17	500°F	1000°F	Pipe Mt.	H ₂ O
TT-18 TE-18 TW-18	490°F	1000°F	Pipe Mt.	H ₂ O

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TEMPERATURE TRANSMITTERS, ELEMENTS, WELLS (Continued)

<u>Symbol</u>	<u>Design Temp.</u>	<u>T max</u>	<u>Line Size</u>	<u>Mat'l in Line</u>
TT-19 TE-19 TW-19	350°F	1000°F	Pipe Size	H ₂ O
TT-20 TE-20 TW-20	480°F	650°F	Pipe Size	Oil
TT, E, W-21		650°F	Pipe Size	Oil
TT, E, W-22		650°F	Pipe Size	Oil
TT, E, W-23		650°F	Pipe Size	Oil
TT, E, W-24		650°F	Pipe Size	Oil
TT, E, W-25		650°F	Pump Mt.	Oil
TT, E, W-26		650°F	Pump Mt.	Oil
TT, E, W-27		650°F	Pump Mt.	Oil
TT, E, W-28		1000°F	Pump Mt.	Salt
TT, E, W-29		1000°F	Pipe Size	Salt
TT, E, W-30		1000°F	Pipe Size	Salt
TT, E, W-31		1000°F	Pump Mt.	Salt

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FLOW TRANSMITTERS AND PIPE SIZE

<u>Symbol</u>	<u>Design Flow</u>	<u>Max Flow</u>	<u>Mat'l</u>	<u>Line Size</u>
FT-1	20,900 lbs/hr	14M lbs/hr	Steam	7.625
FT-2	190 gpm	180K lbs/hr	Salt	4.026
FT-3	190 gpm	180K lbs/hr	Salt	4.026
FT-4	190 gpm	180K lbs/hr	Salt	4.026
FT-5	190 gpm	180K lbs/hr	Salt	4.026
FT-6	20,000 lbs/hr		H ₂ O	4.813
FT-7	20,000 lbs/hr		H ₂ O	4.813
FT-8	4200 gpm	1.5M lbs/hr	Oil	13.25
FT-9	2100 gpm	1.5M lbs/hr	Oil	4.026
FT-10	2100 gpm	1.5M lbs/hr	Oil	4.026
FT-11	4200 gpm	1.5M lbs/hr	Oil	4.026
FT-12	4200 gpm	1.5M lbs/hr	Oil	4.026
FT-13	1200 lbs/hr	120K lbs/hr	H ₂ O	3.826
FT-14	108K lbs/hr	120K lbs/hr	H ₂ O	3.826
FT-15	108K lbs/hr	120K lbs/hr	Steam	7.625
FT-16	1200 lbs/hr	120K lbs/hr	Steam	7.625
FT-17	1200 lbs/hr	120K lbs/hr	Steam	7.625

Orifices

FE-1
FE-2
FE-3
FE-4
FE-5
FE-6
FE-7
FE-8
FE-9
FE-10
FE-11
FE-12
FE-13
FE-14
FE-15
FE-16
FE-17

To meet above requirements

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**SPECIAL INSTRUMENTATION
HITEC & OIL/ROCK TANKS
DATA SHEETS**

40703-V

DESIGN DATA REQUIREMENTS SHEET
SPP THERMAL STORAGE SYSTEM
HITEC TANK
TEMPERATURE RAKE ASSEMBLIES

Bulk Temperature Rake Assemblies

GENERAL

- Construction Carbon steel piping with internal potted T/C lead wires
- Hot Junction Protrude .08m at 90° with stainless steel sheath
- Lead Wire Length 7.6m average
- Operating Range (-18 to +538°C) nominal 454°C
- T/C Type Type J
- Electronics Data logger with cold junction, cal, transmitter with RS-232C interface

RAKE ASSEMBLIES

- Quantity 2 req'd - 10 T/C's spaced nominal .46m apart
- Length 4.2m

HITEC TANK MISCELLANEOUS INSTRUMENTATION

Tank Skin Thermo-couples

- Quantity 2 required (hot)
 2 required (cold)
- Temp Range (-18^oC to +484^oC)
- Type J
- Mounting Welded to skin
- Output Low level to logger

Room Ambient Thermo-couples

- Quantity 2 required (hot)
 2 required (cold)
- Temp Range (-18^oC to +484^oC)
- Type J
- Mounting To read ambient temp
- Output Low level to logger

Room Wall Thermo-couples

- Quantity 3 required (hot)
 3 required (cold)
- Temp Range (-18^oC to +484^oC)
- Type J
- Mounting To read wall temp
- Output Low level to logger

Pump Room Thermo-couples

- Quantity 2 required
- Temp Range (-18^oC to + 234^oC)
- Type J
- Mounting To read ambient temp
- Output Low level to data logger

DESIGN DATA REQUIREMENTS SHEET
SPP THERMAL STORAGE SYSTEM
DATA LOGGER AND TRANSMITTER
FOR
HITEC AND OIL/ROCK STORAGE SYSTEM

Data Logger

- Type . 42m EIA Rack Mount
- Data Input Low level thermocouple inputs
- Quantity Up to 500 T/C inputs
- Compensation Integral cold junction
- Interface to CPU RS-232-C Serial Data
- Rate 300 baud
- Sampling Programmable to 24 hours
(Remote and manual)
- T/C Type Type J with calibration capability
- HI/LO Alarms Programmable remotely
- Printout Hardcopy at local station
- System Accuracy . 6%
- System Resolution . 1%
- Clock Display hours, days, minutes, seconds
- Modem Compatible with RS-232C interface - 2 required

DESIGN DATA REQUIREMENTS SHEET
SPP THERMAL STORAGE SYSTEM
OIL/ROCK STORAGE TANK
TEMPERATURE RAKE ASSEMBLIES

Temperature Profile Rake Assemblies

General

- Construction Carbon steel piping with internal potted T/C lead wires
- Hot Junction Protrude .08m at 90°
- Lead Wire Length 21m Average (12.2 - 36.6 m range)
- Operating Range -18°C to +334°C
- T/C Type Type J
- Hot Junction Protection Stainless Steel Sheath
- Electronics Data logger with cold junction, cal, transmitter with RS 232-C interface

Main Rake Assemblies

- Quantity 6 required - 30 T/C's spaced .6m apart
6 required - 31 T/C's spaced .6m apart
- Length 9 meters

Intermediate Rake Assemblies

- Quantity 108 required - 2 T/C's 4.5m apart
- Length 4.5 meters nominal

Ground Gradient Rake Assemblies

- Quantity 4 required - 10 T/C's .3m apart
- Length 3m nominal

OIL/ROCK STORAGE TANK MISCELLANEOUS INSTRUMENTATION

Ullage Space Thermo-couples

- Quantity 3 required
- Insertion Depth 1.5m
- Mounting Tank Dome
- Operating Range -18°C to $+334^{\circ}\text{C}$
- Spacing 120° around tank

Tank Skin Temperature

- Quantity 12 required
- Distribution 4 each at hi, med, lo levels
- Spacing 90°
- Operating Range -18°C to $+334^{\circ}\text{C}$

Tank Base

- Quantity 12 required
- Hot Junction Welded to tank base at various locations
- Cable Routing Raceway

Manifold Pressures

- Quantity Top: 2 required
Bottom: 2 required
- Operating Range 0-150 kPa

Strain Gauges

- Quantity 16 required - knuckle
8 required - hi level
8 required - mid level
- Range 69 MPa - 345 MPa
- Temperature -18°C to $+334^{\circ}\text{C}$
- Output Transmitters 4-20 ma

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**LOCAL CONTROL ROOM
INSTRUMENTATION
SHEETS**

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DESIGN DATA REQUIREMENTS SHEET
SPP
PROCESS MONITORING INSTRUMENTATION
(LOCAL CONTROL ROOM)

Indicators (Analog)

● Quantity		14 required
Level	5	
Pressure	2	
Flow	2	
Temperature	5	
● Hi Alarms		1 required each (contact closure)
● Lo Alarms		1 required each (contact closure)
● Output		4-20 ma
● Readout and Scale		Analog (0-100)
● Mounting		Standard .42m (19") EIA rack assembly

Local Control Room Indicators

<u>Function</u>	<u>Symbol*</u>
● Steam Temp Outlet Attempt No. 1	TI-1
● Salt Temp Outlet Attempt No. 1	TI-2
● Oil Temp Outlet Condenser	TI-3
● HITEC (hot) Salt Level	LI-1
● HITEC (cold) Salt Level	LI-2
● Condenser H ₂ O Level	LI-4
● Oil Level Indicator	LI-3
● Boiler Level Indicator	LI-5
● Inlet Steam Press	PI-1
● Inlet Steam Temp	TI-5
● Inlet Steam Flow	FI-1
● Outlet Press Steam	PI-2
● Outlet Temp Steam	TI-6
● Outlet Steam Flow	FI-2

* The symbology represents the identification of the indicators on reference P&ID drawings.

DESIGN DATA REQUIREMENTS SHEET

SPP THERMAL STORAGE SYSTEM
PROCESS ANNUNCIATOR PANEL
LOCAL CONTROL ROOMProcess Annunciator Panel

Type	Wall-mounted
Size	.61m x 1.2m nominal
Quantity	1 required
Array	6 x 10 = 60
Power	24 VDC operated
Interface	Control relays with closure to ground to activate lights
Audible	21 required. Capable of activating local audible alarm for specified variables
Construction	Weather-proof, preferably NEMA 4 enclosure
Additional	To distinguish HI/LO alarm capability on specified variables
Lettering	Standard painted or silk-screen on indicator lights
Light Indicators	Red, White

PROCESS ANNUNCIATOR PANEL
LOCAL CONTROL ROOM

<u>Function</u>	<u>Visual</u>	<u>Visual/Audible</u>
● Mode - full, partial, none	x	
● Inlet Steam Flow	x	
● Feedwater flow	x	
● Attempt No. 1 overtemp (steam)	x	x
● Desup overtemp	x	x
● Attempt No. 2 overtemps (salt)	x	x
● Condenser overtemp (oil)	x	x
● Condenser receiver Level (Hi/ Lo)	x	x
● HITEC Pump No. 1 temp	x	x
● HITEC Pump No. 2 temp	x	x
● HITEC Hi/Lo Press	x	x
● HITEC (Hot) Lo Temp	x	x
● HITEC (Cold) Lo Temp	x	x
● HITEC (Hot) Lo Temp	x	
● HITEC (Cold) Lo Temp	x	
● Oil Low Level	x	
● Oil Press (Hi/Lo)	x	x
● Lo N2 Press Supply	x	x

Storage Discharging

● Mode; Full, partial, none	x	
● Steam Outlet Pres/ Lo	x	x
● Temp Outlet Temp/ Lo	x	x
● Boiler Hi/ Lo Level	x	x

<u>Function</u>	<u>Visual</u>	<u>Visual/Audible</u>
<u>Storage Discharging (continued)</u>		
● Feedwater Press Lo	x	x
● Sealing Steam (Lo Flow)	x	
● Tracing Steam (Lo Flow)	x	
● Sealing/ Tracing Mode On/Off	x	
<u>Auxiliary Functions</u>		
● Fire (UV) Area 1	x	x
● Fire (UV) Area 2	x	x
● Extinguisher Operational (1)	x	
● Extinguisher Operational (2)	x	
● Power Outage AC, DC, etc.	x	x
● Pump Room Exhaust Fans	x	
● Oil Sump Well (Level Crud)	x	
● Lower Boiler Tank Hi Level	x	x
● High Boiler Tank, Hi Level	x	x
● Make-up Tank-Lo Level	x	
● Pumps (On/Off)	x	
● Starter/ Motor	x	
● Computer Interlocks	x	
● Miscellaneous	21	21

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Figure B-1. Process Annunciator Panel

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DATA ACQUISITION SYSTEM
DATA SHEETS

40703-V

SPP THERMAL STORAGE SYSTEM
DATA ACQUISITION COMPUTER
SYSTEM REQUIREMENTS
(INTEGRATED)

General Input/Output

● Storage	Disc to mag tape spool
● Core Memory	8-16K availability
● Line Printer	1000 Lines/day
● Mag Tape Store	10 megabits/day
● Asynchronous Lines	1 required
● CRT Display	1 required
● Programming	Assembly language with optional
Fortran compiler
● Support S/W	Disk sort and communication
support
● Analog/Digital I/O System	Per the stand-alone

SPP THERMAL STORAGE SYSTEM
 DATA ACQUISITION COMPUTER SYSTEM
 CENTRAL CONTROL ROOM
 (STAND-ALONE)

Computer Main Frame

Core Memory

- W/ Multi-Dimensional Tasking (MDT) 16K
- Communication Processor (MLCP)
- Assembly Language
- Priority Interrupts (64 level)
- Disk Sort/Comm Support
- Rack & Power Distribution

Input/Output

- Analog Inputs 121
- Analog Outputs 13
- Digital Inputs 145
- Digital Outputs 145
- Asynch. Lines 1
- RS-232-C Modern Bypass 2

Peripherals

- CRT Display 1
- 300 LPM Printer 1
- Disk Cartridge - 10 Mb 1
- Mag. Tape Drive - 800 bpi - 9 track 1

SPP THERMAL STORAGE
STAND-ALONE DATA ACQUISITION
COMPUTER SITE PLAN/LAYOUT

If a stand-alone dedicated computer is utilized for thermal storage, the following layout requirements apply:

The sensor based analog/digital I/O package will be mounted at top of cabinet (Height: approx. 26.7 cm inches).

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Floor space requirements:

DESIGN DATA REQUIREMENTS SHEET

SPP SPECIFICATION THERMAL STORAGE COMPUTER SOFTWARE REQUIREMENTS

Computer Main Frame

- Core Memory 8 - 16 K availability
- Processing 20 - 30% on-line
- Input/Output Sensor based analog/digital input/output
- Asynchronous Line 1

System Software

- Multi-dimensional tasking
- Communication processor
- Assembly Language
- Priority interrupt capability
- Disk sort/communication support
- RS-232C compatible modern bypass

APPLICATION SOFTWARE

IDENTIFICATION OF SOFTWARE MODULES

- 1) Hitec heat transfer module
- 2) Main storage heat transfer module
- 3) Subcooler heat transfer module
- 4) Receiver/storage interaction module
- 5) Totalized energy in/energy out module
- 6) Co-ordinated control demand module
- 7) Auxiliary loss module
- 8) Thermo-cline module
- 9) EGS/storage interaction module
- 10) Failure reporting module
- 11) Annual net energy module
- 12) Bootstrap load theoretical data module
- 13) Direct Interface Module -- To coordinate priority levels and computer I/O
- 14) Direct Digital Control (DDC) Module

Resident Software

The following application modules must reside in memory for on-line computational requirements -- in the master control or data acquisition computer.

Module numbers 1, 2, 3, 5, 6, 9, 10, 13

DESIGN DATA REQUIREMENTS SHEET

SPP THERMAL STORAGE SYSTEM
GRAPHICS DISPLAY PANEL
CENTRAL CONTROL ROOMGraphics Display Panel

- Type Back-lighted with graphic outline of TSS
- Size Stand alone - .42m for EIA rack mounting
Integrated - TBD
- Mode Light Indicators
 - 3 required - storage charge made - HITEC
 - 3 required - storage discharge mode
 - 3 required - receiver supply mode
 - 3 required - storage charge mode - OIL/ROCK
 - 2 required - SEAL (ON/OFF)
 - 2 required - TRACE (ON/OFF)
- Digital Readouts (HITEC)
 - 2 required - 3 digits for charge/discharge rate
 - 1 required - 3 digits for net stored energy
 - 1 required - 2 digits for % energy balance
- Digital Readouts (OIL/ROCK)
 - 2 required - 3 digit for charge/discharge rate
 - 1 required - 3 digit for net energy stored
 - 1 required - 2 digit for % energy balance
- Data Lines BCD computer output to display readouts
- Mounting Central control panel dedicated for thermal storage

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PILOT PLANT
ELECTRICAL & AUXILIARY SYSTEMS
DATA SHEETS

40703-V

10 MW_(e) SOLAR GENERATOR - THERMAL STORAGE

<u>Description</u>	<u>Quantity</u>
1200A MCC Class I Type B	
Main Power Breaker	1
Size 5 FVNR, 2 SP	2
Size 2 FVNR	2
Size 1 FVNR	7
100A/3P Switch w/ Fuses	1
30A/3P Switch w/ Fuses	1
30KVA Transformer	1
100A Lighting Panelboard	1
100A Mag. Contactor	1
3.05m x 6.10m Protected Aisles	1
Walk-Thru Enclosure	
Main Terminal Sections	2
Annunciator	1
Fire Protection Panel	1
Paging System (500w)	1
Intercom Stations	4
Space for I&C Control	1
Total Motor & Control Center	
Data Logger Double Door	1
NEMA 3R Cabinet	
Terminal Cabinet (NEMA 12)	1
Hand Holes 0.91m x 0.91m x 0.91m	5
NEMA 3R Junction Boxes	4
Total - Enclosures & Hand Holes	
Lighting and Rec.	
7.62m Ø Steel Poles	7
400W Metal Halide Luminares	14
200W Inc. Vapor Tight	5
120/208V - 20A WP Rec	7
Total Lighting and Rec.	

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**FIRE PROTECTION
SYSTEM**

40703-V

DESIGN DATA REQUIREMENT SHEET
FIRE PROTECTION SYSTEM

	<u>Pilot</u>	<u>Commercial</u>
<u>Sensor Type</u>	Ultraviolet detectors (UV)	same
• Quantity	7 required	150 required
• Mounting	7.6 m steel poles	same
• Electronics	Controllers in Local Control Room	same
• Operation	Contact closure with test calibration	same
• Zones	2 required	3 required
<u>Agent</u>		
• Type	Light water foam	same
• Proportioning	97% water/3% foam	same
• Capacity (flow)	1893 lpm/zone	1893 lpm/zone
<u>Tanks</u>		
• Quantity (Water)	1-30,000 gal (113 m ³)	2-30,000 gal (113 m ³)
• Quantity (Foam)	1-1500 gal (5.6 m ³)	2-1500 gal (5.6 m ³)
<u>Oscillating Monitors</u>		
• Quantity	2	4
• Controllers	2	4
<u>Station Hydrants (with hose rack)</u>		
• Quantity	4	10
• Hose (Water) Length 30m		50m
• Hose (Foam) Length 30m		50m
• Low velocity fog nozzle	4	10

APPENDIX C

BLOCKAGE OF MANIFOLD ORIFICES
BY PACKED BED MATERIAL

ASSUMPTIONS

- I. Bed is composed of uniform diameter spheres four times the orifice diameter.
- II. The spheres form a close packed array over the manifold surface.
- III. The orifice sees no significant blockage when the average distance between the sphere and the orifice plane ($\bar{h}$) is greater than "r", where "r" is orifice diameter.
- IV. The orifice is completely blocked for $\bar{h} < 0.2r$ with blockage being linearly proportion to $\bar{h}$ for $0.2r < \bar{h} < r$.

The model with an appropriate angular notation is shown in Figure C-1.

The height or distance from the orifice opening to the sphere surface is height h

$$h = R (1 - \cos \emptyset) \quad (C-1)$$

Distance "p" is the distance between the point of contact of the sphere with the plane of the orifice and the center of the orifice and "A" is the distance from the contact point to the particular point on the perimeter of the orifice. The points on the perimeter of the orifice of radius r are defined by r angle $\emptyset^{\text{theta}}$.

Figure C-1. Manifold Orifice Blockage Model

$$A = [(\rho + r \cos \theta)^2 + (r \sin \theta)^2]^{1/2} \quad (C-2)$$

$$A = [\rho^2 + r^2 + 2\rho r \cos \theta]^{1/2} \quad (C-3)$$

The value for h for a particular value of r and θ is that obtained from the following equation.

$$h = R(1 - \cos(\sin^{-1}(1/R(\rho^2 + r^2 + 2\rho r \cos(\theta)^{1/2}))) \quad (C-4)$$

The average value of h is then found by integrating around the perimeter of the orifice and dividing by the circumference.

$$\bar{h}(\rho) = \frac{1}{\pi r} \int_0^\pi r \times h(\theta) d\theta \quad (C-5)$$

Solving Equation (C-5) numerically and plotting $\bar{h}$ as a function of ρ results in the relation:

$$\bar{h}(\rho) = \exp(C_1 + C_2 \times \rho) \quad (C-6)$$

where:

$$C_1 = -5.101$$

$$C_2 = 15.964$$

$$0.03 \leq \rho \leq 0.125$$

After determining the value of $\bar{h}$ as a function of ρ it is a simple step to integrate over the range of ρ for all possible locations of the sphere relative to the orifice. The average orifice opening is the relative opening multiplied by area and divided by the total area of one hexagonal close packed cell (see Figure C-2).

Figure C-2. Schematic Showing Zones of Integration

The first zone $\bar{h} < 0.2r$ has an orifice opening equal to zero. The second zone $0.2r \leq \bar{h} \leq r$ the opening was assumed to be proportional to ρ . And for zone 3 the orifice was assumed to be completely unrestricted. The reason

that a discontinuity exists at approximately $0.2 \bar{r} < \bar{h}$ is that the spherical particle preferentially settles into the orifice for small values of ρ (see Figure C-3).

Figure C-3. Relationship of Spherical Particle to Orifice

The size of the orifice to the size of the sphere was exaggerated to illustrate the point. Changing the point of cut off slightly would not change the final result significantly.

The final results can be expressed as the ratio of areas (A_i probabilities P_i in following equation:

$$\bar{P} = \frac{A_1 \times P_1 + A_2 \times P_2 + A_3 P_3}{A_1 + A_2 + A_3} \quad (C-7)$$

where:

$\bar{P}$ is the average probable orifice opening

A_1, A_2, A_3 are the areas depicted in Figure C-3.

P_1, P_2, P_3 are the average orifice openings calculated for each zone by using Equation (C-8).

C-5

$$P_2 = \frac{1}{\bar{h}(\rho_2) \pi(\rho_2^2 - \rho_1^2)} \int_{\rho_1}^{\rho_2} \bar{h}(\rho)^2 \pi \rho \, d\rho \quad (C-8)$$

Note that $A_1 + A_2 + A_3$ is the total area of one hexagonal close packed cell.

For the specific case of 12.7 mm spheres and 3.2 mm orifices (0.5 in and 0.125 in) the average probable opening was determined to be 0.848 or approximately 18 percent more holes would be required in the lower manifold to attain the same free flow area as a manifold not in a packed bed.

The above method of calculating a percentage of orifices obstructed is an approximate method at best and some of the basic assumptions may be questioned. Its merit is that it appeals to physical arguments and gives order of magnitude predictions to a problem that could only be solved experimentally. It is highly unlikely that experimental results would yield anything more than statistical results with a relatively wide error band.

APPENDIX D

STORAGE SYSTEM DYNAMIC SIMULATION

A dynamic simulation of all major components in the storage discharge system has been used to verify the system design. Flow diagrams and block diagrams of the system are shown in Figures D-1 and D-2. The flow diagram shows examples of the constants and variables that are used in the program and also the flow path through the various units. It may be noted that the paths indicate the number of calculations and sequence of operations. In the block diagrams, the constants and variables used in the simulation are listed for the storage tanks, superheater, boiler, desuperheater, condenser, and preheater. These mnemonic terms are described in greater detail in succeeding paragraphs.

In the study these variables were used to determine the heat transfer from the Hitec and oil storage to the steam. Heat transfer coefficients, shell areas, capacities, weights, and other parameters were obtained from the various component manufacturers and reflect experience on these units over the years. In some cases, estimates had to be made on equipment that was very similar to that used here. Heat transfer coefficients were based on film transfer as if the heat was transferred over a surface that had been in use for sometime.

Early studies with the system used a "cold" condition of 303°C for the boiler and 295°C for the superheater. An initial condition of 4545, 18, 181 and 45,454 lb/hr steam demand was used. System response to this step demand was very stable and the response was very fast. After the system was very fast. After the system was verified, it was incorporated in the total system configuration. Results of these studies are shown in another section of this report.

Figure D-1. Storage Charge Block Diagram - 1

Figure D-2. Storage Charge Block Diagram - 2

Figure D-2 Storage Charge Block Diagram Concluded

In order to simulate the various components such as the superheater, attemperators, condenser, subcooler, preheater, boiler, superheater, Hitec storage and main oil storage have been described with certain transfer functions. These transfer functions describe the transfer of heat in and out of the units and their influence on the remainder of the system. All of the variables used in the simulation are based on the physical characteristics of the various units and as the sizes of these units are selected, the various parameters can be established. These variables are provided in the following paragraphs with a short explanation of each.

COB	Boiler Heat Transfer Coefficient -- This is based on the latest selection - $1061.8 \text{ W/m}^2/\text{hr/K}$ ($187 \text{ Btu/hr/ft}^2/^\circ\text{F}$)
AB	Boiler Heat Transfer -- The area of the tubes in contact with the steam is needed - Tubes 885.7 meter^2 (9534 ft^2)
COP	Preheater heat transfer coefficient - $851.7 \text{ W/hr/m}^2/\text{k}$ ($150 \text{ Btu/hr/ft}^2/^\circ\text{F}$)
AP	Preheater heat transfer area - 168.7 meter^2 (1816 ft^2)
COSU	Superheater heat transfer coefficient - $794.9 \text{ W/m}^2/\text{hr/K}$ ($140^\circ \text{ Btu/hr/ft}^2/^\circ\text{F}$)
AS	Superheater heat transfer area - 100.5 meter^2 (1082 ft^2)
SHCAP	Capacity of the storage tank in lbs of salt (Hitec) - 262175 kg (289 tons of salt each)
TSOI	Temperature of the Hitec tank - 454°C (850°F max.)
TSOO	Temperature of the cold Hitec tank - 303.3°C (578°F)

DSET	Set point of steam drum (liquid level) - Start at 50% - Up to 80% level
ROWB	Average water plus steam density in the drum at 470°F - Saturated vapor = .06 m ³ /kg (.9 ft ³ /lb) Saturated liquid = .001 m ³ /kg (.02 ft ³ /lb)
GMT	Mass of the tubes in the superheater - 4383 kg (9643 lb (estimated)
SMS	Mass of the shell in the superheater - 2904 kg (6565 lb (estimated)
SHCT	Holding capacity of the superheater discharge tubes (lb/fluid) - 1.2 m ² (42.8 ft ³ estimated)
SHCS	Holding capacity of the superheater shell (lb/fluid) - .38 m ² (13.48 ft ³ estimated)
BMT	Mass of the boiler tubes - W = 14809 kg (32580 lb estimated)
BMS	Mass of the boiler shell - W = 33970 kg (74735 lb estimated)
BHCT	Holding capacity of the boiler tubes - 4.03 m ² (144 ft ³ estimated)
RL	Length of the boiler shell - 12.19 meters (40 feet)
R	Radius of the boiler shell - 0.97 meter (38 inches at ends), 1.37 meter (54 inches in middle)
PMT	Mass of the preheater tubes - W = 1129 kg (2484 lb estimated)
PMS	Mass of the preheater shall - W = 1620 kg (3565 lb estimated)

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- PHCT Holding capacity of the preheater tubes - 0.31 m^3 (11 ft^3 estimated)
- PHCS Holding capacity of the preheater shell - 0.2 m^3 (7.3 ft^3 estimated)
- PDROPB Pressure drop across the boiler preheater pump - oil 359.6 KPa (52.2 lb/in^2)
- DROPS Pressure drop across the Hitec pump - 151.6 KPa, Hitec 22.0 lb/in^2
- ROWOIL Density of the oil vs temperature

Figure D-3. Thermal Expansion of Calories HT 43

- CPDB Pressure drop constant for the flow squared N/I valve in the boiler discharge
 29.63 KPa (4.3 lb/in^2 , shell side)
 51.7 KP (7.5 lb/in^2 , tube side)
- ROWHIT Density of the Hitec vs temperature

Figure D-4. Variation of Density and Viscosity of HTS with Temperature

CPDS	Pressure drop constant, in superheater flow squared N/I PSIA/(lb/hr) ² 118.5 KPa (17.2 lb/in ² shell) 2.51 KPa (.364 lb/in ² tube)
CPDP	Pressure drop constant - flow squared for preheater - 131.6 KPa (19.1 lb/in ² shell) 1.87 KPa (.272 lb/in ² tubes)
APFV	Feedwater maximum valve port area - 0.005 m ² (0.05 ft ²)

APBV	Boiler maximum valve port area - 0.03 m^2 (0.35 ft^2)
APSV	Superheater maximum valve port area - 0.005 m^2 (0.05 ft^2)
BPCAP	Capacity of oil tank (lbs) 72% of the tank is rock 28% oil $829538 \text{ kg} = (1,824,948 \text{ lb of oil})$
COCC	Heat transfer coefficient for the condenser - $964.7 \text{ W/hr/m}^2/\text{°K}$ ($169.9 \text{ Btu/hr/ft}^2/\text{°F}$)
COSC	Heat transfer coefficient for the desuperheater - $1362.8 \text{ W/hr/m}^2/\text{K}$ ($240 \text{ Btu/hr/ft}^2/\text{°F}$)
ASD	Area of the desuperheater heat transfer surface 237.2 m^2 (2553 ft^3 tubes, estimated) 17.6 m^2 (189.4 ft^2 shell, estimated)
VC	Holding volume of the condenser on the H_2O side in ft^3 16.52 m^2 (590 ft^3 shell, estimated) 5.17 m^2 (184.5 ft^3 tubes, estimated)
CMT	Mass of the condenser tubes - 18926 kg ($41,639 \text{ lb}$, estimated)
ROWC	Average density of the H_2O in the condenser At 599°F 1425 PSIA 9818 KPa (315°C) Saturated vapor = $0.05 \text{ m}^3/\text{kg}$ ($0.77 \text{ ft}^3/\text{lb}$) Saturated liquid = $0.001 \text{ m}^3/\text{kg}$ ($0.02 \text{ ft}^3/\text{lb}$)
CHCS	Holding capacity of the condenser shell - 16.52 m^3 (590 ft^3 , estimated)

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CMS	Mass of the condenser shell - 9585 kg (21087 lb, estimated)
CSHCT	Holding capacity of the desuperheater tubes - 0.75 m^3 (27.3 ft^3 estimated)
CSMT	Mass of the desuperheater tubes - 2795 kg (6151 lb, estimated)
CSHCS	Holding capacity of the desuperheater shell - 2.39 m^3 (85.5 ft^3 , estimated)
CSOMS	Mass of the desuperheater shell - 2592 kg (5703 lb, estimated)
HCWI	Enthalpy of the steam out of the desuperheater - 386°C 845 Wh/kg (727°F 1308 Btu/lb 1435 psia)
HCOUT	Enthalpy of the steam out of condenser - 9887 KPa (583°F 1174 Btu/lb 1405 psia)
COBS	Boiler heat transfer coefficient on the shell side - 1703.4 W/hr/ $\text{m}^2/^{\circ}\text{K}$ (300 Btu/hr/ $\text{ft}^2/^{\circ}\text{F}$)
ABSH	Area of the boiler shell - 70.6 m^2 (760.0 ft^2 , estimated)
BTUBET	Boiler tube thickness - 0.21 cm (0.083 inch)

APPENDIX E

KSHEL

COMPUTER PROGRAMS FOR THE ANALYSIS
OF AXISYMMETRIC SHELLS

BY

ARTURS KALNINS

CHAPTER 1. GENERAL DESCRIPTION

I. INTRODUCTION

Computer programs described here can calculate elastic deflections and stresses in a thin-walled, axisymmetric shell. Kalnins Shell Program 1 (or KSHEL1) calculates such a response of the shell when it is subjected to arbitrary surface, edge, and ring loads. All loads can be static or vary sinusoidally with time. Kalnins Shell Programs 2 and 3 (or KSHEL2 and KSHEL3) calculate the resonant frequencies and mode shapes of free vibration of the shell, which can be prestressed axisymmetrically. They can also calculate the stability limit of the shell produced by axisymmetric prestress. Kalnins Shell Program 4 (or KSHEL4) calculates the time functions for the response of the shell to transient dynamic surface loads, using as input some results from either KSHEL2 or KSHEL3. The solutions in KSHEL Programs are obtained by the multisegment method of direct numerical integration of boundary value problems which was originally developed by Arturs Kalnins and published in the Journal of Applied Mechanics, Vol. 31, September 1964, pp. 467-476; and in the Journal of the Acoustical Society of America, Vol. 36, July 1964, pp. 1355-1365.

2. LIMITATIONS

The shell which is being analyzed and the results given by the pro-

grams are subjected to all the limitations of a classical shell theory, which is formulated with the requirement that the thickness of the shell must be much smaller than any other dimension of the shell. Therefore, it must be recognized that the predicted solution is not strictly valid in regions of the shell where this requirement is violated.

As it is usual in shell theory, the problem is solved in terms of resultant forces and couples, and the stresses are calculated by assuming a linear distribution through the thickness. Therefore, the solution given by the programs will ensure equilibrium of a reference surface of the shell in terms of resultant forces and couples, but not in terms of stresses.

3. ADMISSIBLE SHELLS

The computer programs are applicable to the analysis of thin shells which are symmetric about one straight axis, called the axis of symmetry. The shell is constructed by revolving the shell profile about the axis of symmetry. An example of an admissible shell profile is shown in Figure E-1. The axisymmetric surfaces enclosing the shell profile are called the bounding surfaces of the shell. As identified in Figure E-1, the shell profile admits any number of branches and box branches. The requirement of symmetry includes all geometric as well as physical parameters of the shell. All properties of the shell must be identical at all points on any one latitude circle, which is defined as the intersection of the shell with a plane perpendicular to the axis of symmetry. However, all properties of the shell can have arbitrary variations along the meridian of the shell, which is defined as the intersection of the shell with a plane passing through the axis of symmetry. The direction along a latitude circle will be called circumferential direction and along the meridian-meridional direction.

The shell wall can consist of any number of layers of different isotropic or orthotropic materials. The principal axes of orthotropy of each layer must be oriented along the circumferential and meridional directions

of the shell. It is assumed that all layers are bonded together perfectly so that no slip occurs between them.

Any axisymmetric portion of the shell can be supported by an elastic foundation (axisymmetric distributed springs) which resist any deflection in the normal direction to the shell surfaces. Springs can also be attached at any latitude circles, including shell edges (see Figure E-1).

4. ADMISSIBLE LOADS

KSHEL2 and 3 admit only surface loads for the calculation of certain integrals that are needed for input of KSHEL4 for the construction of the transient response of the loads. For KSHEL1, mechanical and thermal surface loads are applied to the bounding surfaces of the shell, and forces and couples applied to any latitude circles of the shell. When the latitude circle is at an edge of the shell, such loads are called edge loads; when it is inside the shell, they are called ring loads. Both edge and ring loads can be made proportional to deflections in all directions and rotation, thus simulating springs attached at any latitude circle. By setting a code number and specifying an angular speed of rotation, KSHEL1 automatically accounts for the centrifugal surface loads produced by the spinning of the shell about its axis of symmetry.

Mechanical surface loads are prescribed as force per unit area applied to the bounding surfaces of the shell. Thermal surface loads require the prescription of the temperature distribution over the bounding surfaces of the shell. Surface loads can have arbitrary variations in the circumferential as well as meridional directions. Ring and edge loads can have arbitrary circumferential variations.

Whenever any of the loads vary circumferentially, they must be expanded in Fourier series in that direction. The program accepts the

Figure E-1.

Fourier coefficients of all loads for each circumferential wave number separately and calculates the corresponding coefficients for the Fourier series of the response. If desired, the separate Fourier series terms of the response are added together, in any combination, and the sum is printed at specified stations on the meridian as well as on the latitude circles. A separate program, KSHEL5, calculates the Fourier coefficients from point-by-point input of loads around the circumference.

600°F Run
(OT = 530°F)

1:	2	2	0	1	0	0			
2:	0.0		90.		10	2	7	0	1
3:	0.0		336.		24.		1.0		
4:	25700000.		0.3					.00000723	.00000723
5:	-.4375		.4375						
6:	0.0		84.		7	4	2	0	1
7:	0.0		360.		90.				
8:	25700000.		0.3					.00000723	.00000723
9:	-.40625		.40625						
10:	0	0	0.0		0.0				
11:	1			3			6	-11255	7
12:	2			4			6		8
13:	0.0								
14:	41.167						530.	530.	1
15:	1								
16:	PRESS	7							
17:	0.0		41.167	15.0			40.279	30.	36.636
18:		31.678							45
19:	60.		26.732	75.			23.134	90.	21.593
20:	0.0								
21:	21.593						530.	530.	1
22:	1								
23:	Pl. SS	2							
24:	0.		21.593	84.			18.660		

1 KSHL1-IBM FOR ANALYSIS OF AXISYMMETRIC SHELLS BY ARTURS KALNINS JANUARY 1 1974

0 RESPONSE ANALYSIS PARTS# 2 BRANCHES# 0 NUMBER OF SUBCASES# 1 OUTPUT TYPE 2 SUBCASE ADDITION 0

40703-V
PART NO 1
OSI# .00000E+00 SX# .90000E+02 SEGMENTS# 10 OUTPUT POINTS# 2 STANDARD SURFACE NO. 1 NTP# 0 LAYERS MLY# 1
TOROIDAL SHELL NO. 7 K# .00000E+00 A# .33600E+03 B# .24000E+02 DIRECTION INDEX# 1.0
LAYER NO 1 FROM Z# -.43750E+00 TO Z# .43750E+00
CONSISTS OF ISOTROPIC MATERIAL, YOUNGS MODULUS E# .25700E+08 POISSONS RATIO NU# .30000E+00
COEFFS OF THERMAL EXPANSION AFI# .72300E-05 ATHTA# .72300E-05 MASS DENSITY RHO# .00000E+00 COND# .10000E+01

E-7

PART NO 2
OSI# .00000E+00 SX# .84000E+02 SEGMENTS# 7 OUTPUT POINTS# 4 STANDARD SURFACE NO. 2 NTP# 0 LAYERS MLY# 1
CYLINDRICAL SHELL NO 2 K# .00000E+00 R# .36000E+03 PHI# 90.000 DEGREES
LAYER NO 1 FROM Z# -.40625E+00 TO Z# .40625E+00
CONSISTS OF ISOTROPIC MATERIAL, YOUNGS MODULUS E# .25700E+08 POISSONS RATIO NU# .30000E+00
COEFFS OF THERMAL EXPANSION AFI# .72300E-05 ATHTA# .72300E-05 MASS DENSITY RHO# .00000E+00 COND# .10000E+01

1 KSHL1-IBM FOR ANALYSIS OF AXISYMMETRIC SHELLS BY ARTURS KALNINS JANUARY 1 1974
0 SUBCASE NO 1 FOR FOURIER HARMONIC COS 0 THETA

OROUND C MC AT START EDGE	1#	.0000E+00	3#	.1039E 1	6#	-.1126E+05	7#	.0000E+00	ALFA#	.000 DEG
OROUND C MC AT FINAL EDGE	2#	.0000E+00	4#	.0000E 00	6#	.0000E+00	8#	.0000E+00	ALFA#	.0000 DEG

LOADS FOR PART NO 1 SUBCASE NO 1
 ORING LOADS AT END OF THIS PART ARE Q= .00000E+00 NPHI# .00000E+00 MPHI# .00000E+00 N# .00000E+00
 OSURFACE AND TEMP LOADS P# .41167E+02 FFI# .05000E+00 PTHETA# .00000E+00 TIN# .53000E+03 TOUT# .53000E+03
 0 CODE NUMBERS OF VARIABLE LOADS OVER THIS PART, GIVEN BY FGNS BELOW, ARE 1
 0 PRESS LINEAR FUNCTION GENERATOR NO. 1 FROM 7 POINTS
 OYS# .4117E+02 .4028E+02 .3664E+02 .3168E+02 .2673E+02 .2319E+02 .2159E+02
 OXS# .0000E+00 .1500E+02 .3000E+02 .4500E+02 .6000E+02 .7500E+02 .9000E+02
 0 AT BEGINNING AND END OF PART 1 PARAMETERS ARE

RFI# .2400E+02 R# .3600E+03 FI# .0000E+00 RAD .0000E+00 DEGREES S# .0000E+00 C# .1000E-01 H# .8750E+00
 P OR P1# .4117E+02 FFI OR P2# .0000E-00 PTHETA# .0000E+00 TIN# .5300E+03 TOUT# .5300E+03 INORM# 0
 TEMPERATURE IN LAYER NO. 1 AT INSIDE IS .5300E+03 AT OUTSIDE IS .5300E+03 DEGREES

RFI# .2400E+02 R# .3600E+03 FI# .157E+01 RAD .9000E+02 DEGREES S# .1000E+01 C# .1873E-06 H# .8750E+00
 P OR P1# .2159E-02 FFI OR P2# .0000E-00 PTHETA# .0000E+00 TIN# .5300E+03 TOUT# .5300E+03 INORM# 0
 TEMPERATURE IN LAYER NO. 1 AT INSIDE IS .5300E+03 AT OUTSIDE IS .5300E+03 DEGREES

40703-V

12-8

LOADS FOR PART NO 2 SUBCASE NO 1
 ORING LOADS AT END OF THIS PART ARE Q= .00000E+00 NPHI# .00000E+00 MPHI# .00000E+00 N# .00000E+00
 OSURFACE AND TEMP LOADS P# .21593E+02 FFI# .00000E+00 PTHETA# .00000E+00 TIN# .53000E+03 TOUT# .53000E+03
 0 CODE NUMBERS OF VARIABLE LOADS OVER THIS PART, GIVEN BY FGNS BELOW, ARE 1
 0 PRESS LINEAR FUNCTION GENERATOR NO. 2 FROM 2 POINTS
 OYS# .2159E+02 .1867E+02
 OXS# .0000E+00 .8400E+02
 0 AT BEGINNING AND END OF PART 2 PARAMETERS ARE

RFI# .9999E+10 R# .3600E+03 FI# .1571E+01 RAD .9000E+02 DEGREES S# .1000E+01 C# .0000E+00 H# .8125E+00
 P OR P1# .2159E+02 FFI OR P2# .0000E+00 PTHETA# .0000E+00 TIN# .5300E+03 TOUT# .5300E+03 INORM# 0
 TEMPERATURE IN LAYER NO. 1 AT INSIDE IS .5300E+03 AT OUTSIDE IS .5300E+03 DEGREES

RFI# .9999E+10 R# .3600E+03 FI# .1571E+01 RAD .00E+02 DEGREES S# .1000E+01 C# .0000E+00 H# .8125E+00
 P OR P1# .1867E+02 FFI OR P2# .0000E+00 PTHETA# .0000E+00 TIN# .5300E+03 TOUT# .5300E+03 INORM# 0
 TEMPERATURE IN LAYER NO. 1 AT INSIDE IS .5300E+03 AT OUTSIDE IS .5300E+03 DEGREES

KSHELL-IBM FOR ANALYSIS OF AXISYMMETRIC SHELLS BY ARTURS KALNINS JANUARY 1 1974											
ODEFLECTIONS AND STRESS RESULTANTS			FOR SUBCASE NO. 1			N# 0					
X	W	O	UPHI	NPHI	BPHI	MPHI	UTHETA	N	NTHETA	MTHETA	
0 MAIN SHELL PART NO 1											
.000	.0000E+00	.8639E+03	.1039E+01	.1204E+04	.2252E-01	-.1126E+05	.0000E+00	.0000E+00	-.163E+05	-.328E+04	
4.500	.5149E-01	.8661E+03	.1045E+01	.1038E+04	.1004E-01	-.9580E+04	.0000E+00	.0000E+00	-.163E+05	-.283E+04	
9.000	.1249E+00	.8491E+03	.1046E+01	.8759E+03	-.4312E-03	-.7927E+04	.0000E+00	.0000E+00	-.162E+05	-.238E+04	
9.000	.1249E+00	.8491E+03	.1046E+01	.8759E+03	-.4312E-03	-.7927E+04	.0000E+00	.0000E+00	-.162E+05	-.238E+04	
13.500	.2160E+00	.8133E+03	.1040E+01	.7184E+03	-.8938E-02	-.6330E+04	.0000E+00	.0000E+00	-.161E+05	-.194E+04	
18.000	.3206E+00	.7605E+03	.1027E+01	.5692E+03	-.1558E-01	-.4824E+04	.0000E+00	.0000E+00	-.156E+05	-.151E+04	
18.000	.3206E+00	.7605E+03	.1027E+01	.5692E+03	-.1558E-01	-.4824E+04	.0000E+00	.0000E+00	-.156E+05	-.151E+04	
22.500	.4347E+00	.6938E+03	.1005E+01	.4316E+03	-.2047E-01	-.3437E+04	.0000E+00	.0000E+00	-.147E+05	-.111E+04	
27.000	.5544E+00	.6153E+03	.9737E+00	.3082E+03	-.2379E-01	-.2192E+04	.0000E+00	.0000E+00	-.135E+05	-.745E+03	
27.000	.5544E+00	.6153E+03	.9737E+00	.3082E+03	-.2379E-01	-.2192E+04	.0000E+00	.0000E+00	-.135E+05	-.745E+03	
31.500	.6762E+00	.5299E+03	.9329E+00	.2015E+03	-.2571E-01	-.1106E+04	.0000E+00	.0000E+00	-.120E+05	-.422E+03	
35.000	.7969E+00	.4399E+03	.8826E+00	.1129E+03	-.2643E-01	-.1901E+03	.0000E+00	.0000E+00	-.102E+05	-.145E+03	
35.000	.7969E+00	.4399E+03	.8826E+00	.1129E+03	-.2643E-01	-.1901E+03	.0000E+00	.0000E+00	-.102E+05	-.145E+03	
40.500	.9136E+00	.3499E+03	.8228E+00	.4269E+02	-.2616E-01	.5531E+03	.0000E+00	.0000E+00	-.819E+04	.847E+02	
45.000	.1024E+01	.2623E+03	.7541E+00	-.9477E+01	-.2511E-01	.1127E+04	.0000E+00	.0000E+00	-.607E+04	.266E+03	
45.000	.1024E+01	.2623E+03	.7541E+00	-.9477E+01	-.2511E-01	.1127E+04	.0000E+00	.0000E+00	-.607E+04	.266E+03	
49.500	.1126E+01	.1820E+03	.6770E+00	-.4491E+02	-.2347E-01	.1541E+04	.0000E+00	.0000E+00	-.392E+04	.401E+03	
54.000	.1218E+01	.1097E+03	.5921E+00	-.6555E+02	-.2144E-01	.1811E+04	.0000E+00	.0000E+00	-.180E+04	.492E+03	
54.000	.1218E+01	.1097E+03	.5921E+00	-.6555E+02	-.2144E-01	.1811E+04	.0000E+00	.0000E+00	-.180E+04	.492E+03	
58.500	.1300E+01	.4773E+02	.5004E+00	-.7382E+02	-.1915E-01	.1953E+04	.0000E+00	.0000E+00	.208E+03	.546E+03	
63.000	.1369E+01	-.2833E+01	.4027E+00	-.7241E+02	-.1677E-01	.1990E+04	.0000E+00	.0000E+00	.206E+04	.567E+03	
63.000	.1369E+01	-.2833E+01	.4027E+00	-.7241E+02	-.1677E-01	.1990E+04	.0000E+00	.0000E+00	.206E+04	.567E+03	
67.500	.1426E+01	-.4225E+02	.3000E+00	-.6403E+02	-.1440E-01	.1943E+04	.0000E+00	.0000E+00	.373E+04	.561E+03	
72.000	.1470E+01	-.7061E+02	.1933E+00	-.5131E+02	-.1213E-01	.1833E+04	.0000E+00	.0000E+00	.520E+04	.535E+03	
72.000	.1470E+01	-.7061E+02	.1933E+00	-.5131E+02	-.1213E-01	.1833E+04	.0000E+00	.0000E+00	.520E+04	.535E+03	
76.500	.1502E+01	-.8853E+02	.8350E-01	-.3664E+02	-.1002E-01	.1679E+04	.0000E+00	.0000E+00	.645E+04	.494E+03	
81.000	.1521E+01	-.9773E+02	-.2827E-01	-.2214E+02	-.8118E-02	.1501E+04	.0000E+00	.0000E+00	.749E+04	.445E+03	
81.000	.1521E+01	-.9773E+02	-.2827E-01	-.2214E+02	-.8118E-02	.1501E+04	.0000E+00	.0000E+00	.749E+04	.445E+03	
85.000	.1528E+01	-.9971E+02	-.1411E+00	-.9474E+01	-.32E-02	.1314E+04	.0000E+00	.0000E+00	.933E+04	.392E+03	
90.000	.1524E+01	-.9577E+02	-.2540E+00	-.1033E-03	-.4972E-02	.1129E+04	.0000E+00	.0000E+00	.900E+04	.339E+03	

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0 MAIN SHELL PART NO 2

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.000	.1524E+01	-.9572E+02	-.2540E+00	.7105E-13	-.4970E-02	.1129E+04	.0000E+00	.0000E+00	.836E+04	.339E+03
3.000	.1535E+01	-.8767E+02	-.2425E+00	.7105E-13	-.2622E-02	.8521E+03	.0000E+00	.0000E+00	.901E+04	.256E+03
6.000	.1540E+01	-.7543E+02	-.2318E+00	.7105E-13	-.8952E-03	.6068E+03	.0000E+00	.0000E+00	.931E+04	.182E+03
9.000	.1541E+01	-.6152E+02	-.2207E+00	.7105E-13	.2943E-03	.4012E+03	.0000E+00	.0000E+00	.935E+04	.120E+03
12.000	.1539E+01	-.4766E+02	-.2096E+00	.7105E-13	.1045E-02	.2376E+03	.0000E+00	.0000E+00	.923E+04	.713E+02
12.000	.1539E+01	-.4762E+02	-.2096E+00	.1310E-13	.1047E-02	.2381E+03	.0000E+00	.0000E+00	.923E+04	.714E+02
15.000	.1535E+01	-.3493E+02	-.1985E+00	.1310E-13	.1459E-02	.1146E+03	.0000E+00	.0000E+00	.901E+04	.344E+02
18.000	.1530E+01	-.2401E+02	-.1874E+00	.1310E-13	.1620E-02	.2670E+02	.0000E+00	.0000E+00	.874E+04	.801E+01
21.000	.1525E+01	-.1510E+02	-.1763E+00	.1310E-13	.1609E-02	.3145E+02	.0000E+00	.0000E+00	.846E+04	-.944E+01
24.000	.1521E+01	-.8205E+01	-.1652E+00	.1310E-13	.1489E-02	.6593E+02	.0000E+00	.0000E+00	.819E+04	-.198E+02
24.000	.1521E+01	-.8213E+01	-.1652E+00	.1554E-13	.1489E-02	.6600E+02	.0000E+00	.0000E+00	.819E+04	-.198E+02
27.000	.1516E+01	-.3153E+01	-.1540E+00	.1554E-13	.1309E-02	.8262E+02	.0000E+00	.0000E+00	.794E+04	-.248E+02
30.000	.1513E+01	.3234E+00	-.1425E+00	.1554E-13	.1106E-02	.8651E+02	.0000E+00	.0000E+00	.773E+04	-.260E+02
33.000	.1510E+01	.2509E+01	-.1317E+00	.1554E-13	.9048E-03	.8197E+02	.0000E+00	.0000E+00	.756E+04	-.246E+02
36.000	.1507E+01	.3694E+01	-.1205E+00	.1554E-13	.7206E-03	.7245E+02	.0000E+00	.0000E+00	.741E+04	-.217E+02
36.000	.1507E+01	.3707E+01	-.1205E+00	.6370E-14	.7209E-03	.7234E+02	.0000E+00	.0000E+00	.741E+04	-.217E+02
39.000	.1505E+01	.4157E+01	-.1093E+00	.6370E-14	.5629E-03	.6039E+02	.0000E+00	.0000E+00	.730E+04	-.181E+02
42.000	.1504E+01	.4101E+01	-.9815E-01	.6370E-14	.4343E-03	.4790E+02	.0000E+00	.0000E+00	.722E+04	-.144E+02
45.000	.1503E+01	.3725E+01	-.8697E-01	.6370E-14	.3347E-03	.3610E+02	.0000E+00	.0000E+00	.715E+04	-.108E+02
48.000	.1502E+01	.3175E+01	-.7576E-01	.6370E-14	.2615E-03	.2572E+02	.0000E+00	.0000E+00	.710E+04	-.772E+01
48.000	.1502E+01	.3189E+01	-.7576E-01	-.9294E-14	.2620E-03	.2559E+02	.0000E+00	.0000E+00	.710E+04	-.768E+01
51.000	.1501E+01	.2568E+01	-.6455E-01	-.9294E-14	.2118E-03	.1695E+02	.0000E+00	.0000E+00	.706E+04	-.508E+01
54.000	.1501E+01	.1952E+01	-.5340E-01	-.9294E-14	.1800E-03	.1018E+02	.0000E+00	.0000E+00	.702E+04	-.305E+01
57.000	.1500E+01	.1387E+01	-.4220E-01	-.9294E-14	.1621E-03	.5183E+01	.0000E+00	.0000E+00	.699E+04	-.156E+01
60.000	.1500E+01	.8991E+00	-.3101E-01	-.9294E-14	.1541E-03	.1776E+01	.0000E+00	.0000E+00	.697E+04	-.533E+00
60.000	.1500E+01	.9187E+00	-.3101E-01	-.1543E-13	.1548E-03	.1585E+01	.0000E+00	.0000E+00	.697E+04	-.475E+00
63.000	.1499E+01	.5187E+00	-.1981E-01	-.1543E-13	.1538E-03	.5488E+00	.0000E+00	.0000E+00	.694E+04	.165E+00
66.000	.1499E+01	.2088E+00	-.8614E-02	-.1543E-13	.1566E-03	.1618E+01	.0000E+00	.0000E+00	.691E+04	.485E+00
69.000	.1498E+01	-.1473E-01	.2585E-02	-.1543E-13	.1609E-03	.1886E+01	.0000E+00	.0000E+00	.689E+04	.566E+00
72.000	.1498E+01	-.1579E+00	.1376E-01	-.1543E-13	.1651E-03	.1610E+01	.0000E+00	.0000E+00	.686E+04	.483E+00
72.000	.1498E+01	-.1370E+00	.1376E-01	-.1746E-13	.1658E-03	.1804E+01	.0000E+00	.0000E+00	.686E+04	.541E+00
75.000	.1497E+01	-.2074E+00	.2496E-01	-.1746E-13	.1695E-03	.1270E+01	.0000E+00	.0000E+00	.683E+04	.381E+00
78.000	.1497E+01	-.2097E+00	.3615E-01	-.1746E-13	.17E-03	.6278E+00	.0000E+00	.0000E+00	.680E+04	.188E+00
81.000	.1496E+01	-.1473E+00	.4735E-01	-.1746E-13	.25E-03	.7637E-01	.0000E+00	.0000E+00	.677E+04	.229E-01
84.000	.1496E+01	-.2125E-01	.5855E-01	-.1746E-13	.1723E-03	.1923E+00	.0000E+00	.0000E+00	.674E+04	-.577E-01

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KSHELL-IBM FOR ANALYSIS OF AXISYMMETRIC SHELLS BY ARTURS KALNINS JANUARY 1 1974

ODEFLECTIONS AND STRESSES FOR SUBCASE NO. 1 N# 0

0	X	W	OPHI	MFITHETA	MFITHETA	SPHI IN	SPHI OUT	STHETA IN	STHETA OUT	SFITH IN	SFITH OT
0	MAIN SHELL PART NO 1										
	.000	.0000E+00	.8637E+03	.0000E+00	.0000E+00	.8958E+05	-.8683E+05	.7111E+04	-.4430E+05	.000E+00	.000E+00
	4.500	.5149E-01	.8661E+03	.0000E+00	.0000E+00	.7626E+05	-.7389E+05	.3603E+04	-.4078E+05	.000E+00	.000E+00
	9.000	.1249E+00	.8491E+03	.0000E+00	.0000E+00	.6312E+05	-.6112E+05	.7994E+02	-.3722E+05	.000E+00	.000E+00
	9.000	.1249E+00	.8491E+03	.0000E+00	.0000E+00	.6312E+05	-.6112E+05	.7994E+02	-.3722E+05	.000E+00	.000E+00
	13.500	.2160E+00	.8133E+03	.0000E+00	.0000E+00	.5043E+05	-.4879E+05	.3177E+04	-.3351E+05	.000E+00	.000E+00
	18.000	.3206E+00	.7605E+03	.0000E+00	.0000E+00	.3846E+05	-.3715E+05	-.5959E+04	-.2961E+05	.000E+00	.000E+00
	18.000	.3206E+00	.7605E+03	.0000E+00	.0000E+00	.3846E+05	-.3715E+05	-.5959E+04	-.2961E+05	.000E+00	.000E+00
	22.500	.4347E+00	.6938E+03	.0000E+00	.0000E+00	.2743E+05	-.2644E+05	-.8128E+04	-.2552E+05	.000E+00	.000E+00
	27.000	.5544E+00	.6158E+03	.0000E+00	.0000E+00	.1753E+05	-.1682E+05	-.9613E+04	-.2129E+05	.000E+00	.000E+00
	27.000	.5544E+00	.6158E+03	.0000E+00	.0000E+00	.1753E+05	-.1682E+05	-.9613E+04	-.2129E+05	.000E+00	.000E+00
	31.500	.6762E+00	.5299E+03	.0000E+00	.0000E+00	.8898E+04	-.8437E+04	-.1040E+05	-.1701E+05	.000E+00	.000E+00
	36.000	.7969E+00	.4399E+03	.0000E+00	.0000E+00	.1619E+04	-.1361E+04	-.1051E+05	-.1278E+05	.000E+00	.000E+00
	36.000	.7969E+00	.4399E+03	.0000E+00	.0000E+00	.1619E+04	-.1361E+04	-.1051E+05	-.1278E+05	.000E+00	.000E+00
	40.500	.9136E+00	.3498E+03	.0000E+00	.0000E+00	-.4286E+04	.4383E+04	-.1002E+05	-.8693E+04	.000E+00	.000E+00
	45.000	.1024E+01	.2628E+03	.0000E+00	.0000E+00	-.8843E+04	.8821E+04	-.9020E+04	-.4852E+04	.000E+00	.000E+00
	45.000	.1024E+01	.2628E+03	.0000E+00	.0000E+00	-.8844E+04	.8822E+04	-.9020E+04	-.4852E+04	.000E+00	.000E+00
	49.500	.1126E+01	.1820E+03	.0000E+00	.0000E+00	-.1213E+05	.1203E+05	-.7615E+04	-.1335E+04	.000E+00	.000E+00
	54.000	.1218E+01	.1097E+03	.0000E+00	.0000E+00	-.1427E+05	.1412E+05	-.5918E+04	.1799E+04	.000E+00	.000E+00
	54.000	.1218E+01	.1097E+03	.0000E+00	.0000E+00	-.1427E+05	.1412E+05	-.5918E+04	.1799E+04	.000E+00	.000E+00
	58.500	.1300E+01	.4778E+02	.0000E+00	.0000E+00	-.1539E+05	.1522E+05	-.4040E+04	.4515E+04	.000E+00	.000E+00
	63.000	.1369E+01	-.2833E+01	.0000E+00	.0000E+00	-.1568E+05	.1552E+05	-.2081E+04	.6799E+04	.000E+00	.000E+00
	63.000	.1369E+01	-.2823E+01	.0000E+00	.0000E+00	-.1568E+05	.1552E+05	-.2080E+04	.6800E+04	.000E+00	.000E+00
	67.500	.1426E+01	-.4225E+02	.0000E+00	.0000E+00	-.1530E+05	.1515E+05	-.1276E+03	.8663E+04	.000E+00	.000E+00
	72.000	.1470E+01	-.7061E+02	.0000E+00	.0000E+00	-.1442E+05	.1430E+05	.1748E+04	.1013E+05	.000E+00	.000E+00
	72.000	.1470E+01	-.7058E+02	.0000E+00	.0000E+00	-.1442E+05	.1430E+05	.1749E+04	.1013E+05	.000E+00	.000E+00
	76.500	.1502E+01	-.8853E+02	.0000E+00	.0000E+00	-.1320E+05	.1312E+05	.3493E+04	.1124E+05	.000E+00	.000E+00
	81.000	.1521E+01	-.9778E+02	.0000E+00	.0000E+00	-.1179E+05	.1174E+05	.5068E+04	.1205E+05	.000E+00	.000E+00
	81.000	.1521E+01	-.9773E+02	.0000E+00	.0000E+00	-.1179E+05	.1174E+05	.5068E+04	.1205E+05	.000E+00	.000E+00
	85.000	.1528E+01	-.9971E+02	.0000E+00	.0000E+00	-.1179E+05	.1029E+05	.6452E+04	.1260E+05	.000E+00	.000E+00
	90.000	.1524E+01	-.9577E+02	.0000E+00	.0000E+00	-.8845E+04	.8844E+04	.7637E+04	.1294E+05	.000E+00	.000E+00

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O MAIN SHELL PART No 2

.000	.1524E+01	-.9572E+02	.0000E-00	.0000E+00	-.1026E+05	.1026E+05	.7213E+04	.1337E+05	.000E+00	.000E+00
3.000	.1535E+01	-.3767E+02	.0000E-00	.0000E+00	-.7745E+04	.7745E+04	.8768E+04	.1342E+05	.000E+00	.000E+00
6.000	.1540E+01	-.7543E+02	.0000E-00	.0000E+00	-.5515E+04	.5515E+04	.9803E+04	.1311E+05	.000E+00	.000E+00
9.000	.1541E+01	-.5152E+02	.0000E-00	.0000E+00	-.3646E+04	.3646E+04	.1042E+05	.1261E+05	.000E+00	.000E+00
12.000	.1539E+01	-.4766E+02	.0000E+00	.0000E+00	-.2159E+04	.2159E+04	.1072E+05	.1201E+05	.000E+00	.000E+00
12.000	.1539E+01	-.4762E+02	.0000E+00	.0000E+00	-.2164E+04	.2163E+04	.1071E+05	.1201E+05	.000E+00	.000E+00
15.000	.1535E+01	-.3493E+02	.0000E+00	.0000E+00	-.1042E+04	.1042E+04	.1078E+05	.1140E+05	.000E+00	.000E+00
18.000	.1530E+01	-.2401E+02	.0000E+00	.0000E+00	-.2428E+03	.2426E+03	.1068E+05	.1083E+05	.000E+00	.000E+00
21.000	.1525E+01	-.1510E+02	.0000E+00	.0000E+00	.2858E+03	-.2860E+03	.1049E+05	.1032E+05	.000E+00	.000E+00
24.000	.1521E+01	-.3206E+01	.0000E+00	.0000E+00	.5991E+03	-.5994E+03	.1025E+05	.9894E+04	.000E+00	.000E+00
24.000	.1521E+01	-.3213E+01	.0000E+00	.0000E+00	.5998E+03	-.5999E+03	.1025E+05	.9894E+04	.000E+00	.000E+00
27.000	.1516E+01	-.3153E+01	.0000E+00	.0000E+00	.7509E+03	-.7510E+03	.9999E+04	.9549E+04	.000E+00	.000E+00
30.000	.1513E+01	.3234E+00	.0000E+00	.0000E+00	.7861E+03	-.7864E+03	.9751E+04	.9279E+04	.000E+00	.000E+00
33.000	.1510E+01	.2509E+01	.0000E+00	.0000E+00	.7448E+03	-.7452E+03	.9523E+04	.9076E+04	.000E+00	.000E+00
36.000	.1507E+01	.3694E+01	.0000E+00	.0000E+00	.6583E+03	-.6587E+03	.9324E+04	.8929E+04	.000E+00	.000E+00
36.000	.1507E+01	.3707E+01	.0000E+00	.0000E+00	.6574E+03	-.6577E+03	.9323E+04	.8929E+04	.000E+00	.000E+00
39.000	.1505E+01	.4157E+01	.0000E+00	.0000E+00	.5488E+03	-.5489E+03	.9154E+04	.8824E+04	.000E+00	.000E+00
42.000	.1504E+01	.4101E+01	.0000E+00	.0000E+00	.4352E+03	-.4355E+03	.9014E+04	.8752E+04	.000E+00	.000E+00
45.000	.1503E+01	.3725E+01	.0000E+00	.0000E+00	.3280E+03	-.3283E+03	.8899E+04	.8703E+04	.000E+00	.000E+00
48.000	.1502E+01	.3175E+01	.0000E+00	.0000E+00	.2337E+03	-.2338E+03	.8808E+04	.8667E+04	.000E+00	.000E+00
48.000	.1502E+01	.3189E+01	.0000E+00	.0000E+00	.2325E+03	-.2327E+03	.8807E+04	.8668E+04	.000E+00	.000E+00
51.000	.1501E+01	.2568E+01	.0000E+00	.0000E+00	.1539E+03	-.1541E+03	.8733E+04	.8641E+04	.000E+00	.000E+00
54.000	.1501E+01	.1952E+01	.0000E+00	.0000E+00	.9225E+02	-.9269E+02	.8673E+04	.8618E+04	.000E+00	.000E+00
57.000	.1500E+01	.1387E+01	.0000E+00	.0000E+00	.4688E+02	-.4725E+02	.8623E+04	.8595E+04	.000E+00	.000E+00
60.000	.1500E+01	.3991E+00	.0000E+00	.0000E+00	.1600E+02	-.1625E+02	.8580E+04	.8570E+04	.000E+00	.000E+00
60.000	.1500E+01	.9187E+00	.0000E+00	.0000E+00	.1425E+02	-.1450E+02	.8580E+04	.8571E+04	.000E+00	.000E+00
63.000	.1499E+01	.5187E+00	.0000E+00	.0000E+00	-.5125E+01	.4813E+01	.8541E+04	.8544E+04	.000E+00	.000E+00
66.000	.1499E+01	.2086E+00	.0000E+00	.0000E+00	-.1488E+02	.1456E+02	.8505E+04	.8513E+04	.000E+00	.000E+00
69.000	.1498E+01	-.4473E-01	.0000E+00	.0000E+00	-.1731E+02	.1700E+02	.8470E+04	.8480E+04	.000E+00	.000E+00
72.000	.1498E+01	-.4579E+00	.0000E+00	.0000E+00	-.1475E+02	.1450E+02	.8436E+04	.8445E+04	.000E+00	.000E+00
72.000	.1498E+01	-.1370E+00	.0000E+00	.0000E+00	-.1650E+02	.1625E+02	.8435E+04	.8445E+04	.000E+00	.000E+00
75.000	.1497E+01	-.2074E+00	.0000E+00	.0000E+00	-.1153E+02	.1150E+02	.8401E+04	.8408E+04	.000E+00	.000E+00
78.000	.1497E+01	-.2097E+00	.0000E+00	.0000E+00	-.5875E+01	.5563E+01	.8366E+04	.8369E+04	.000E+00	.000E+00
81.000	.1495E+01	-.1473E+00	.0000E+00	.0000E+00	-.50E+00	.5625E+00	.8330E+04	.8331E+04	.000E+00	.000E+00
84.000	.1495E+01	-.2125E-01	.0000E+00	.0000E+00	-.525E+01	-.1875E+01	.8294E+04	.8293E+04	.000E+00	.000E+00

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*L

1:	2	2	0	1	0	0			
2:	0.0		90.		10	2	7	0	1
3:	0.0		336.		24.		1.0		
4:	29000000.		0.3						
5:	-.4375		.4375						
6:	0.0		84.		7	4	2	0	1
7:	0.0		360.		90.				
8:	29000000.		0.3						
9:	-.40625		.40625						
10:	0	0	0.0		0.0				
11:	1			3			6	-13398	7
12:	2			4			6		8
13:	0.0								
14:	53.470								1
15:	1								
16:	PRESS	7							
17:	0.0		53.470		15.0		51.955	30.	47.824
18:		42.198							45
19:	60.		36.572		75.		32.388	90.	30.641
20:	0.0								
21:	30.641								1
22:	1								
23:	PRESS	2							
24:	0.0		30.641		84.		25.768		

DATA FILE:KIRT

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KSHFL1-IBM FOR ANALYSIS OF AXISYMMETRIC SHELLS BY ANTONIS KALNINS JANUARY 1 1974

0 RESPONSE ANALYSIS PARTS# 2 BRANCHES# 0 NUMBER OF SUBCASES# 1 OUTPUT TYPE 2 SUBCASE ADDITION 0

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PART NO 1
OSI# .00000E+00 SX# .90000E+02 SEGMENTS# 10 OUTPUT POINTS# 2 STANDARD SURFACE NO. 7 NTP# 0 LAYERS MLY# 1
TOROIDAL SHELL NO. 7 K# .00000E+00 A# .33600E+03 B# .24000E+02 DIRECTION INDEX# 1.0
OLAYER NO 1 FROM Z# -.43750E+00 TO Z# .43750E+00
CONSISTS OF ISOTROPIC MATERIAL, YOUNGS MODULUS E# .29000E+08 POISSONS RATIO NU# .30000E+00
COEFFS OF THERMAL EXPANSION AFI# .00000E+00 ATHETA# .00000E+00 MASS DENSITY RHOF .00000E+00 COND# .10000E+01

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PART NO 2
OSI# .00000E+00 SX# .84000E+02 SEGMENTS# 7 OUTPUT POINTS# 4 STANDARD SURFACE NO. 2 NTP# 0 LAYERS MLY# 1
CYLINDRICAL SHELL NO 2 K# .00000E+00 R# .36000E+03 PHI# 90.000 DEGREES
OLAYER NO 1 FROM Z# -.40625E+00 TO Z# .40625E+00
CONSISTS OF ISOTROPIC MATERIAL, YOUNGS MODULUS E# .29000E+08 POISSONS RATIO NU# .30000E+00
COEFFS OF THERMAL EXPANSION AFI# .00000E+00 ATHETA# .00000E+00 MASS DENSITY RHOF .00000E+00 COND# .10000E+01

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KSHFL1-IBM FOR ANALYSIS OF AXISYMMETRIC SHELLS BY ANTONIS KALNINS JANUARY 1 1974
SUBCASE NO 1 FOR FOURIER HARMONIC COS 0 THETA

GROUND COND AT START EDGE	1#	.0000E+00	3#	.0000E+00	5#	-.1340E+05	7#	.0000E+00	ALFA#	.0000E+00
GROUND COND AT FINAL EDGE	2#	.0000E+00	4#	.0000E+00	6#	.0000E+00	8#	.0000E+00	ALFA#	.0000E+00

LOADS FOR PART NO 1 SUBCASE NO 1
 ORING LOADS AT END OF THIS PART ARE Q= .00000E+00 NPHI# .00000E+00 NPHI# .00000E+00 N# .00000E+00
 SURFACE AND TEMP LOADS P# .53470E+02 PFI# .00000E+00 PTHETA# .00000E+00 TIN# .00000E+00 TOUT# .00000E+00
 CODE NUMBERS OF VARIABLE LOADS OVER THIS PART, GIVEN BY FGNS BELOW, ARE 1
 0 PRESS LINEAR FUNCTION GENERATOR NO. 1 FROM 7 POINTS
 OYS# .5347E+02 .5196E+02 .4782E+02 .4220E+02 .3557E+02 .3239E+02 .3064E+02
 OXS# .0000E+00 .1500E+02 .3000E+02 .4500E+02 .6000E+02 .7500E+02 .9000E+02
 0 AT BEGINNING AND END OF PART 1 PARAMETERS ARE

RFI# .2400E+02 R# .3360E+03 FI# .0000E+00 RAD .0000E+00 DEGREES S# .0000E+00 C# .1000E+01 H# .8750E+00
 P OR PI# .5347E+02 PFI OR P2# .0000E+00 PTHETA# .0000E+00 TIN# .0000E+00 TOUT# .0000E+00 INORM# 0
 TEMPERATURE IN LAYER NO. 1 AT INSIDE IS .0000E+00 AT OUTSIDE IS .0000E+00 DEGREES

RFI# .2400E+02 R# .3600E+03 FI# .1571E+01 RAD .9000E+02 DEGREES S# .1000E+01 C# .1873E+00 H# .8750E+00
 P OR PI# .3064E+02 PFI OR P2# .0000E+00 PTHETA# .0000E+00 TIN# .0000E+00 TOUT# .0000E+00 INORM# 0
 TEMPERATURE IN LAYER NO. 1 AT INSIDE IS .0000E+00 AT OUTSIDE IS .0000E+00 DEGREES

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LOADS FOR PART NO 2 SUBCASE NO 1
 ORING LOADS AT END OF THIS PART ARE Q= .00000E+00 NPHI# .00000E+00 NPHI# .00000E+00 N# .00000E+00
 SURFACE AND TEMP LOADS P# .30641E+02 PFI# .00000E+00 PTHETA# .00000E+00 TIN# .00000E+00 TOUT# .00000E+00
 CODE NUMBERS OF VARIABLE LOADS OVER THIS PART, GIVEN BY FGNS BELOW, ARE 1
 0 PRESS LINEAR FUNCTION GENERATOR NO. 2 FROM 2 POINTS
 OYS# .3064E+02 .2577E+02
 OXS# .0000E+00 .8400E+02
 0 AT BEGINNING AND END OF PART 2 PARAMETERS ARE

RFI# .9999E+10 R# .3600E+03 FI# .1571E+01 RAD .9000E+02 DEGREES S# .1000E+01 C# .0000E+00 H# .8125E+00
 P OR PI# .3064E+02 PFI OR P2# .0000E+00 PTHETA# .0000E+00 TIN# .0000E+00 TOUT# .0000E+00 INORM# 0
 TEMPERATURE IN LAYER NO. 1 AT INSIDE IS .0000E+00 AT OUTSIDE IS .0000E+00 DEGREES

RFI# .9999E+10 R# .3600E+03 FI# .1571E+01 RAD .9000E+02 DEGREES S# .1000E+01 C# .0000E+00 H# .8125E+00
 P OR PI# .2577E+02 PFI OR P2# .0000E+00 PTHETA# .0000E+00 TIN# .0000E+00 TOUT# .0000E+00 INORM# 0
 TEMPERATURE IN LAYER NO. 1 AT INSIDE IS .0000E+00 AT OUTSIDE IS .0000E+00 DEGREES

KSHELL-IBM FOR ANALYSIS OF AXISYMMETRIC SHELLS BY ARTURS KALNINS JANUARY 1 1974											
1 DEFECTIONS AND STRESS		RESULTS		FOR SUBCASE NO. 1		N# 0		MPHI		UTHRFLA	
X	Y	Q	UPHI	NPHI	BPHI	MPHI	UTHRFLA	N	NIHETA	MIHETA	
0 MAIN SHELL PART NO 1											
0.000	.0000E+00	.1137E+04	.0000E+00	.4601E+03	.4211E-01	-.1340E+05	.0000E+00	.0000E+00	.138E+03	-.382E+04	
4.500	-.6653E-01	.1063E+04	.2807E-02	.3717E+03	.2899E-01	-.1127E+05	.0000E+00	.0000E+00	-.706E+02	-.324E+04	
9.000	-.1101E+00	.9835E+03	.9915E-02	.2881E+03	.1807E-01	-.9305E+04	.0000E+00	.0000E+00	-.469E+03	-.271E+04	
9.000	-.1101E+00	.9835E+03	.9915E-02	.2881E+03	.1807E-01	-.9305E+04	.0000E+00	.0000E+00	-.469E+03	-.271E+04	
13.500	-.1343E+00	.8985E+03	.1966E-01	.2092E+03	.9159E-02	-.7498E+04	.0000E+00	.0000E+00	-.346E+03	-.221E+04	
18.000	-.1427E+00	.8086E+03	.3067E-01	.1360E+03	.2087E-02	-.5863E+04	.0000E+00	.0000E+00	-.106E+04	-.175E+04	
18.000	-.1427E+00	.8086E+03	.3067E-01	.1360E+03	.2087E-02	-.5863E+04	.0000E+00	.0000E+00	-.106E+04	-.175E+04	
22.500	-.1384E+00	.7155E+03	.4181E-01	.7015E+02	-.3337E-02	-.4408E+04	.0000E+00	.0000E+00	-.103E+04	-.134E+04	
27.000	-.1245E+00	.6205E+03	.5221E-01	.1300E+02	-.7309E-02	-.3136E+04	.0000E+00	.0000E+00	-.727E+03	-.971E+03	
27.000	-.1245E+00	.6205E+03	.5221E-01	.1300E+02	-.7309E-02	-.3136E+04	.0000E+00	.0000E+00	-.727E+03	-.971E+03	
31.500	-.1035E+00	.5252E+03	.6121E-01	-.3411E+02	-.1003E-01	-.2048E+04	.0000E+00	.0000E+00	-.147E+03	-.654E+03	
36.000	-.7777E-01	.4321E+03	.6835E-01	-.7036E+02	-.1169E-01	-.1141E+04	.0000E+00	.0000E+00	.673E+03	-.386E+03	
36.000	-.7777E-01	.4321E+03	.6835E-01	-.7036E+02	-.1169E-01	-.1141E+04	.0000E+00	.0000E+00	.673E+03	-.386E+03	
40.500	-.4930E-01	.3435E+03	.7332E-01	-.9554E+02	-.1248E-01	-.4093E+03	.0000E+00	.0000E+00	.168E+04	-.166E+03	
45.000	-.1971E-01	.2612E+03	.7597E-01	-.1100E+03	-.1258E-01	.1596E+03	.0000E+00	.0000E+00	.283E+04	.708E+01	
45.000	-.1971E-01	.2612E+03	.7597E-01	-.1100E+03	-.1258E-01	.1596E+03	.0000E+00	.0000E+00	.283E+04	.708E+01	
49.500	.9673E-02	.1870E+03	.7628E-01	-.1148E+03	-.1216E-01	.5796E+03	.0000E+00	.0000E+00	.404E+04	.138E+03	
54.000	.3783E-01	.1222E+03	.7429E-01	-.1112E+03	-.1137E-01	.8676E+03	.0000E+00	.0000E+00	.527E+04	.230E+03	
54.000	.3783E-01	.1222E+03	.7429E-01	-.1112E+03	-.1137E-01	.8676E+03	.0000E+00	.0000E+00	.527E+04	.230E+03	
58.500	.6401E-01	.6786E+02	.7013E-01	-.1011E+03	-.1034E-01	.1043E+04	.0000E+00	.0000E+00	.646E+04	.288E+03	
63.000	.8771E-01	.2420E+02	.6399E-01	-.8627E+02	-.9179E-02	.1126E+04	.0000E+00	.0000E+00	.759E+04	.319E+03	
63.000	.8771E-01	.2418E+02	.6399E-01	-.8626E+02	-.9179E-02	.1126E+04	.0000E+00	.0000E+00	.759E+04	.319E+03	
67.500	.1086E+00	-.9322E+01	.5608E-01	-.6877E+02	-.7969E-02	.1137E+04	.0000E+00	.0000E+00	.861E+04	.327E+03	
72.000	.1265E+00	-.3303E+02	.4662E-01	-.5046E+02	-.6779E-02	.1094E+04	.0000E+00	.0000E+00	.951E+04	.319E+03	
72.000	.1265E+00	-.3303E+02	.4662E-01	-.5046E+02	-.6779E-02	.1094E+04	.0000E+00	.0000E+00	.951E+04	.319E+03	
76.500	.1415E+00	-.4769E+02	.3585E-01	-.3308E+02	-.5656E-02	.1016E+04	.0000E+00	.0000E+00	.103E+05	.299E+03	
81.000	.1535E+00	-.5517E+02	.2401E-01	-.1811E+02	-.4630E-02	.9169E+03	.0000E+00	.0000E+00	.110E+05	.272E+03	
81.000	.1535E+00	-.5515E+02	.2401E-01	-.1812E+02	-.4630E-02	.9169E+03	.0000E+00	.0000E+00	.110E+05	.272E+03	
85.500	.1628E+00	-.5686E+02	.1132E-01	-.6776E+01	-.3714E-02	.8102E+03	.0000E+00	.0000E+00	.115E+05	.243E+03	
90.000	.1664E+00	-.5399E+02	-.2003E-02	-.1978E-03	-.2911E-02	.7049E+03	.0000E+00	.0000E+00	.119E+05	.211E+03	

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0 MAIN SHELL PART NO 2

0.000	.1694E+00	-.5399E-02	-.2004E-02	-.3553E-14	-.2911E-02	.7050E+03	.0000E+00	.0000E+00	.111E+05	.211E+03
3.000	.1760E+00	-.5128E-02	-.2437E-02	-.3553E-14	-.1595E-02	.5460E+03	.0000E+00	.0000E+00	.115E+05	.164E+03
6.000	.1793E+00	-.4539E-02	-.2282E-02	-.3553E-14	-.6017E-03	.4004E+03	.0000E+00	.0000E+00	.117E+05	.120E+03
9.000	.1799E+00	-.3796E-02	-.3331E-02	-.3553E-14	.1059E-03	.2752E+03	.0000E+00	.0000E+00	.118E+05	.126E+02
12.000	.1789E+00	-.3014E-02	-.3780E-02	-.3553E-14	.5738E-03	.1731E+03	.0000E+00	.0000E+00	.117E+05	.519E+02
12.000	.1789E+00	-.3013E+02	-.3780E-02	.4441E-15	.5741E-03	.1732E+03	.0000E+00	.0000E+00	.117E+05	.519E+02
15.000	.1767E+00	-.2271E-02	-.4225E-02	.4441E-15	.8516E-03	.9405E+02	.0000E+00	.0000E+00	.118E+05	.282E+02
18.000	.1739E+00	-.1614E+02	-.4663E-02	.4441E-15	.9851E-03	.3603E+02	.0000E+00	.0000E+00	.114E+05	.108E+02
21.000	.1709E+00	-.1064E+02	-.5094E-02	.4441E-15	.1016E-02	-.3865E+01	.0000E+00	.0000E+00	.112E+05	-.116E+01
24.000	.1679E+00	-.6280E+01	-.5517E-02	.4441E-15	.9792E-03	-.2697E+02	.0000E+00	.0000E+00	.110E+05	-.869E+01
24.000	.1679E+00	-.6273E+01	-.5517E-02	.5107E-14	.9794E-03	-.2891E+02	.0000E+00	.0000E+00	.110E+05	-.867E+01
27.000	.1650E+00	-.2985E+01	-.5933E-02	.5107E-14	.9025E-03	-.4254E+02	.0000E+00	.0000E+00	.108E+05	-.128E+02
30.000	.1625E+00	-.6482E+00	-.6343E-02	.5107E-14	.8062E-03	-.4777E+02	.0000E+00	.0000E+00	.106E+05	-.143E+02
33.000	.1602E+00	.8918E+00	-.6746E-02	.5107E-14	.7053E-03	-.4722E+02	.0000E+00	.0000E+00	.105E+05	-.142E+02
36.000	.1582E+00	.1799E+01	-.7144E-02	.5107E-14	.6098E-03	-.4305E+02	.0000E+00	.0000E+00	.104E+05	-.129E+02
36.000	.1582E+00	.1804E+01	-.7144E-02	.2900E-14	.6099E-03	-.4301E+02	.0000E+00	.0000E+00	.104E+05	-.129E+02
39.000	.1565E+00	.2233E+01	-.7537E-02	.2900E-14	.5256E-03	-.3685E+02	.0000E+00	.0000E+00	.102E+05	-.111E+02
42.000	.1551E+00	.2323E+01	-.7927E-02	.2900E-14	.4552E-03	-.2995E+02	.0000E+00	.0000E+00	.101E+05	-.398E+01
45.000	.1538E+00	.2188E+01	-.8313E-02	.2900E-14	.3993E-03	-.2314E+02	.0000E+00	.0000E+00	.101E+05	-.694E+01
48.000	.1526E+00	.1920E+01	-.8696E-02	.2900E-14	.3572E-03	-.1695E+02	.0000E+00	.0000E+00	.999E+04	-.509E+01
48.000	.1526E+00	.1925E+01	-.8696E-02	.3058E-14	.3574E-03	-.1691E+02	.0000E+00	.0000E+00	.999E+04	-.507E+01
51.000	.1516E+00	.1593E+01	-.9076E-02	.3058E-14	.3275E-03	-.1162E+02	.0000E+00	.0000E+00	.992E+04	-.349E+01
54.000	.1507E+00	.1245E+01	-.9454E-02	.3058E-14	.3077E-03	-.7363E+01	.0000E+00	.0000E+00	.986E+04	-.221E+01
57.000	.1498E+00	.9153E+00	-.9829E-02	.3058E-14	.2958E-03	-.4129E+01	.0000E+00	.0000E+00	.980E+04	-.124E+01
60.000	.1489E+00	.6225E+00	-.1020E-01	.3058E-14	.2897E-03	-.1833E+01	.0000E+00	.0000E+00	.975E+04	-.550E+00
60.000	.1489E+00	.6269E+00	-.1020E-01	.2554E-14	.2898E-03	-.1795E+01	.0000E+00	.0000E+00	.975E+04	-.539E+00
63.000	.1480E+00	.3815E+00	-.1057E-01	.2554E-14	.2877E-03	-.2950E+00	.0000E+00	.0000E+00	.969E+04	-.885E-01
66.000	.1472E+00	.1871E+00	-.1094E-01	.2554E-14	.2881E-03	.5452E+00	.0000E+00	.0000E+00	.963E+04	.104E+00
69.000	.1463E+00	.4336E-01	-.1131E-01	.2554E-14	.2896E-03	.8766E+00	.0000E+00	.0000E+00	.953E+04	.264E+00
72.000	.1454E+00	-.5226E-01	-.1167E-01	.2554E-14	.2915E-03	.8536E+00	.0000E+00	.0000E+00	.952E+04	.256E+00
72.000	.1454E+00	-.4620E-01	-.1167E-01	.6332E-15	.2917E-03	.9142E+00	.0000E+00	.0000E+00	.952E+04	.274E+00
75.000	.1445E+00	-.9726E-01	-.1204E-01	.6332E-15	.2934E-03	.6881E+00	.0000E+00	.0000E+00	.946E+04	.205E+00
78.000	.1437E+00	-.1062E+00	-.1240E-01	.6332E-15	.2945E-03	.3727E+00	.0000E+00	.0000E+00	.940E+04	.112E+00
81.000	.1428E+00	-.7499E-01	-.1276E-01	.6332E-15	.2950E-03	.9088E-01	.0000E+00	.0000E+00	.935E+04	.273E-01
84.000	.1419E+00	-.4268E-02	-.1311E-01	.6332E-15	.2950E-03	-.3780E-01	.0000E+00	.0000E+00	.929E+04	-.114E-01

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Z	W	CPH1	HFETHETA	HFITHETA	SPH1 IN	SPH1 OUT	STHETA IN	STHETA OUT	SFTH1 IN	SFTH1 OUT
0.000	0.000E+00	1.137E-04	0.000E+00	0.000E+00	1.055E+06	-1.045E+06	3.007E+0E	-2.975E+0E	0.00E+00	0.00E+00
4.500	-0.665E-01	1.603E+04	0.000E+00	0.000E+00	8.878E+05	-8.793E+05	2.534E+0E	-2.550E+0E	0.00E+00	0.00E+00
9.000	-0.110E+00	9.835E+03	0.000E+00	0.000E+00	7.325E+05	-7.259E+05	2.067E+0E	-2.174E+0E	0.00E+00	0.00E+00
9.000	-0.110E+00	9.835E+03	0.000E+00	0.000E+00	7.325E+05	-7.259E+05	2.067E+0E	-2.174E+0E	0.00E+00	0.00E+00
13.500	-0.134E+00	8.885E+03	0.000E+00	0.000E+00	5.900E+05	-5.852E+05	1.633E+0E	-1.826E+0E	0.00E+00	0.00E+00
18.000	-0.142E+00	8.826E+03	0.000E+00	0.000E+00	4.611E+05	-4.579E+05	1.250E+0E	-1.493E+0E	0.00E+00	0.00E+00
22.500	-0.138E+00	7.155E+03	0.000E+00	0.000E+00	3.463E+05	-3.447E+05	9.296E+04	-1.166E+0E	0.00E+00	0.00E+00
27.000	-0.124E+00	6.205E+03	0.000E+00	0.000E+00	2.459E+05	-2.456E+05	6.720E+04	-8.441E+04	0.00E+00	0.00E+00
27.000	-0.124E+00	6.205E+03	0.000E+00	0.000E+00	2.459E+05	-2.456E+05	6.720E+04	-8.441E+04	0.00E+00	0.00E+00
31.500	-0.103E+00	5.252E+03	0.000E+00	0.000E+00	1.601E+05	-1.609E+05	4.953E+04	-5.294E+04	0.00E+00	0.00E+00
36.000	-0.777E-01	4.321E+03	0.000E+00	0.000E+00	8.865E+04	-9.026E+04	3.793E+04	-2.257E+04	0.00E+00	0.00E+00
36.000	-0.777E-01	4.321E+03	0.000E+00	0.000E+00	8.865E+04	-9.026E+04	3.793E+04	-2.257E+04	0.00E+00	0.00E+00
40.500	-0.493E-01	3.345E+03	0.000E+00	0.000E+00	3.098E+04	-3.317E+04	3.229E+04	-6.202E+03	0.00E+00	0.00E+00
45.000	-0.197E-01	2.512E+03	0.000E+00	0.000E+00	1.137E+04	-1.125E+04	3.175E+04	-3.286E+04	0.00E+00	0.00E+00
45.000	-0.197E-01	2.512E+03	0.000E+00	0.000E+00	1.137E+04	-1.125E+04	3.175E+04	-3.286E+04	0.00E+00	0.00E+00
49.500	0.967E-02	1.870E+03	0.000E+00	0.000E+00	-4.673E+04	4.411E+04	3.538E+04	5.698E+04	0.00E+00	0.00E+00
54.000	0.378E-01	1.222E+03	0.000E+00	0.000E+00	-6.927E+04	6.672E+04	4.221E+04	7.823E+04	0.00E+00	0.00E+00
54.000	0.378E-01	1.222E+03	0.000E+00	0.000E+00	-6.927E+04	6.672E+04	4.221E+04	7.823E+04	0.00E+00	0.00E+00
58.500	0.640E-01	6.786E+02	0.000E+00	0.000E+00	-8.290E+04	8.059E+04	5.127E+04	9.647E+04	0.00E+00	0.00E+00
63.000	0.877E-01	2.420E+02	0.000E+00	0.000E+00	-8.924E+04	8.727E+04	6.169E+04	1.117E+05	0.00E+00	0.00E+00
63.000	0.877E-01	2.420E+02	0.000E+00	0.000E+00	-8.924E+04	8.727E+04	6.169E+04	1.117E+05	0.00E+00	0.00E+00
67.500	0.108E+00	-9.222E-01	0.000E+00	0.000E+00	-8.883E+04	8.830E+04	7.273E+04	1.240E+05	0.00E+00	0.00E+00
72.000	0.126E+00	-9.303E-02	0.000E+00	0.000E+00	-8.631E+04	8.515E+04	8.375E+04	1.337E+05	0.00E+00	0.00E+00
72.000	0.126E+00	-9.303E-02	0.000E+00	0.000E+00	-8.631E+04	8.515E+04	8.375E+04	1.337E+05	0.00E+00	0.00E+00
76.500	0.141E+00	-4.769E-02	0.000E+00	0.000E+00	-7.996E+04	7.921E+04	9.426E+04	1.411E+05	0.00E+00	0.00E+00
81.000	0.153E+00	-5.517E-02	0.000E+00	0.000E+00	-7.206E+04	7.165E+04	1.039E+05			

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E-18

0 MAIN SHELL PART HQ 2

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3.000	.1694E+00	-.5399E+02	.0000E+00	.0000E+00	-.6407E+04	.6407E+04	.1172E+05	.1550E+05	.000E+00	.000E+00
6.000	.1700E+00	-.5124E+02	.0000E+00	.0000E+00	-.4963E+04	.4963E+04	.1269E+05	.1507E+05	.000E+00	.000E+00
9.000	.1793E+00	-.4539E+02	.0000E+00	.0000E+00	-.3640E+04	.3640E+04	.1335E+05	.1553E+05	.000E+00	.000E+00
12.000	.1799E+00	-.3796E+02	.0000E+00	.0000E+00	-.2501E+04	.2501E+04	.1374E+05	.1524E+05	.000E+00	.000E+00
15.000	.1789E+00	-.3014E+02	.0000E+00	.0000E+00	-.1573E+04	.1573E+04	.1394E+05	.1488E+05	.000E+00	.000E+00
18.000	.1769E+00	-.3013E+02	.0000E+00	.0000E+00	-.1574E+04	.1574E+04	.1394E+05	.1488E+05	.000E+00	.000E+00
21.000	.1767E+00	-.2271E+02	.0000E+00	.0000E+00	-.8543E+03	.8543E+03	.1393E+05	.1449E+05	.000E+00	.000E+00
24.000	.1739E+00	-.1614E+02	.0000E+00	.0000E+00	-.3274E+03	.3274E+03	.1391E+05	.1411E+05	.000E+00	.000E+00
27.000	.1709E+00	-.1064E+02	.0000E+00	.0000E+00	-.3514E+02	.3513E+02	.1377E+05	.1375E+05	.000E+00	.000E+00
30.000	.1679E+00	-.6260E+01	.0000E+00	.0000E+00	.2633E+03	-.2633E+03	.1360E+05	.1344E+05	.000E+00	.000E+00
33.000	.1679E+00	-.6273E+01	.0000E+00	.0000E+00	.2627E+03	-.2627E+03	.1360E+05	.1344E+05	.000E+00	.000E+00
36.000	.1650E+00	-.2985E+01	.0000E+00	.0000E+00	.3866E+03	-.3866E+03	.1341E+05	.1318E+05	.000E+00	.000E+00
39.000	.1625E+00	-.6482E+00	.0000E+00	.0000E+00	.4341E+03	-.4341E+03	.1322E+05	.1296E+05	.000E+00	.000E+00
42.000	.1602E+00	.8916E+00	.0000E+00	.0000E+00	.4292E+03	-.4292E+03	.1303E+05	.1273E+05	.000E+00	.000E+00
45.000	.1582E+00	.1799E+01	.0000E+00	.0000E+00	.3913E+03	-.3913E+03	.1266E+05	.1263E+05	.000E+00	.000E+00
48.000	.1582E+00	.1804E+01	.0000E+00	.0000E+00	.3909E+03	-.3909E+03	.1286E+05	.1263E+05	.000E+00	.000E+00
51.000	.1565E+00	.2233E+01	.0000E+00	.0000E+00	.3350E+03	-.3350E+03	.1271E+05	.1251E+05	.000E+00	.000E+00
54.000	.1551E+00	.2323E+01	.0000E+00	.0000E+00	.2722E+03	-.2722E+03	.1257E+05	.1241E+05	.000E+00	.000E+00
57.000	.1538E+00	.2188E+01	.0000E+00	.0000E+00	.2103E+03	-.2103E+03	.1245E+05	.1232E+05	.000E+00	.000E+00
60.000	.1526E+00	.1920E+01	.0000E+00	.0000E+00	.1541E+03	-.1541E+03	.1234E+05	.1225E+05	.000E+00	.000E+00
63.000	.1526E+00	.1925E+01	.0000E+00	.0000E+00	.1537E+03	-.1537E+03	.1234E+05	.1225E+05	.000E+00	.000E+00
66.000	.1516E+00	.1593E+01	.0000E+00	.0000E+00	.1056E+03	-.1056E+03	.1225E+05	.1218E+05	.000E+00	.000E+00
69.000	.1507E+00	.1245E+01	.0000E+00	.0000E+00	.6692E+02	-.6692E+02	.1216E+05	.1212E+05	.000E+00	.000E+00
72.000	.1498E+00	.9153E+00	.0000E+00	.0000E+00	.3753E+02	-.3753E+02	.1208E+05	.1205E+05	.000E+00	.000E+00
75.000	.1489E+00	.6225E+00	.0000E+00	.0000E+00	.1666E+02	-.1666E+02	.1200E+05	.1199E+05	.000E+00	.000E+00
78.000	.1489E+00	.6269E+00	.0000E+00	.0000E+00	.1632E+02	-.1632E+02	.1200E+05	.1199E+05	.000E+00	.000E+00
81.000	.1480E+00	.3815E+00	.0000E+00	.0000E+00	.2682E+01	-.2680E+01	.1193E+05	.1192E+05	.000E+00	.000E+00
84.000	.1472E+00	.1871E+00	.0000E+00	.0000E+00	.4954E+01	.4950E+01	.1185E+05	.1186E+05	.000E+00	.000E+00
87.000	.1463E+00	.4336E-01	.0000E+00	.0000E+00	.7984E+01	.7986E+01	.1178E+05	.1179E+05	.000E+00	.000E+00
90.000	.1454E+00	-.5226E-01	.0000E+00	.0000E+00	.7757E+01	.7759E+01	.1171E+05	.1172E+05	.000E+00	.000E+00
93.000	.1454E+00	-.4620E-01	.0000E+00	.0000E+00	.8308E+01	.8310E+01	.1171E+05	.1172E+05	.000E+00	.000E+00
96.000	.1445E+00	-.9726E-01	.0000E+00	.0000E+00	.6253E+01	.6255E+01	.1164E+05	.1165E+05	.000E+00	.000E+00
99.000	.1437E+00	-.1062E+00	.0000E+00	.0000E+00	.6386E+01	.6388E+01	.1157E+05	.1157E+05	.000E+00	.000E+00
102.000	.1428E+00	-.7499E-01	.0000E+00	.0000E+00	.8250E+00	.8269E+00	.1150E+05	.1150E+05	.000E+00	.000E+00
105.000	.1419E+00	-.4286E-02	.0000E+00	.0000E+00	.3452E+00	-.3430E+00	.1143E+05	.1143E+05	.000E+00	.000E+00

APPENDIX F

THERMAL STORAGE SUBSYSTEM (TSS) AVAILABILITY MODEL.

This Appendix contains a detailed description of the availability model as shown in Figure F-1, used to evaluate the thermal storage subsystem

availability. The model groups the

elements of TSS in descending order from most used to least used to non-critical (depending on the mode) in terms of the daily power generation profile. As reflected in the model, a number of the elements are non-critical; i.e., TSS capability greater than 98% will be retained with any one or more of the non-critical elements failed during a 24 hour period.

Loss of any indicator, sensor or transmitter can be tolerated during the time to repair, without impacting operational capability. Losses are accommodated by deducing necessary information from other readings. All critical indicators, sensors or transmitters have at least one back-up.

Loss of any other portion of the TSS will result in less than 98% TSS capability. This reduction doesn't necessarily result in reduction of Pilot Plant capability as TSS degradation will impact Pilot Plant capability only during the TSS discharge mode.

Failure rates predicted for the TSS are shown in Table F-1. Each of the items in the subsystem has been assumed equivalent (for prediction purposes) to one of the items tabulated in Table F-2. Each subsystem item type is identified by a number on the model which corresponds to one of the Table F-2 items. The order of preference for the failure rates selected from Table F-2, as data is available, is (1) Ref. Edison Electric Institute data for 10 MW_e units, (2) EEI data for 60-89 MW_e units or (3) the mean failure rates from Table 18.3 of

Figure F-1. Thermal Storage Subsystem Availability Model

Figure F-1. Thermal Storage Subsystem Availability Model
(Continued)

Table F-1 TSS Component Failure Rates

	Failures/ 10 ⁶ Hours	Quantity	nλ
	λ	n	nλ
24 hrs/ day	Gate Valves	7	163
	Automatic Control Valves	4	340
	Pressure Switches	2	70
	Desuperheater	1	2.3
	Attemperator No. 2	1	2.3
	Condenser	1	23.3
	Condensate Receiver	1	1.5
	Hot HiTec Tank	1	46.5
	Cold HiTec Tank	1	46.5
	Superheater	1	44
	Boiler	1	44
	Preheater	1	44
	Auxiliary Discharge Pump	1	2.3
	Rock/Oil Tank	1	1.5
			831x1.1 = 914
6.5 hrs/ day	Gate Valves	6	140
	Automatic Control Valves	5	425
	Attemperator No. 1	1	44
	Sub Cooler	1	44
	Main Charge Pump	1	2.3
	*Pressure Transmitter	1	18
	*Temperature Transmitter/ Element/Well	1	3.2
	*Pressure Indicator	1	.2

* These items are redundant only

677x1.1 = 745

*1 of 2 required during 12 hour cycle, nλ = frequency of 2 simultaneous failures in 12 hours.

Table F-1.. TSS Component Failure Rates (Continued)

	Failures/ 10 ⁶ Hours	Quantity	
	λ	n	$n\lambda$
5 hrs/ day	Gate Valves	5	117
	Automatic Control Valves	4	340
	HiTec Discharge Pump	1	2.3
	Main Discharge Pump	1	2.3
	* Pressure Transmitter	1	4.4
	* Temperature Transmitter/ Element/Well	1	.8
			<u>467x1.1 = 514</u>
on- tical	Gate Valves	5	
	Automatic Control Valves	5	
	Main Oil Pump	1	
	Pressure Transmitters	16	
	Temperature Transmitter/ Element/Well	16	
	Pressure indicators	4	
	Level Transmitters/ Indicators	5	
	Flow Transmitters	14	
	Oil Cleaner	1	
	Level Sensors	8	

*. These items redundant only 1 of 2 required during 12 hour cycle,

$n\lambda$ = frequency of 2 simultaneous failures in 12 hours.

Table F-1. Typical Power Plant Component Failure Rates

Item No.	Item	Failures Per 10 ⁶ Hours		
		Per EEI		Per Mech.
		10 MW _e Data	60-89 MW _e Data	Des. Handbook
1	Superheater (103)	44	76	150
2	Pump, Elec. Drive (905, 922)	--	2.3	135
3	Valves (116, 117)	23.3	18.3	51
4	Control Valve	--	--	85
5	Sensor, Pressure	--	--	35
6	Condenser (800, 802, 806, 808, 809, 899)	23.3	47	--
7	Attemperator or Desuperheater (112)	--	2.3	--
8	Tank	--	--	1.5
9	Pressure Transducer	--	--	350
10	Transducer, Thermistor	--	--	150
11	Gage, Pressure	--	--	40
12	Boiler (101, 102, 114, 115, 116, 117, 118, 126)	180	71	--
13	Heater (104, 105)	--	45	--

ef. 3, "Mechanical Design and Systems Handbook". For those failure rates selected from the handbook, a severity factor (K_f) of 10 has been applied to account for the effect of a ground equipment environment as compared to a laboratory environment (per handbook direction). To account for miscellaneous plumbing, structural items, etc., 10% is added to each subsystem predicted failure rate.

The mean repair time (MTTR) for each mode is also based on the predicted mode failure rate, the free maintenance time for that mode, and an approximation of the boiler/condenser elements from the 10 MW_e plant data (14.8 hours) as follows:

- 24 hour cycle - 14.8 hours is the mean
- 6.5 hour cycle - 14.8 hours requires from -2.7 to 6.5 hours of the load cycle or a weighted average of 2.3 hours; therefore 2.3 hours of the load cycle would be the normalized mean.
- 4.5 hour cycle - 14.8 hours requires from -4.7 to 4.5 hours of the load cycle or a weighted average of 1.1 hours; therefore 1.1 hours of the load cycle would be the normalized mean.

Availability of the Thermal Storage Subsystem (A_t) is as follows:

$$A_t = A_{t(24 \text{ hrs})} \times A_{t(6.5 \text{ hrs})} \times A_{t(4.5 \text{ hrs})}$$

$$A_{t(24 \text{ hrs})} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

where MTBF = mean operating time (load cycle hours) between
failure in hours = $\frac{10^6}{\lambda}$

MTTR = (as above)

$$A_{t(24 \text{ hrs})} = \frac{1094}{1094 + 14.8} = .987$$

$$A_{t(6.5 \text{ hrs})} = \frac{1342}{1342 + 2.3} = .998$$

$$A_{t(4.5 \text{ hrs})} = \frac{1945}{1945 + 1.1} = .999$$

$$A_t = .985$$

APPENDIX G
DESIGN REPORTS FOR HITEC TANK AND
OIL/ROCK TANK

DESIGN REPORT

FOR

HITEC TANK

20 Ft. Diameter x 18' - 0" Ft. Shell ht.

BMT Contract No. 441102

Honeywell, Inc. No. 426699-AA

40703-V

SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.	
	DATE	DATE		DATE	DATE	SHT.	OF

SCOPE:

The intent of this Design Report is to design a Hitec (heat transfer fluid) Tank for a Solar Energy Power Pilot Plant. The design will consider the earthquake and product loads. As this tank is located in a vault, wind loading is not considered.

The design for the earthquake loads will be based on a more conservative of a UBC type approach or TID-7024 type approach.

As this tank contains the heat transfer fluid and the various pressure retaining parts are free to move to release the temperature stresses and free to expand or contract with the fluid, temperature stresses are not a problem and hence not considered.

The density used in this design report to evaluate the stresses is based on 108 lbs/cuft density that corresponds to 900°F, because of the reduced allowable stresses at this elevated temperature.

Even though the density of the product is ≈ 130 lbs/cu ft at 70°F, the stresses are not evaluated due to the fact that the allowable stresses at 70°F is 1.85 times the allowable stresses at 900°F.

40703-V

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	DATE	DATE		DATE	DATE	SHT. OF

RESULTS:

The extent of this analysis and design work performed is to establish design thicknesses of various parts of this tank for a structurally sound tank.

As this is of comparatively small size, providing knuckles at the areas of discontinuity is not justified and therefore spherical dome shaped roof and bottoms are provided. The discontinuity stresses are taken care of using compression rings at the junctions of roof to shell and bottom to shell.

The base plate will have a lubrite plate under it, to allow for the radial growth of the shell. Lubrite material is Manganese Bronze ASTM B 147 (8 B). This material will allow the base plate to slide freely and is good for 800°F.

As this tank is going to be located in a vault, the tank is not insulated.

The TID-7024 type earthquake analysis governs over UBC type earthquake analysis evaluating the bending moment and overturning moments.

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SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
	DATE	DATE		DATE	DATE	SHT. OF

TANK DATA SHEET

Code: APR 620; but no label allowable stresses from ASME VIII Div. I

Mat'l: A240T304 for all items except as noted

$$S_{at\ 900^{\circ}F} = 10.100\ psi$$

Anchor Bolts = A320 gr. B 8

Radiography: Spot per API 620. No X-ray on roof dome.

Joint Efficiency: 0.85 for butt welds except as noted; 0.7 for roof butt weld.

Corrosion allowance: $1/32''$

Seismic Loading: Yes (0.25 g horiz. and vert.)

Design Pressure: 0.1 psig at top

Density: 108 lbs/ft³ at 900°F
130 lbs/ft³ at 70°F

Note:

- 1) For the calculation of thicknesses of pressure retaining parts and compression ring design the actual loadings are used without taking into account 0.25 g as otherwise the allowable stresses will

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SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
	DATE	DATE		DATE	DATE	SHT. OF

SUBJECT: ALL PRESSURE RETAINING PARTS INCLUDING
IMPRESSION RINGS AND
IRT: A240 T304
BASE PLATE A240 T304
ANCHOR BOLTS A320 GR B8

Figure G-1. Hitec Tank

MADE BY	CHKD BY	MADE BY	CHKD BY	CONTRACT NO.
DATE	DATE	DATE	DATE	SHT. OF
REV.				

also be increased by 33% which will compensate more than the 25% increase in load.

- 2) No X-ray for roof seams. Spot X-ray for shell and bottom dome.

PERIOD OF PRODUCT

$$h = 14' + 2.68' = 16.68'$$

$$\omega^2 = \frac{1.84}{R} g \tan k \left(1.84 \frac{h}{R} \right)$$

$$= \frac{1.84}{10} \times 32.2 \tan k \left(1.84 \times \frac{16.68}{10} \right)$$

$$\omega^2 = 5.899 \text{ rad}^2/\text{sec}^2$$

$$\omega = 2.428 \text{ rad. /sec.}$$

$$T = \frac{2\pi}{\omega} = \frac{2\pi}{2.428} = 2.587 \text{ sec}$$

$$f = \frac{1}{T} = \frac{1}{2.587} = 0.386 \text{ cps}$$

Note: As the height of the skirt is only 2.75' below the bottom of the dome bottom, the tank is assumed to undergo the same max. horizontal acceleration of the ground.

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SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
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Seismic Analysis

A. Analysis is per T/D-7024

Weight of tank = 26 Kips (assumed)

= W_t

Weight of fluid = Volume x density

= $(4830^{\text{cu ft}} \times 108^{\text{lb}}) \div 1000$

= 521.64 Kips

Say 522 Kips

Note: Volume of liquid specified here is based on a density of 130 lbs/cu ft for given salt capacity of 289 tons as we should allow for thermal expansion of the salt, during operating conditions.

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SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
	DATE	DATE		DATE	DATE	SHT. OF

Acceleration Response

Ground acceleration, $\ddot{U}_0 = 0.25 \text{ g's}$

From Figure G-2 for $f = 0.386$, $S_a = 0.32 \text{ g's}$

Wave Height

Max. horizontal displacement of slashing product

$$A_1 = \frac{S_a g}{W^2}$$

$$A_1 = \frac{0.32 \times 32.2}{5.899} = 1.75'$$

$$\theta_h = 1.534 \frac{A_1}{R} \tanh \left(1.84 \times \frac{h}{R} \right)$$

$$= 1.534 \times \frac{1.75}{10} \tanh \left(1.84 \times \frac{16.68}{10} \right)$$

$$= 0.267$$

$$d = \frac{0.408R \coth \left(1.84 \frac{h}{R} \right)}{\frac{g}{W^2 \theta_h R} - 1}$$

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SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
	DATE	DATE		DATE	DATE	SHT. OF

$$d = \frac{0.408 \times 10 \operatorname{Coth} \left(\frac{1.84 \times 16.68}{10} \right)}{\frac{32.2}{5.899 \times 0.267 \times 10} - 1}$$

$$= 3.923' \approx 4'$$

$$\frac{h}{R} = \frac{16.68}{10} = 1.68 > 1.5$$

The tank is considered slender tank per TID 7024.

Impulsive Force

$$W = \frac{\pi}{4} (20)^2 \times 15' \times \frac{108}{1000} = 509 \text{ Kips}$$

$$W = \frac{\pi}{4} (20)^2 \times 1.68 \times \frac{108}{1000} = 57 \text{ Kips}$$

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SI_____T	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
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Figure G-2. Horizontal Design Response Spectra - Scaled 1g Horizontal Ground Acceleration

Calculation of Convective Forces

Figure or Equation	Value of Parameter	Calculation
Fig. 6.6	$\frac{W_o}{W} = 0.708$	$W_o = 0.708 \times 509 \text{ K} = 360.4 \text{ K}$
Eq. 6.13	$h_o = 3/8 h$	$h_o = 0.375 \times 15 = 5.63 \text{ (EBP)}$
Fig. 6.7	$\frac{h_o}{h} = 0.581$	$h_o = 0.581 \times 15 = 8.72 \text{ (IBP)}$
Fig. 6.12	$\frac{W_1}{W} = 0.189$	$W_1 = 0.189 \times 522 \text{ K} = 98.7 \text{ K}$
Fig. 6.13	$\frac{h_1}{h} = 0.72$	$H_1 = 0.72 \times 16.68 = 12 \text{ (EBP)}$
Fig. 6.14	$\frac{h_1}{h} = 0.75$	$h_1 = 0.75 \times 16.68 = 12.5 \text{ (IBP)}$

$$\begin{aligned}
 W_o^{11} &= W_o + W_t + W_2 \\
 &= 360.4 + 26 + 57 \\
 &= 443.4 \text{ K}
 \end{aligned}$$

$$\begin{aligned}
 h_o^{11} &= \frac{360.4 (5.63 + 1.68) + (26 \times 11.68) + (\frac{57 \times 1.68}{2})}{443.4} = 6.73 \text{ (EBP)} \\
 h_o^{11} &= \frac{360.4 \times (8.72 + 1.68) + (26 \times 11.68) + (57 \times \frac{1.68}{2})}{443.4} = 9.25 \text{ (IBP)}
 \end{aligned}$$

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SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
	DATE	DATE		DATE	DATE	SHT. OF

Convective Force, P_1

$$P_1 = 1.2 W_1 O_h \sin Wt$$

Set $\sin Wt = 1$ for max.

$$P_1 = 1.2 \times 98.7 \times 0.267 \times 1.0$$

$$= 32 \text{ K.}$$

Impulsive Force, P_0

$$P_0 = V_0 \times W_o^{11}$$

$$= 0.25 \times 443.4 = 111 \text{ K}$$

Max. Base Shear, F_v

$$F_v = P_0 + P_1 = 111 + 32 = 143 \text{ K}$$

Max. Base Bending Moment, M_{BM}

$$M_{BM} = P_o h_o^{11} + P_1 h_1$$

$$= 111 \times 6.73 + 32 \times 12 = 1131 \text{ k-ft (EBP) (acts on tank)}$$

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Max. Overturning Moment, M_{OTM}

$$M_{OTM} = P_0(h_o^{11} + e) + P_1(h_1 + e)$$

$$M_{OTM} = 111 (9.25 + 2.75) + 32 (12.5 + 2.75)$$

$$= 1820 \text{ k-ft (IBP) acts on foundation}$$

Hoop Force Due to Vertical Acceleration

$$\gamma = 108 \text{ lbs/cuft}$$

$$P = \frac{108}{144} \times h (1 \pm 0.25)$$

vert. acc

$$\text{Max } P = 0.9375 h$$

$$\text{Hoop force} = F_H = P \times R$$

$$= 0.9375h \times (10 \times 12)$$

$$= 112.5h$$

h varies from 0' to 14' for shell

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B. Analysis per O.B.C.

Figure III

Weight of Fluid

Weight of fluid = 522 K (from page 6)

$$H_L = \frac{16.68}{2} + 2.75' = 11.09'$$

Weight of Tank

$$W_t = 26K \text{ (assumed)}$$

$$H_T = \frac{26.11}{2} = 13.055'$$

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Base Shear, F_v

$$F_v = 0.25 (522 + 26)$$

$$= 137 \text{ K}$$

Base Moment, M_B

$$M_B = 0.25 [522 \times 11.09 + 26 \times 13.055]$$

$$= 1533 \text{ k. b ft}$$

Hoop Force Due to Vertical Acceleration

$$P = \frac{108}{144} h (1 \pm 0.25) \quad \gamma = 108 \text{ lb/cuft}$$

$$\text{Max } P = \frac{108}{144} \times h (1 + 0.25)$$

$$= 0.9375 h$$

$$\text{Hoop force } F_H = 0.9375 \times h \times R$$

$$= 0.9375 \times h \times 120''$$

$$= 112.5 h$$

h varies from 0' to 14' for shell

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Comparison of Seismic Analysis Methods

The results of the seismic analysis done in Part A and Part B will be compared and the more conservative method will be used to design the tank.

Force	Method A TID 7024	Method B UBC
Overturning Moment	1820 k-ft	1533 k-ft
Base Shear	143 k	137 k
Hoop Force	112.5 h	112.5 h

Method 'A' governs over method 'B' and the dynamic approach of seismic analysis will be used.

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ROOF PLATE THICKNESS

For internal pressure $t = \frac{T_1 \text{ or } T_2}{SE}$

C. A. = 1/32"

$T_1 = T_2 = 1/2 P R_s$

$= \frac{12}{10100 \times 0.7}$

$= 1/2 \times 0.1 \times 240$

$= 0.002" + C. A.$

$= 0.033" < 3/16"$

$= 12 \text{ lbs. /in.}$

For external load (dead load + live load)

When internal pressure = 0 and $\frac{W}{A} = - \frac{(7.75 + 25)}{144} = -0.227 \text{ psi}$

using equations 3 and 4 from Par. 3.10.2(a) API 620

$T_1 = \frac{R_s}{2} (P + \frac{W+F}{A_T})$

$= \frac{240}{2} (-0.227) = -27.24 \text{ \#/inch}$

$T_2 = 240 (-0.227) - (-27.24) = -27.24 \text{ \#/inch}$

thickness of roof plate for ext. pressure = $\frac{T_1 \text{ or } T_2}{S_{ca}} + c$

$\frac{t-c}{R} = \frac{0.1875 - 0.031}{240} = 0.00065$

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$$S_{ca} = 1,000,000 \left(\frac{t-c}{R} \right)$$

$$= 1 \times 10^6 \times 0.00065$$

$$= 650$$

$$\text{Roof plate } t = \frac{27.24}{650} - 0.042 \text{ C.A.}$$

$$= 0073''$$

Use 3/16" min.

Bottom (dome) thickness

$$t = \frac{T_1 \text{ of } T_2}{SE}$$

$$\text{ratio } \frac{108}{62.4} = 1.73$$

$$P = (14 + 2.68) 0.4333 \times 1.73 + 0.1$$

$$= 12.6 \text{ psig}$$

$$T_1 = \frac{1}{2} P R_s = T_2$$

$$= \frac{1}{2} 12.60 \times 240$$

$$= 1512 \text{ lbs/inch}$$

$$\therefore t = \frac{1512}{10100 \times 0.85}$$

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$$= 0.176 + 0.031$$

$$= 0.207''$$

Use 5/16" plate (To cut down the size of the lower comp. ring)

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SHELL THICKNESS FOR INTERNAL PRESSURE

$$t_{\text{bottom course}} = \frac{T_2}{SE} = \frac{P_1 R_c}{SE}$$

$$P_1 = 14 \times 0.4333 \times 1.73 + 0.1$$

$$= \frac{10.6 \times 120}{10100 \times 0.85} = 10.6$$

$$= 0.148 + 0.031$$

$$= 0.179''$$

1/4" plate is used

$$t_{\text{top course}} = \frac{3.85 \times 120}{10100 \times 0.85} = 0.054 + 0.031''$$

$$P_2 = 5' \times 0.4333 \times 1.73 + 0.1$$

$$= 3.85$$

$$= .085'' \text{ use } 3/16'' \text{ plate}$$

TOP COMPRESSION RING

Compression force
on ring

$$Q = T_2 W_h + T_{25} W_c - T_1 R_c \sin \alpha$$

$$T_1 = T_2 = 12 \text{ lbs/inch from page 18}$$

$$T_{25} = P R_c = 0.1 \times 120 = 12 \text{ \#/in.}$$

$$W_h = 0.6 \sqrt{R_2 (t_h - c)}$$

$$= 0.6 \sqrt{240 (0.1875 - 0.031)} = 3.677''$$

$$\alpha = \cos^{-1} \frac{10}{20} = 60^\circ$$

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$$W_c = 0.6 \sqrt{R_c (t_c - c)}$$

$$= 0.6 \sqrt{120 (0.1875 - 0.031)} = 2.600''$$

$$Q = (12 \times 3.677) + (12 \times 2.6) - (12 \times 120 \sin 60^\circ)$$

$$= -1172 \text{ lbs.}$$

$$\text{Area of comp. ring} = \frac{1172}{10100} = 0.116''$$

Use 2-1/2" x 2-1/2" x 1/4" < - SS304

BOTTOM COMPRESSION RING

From page 19, $T_1 = T_2 = 1512 \text{ lbs/inch}$

$$T_{2S} = 12.6 \times 120 = 1512 \text{ lbs/inch}$$

$$W_h = 0.6 \sqrt{240 \times (0.3125 - 0.031)}$$

$$= 4.93''$$

$$W_c = 0.6 \sqrt{120 (0.4375 - 0.031)}$$

$$= 4.19''$$

$$Q = (1512.0 \times 4.93) + (1512.0 \times 4.19)$$

$$- (1512.0 \times 120 \sin 60^\circ)$$

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$$= -143342 \text{ lbs.}$$

$$\text{Area req'd} - \frac{143342}{10100} = 14.19$$

$$\text{Additional area req'd} = 14.19 - (4.93 \times 0.282) - 2(4.19 \times 0.407)$$

$$= 9.39 \text{ in}^2 \text{ Say } 12 \text{ sq in } A = 3/4 (8 + 8) = 12 \text{ sq in}$$

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SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
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VOLUMES AND WEIGHTS

$$\text{Vol. of Top Dome} = \pi(2.68) \left(\frac{20^2}{8} + \frac{2.68^2}{6} \right) = 432 \text{ cuft}$$

$$\text{Vol. of Cylinder} = \frac{\pi}{4} (20)^2 \times 18 = 5655 \text{ cuft}$$

$$\text{Vol. of Bottom Dome} = \pi(2.68) \left(\frac{20^2}{8} + \frac{2.68^2}{6} \right) = 432 \text{ cuft}$$

$$\text{Vol. of Fluid in Cyl. Portion} = \frac{\pi}{4} (20)^2 \times 14 = 4399 \text{ cuft}$$

$$\text{Weight of Liquid} = (4399 + 432) \frac{108}{1000} = 522 \text{ kips}$$

$$\text{Weight of Top Dome (3/16" } R_L) = 2\pi \times 20' \times 2.68' \times 7.75 = 2610 \text{ lbs.}$$

$$\text{Weight of Cylinder (t average = 7/32")} = \pi(20) 18 \times 9.042 = 10226 \text{ lbs.}$$

$$\text{Weight of bottom dome (5/16" } R_L) = 2\pi \times 20 \times 2.68 \times 12.92 = 4351 \text{ lbs.}$$

$$\text{Weight of Skirt (7/16" } R_L) = \pi(20) 5.43 \times 18.03 = 6152 \text{ lbs.}$$

$$\text{Total Empty Weight} = 2610 + 10226 + 4351 + 6152$$

$$= 17187 + 6152$$

$$= 23339 \text{ lbs.}$$

Say 26500 lb.

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COMBINED STRESS IN SHELL

$$V = 0.25 \times W$$

$$= 0.25 \times 549$$

$$= 138 \text{ kips}$$

$$V = 1.25 W$$

$$= 1.25 \times 549$$

$$= 687 \text{ kips}$$

$$H = F_v = 143 \text{ K (from page 13)}$$

$$M_1 = \text{Earthquake moment at 1-2} = M_{BM} = 1131 \text{ k-ft}$$

$$M_3 = \text{Earthquake moment at 3-4} = M_{OTM} = 1820 \text{ k-ft}$$

W = total D. L. + wt. of contents

$$= 26500 + 522000$$

$$= 548.5 \times 10^3 \text{ lbs.}$$

Say 549 kips

Say 1200 k-ft

Say 2000 kip-ft

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COMBINED STRESS AT POINT 3 DURING DOWNWARD (VERT.) ACC

$$\begin{aligned}
 &= \frac{M_3}{\pi R^2 t} + \frac{V}{2\pi R t} \\
 &= \frac{2000 \times 10^3 \times 12}{\pi \times 120^2 \times (0.4375 - 0.031)} + \frac{687000}{2 \times \pi \times 120 \times (0.4375 - 0.031)} \\
 &= 1306 + 2242 \\
 &= 3548 \text{ psi} < 4208 \text{ psi}
 \end{aligned}$$

$$\begin{aligned}
 \text{Allow. Stress} &= 1.8 \times 10^6 \left(\frac{t-c}{R} \right) \times \frac{E_{\text{at } 900^\circ\text{F}}}{E_{\text{at amb.}}} \quad \left| \quad \frac{t-c}{R} = \frac{0.4375 - 0.031}{120} \right. \\
 &= 1.8 \times 10^6 (.00339) \frac{20000 \times 10^3}{29000 \times 10^3} \quad \left| \quad = 0.00339 \right. \\
 &= 4208.28 \text{ psi}
 \end{aligned}$$

COMBINED STRESS JUST ABOVE POINT ONE (1/4" shell)

$$\begin{aligned}
 &= \frac{M_1}{\pi R^2 t} + \frac{\text{Dead load at point under consideration} \times 1.25}{2\pi R t} \\
 &\quad \text{Extra load} \\
 &= \frac{1200 \times 10^3 \times 12}{\pi (120)^2 \times (0.25 - 0.031)} + \frac{(2610 + 10226 + 300) \times 1.25}{2\pi \times 120 \times (0.25 - 0.031)}
 \end{aligned}$$

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$$= 1454 + 100 = 1554 \text{ psi}$$

$$\begin{array}{l} \text{Allow.} \\ \text{Stress} \end{array} = 1.8 \times 10^6 \frac{(0.25 = 0.031)}{120} \times \frac{20}{29} = 2265.5 \text{ psi}$$

It is evident that the combined stresses on either side of the center line will be smaller during upward acceleration. Hence the stresses are not checked. Also the allowable stresses in tension are greater than compressive allowable stresses.

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ANCHOR BOLTS

T = Design tension in each bolt
(in full condition and Eq

acting) w/upward acceleration = $\frac{4M}{ND} - \frac{(W - V)}{N}$

$$= \frac{4 \times 2000}{8 \times 20} - \frac{(549 - 138)}{8}$$

$$= -1.375 \text{ kips (compressive)}$$

After 25%
decrease

T₂ = Design tension during empty
condition w/eq upward
acceleration

$$= \frac{4M_2}{ND} - \frac{(W_{\text{empty}}) \times 0.75}{N}$$

Moment M₂ = 6.625 x (9 + 2.68' + 2.75')

W_{empty} = 26500 lbs

$$= 95.6 \text{ kip-ft}$$

$$H_2 = 0.25 \times 26.5$$

$$= 6.625 \text{ kips}$$

$$T_2 = \frac{4 \times 95.6}{8 \times 20} - \frac{26.5 \times 0.75}{8} = -0.094 \text{ kips (compression)}$$

As there is no uplift the anchor bolts are designed for shear load only.

Shear force in each bolt = $\frac{H}{0.5 \times \text{no. of anchor bolts}}$

$$= \frac{143}{0.5 \times 16}$$

$$= 17.88 \text{ kips}$$

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$$\text{Area required} = \frac{17.88}{8.28}$$

$$= 2.16 \text{ sq."}$$

Use 16 - 2" ϕ A-320 GR. B 8 anchor bolts.

$$F_v = \text{shear stress}$$

$$= 0.4 F_y$$

$$= 0.4 \times 30 \times \frac{E_{900}}{E_{AMB}}$$

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BASE PLATE

Ref: Pressure vessel handbook by Eugene Megyesy, page 65, third edition.

$$\text{Maximum compression} = \frac{12M}{A_s} + \frac{V}{C_s} \text{ lbs/lin. in.}$$

$$M = 2000 \text{ kip-ft}$$

$$V = 687 \text{ kips}$$

$$A_s = \frac{\pi}{4} [240 + 2(7/16)] = 45569 \text{ in}^2 \quad C_s = \pi(240 + 2 + 7/16)$$

$$= 756.7 \text{ in.}$$

$$P_c = \text{compression} = \frac{12 \times 2000 \times 10^3}{45569} + \frac{687 \times 10^3}{756.7}$$

$$= 1435 \text{ lbs/lin. in.}$$

$$P = \frac{P_c}{l}$$

$$= \frac{1435}{6.5} = 221$$

Say 225 psi

$$\text{B. M.} = \frac{P(l_2 + l_3)^2}{2}$$

$$= \frac{225(4.25)^2}{2}$$

$$= 2032 \text{ in-lbs.}$$

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$$\begin{aligned} \text{Thickness of base plate} &= t_B = \sqrt{\frac{6M}{f}} \\ &= \frac{6 \times 3032}{12896} \\ &= 0.972" \end{aligned}$$

$$\begin{aligned} f &= \text{Stress at amb} \times \frac{E_{\text{at } 900^\circ}}{E_{\text{at amb}}} \\ &= 18700 \times \frac{20 \times 10^6}{29 \times 10^6} \\ &= 12896 \text{ psi} \end{aligned}$$

Use 1" TK

CONCLUSION

The above calculation is for operating condition with simultaneous earthquake action. The density used is corresponding to 900°F. As the allowable stress of tank material is greater (18700psi) at 70°F, the stresses at the membranes are not evaluated even though the density is 130 lbs/cuft which is 1.2 (approx.) times the density of salt at 900°F.

$$\text{Ratio of stresses} = \frac{18700}{10100} = 1.85$$

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D

I

C

G-33

B

A

Figure G-4. 40x 32-foot Commercial Tank

DATA SHEET

DESCRIPTION	40' x 32' HIGH HITEC TANK
NUMBER REQUIRED	ONE
CAPACITY	289 TONS
DESIGN PRESSURE	PRODUCT HEAD 7.15 PSI @ 32'
OPERATING PRESSURE	HYDROSTATIC HEAD + 0.125 PSIG
TEST PRESSURE	900 PSF
DESIGN TEMPERATURE	AMBIENT
TEST TEMPERATURE	AS ON SHELL & BOTTOM HEAD
JOINT EFFICIENCY	75% ON WELDED SURFACES
CORROSION ALLOWANCE	API STD 620 NO STAMP
CODE & STAMP	EXHIBIT A
CUSTOMER SPECIFICATION	
SHELL	A 240-304
TOP BOTTOM	NONE
HEADS	A 240-304
NOZZLE	NECK A 125-F-504
MANWAY	NECK A 240-304 FLANGE A 125-F-504 COVER A 240-304
REINFORCING PADS	A 240-304
PIPING	NONE
COUPLINGS	NONE
STIFFENER RINGS	A 240-304
INTERNAL	NONE
BOLTING	BOLTS A 193-B NUTS A 193-B STUDS NONE
GASKETS	COMP. FIBERGLASS
STRUCTURAL	A 240-304
ELECTRODES	A 308
STRESS RELIEF	N.A.
CLEANING	N.A.
SURFACE PREPARATION	N.A.
INTERNAL PAINTING	N.A.
EXTERNAL PAINTING	N.A.
LINING	N.A.
INSULATION	N.A.
LADDERS & PLATFORMS	N.A.
CATHODIC PROTECTION	N.A.
FOUNDATIONS	N.A.
Q.A. MANUAL	NOT APPLICABLE
MILL CERTIFICATIONS	REQD ON ALL PRESSURE RETAINING PARTS
WELDERS	A 5 ME. SECTION IS QUALIFIED
WELDING	PER API STD 620
NONDESTRUCTIVE TESTING	RADIOGRAPH SHELL & BOTTOM HEAD PER API STD 620
SPECIAL TESTING	NONE
TESTING	HYDROTEST + 0.125 PSIG
ROOF	0.125 PSIG W/ SOAP SUDS

NOTES: 1. FLANGE BOLT HOLES STRADDLE TANK VERTICAL & RADIAL CENTER LINES - UNLESS OTHERWISE SPECIFIED.

PROJECT ENGINEER APPROVAL & DATE	CHECKED BY & DATE	DRAWN BY & DATE K 4-5-77	NO.	REVISION
			THIS DRAWING IS THE PROPERTY OF BROWN-MINNEAPOLIS TANK AND IS TO BE USED ONLY IN CONNECTION WITH WORK PERFORMED BY BROWN-MINNEAPOLIS TANK. THE DRAWING IS NOT TO BE COPIED IN WHOLE OR IN PART AND MUST BE RETURNED UPON REQUEST.	
			PURCHASER'S NO.	
DESCRIPTION: 40' x 32' HIGH HITEC TANK FOR HONEYWELL			DRAWING NUMBER 77-0441104	ORDER NUMBER
			SHEET	REVISION 1

REFERENCES

- 1) Design and construction of large welded low pressure storage tanks API 620.
- 2) American Institute of Steel Construction.
- 3) Pressure vessel handbook by Eugene Megyesy, third edition.
- 4) ASME VIII, Div. I.
- 5) U. S. Atomic Energy Commission, Regulatory Guide 1.6, Rev. 1 Fig. 1.

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DESIGN REPORT

FOR

OIL/ROCK TANK

60 Ft. Diameter x 48 Ft. High

BMT Contract No. 441101

Honeywell, Inc. No. 426699-AA

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SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
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SCOPE:

The intent of this Design Report is to design an Oil/Rock tank for a Solar Energy Power Pilot Plant. The design considers earthquake, wind, thermal and product loads.

The design for earthquake loads is based on the more conservative of a UBC type analysis or a TID-7024 type analysis.

The design for wind loads considers overturning of the tank and stability of the shell.

The design for thermal loads considers the effect of differential expansion between the steel shell and granite rocks.

The design for the product head considers the varying oil density, and the compaction and angle of repose of the rock.

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RESULTS:

The extent of analysis and design work performed in this Design Report is inclusive enough to result in a design for the Oil/Rock tank which is workable and structurally sound. This design has considered special problem areas which are unique for storage tanks.

The use of a knuckle at the shell to bottom connection has been used to reduce discontinuities and stress concentration and to give the tank more flexibility in that region. The effects of the plastic moment which develops in the bottom of a steel tank setting on concrete foundation has been considered in the stress analysis of the knuckle.

The use of a knuckle at the shell to roof connection has again been used to reduce discontinuities and stress concentrations and to give the tank a more aesthetically pleasing appearance.

Considering the differential thermal expansion between the steel shell and granite rock has resulted in a slightly heavier shell plate, but this problem is one that should be considered so that the tank has the ability to safely cooldown to ambient temperatures, $\approx 70^{\circ}\text{F.}$, from the operating temperature of $\approx 500^{\circ}\text{F.}$

A533 Class 2 Grade A steel was selected for the shell, bottom, bottom knuckle and anchor chairs for its high yield strength and weldability. The use of this material permits the thermal and product loads to remain in the elastic range for a ΔT of $\approx 530^{\circ}\text{F.}$ A 516-60 was selected for the roof and roof knuckle for its high temperature properties and weldability. The tank should be PWHT in accordance with ASME

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Section VIII, Division I, paragraph UCS-S6, since A533 steel has been used.

Lubrite material will be used under the base plate of the anchor chairs to allow the anchor chairs to slide freely for radial growth of the shell.

The roof is equipped with (7) large diameter openings (1) 48" $\emptyset$ at the center and (6) 24" $\emptyset$ equally spaced on a 32' diameter, for each access to the manifold and for the initial filling of the tank with rock.

The bottom is sloped towards a drain/sump arrangement for draining of the tank.

Pittsburgh Corning has recommended in their Energy Analysis Report #738 that 9" of foamglass on the shell and roof is adequate to limit the hourly heat loss through the shell and roof to 140 KW or 477000 BTU's. They recommend foamglass because it won't absorb any spilled or leaked oil.

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DESIGN DATA:

- Design Code: a. Roof & Roof Knuckle
1. API-650 (ext. press)
 2. ASME Section VIII, Div. 1 (int. press)
- b. Shell & Bottom Knuckle
1. API-650 App. D (w/modification for thermal loads.)
- c. Bottom
1. API-650
- d. Anchor Chairs
1. AISC
- e. Foundation
1. ACI 318-63 (Anchor bolts)
 2. ACI 317-71 (Remainder)

Fabrication & Erection Code: API-650

Examination & Testing Code: API-650 App. D

Type of Construction: Shell - double butt
 Roof Knuckle - double butt
 Bottom Knuckle - double butt where accessible,
 remainder single butt with
 back-up strip
 Roof & Bottom - single butt with back-up strip
 Shell fittings - full pen

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Design Pressure: 43' of Rock at 72% compaction and $\phi = 32^\circ$,
 $\gamma = 170$ PCF
 44' of Oil, $\gamma = 54.4$ PCF at 70°F
 $\gamma = 41.6$ PCF at 600°F

Design Temperature: 600°F with a cool-down to 70°F (ambient)

Earthquake: 0.25 g's horizontal and vertical ground acceleration acting simultaneously.

Wind: 110 MPH

- Material:
- a. Shell, bottom and knuckle, anchor chairs
 - 1. A533 Grade A Class 2
 $F_y = 58.8$ MSI at 600°F
 $F_y = 70.0$ KSI at 70°F
 - b. Roof, roof knuckle
 - 1. A515-60
 - c. Footing and pad
 - 1. 3000 psi concrete
 - 2. A615-60 re bars
 - 3. A36 anchor bolts
 - 4. Lubrite ASTM B148 (9D)
 - d. Insulation
 - 1. 9" of foamglass® by Pittsburgh Corning

Head loss hourly: 140 KW_t through roof and shell

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SEISMIC ANALYSIS

A. ANALYSIS IS PER TID-7024 (REF 13)

Weight of Oil and Rock

$$W_{\text{rock}} = 30^2 \pi 43 \times \frac{170}{1000} (.72) = 14881 \text{ K}$$

$$W_{\text{oil}} = 30^2 \pi [(43 \times .28) + 1'] \times \frac{54.4}{1000} = 2006 \text{ K}$$

$$W_{\text{total}} = 16887 \text{ K}$$

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Figure G-5. Horizontal Design Response Spectra - Scaled to 1g Ground Acceleration

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Weight of Tank

$$W_t = 450 \text{ K (assumed)}$$

Period of Product

The rock is assumed to be in plastic state since Rankine's coefficient K_1 goes to 1.0 for seismic conditions. Therefore, the rock will act like a fluid and will act with the oil.

$$\begin{aligned}\omega^2 &= \frac{1.84}{R} g \text{ tank } (1.84 \frac{h}{R}) \\ &= \frac{1.84}{30} \times 32.2 \text{ tank } (1.84 \frac{44}{30})\end{aligned}$$

$$\omega^2 = 1.957 \text{ rod}^2/\text{sec}^2$$

$$\omega = 1.399 \text{ rad/sec}$$

$$T = \frac{2\pi}{\omega} = \frac{2\pi}{1.399}$$

$$T = 4.491 \text{ sec}$$

$$f = \frac{1}{T} = \frac{1}{4.491} = 0.22 \text{ cps}$$

Acceleration Response

$$\text{Ground acceleration, } \ddot{U}_o = .25 \text{ g's}$$

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From Figure #B-2, for $f = 0.22$ cps

$$S_a = 0.15 \text{ g's}$$

Tank is considered as rigid and acting with ground motion.

Waveheight

Maximum horizontal displacement of sloshing product, $A_1 = \frac{S_a g}{\omega^2}$

$$A_1 = \frac{.15 \times 32.2}{1.957} = 2.47$$

$$\begin{aligned} \theta_h &= 1.534 \times \frac{A_1}{R} \tanh(1.84 \frac{h}{R}) \\ &= 1.534 \times \frac{2.47}{30} \tanh(1.84 \frac{44}{30}) \end{aligned}$$

$$\theta_h = 0.125$$

$$d = \frac{0.408 \times R \coth(1.84 \frac{h}{R})}{\frac{g}{\omega^2 \theta_h R} - 1}$$

$$d = \frac{0.408 \times 30 \coth(1.84 \frac{44}{30})}{\frac{32.2}{1.957 \times 0.125 \times 30} - 1}$$

$$d = 3.65'$$

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The freeboard in tank is $4' > 3.65'$.

Figure G-6. Mathematical Model

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Calculation of Convective Forces

Fig. or Eq.	Value of Parameter	Calculation
Fig. 6.6	$\frac{W_o}{W} = 0.701$	$W_o = 0.701 \times 16887 = 11838 \text{ K}$
Eq. 6.13	$h_o = \frac{3}{8} h$	$h_o = 0.375 \times 44 = 16.5 \text{ (EBP)}$
Fig. 6.7	$\frac{h_o}{h} = .588$	$h_o = 0.588 \times 44 = 25.89 \text{ (IBP)}$
Fig. 6.12	$\frac{W_1}{W} = .215$	$W_1 = 0.215 \times 16887 = 3628 \text{ K}$
Fig. 6.13	$\frac{h_1}{h} = .676$	$h_1 = 0.676 \times 44 = 29.74' \text{ (EBP)}$
Fig. 6.14	$\frac{h_1}{h} = .727$	$h_1 = 0.727 \times 44 = 31.98' \text{ (IBP)}$

$$W_o'' = W_o + W_T$$

$$= 11838 + 450$$

$$= 12288 \text{ K}$$

$$h_o'' = \frac{11838 \times 16.5 + 450 \times 24}{12288} = 16.77' \text{ (EBP)}$$

$$h_o'' = \frac{11838 \times 25.89 + 450 \times 24}{12288} = 25.82' \text{ (IBP)}$$

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Convective Force, P_1

$$P_1 = 1.2 W_1 \theta_h \sin \omega t$$

Set $\sin \omega t = 1$ for max

$$P_1 = 1.2 \times 3628 \times 0.125 = 544 \text{ K}$$

Impulsive Force, P_o

$$P_o = \ddot{U} \times W_o''$$

$$P_o = .25 \times 12288 = 3072 \text{ K}$$

Max. Base Shear, F_v

$$F_v = P_o + P_1 = 3072 + 544 = 3616 \text{ K}$$

Max. Base Bending Moment, M_{BM}

$$M_{BM} = P_o \times h_o'' + P_1 \times h_1$$

$$= 3072 \times 16.77 + 544 \times 29.74$$

$$= 67696 \text{ K-ft (EBP) (acts on tank)}$$

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Max. Overturning Moment, M_{OTM}

$$\begin{aligned} M_{OTM} &= P_o \times h_o'' + P_1 \times h_1 \\ &= 3072 \times 25.82 + 544 \times 31.98 \\ &= 96716 \text{ K-ft (IBP) (acts on foundation)} \end{aligned}$$

Hoop Force Due to Vertical Acceleration

Since Rankine's coefficient, K , is equal to 1.0, an equivalent fluid density can be determined.

$$\gamma_{eq} = \frac{16887 \times 1000}{30^2 \pi 44} = 136 \text{ PCF}$$

$$\therefore P_{eq} = \frac{136}{144} \times h \times (1 \pm .25)$$

$$\max P_{eq} = 1.1806 h$$

$$\text{Hoop Force, } F_H = P_{eq} R = 1.1806 h \times 30 \times 12$$

$$F_H = 425 h$$

Where h goes from 0' to 44'.

The thermal stress due to the differential expansion of the rocks and tank shell is not added to the hoop stress from vertical acceleration since the rocks are considered as being plastic ($K=1$) and therefore the thermal stress will dissipate.

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B. ANALYSIS IS PER UBC (REF. 14)

Weight of Oil and Rock

$$W_{\text{rock}} = 30^2 \pi \cdot 43 \times \frac{170}{1000} (.72) = 14881 \text{ lb}$$

$$H_R = 43/2 = 21.5'$$

above rocks,

$$W_{\text{oil}_1} = 30^2 \pi \cdot 1 \times \frac{54.4}{1000} = 154 \text{ K}$$

$$H_{o1} = 43 + .5 = 43.5'$$

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around rocks,

$$W_{oil_2} = 30^2 \pi 43 \times \frac{54.4}{1000} \times .28 = 1852 \text{ K}$$

$$H_{O_2} = 43/2 = 21.5'$$

$$H_O = \frac{154 \times 43.5 + 1852 \times 21.5}{154 + 1852} = 23.19'$$

$$W_{oil} = 154 + 1852 = 2006 \text{ K}$$

Weight of Tank

$$W_t = 450 \text{ K (assumed)}$$

$$H_T = 48/2 = 24'$$

The tank, rocks and oil are taken to be a rigid mass with a natural frequency greater than 33 CPS. Therefore the entire mass is acted on by .25 gs in both the horizontal and vertical directions.

Base Shear, F_v

$$F_v = .25 [14881 + 2006 + 450]$$

$$= 4334 \text{ K}$$

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Base Moment, M_B

$$\begin{aligned}
 M_B &= .25 [14881 \times 21.5' + 2006 \times 23.19 + 450 \times 29'] \\
 &= 94315 \text{ K-ft}
 \end{aligned}$$

Hoop Force Due to Vertical Acceleration

Since rocks were taken as a rigid mass, Rankines coefficient, K_1 will not be taken as 1.0 but as 0.31 as in the static case. Therefore, the pressure distribution on the shell and knuckle will be increased by 25% for the maximum pressure. In this analysis the thermal stress, due to the differential expansion of the rocks and tank shell, will be additive to the hoop stress due to the vertical acceleration since the rocks are considered as being rigid with $K = .31$.

$$P_{oil} = \frac{54.4}{144} h_o \times 1.25$$

$$P_{rock} = \left(\frac{170 - 54.4}{144} \right) .72 \times .31 h_R \times 1.25$$

$$P_T = 0.472 h_o + 0.224 h_R$$

$$F_H = P_T R = (.472 h_o + 0.224 h_R) 360$$

$$= 170 h_o + 81 h_R$$

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$$t = \frac{1.3 \times 600 \times 1.634}{2 \times 15000 \times .65 - .2 \times 1.3}$$

$$t = 0.0654''$$

3. EXTERNAL PRESSURE DESIGN (REF 1)

The roof shall be designed for a 25 PSF live load, a 8 PSF insulation load and the dead load of the roof plate.

The formula for dome roofs, $t = \frac{R}{200}$, is based on a uniform load of 45 PSF (line and dead load combined) and ambient temperatures. It shall be modified for additional weight and 600°F temperature as follows.

$$t = \frac{R}{200} \left(\frac{E_s @ 70^\circ}{E_s @ 600^\circ} \right) \sqrt{\frac{\text{Ins.} + \text{L. L.} + \text{D. L.}}{45}}$$

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$$E_s = 29.0 \times 10^6 \text{ PSI} \\ @70^\circ\text{F}$$

$$E_s = 25.7 \times 10^8 \text{ PSI} \\ @600^\circ\text{F}$$

$$\text{Ins.} = 8 \text{ PSF}$$

$$\text{LL} = 25 \text{ PSF}$$

$$\text{D. L.} = 40.8 \times 5/16 = 12.75 \text{ PSF (based on 5/16" PL)}$$

$$t = \frac{50}{200} \left(\frac{29.0}{25.7} \right) \sqrt{\frac{8 + 25 + 12.75}{45}}$$

$$t = 0.284"$$

use 5/16" PL for spherical section and knuckle.

CHECK OF ROOF FOR EARTHQUAKE

The insulation and dead load of roof will be increased by 25% from the vertical acceleration but the increase in stress allowable is 33%, therefore the roof as designed is acceptable.

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1. SHELL DESIGN A533 CLASS 2

The shell shall be designed to contain the oil and rock at 600°F and 70°F for normal and earthquake conditions. The critical design temperature will be when the shell has cooled down from 600°F to 70°F since a thermal hoop stress develops in the shell due to differential expansion between the shell and rocks.

1. DESIGN FOR 600°F (REF. 1)

The required shell thickness is based on $t = \frac{2.6D(H-1)G}{21000}$ from Appendix D of API-650. $2.6D(H-1)G$ is equal to PR , where; P = pressure 1' above point of consideration and R = radius. The effects of the vertical acceleration of an earthquake are considered by;

$$P_{EQ} = P(1 \pm A_V) \therefore P_{EQ} = P(1.25)_{\max}$$

A 2' radius knuckle will be used at bottom.

$$\gamma_{oil} = 40.6 \text{ PCF at } 600^\circ\text{F}$$

$$H_o = 44' \text{ max}$$

$$\gamma_{rock} = 170 \text{ PCF} \quad \phi = 32^\circ$$

$$H_R = 43 @ 72\% \text{ compaction}$$

$$K = \frac{1 - \sin \phi}{1 + \sin \phi} = 0.31$$

$$P_o = \left(\frac{40.6}{144} \right) (h_o - 1)$$

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$$P_R = \left(\frac{170 - 40.6}{144} \right) .72 \times .31 (h_R - 1)$$

$$P_T = P_U + P_R + 1.3$$

$$P_{EQ} = P_T \times 1.25$$

Since P_{EQ} is only 1.25 times greater than P_T and the allowable stress for earthquake conditions is 1.33, the earthquake pressure P_{EQ} does not govern. $\therefore t = \frac{P_T R}{21000}$.

Course	$h_o - 1$	$h_R - 1$	P_T (PSI)	t_{cal}	t_{min}
1 @ 7'	4 1'	40'	20.88	0.358	3/8
2 @ 7'	3 4	33	17.50	0.3001	5/16
3 - 6 @ 8'	-	-	-	-	5/16

2. DESIGN FOR COOLDOWN TO 70°F FROM 600

The thermal stress due to differential expansion must first be determined in order to design the shell for the product head, since the thermal stress is independent of the shell plate thickness. The vertical acceleration of the earthquake shall be included in the design of the shell plate. As before; $P_{EQ} = P_T (1.25)$.

The allowable stress for the combined stresses due to differential expansion, earthquake and product head will be $0.9 F_y @ 70^\circ F$. The max. stress for the product head under vertical acceleration will be $0.9 F_y @ 70^\circ F$ minus the thermal stress.

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Thermal Stress

Assume tank is built at ambient or room temperature of 70°F. Tank is to be designed for 600°F with a cool down to ambient 70°F.

$$@600^{\circ}\text{F}, \epsilon_S = 7.23 \times 10^{-6} \text{ in/in-}^{\circ}\text{F from } 70^{\circ}\text{F} \quad (\text{Ref. 4})$$

$$@70^{\circ}\text{F}, \epsilon_S = 6.07 \times 10^{-6} \text{ in/in-}^{\circ}\text{F}$$

$$@70^{\circ}\text{F to } \epsilon_R \cong 4 \times 10^{-6} \text{ in/in-}^{\circ}\text{F } 600^{\circ}\text{F}$$

Radial growth of shell from 70°F to 600°F

$$\Delta_{R1} = 7.23 \times 10^{-6} \times 360 \times (600-70) = 1.379 \text{ in}$$

Radial growth of rocks from 70°F to 600°F

$$\Delta_{R2} = 4.0 \times 10^{-6} \times 360 (600^{\circ} - 70^{\circ}) = 0.763 \text{ in}$$

Rocks will slide out to shell

$$\therefore R_S \text{ and } R_R \text{ at } 600^{\circ}\text{F} = 360'' + 1.379'' = 361.379''$$

Since the rock mass is so much greater than the shell, rocks will not be compressed by the inward shrinking of the shell. Therefore the shell must take the differential expansion ($\Delta R_1 - \Delta R_2$)

$$\text{Strain in shell} = \frac{1.379 - .763}{361.379 - .763} = 0.001708''/\text{in}$$

$$\sigma_m = \epsilon_S E_S = 0.001708 \times 29 \times 10^6 = 49537 \text{ PSI}$$

70°F use 49600 PSI

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Shell Plate Thickness

The allowable stress for loop stresses due to the product head is,

$$S = 0.9 F_y @ 70^\circ F - \sigma_m$$

$$\therefore S = 0.9 \times 70000 - 49600 = 13400 \text{ PSI}$$

The shell plate thickness, t , can now be determined by: $t = \frac{P_{EQ} \times R}{S}$
where $P_{EQ} = P_T \times 1.25$ and $R = 360''$

$$S = 13400 \text{ PSI}$$

$$\gamma_{oil} = 54.4 \text{ PCF at } 70^\circ F$$

$$H_o = 44' \text{ max.}$$

$$\gamma_{rock} = 170 \text{ PCF } \phi = 32^\circ$$

$$H_R = 43' \text{ max. @ 72\% compaction}$$

$$K = \frac{1 - \sin \phi}{1 + \sin \phi} = 0.31$$

$$P_o = \frac{54.4}{144} (h_o - 1)$$

$$P_R = \frac{170 - 54.4}{144} \times .72 \times .31 (h_R - 1)$$

$$P_T = P_o + P_R + 1.3$$

$$\therefore P_{EQ} = 1.25 \times P_T$$

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Course	h_o^{-1}	h_R^{-1}	P_o	P_R	P_T	$t_{cal.}$	t_{use}
1 @ 7'	41	40	15.489	7.167	23.956	0.804	13/16
2 @ 7'	34	33	12.844	5.913	20.057	0.674	11/16
3 @ 8'	27	26	10.200	4.659	16.159	0.543	9/16
4 @ 8'	19	18	7.178	3.225	11.703	0.393	7/16
5 @ 8'	11	10	4.156	1.792	7.247	0.243	5/16
6 @ 8'	3	2	1.133	0.358	2.792	0.094	5/16

The knuckle will be tried as 7/8" and analyzed by KSHEL1.

KSHEL1 ANALYSIS OF BOTTOM KNUCKLE

Due to the complex stress situation which exists in a knuckle, the knuckle along with the 1st shell course will be analyzed by KSHEL1, a stress analysis program for axisymmetric shells. Since this analysis considers the effects of discontinuities and temperatures the allowable stress for the combined loads will be $3 S_m$ as shown in Figure NB-3222-1 of ASME Section III, Div. 1 Subsection NB. For A533 Class 2, $S_m = 30 \text{ KSI} @ 70^\circ < 600^\circ\text{F}$ from Table I-1.1 of the above code.

The knuckle and 1st shell course will be analyzed for 600°F and 70°F. The effects of the vertical acceleration will be included in the 70°F analysis since this was the critical temperature for the thermal stress from the differential expansion.

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PRESSURE DISTRIBUTION

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PRESSURES ON KNUCKLE DUE TO PRODUCT HEAD

Pressure at 70°F

$$P_{oil} = \frac{54.4}{144} (42 + X)$$

$$\text{vert, } P_{rock V} = \frac{170 - 54.9}{144} \times .72 (41 + X)$$

$$\text{normal, } P_{rock} = P_{rock V} (K \cos^2 \theta + \sin^2 \theta)$$

$$P_T = P_{oil} + P_{rock} + 1.3$$

θ	X	P_{oil} (PSI)	P_{rock} (PSI)	P_T (PSI)	E. Q. P_T (PSI)
0°	0	15.867	7.346	24.513	30.641
15°	0.518	16.062	8.548	25.911	32.388
30°	1.000	16.244	11.713	29.258	36.572
45°	1.414	16.401	16.058	33.758	42.198
60°	1.732	16.521	20.439	38.259	47.824
75°	1.932	16.597	23.668	41.564	51.955
90°	2.000	16.622	24.854	42.776	53.470

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Pressure at 600°F

$$P_{oil} = \frac{41.6}{144} (42 + X)$$

$$\text{vert, } P_{rock V} = \frac{170 - 41.6}{144} 0.72 (41 + X)$$

$$\text{normal, } P_{rock} = P_{rock} (K \cos^2 \theta + \sin^2 \theta)$$

$$P_T = P_{oil} + P_{rock} + 1.3$$

θ	X	P_{oil} (PSI)	P_{rock} (PSI)	P_T (PSI)
0°	0	12.133	8.160	21.593
15°	0.518	12.283	9.605	23.188
30°	1.0	12.422	13.010	26.732
45°	1.414	12.542	17.836	31.678
60°	1.732	12.634	22.702	36.636
75°	1.932	12.691	26.288	40.279
90°	2.0	12.711	27.606	41.617

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Pressure on Shell Due to Product Head

Pressure at 70°F

$$P_{oil} = \frac{54.4}{144} (h_o)$$

$$P_{rock} = \frac{170-54.4}{144} \times .72 \times .31 h_R$$

$$P_T = P_{oil} + P_{rock} + 1.3$$

<u>Course</u>	<u>P_{oil}</u> <u>(PSI)</u>	<u>P_{rock}</u> <u>(PSI)</u>	<u>P_T</u> <u>(PSI)</u>	<u>E. Q.</u> <u>P_T</u> <u>(PSI)</u>
1	15.867	7.346	24.513	30.641
2	13.222	6.092	20.614	25.768
3	10.578	4.838	16.716	20.895
4	7.556	3.404	12.260	15.325
5	4.156	1.971	6.127	7.658
6	1.511	0.538	3.349	4.186

Pressure at 600°F

$$P_{oil} = \frac{41.6}{144} h_o$$

$$P_{rock} = \frac{170 - 41.6}{144} \times .72 \times .31 h_R$$

$$P_T = P_{oil} + P_{rock} + 1.3$$

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<u>Course</u>	<u>P_{oil}</u> <u>(PSI)</u>	<u>P_{rock}</u> <u>(PSI)</u>	<u>P_T</u> <u>(PSI)</u>
1	12.133	8.160	21.593
2	10.400	6.966	18.666
3	8.089	5.374	14.762
4	5.778	3.781	10.859
5	3.467	2.189	6.956
6	1.156	0.597	3.053

Boundary Conditions at Bottom

1. The bottom will try to grow radially as the tank heats up to 600°F. This radial growth will be partially restrained by frictional forces developed as the bottom slides over the concrete foundation and under the rock mass. The coefficient of friction between the steel bottom and concrete foundation and

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rock mass will be taken as unity, $C_f = 1.0$, for maximum frictional resistance.

Weight of rocks and oil on bottom, W_P

$$W_P = \left\{ \frac{41.6}{1000} \times [1' + 43' \times .28] + \frac{170}{1000} [43 \times .72] \right\} 28^2 \pi$$

$$= 14299 \text{ K @ } 600^\circ\text{F}$$

Weight of bottom and lower manifold, W_T

$$W_T = W_B + \frac{W_m}{2}$$

$$= 33.9 + 16 = 49.9\text{K; say } 50\text{K}$$

Friction force, $F_f = 1.0 (14299 + 50)$

$$= 14349\text{K}$$

The frictional force, F_f , can be applied at periphery of bottom as resisting the thermal radial growth.

restrained, $W_1 = \frac{R (1-\gamma) Q}{Et}$ (Ref. 4)

where $Q = \frac{F_f}{2\pi R} = \frac{14349}{2 \times 28 \times 12}$

$$= 6.80 \text{ KLI}$$

$$W_1 = \frac{28 \times 12 (1 - .3) 6.80}{25.7 \times 10^3 \times .25} = 0.249'' \quad 600^\circ\text{F}$$

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The free thermal radial growth, W_2

$$W_2 = \epsilon_S R \Delta T = 7.23 \times 10^{-6} \times 28 \times 12 (600^\circ - 70^\circ) @ 600^\circ$$

$$= 1.288" \text{ at } 600^\circ\text{F}$$

The net radial growth = $1.288 - .249$

$$W_{\text{Net}} = 1.039" @ 600^\circ\text{F}$$

2. The portion of the knuckle that connects to the bottom plate will develop a moment which resists rotation equal to the plastic moment of the plate.

$$M_O = S_{PL} \times F_6$$

$$\text{For } 600^\circ\text{F}, M_O = \frac{1 \times (7/8)^2}{4} \times 58,800$$

$$= 11255 \text{ in-lb/in}$$

$$\text{For } 70^\circ\text{F}, M_O = \frac{1 \times (7/8)^2}{4} \times 70,000$$

$$= 13398 \text{ in-lb/in}$$

The 7/8" plate in the knuckle shall extend inward on the bottom as to resist the plastic moment.

$$M_O = P_T \frac{t^2}{2}$$

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BROWN-MINNEAPOLIS TANK

For 600°F, $P_T = 41.617$ PSI

$$\therefore l = \sqrt{\frac{2 \times 11255}{41.617}} = 23.3''$$

For 70°F, $P_T = 42.776$ PSI

$$\therefore l = \sqrt{\frac{2 \times 13398}{42.776}} = 25.0'' \text{ governs}$$

RESULTS OF 70°F ANALYSIS

Maximum Stress Intensity in 1st Shell Course

The maximum stress intensity occurs at shell to knuckle seam on inside of shell. The shear stress is negligible.

$$\sigma_\theta = 11720 + 49600 = 61320 \text{ PSI}$$

STHETA IN Thermal stress

$$\sigma_\phi = -6407 \text{ PSI}$$

SPHI IN

$$\therefore S = |\sigma_\theta - \sigma_\phi| = |61320 - (-6407)|$$

$$= 67727 \text{ PSI} < 3 S_m = 90000 \text{ PSI}$$

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Maximum Stress Intensity in Knuckle

The max stress intensity occurs in the lower region of the knuckle. The shear stress is negligible. The bending stresses in SPHI IN and SPHI OUT are calculated as elastic stresses which are not true, since a plastic moment was input for a boundary condition which directly effects MPHI. Therefore the SPHI IN and SPHI OUT stresses in the lower knuckle region (from 0° to 9°), shall be determined as follows:

$$SPHI = \pm \frac{4 \times MPHI}{t^2} + \frac{NPHI}{t}$$

At 0°;

$$SPHI IN = \frac{4 \times 13400}{.875^2} + \frac{460}{.875} = 70534 \text{ PSI}$$

$$SPHI OUT = - \frac{4 \times 13400}{.875^2} + \frac{460}{.875} = - 69482 \text{ PSI}$$

$$STHETA IN = 30070 \text{ PSI}$$

$$STHETA OUT = -29750 \text{ PSI}$$

$$\text{inside} \begin{cases} \sigma_{\theta} = 30070 + 49600 = 79670 \text{ PSI} \\ \sigma_{\phi} = 70534 \text{ PSI} \end{cases}$$

$$\therefore S = 79670 \text{ PSI} < 3 S_m = 90000 \text{ PSI}$$

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RESULTS OF 600°F ANALYSIS

Maximum Stress Intensity in 1st Shell Course

The maximum stress intensity occurs at shell to knuckle seam on inside of shell. The shear stress is negligible.

$$\sigma_{\theta} = 7213 \text{ PSI}$$

STHETA IN

$$\sigma_{\phi} = - 10260 \text{ PSI}$$

SPHI IN

$$S = |\sigma_{\theta} - \sigma_{\phi}| = |7213 - (-10260)|$$

$$S = 17473 \text{ PSI} < 3 S_m = 90000 \text{ PSI}$$

Maximum Stress Intensity in Knuckle

The maximum stress intensity occurs in the lower region of the knuckle. The shear stress is negligible. The bending stresses in SPHI IN and SPHI OUT must be re-calculated as previously described.

At 0°,

$$\text{SPHI IN} = \frac{4 \times 11260}{.875^2} + \frac{1204}{.875} = 60204 \text{ PSI}$$

$$\text{SPHI OUT} = \frac{4 \times 11260}{.875^2} + \frac{1204}{.875} = -57452 \text{ PSI}$$

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$$\text{STHETA IN} = 71110 \text{ PSI}$$

$$\text{STHETA OUT} = -44300 \text{ PSI}$$

$$\text{inside} \begin{cases} \sigma_{\theta} = 71110 \text{ PSI} \\ \sigma_{\phi} = 60204 \text{ PSI} \end{cases}$$

$$S = 71110 \text{ PSI} < 3 S_m = 90000 \text{ PSI}$$

The 7/8" PL knuckle at a 2' radius is adequate for both the 70°F analysis and 600°F analysis.

WEIGHT OF TANK (BARE)

Weight of shell, W_S

$$\begin{aligned} W_S &= 60\pi \times \frac{40.8}{1000} [7 (13/16 + 11/16) + 8 (9/16 + 7/16 + 5/16 \times 2)] \\ &= 180.7K \end{aligned}$$

Weight of bottom, W_B

$$\begin{aligned} W_B &= \pi(28^2 - 26^2) \frac{40.8}{1000} \times 7/8 + \pi 26^2 \times \frac{40.8}{1000} \times 1/4 \\ &= 33.8K \end{aligned}$$

Weight of dome roof, W_{DR}

$$\begin{aligned} W_{DR} &= 2\pi 50 \times 8.75 \times \frac{40.8}{1000} \times 5/16 \\ &= 35.1K \end{aligned}$$

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Weight of roof knuckle, W_{RK}

$$W_{RK} \approx 2 \frac{(28.26 + 30)}{2} \pi \times 3.88 \times \frac{40.8}{1000} \times 5/16$$

$$\approx 9.1K$$

Weight of bottom knuckle, W_{BK}

$$W_{BK} \approx 2 \frac{(28 + 30)}{2} \pi \times 3.14 \times \frac{40.8}{1000} \times 7/8$$

$$\approx 20.4K$$

Weight of (2) manifolds, $W_m \approx 32K$

Weight of tank, W_T

$$\begin{aligned} W_T &= [W_S + W_B + W_{DR} + W_{RK} + W_{BK} + W_m] \\ &= [180.7 + 33.8 + 35.1 + 9.1 + 20.4 + 32] \end{aligned}$$

$$W_T = 311.1K$$

Increase W_T by 5% to account for fittings, anchor chairs, etc.

$$W_T = 1.05 [311.1] = 327K$$

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WEIGHT OF INSULATED TANK

From the Pittsburgh Corning Energy Analysis Report, EAR 738, 9" of foamglass insulation is recommended. This insulation does not go under tank. The density of foamglass is 8.5 lb/ft^3 , therefore 9" of foamglass weighs 6.4 lb/ft^2 . 8 lb/ft^2 will be used to account for any weather proof coverings and insulation straps, etc.

Surface area of shell, A_S

$$A_S = 60\pi \times 46 = 8671 \text{ ft}^2$$

Surface area of dome roof, A_{DR}

$$A_{DR} = 2\pi \times 50 \times 8.75 = 2749 \text{ ft}^2$$

Surface area of roof knuckle, A_{RK}

$$A_{RK} \approx 2 \frac{(28.26 + 30)}{2} \pi \times 3.88 = 710 \text{ ft}^2$$

Surface area of bottom knuckle, A_{BK}

$$A_{BK} \approx 2 \frac{(28 + 30)}{2} \pi \times 3.14 = 572 \text{ ft}^2$$

Total surface area = $A_S + A_{DR} + A_{RK} + A_{BK}$

$$= 8671 + 2749 + 710 + 572$$

$$= 12702 \text{ ft}^2$$

use 13250 ft^2 to include extra insulation around fittings, anchor chairs, etc.

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BROWN-MINNEAPOLIS TANK

G-75

Weight of insulation, W_I

$$W_I = \frac{8}{1000} \times 13250 = 106K$$

Weight of Insulated Tank, W_T

$$W_T = 327 + 106 = 433K$$

CHECK OF COMPRESSIVE STRESS IN SHELL FOR EARTHQUAKE

Check the bottom course only. Compressive load, F_{EQ}

$$F_{EQ} = F_m + F_{DL} + F_{LL}$$

$$F_m = \frac{M_B}{R^2 \pi} = \frac{94315 \times 1000}{30^2 \pi \times 12} = 2780 \text{ PLI}$$

$$F_{DL} = \frac{[W_{TI} - W_B]}{2R \pi} + .25 = \frac{[433 - 33.9]}{2 \times 30 \pi \times 12} \times 1.25 \times 1000$$

$$= 221 \text{ PLI}$$

$$F_{LL} = \frac{25 \text{ PSF} \times R}{2} = \frac{25 \text{ PSF} \times 30}{12 \times 2} = 31 \text{ PLI}$$

$$\text{max. } F_{EQ} = 2780 + 221 + 31 = 3032 \text{ PLI}$$

$$\sigma_c = \frac{3032}{t}$$

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Allowable stress, δ_{ca} , at 600°F

$$\delta_{ca} = 1.8 \times 10^6 \frac{t}{R} \times 1 \frac{1}{3} \frac{E_s @ 600^\circ}{E_s @ 70^\circ} \quad (\text{Ref. 2})$$

$$\delta_{ca} = 1.8 \times 10^6 \frac{t}{360} \times 1 \frac{1}{3} \left[\frac{25.7}{29.0} \right] = 5908 t$$

$$t = \sqrt[3]{\frac{3032}{5908}} = 0.716 < 13/16" \text{ PL}$$

Therefore the Earthquake is not going to govern the shell thickness in overturning.

CHECK FOR WIND STABILITY OF SHELL

Max height of shell unstiffening for 110 MPH, h. (Ref. 1)

$$h = 600 t_{ave} \sqrt{\left(\frac{100 t_{ave}}{D} \right)^3} \left(\frac{100}{V} \right)^2 \left(\frac{E_{600}}{E_{70}} \right)$$

$$= 600 t_{ave} \sqrt{\left(\frac{100 t_{ave}}{60} \right)^3} \left(\frac{100}{110} \right)^2 \left[\frac{25.7}{29} \right]$$

$$h = 945 t_{ave}^{5/2}$$

t_{ave}	H		h	Course	t_{act}
.3125	16'	<	51.6	5-6	.3125

Since 51.6' > 48' there is no need to further shell.

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ANCHORAGE DESIGN

The maximum moment is at the base of the tank, $M_B = 94315$ K-ft. The rocks and oil above the bottom knuckle along with the tank weight will resist part of the overturning moment, M_B . The balance of the overturning moment and uplift from the 1.3 PSI internal pressure will be resisted by anchor bolts.

1. Moment resisted by tank, oil and rock weight, M'

Weight of tank w/o bottom, W_T'

$$W_T' = 433 - 33.9 = 399K$$

Weight of oil and rock above knuckle, W_P'

$$\begin{aligned} W_P' &= 14881 + 2006 - 28^2 \pi 43 \\ &\quad - 28^2 \pi 43 \cdot \frac{54.5}{1000} + [(.72 \times 170 + .28 \times 54.4)43'] \\ &= 2173K \end{aligned}$$

Weight resisting, $W' = 399 + 2173 = 2572K$

$$F = \frac{M'}{R^2 \pi} = \frac{W'}{2R \pi} (1 \pm .25)$$

$$\therefore M'_{\min} = \frac{RW'}{2} = \frac{30}{2} \times 2572 \times .75$$

$$M' = 28935 \text{ K-ft}$$

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2. Moment resisted by anchorage, M_B'

$$M_B' = 94315 - 28935 = 65380 \text{ K-ft}$$

ANCHOR BOLTS A36

Try (48) anchor bolts

$$T = \frac{4M}{ND} + \frac{1.3 R^2 \pi}{N}$$

$$= \frac{4 \times 65380}{48 \times 60} + \frac{1.3 \times 360^2}{48 \times 1000}$$

$$T = 102K$$

The shear force, 4334K, is from the horizontal acceleration of 0.25 g's. Since the coefficient of friction of steel on concrete is 0.5 (1 ± .25) under .25 g's vertical acceleration, the minimum coefficient of friction, $C_f = 0.5 \times .75 = .375$ is greater than the horizontal acceleration of 0.25 g's. Therefore frictional forces will resist the horizontal base shear.

Area of anchor bolt required, A_{Root}

$$A_{root} = \frac{T}{F_T \times 1 1/3}$$

where $F_T = .6 F_y = .6 \times 36 \text{ KSI from AISC}$

$$= 21.6 \text{ KSI} \quad \text{for A36}$$

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3/4 IN.
RE-PAD

13/16 IN. R

$$A_{\text{root}} = \frac{102}{21.6 \times 1 \frac{1}{3}} = 3.54 \text{ in}^2$$

use (48) 2 1/2" ϕ A Bolts

ANCHOR CHAIN

$$T = 102K$$

$$C = \frac{4 \times 94315}{48 \times 60} + \frac{399}{48}$$

$$C = 139K$$

The anchor chain will be designed for the compressive force, C, and tensile force, T.

Try the section shown.

	A	Y	AY	d	d ² A	I
1	6	.375	2.25	1.706	17.46	.28

$$2 \quad \Sigma A = \frac{7.875}{13.875} \quad 3.375 \quad \Sigma AY = \frac{26.625}{28.875} \quad 1.294 \quad I_T = \frac{13.19}{30.65} + \frac{18.09}{18.37} = 49.02 \text{ in}^4$$

$$\bar{Y} = \frac{28.875}{13.875} = 2.081''$$

$$r = \sqrt{\frac{49.02}{13.875}} = 1.88''$$

$$S_1 = \frac{49.02}{2.081} = 23.55 \text{ in}^3$$

$$S_O = \frac{49.02}{6-2.081} = 12.51 \text{ in}^3$$

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1. Check of Chair for Compressive Load

$$C = 139K$$

$$\text{Eccentric moment, } M_e = e \times C$$

$$\text{where } e = 2.081 + \frac{13/16}{2} + 3/4 = 3.237''$$

Y' 1/2 shell repad

$$\text{use } e = 3.25''$$

$$M_e = 3.25 \times 139 = 452 \text{ K-in}$$

Stresses in Chair --

$$f_a = \frac{139}{13.875} = -10.02 \text{ KSI}$$

$$f_{hi} = \frac{452}{23.55} = 19.19 \text{ KSI}$$

$$f_{bb} = -\frac{452}{12.51} = -36.13 \text{ KSI}$$

Allowable stresses at 600°F

$$F_a = \frac{\left[1 - \frac{(Kl/r)^2}{3C_c^2} \right] F_y}{\frac{5}{3} + \frac{3(Kl/r)}{8C_c} - \frac{(Kl/r)^3}{8C_c^3}} \quad (\text{Ref. 9})$$

$$\text{where } C_c = \sqrt{\frac{2\pi^2 E}{F_y}}$$

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$$\left. \begin{array}{l} F_y = 58.8 \text{ KSI} \\ E = 25.7 \times 10^3 \text{ KSI} \end{array} \right\} @600^\circ\text{F}$$

$$Kl/r = \frac{1 \times 30''}{1.88} = 16$$

$$C_c = \sqrt{\frac{2 \pi^2 \times 25.7 \times 10^3}{58.8}} = 93$$

$$F_a = \frac{\left[1 - \frac{16^2}{2 \times 93^2} \right] 58.8}{\frac{5}{3} + \frac{3 \times 16}{8 \times 93} - \frac{16^3}{8 \times 93^3}}$$

$$F_a = 33.47 \text{ KSI}$$

$$F_b = 0.66 F_y = 0.66 \times 58.8 = 38.81 \text{ KSI (Ref. 9)}$$

$$\frac{f_a}{F_a} + \frac{f_b}{F_b} \leq 1.0 \times 1 \frac{1}{3}$$

$$\frac{10.03}{33.47} + \frac{36.13}{38.81} = 1.23 < 1 \frac{1}{3}$$

Chain is okay in compression.

2. Check of Chain for Tensile Load

$$T = 102\text{K}$$

$$\text{Eccentric moment, } M_e = e \times C$$

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$$\text{where } e = 3 + \frac{13/16}{2} + 3/4 = 4.16''$$

$$\text{use } e = 4 \frac{1}{4}''$$

$$M_e = 4 \frac{1}{4} \times 102 = 434 \text{ K-in}$$

Stresses in Chain --

$$f_a = \frac{102}{13.875} = 7.35 \text{ KSI}$$

$$f_{bi} = - \frac{434}{23.55} = - 18.43 \text{ KSI}$$

$$f_{bo} = \frac{434}{12.51} = 34.69 \text{ KSI}$$

Allowable stresses at 600°F

$$(\text{Ref. 9}) \quad F_a = 0.6 F_y = 0.6 \times 58.8 = 35.28 \text{ KSI}$$

$$F_b = 0.66 F_y = 0.66 \times 58.8 = 38.81 \text{ KSI}$$

$$\frac{7.35}{35.28} + \frac{34.69}{38.81} = 1.10 < 1/13$$

Chain is okay in tension.

3. Attachment of Chair to Shell

Compressive load governs.

$$C = 139\text{K}$$

$$e = 3 \frac{1}{4}''$$

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Try 30" attachment,

$$f_{bx} = \frac{.9 C_e \sqrt[4]{R t_s}}{h \sqrt{a} (t_s^2 + t_B^2)} \quad (\text{Ref. 10})$$

$$t_s = 13/16''$$

$$h = 30''$$

$$a = 8'' \text{ (width of chain)}$$

$$R = 360''$$

$$t_B = 0'' \text{ (chair is not close enough to bottom, to consider effects of bottom plate)}$$

$$f_{bX} = \frac{.9 \times 139 \times 3 \frac{1}{4} \times \sqrt[4]{360 \times 13/16}}{30 \times \sqrt{8} \times (.8125^2)}$$

$$f_{bX} = 30.02 \text{ KSI}$$

$$F_{bX} = .9 F_y = .9 \times 58.8 = 52.92 \text{ KSI}$$

BASE PLATE

$$C = 139 \text{ K}$$

$$T = 102 \text{ K}$$

Try PL 10" x 12"

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1. Design for Compressive Load

$$\text{Bearing on concrete, } f_p = \frac{139}{120} = 1.16 \text{ KSI}$$

$$F_p = 0.35 f'_c \times 1 \frac{1}{3} = 0.35 \times 3000 \times 1 \frac{1}{3}$$

$$= 1400 \text{ PSI} > 1.16 \text{ KSI}$$

use 12" x 10" base plate.

$$M = 1.16 \times \frac{3^2}{2} = 5.22 \text{ K-in}$$

$$t = \left[\frac{6 M}{.75 F_y 1 \frac{1}{3}} \right]^{1/2} = \left[\frac{6 \times 5.22}{.75 \times 58.8 \times 1 \frac{1}{3}} \right]^{1/2}$$

$$t = 0.73''$$

2. Design for Tensile Load

$$f = 1 \frac{7}{8}''$$

$$G = 6''$$

$$t = \left[\frac{T}{F_b F} \left[.375 G - .22 D_B \right] \right]^{1/2} \quad (\text{Ref. 10})$$

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G-85

$$= \frac{102}{.66 \times 58.8 \times 1 \frac{1}{3} \times 1 \frac{7}{8}} [.375 \times 6 - .22 \times 2.5]^{1/2}$$

t = 1.34" use 1 3/8" Base Plate and put a lubrite pad under base plate to let anchor chain slide during heating and cooling of tank.

CHECK FOR OVERTURNING OF TANK DUE TO WIND

Wind pressure 110 MPH, P

$$P = .00256 \times 110^2 = 31 \text{ PSF}$$

Shape factor = 0.6

For a conservative analysis, consider tank as a cylinder 60.05', (12.05 + 48), tall. Add 9" of insulation thickness to find overall dimensions.

$$D' = 60 + 2 \times 9'' = 61.5'$$

$$H' = 60.05 + 9'' = 60.8'$$

$$\begin{aligned} \text{Moment at base, } M_B &= \frac{31}{1000} \times .6 \times \frac{[60.8^2]}{2} \times 61.5 \\ &= 2114 \text{ K-ft} \end{aligned}$$

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$$\begin{aligned} \text{Shear at base, } F_v &= \frac{31 \times .6}{1000} [60.8 \times 61.5] \\ &= 70K \end{aligned}$$

Check for load in anchor bolt,

$$T = \frac{4 \times 2114}{48 \times 60} - \frac{(433 - 33.9)}{48} = 5.38 K \quad \text{no uplift}$$

Check for sliding of tank,

$$\begin{aligned} \text{Frictional force} &= 399 \times .5 \\ &= 199.5K > 70K \quad \text{no sliding} \end{aligned}$$

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Figure Oil/Rock Tank

G-89

SUMP DETAIL A533 CLASS 2

BOTTOM @70°F

$$P_o = 44 \times \frac{54.5}{144} = 16.65 \text{ PSI}$$

$$P_T = 16.65 + 1.3 = 17.95 \text{ PSI} \quad \text{use } 18 \text{ PSI}$$

$$t = \sqrt{\frac{K_1 W}{S_m}} \quad \text{from Plate Formulas by William Griffel Case 15.}$$

$$t = \frac{.398 \times 18 \times 18^2 \pi}{.66 \times 70000} = 0.40'' \quad \text{use } 1/2'' \text{ PL}$$

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G-90

TOP @ 600°F

$$P_R = 43 \times .72 \frac{(170 - 41.6)}{144}$$

$$P_T = 27.61 \text{ PSI} \quad \text{use 28}$$

$$S_1 = K_1 \frac{W}{t^2} \quad \text{from Case 19 (Ref. 11)}$$

$$K_1 = .735 \text{ for } \frac{a}{b} = \frac{18}{4} = 4.5$$

$$W = 28 \pi (18^2 - 4^2) = 2709.3 \text{ U}$$

$$S_2 = \frac{K_1 W}{t^2} \quad \text{from Case 20 (Ref. 11)}$$

$$K_1 = 2.255 \text{ for } \frac{a}{b} = 4.5$$

$$W = 28 \times 4^2 \pi = 1407 \text{ U}$$

$$t = \sqrt{\frac{.735 \times 27093 + 2.255 \times 1407}{.66 \times 58800}} = 0.771" \quad \text{use 7/8 PL}$$

NECK

Use (8) 2" x 2" opening.

$$A_s = t (36" \pi - 8 \times 2") = 97.1t$$

$$W_c = 27093 + 1407 = 28500 \text{ lb}$$

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G-91

$$\delta_c = \frac{28500}{97.1 t} = \frac{294}{t}$$

$$\delta_{call} = 1.8 \times 10^6 \frac{t}{R} \frac{E_{600^\circ}}{E_{70^\circ}} \quad (\text{Ref. 2})$$

$$= 1.8 \times 10^6 \frac{t}{18} \left[\frac{25.7}{29} \right]$$

$$= 88621 t$$

$$t = \sqrt{\frac{294}{88621}} = .06'' \text{ use } 1/2'' \text{ PL}$$

RE-PAD @ 600°F

$$S_1 = \frac{K_1 W}{t} \quad \text{from Case 19 (Ref. 11)}$$

$$K = .524 \text{ for } \frac{a}{b} = \frac{22 \frac{1}{2}}{18} = 1.25$$

$$W = \pi (22.5^2 - 18^2) 41.617 = 23828 \text{ PSI}$$

$$S_2 = \frac{K_1 W}{t} \quad \text{from Case 20}$$

$$K = 1.1 \text{ for } \frac{a}{b} = 1.25$$

$$W = \pi 22.5^2 \times 41.617 = 66189 \text{ lb}$$

$$t = \sqrt{\frac{23828 \times .524 + 66189 \times 1.1}{.66 \times 58800}} = 1.48'' \quad \text{use } 1 \frac{1}{2}'' \text{ PL}$$

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G-92

Figure G-9 Sump/Drain

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G-93

FOUNDATION DESIGN

DESIGN CRITERIA

Soil bearing capacity = 10000 PSF at 10' below grade

$$\text{Tank weight (excl. bottom)} = \frac{399}{60\pi} = 2.12 \text{ K/ft}$$

$$\text{Product head} = \frac{41.617}{1000} \times 144 = 5.99 \text{ K/ft}^2$$

$$\text{Product on knuckle} = \frac{2172}{56\pi} = 12.35 \text{ K/ft}$$

$$\text{Earthquake load} = \frac{94315}{30^2\pi} = \pm 33.36 \text{ K/ft}$$

$$\text{Uplift due to pressure} = \frac{1.3 \times 360^2}{1000 \times 60} = 2.81 \text{ K/ft}$$

$$\text{Soil density} = 100 \text{ lb/ft}^3$$

$$\text{Concrete density} = 140 \text{ lb/ft}^3$$

$$\text{Concrete strength} = f'_c = 3000 \text{ psi}$$

$$\text{Reinforcement (A615-60)} \therefore f_y = 60000 \text{ KSI}$$

$$\text{Vertical acceleration} = \pm .25 \text{ g's}$$

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G-94

PRELIMINARY SIZING OF FOOTING

Find required mass of footing and soil above footing needed to resist internal pressure and overturning of earthquake.

$$M_B = 94315 \text{ K-ft}$$

$$P_{\text{Press}} = 1.3 \text{ PSI} \times \frac{360^2}{1000} \pi = 529.3 \text{ K}$$

$$\frac{M_B'}{R^2 \pi} = \frac{W_{\text{Foot \& Soil}}}{2 \pi R}$$

$$W_{\text{Foot \& Soil}} = \frac{2M}{R} = \frac{2 \times 94315}{30} = 6287.7 \text{ K}$$

$$\text{Required weight} = 6287.7 + 529.3 = 6817 \text{ K}$$

The effect of vertical acceleration due to E. Q. is considered by using 75%, (1g-0.25g's), of the actual footing and soil weight.

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Try the footing shown.

Fig. G-10

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SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
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G-96

$$W_{(1)} = \pi (38^2 - 31^2) 8 \times .1 \times .75 = 910 \text{ K}$$

$$W_{(2)} = \pi (31^2 - 24.5^2) 8 \times .1 \times .75 = 680 \text{ K}$$

$$W_{(3)} = \pi (31^2 - 28^2) 8.5 \times .14 \times .75 = 496 \text{ K}$$

$$W_{(4)} = \pi (38^2 - 24.5^2) 2.0 \times .14 \times .75 = 557 \text{ K}$$

$$W_{(5)} = \pi (28^2 - 24.5^2) .5 \times .14 \times .75 = 30 \text{ K}$$

$$W_6 = \pi (28^2 - 24.5^2) 5.99 \times .75 = 2593 \text{ K}$$

$$W_7 = \pi 28 \times 2 \times 12.35 \times .75 = 1630 \text{ K}$$

$$W_8 = 399 \text{ K} \times .75 = 299 \text{ K}$$

$$W_{\text{Total}} = 7195 \text{ K} > 6817 \text{ K}$$

Use section as shown as minimum overall size.

CENTER OF GRAVITY OF FOOTING

40703-V

SUBJECT	MADE BY	CHKD BY	REV	MADE BY	CHKD BY	CONTRACT NO.
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G-97

Axis X-X			Axis Y-Y		
Area	Y	AY	Area	X	AX
③ 25.5	1.0	25.5	③ 25.5	8.5	216.75
④ 27.0	6.25	168.75	④ 27.0	6.75	182.25
52.5		194.25	52.5		399.0

$$\therefore \bar{Y} = \frac{194.25}{52.5} = 3.70$$

$$\bar{X} = \frac{399}{52.5} = 7.60'$$

BEARING PRESSURE ON SOIL

W₁

$$\text{Tank weight} = 2.12 \times 1.25 = 2.65$$

$$\text{Live load} = .38 \text{ K-ft}$$

$$\begin{aligned} \text{E. Q.} &= 33.36 \text{ K-ft} \\ W_1 &= 36.39 \text{ K-ft} \end{aligned}$$

W₂

$$\text{Weight of rock and oil in knuckle} = 12.35 \times 1.25 = 15.44 \text{ K-ft}$$

P_{EQ}

$$\text{Product press.} = 5.99 \text{ KSF}$$

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						SHT. OF

Take moments about pt. X.

$$\textcircled{1} \quad M_{\textcircled{1}} = (.1 \times 7 \times 8) \times \frac{7'}{2} \times 1.25 = 25$$

$$\textcircled{2} \quad M_{\textcircled{2}} = (.1 \times 8 \times 3.5) \times (10 + \frac{3.5}{2}) \times 1.25 = 41$$

$$\textcircled{3} \quad M_{\textcircled{3}} = (.14 \times 3 \times 8.5) \times (7 + \frac{3}{2}) \times 1.25 = 38$$

$$\textcircled{4} \quad M_{\textcircled{4}} = (.14 \times 13.5 \times 2) \times \frac{13.5}{2} \times 1.25 = 32$$

$$\textcircled{5} \quad M_{\textcircled{5}} = (.14 \times 3.5 \times 5) \times (10 + \frac{3.5}{2}) \times 1.25 = 4$$

$$W_1 \quad M_{\textcircled{6}} = 36.39 \times 8' = 291.12$$

$$W_2 \quad M_{\textcircled{7}} = 15.44 \times 10 \times 1.25 = 193.0$$

$$P_{EQ} \quad M_{\textcircled{8}} = (5.99 \times 3.5) \times (10 + \frac{3.5}{2}) \times 1.25 = 307.9$$

$$\Sigma W = 101.9 \text{ K}$$

$$\Sigma M = 932.0 \text{ K-ft}$$

$$\text{Resultant acts at } X, = \frac{932.0}{101.9} = 9.15''$$

$$\text{Eccentricity} = 9.15 - 7.60 = 1.55$$

$$\begin{aligned} \text{Soil pressure} &= \frac{\Sigma W}{13.5} \left(1 \pm \frac{6e}{13.5} \right) \\ &= \frac{101.90}{13.5} \left(1 \pm \frac{6 \times 1.55}{13.5} \right) \end{aligned}$$

$$\text{Soil press at outer edge} = 2.35 \text{ KSF}$$

$$\text{Soil press at inner edge} = 12.75 \text{ KSF}$$

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SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
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DESIGN OF FOOTING (REF. 7)

Bearing Load, W_u

$$\begin{aligned}
 W_u &= .75 [1.7 L + 1.4 D + 1.7 (1.1 E)] \\
 &= .75 \left[\begin{array}{ccc} W_2 & W_P & W_{LL} \\ 1.7 (12.35 + 20.9 + 3.8) \end{array} \right] \\
 &+ 1.4 \begin{array}{ccccc} \textcircled{1} & \textcircled{2} & \textcircled{4} & \textcircled{3} & \textcircled{5} \\ (5.6 + 2.8 + 3.57 + 3.78 + .25 + 2.12) \end{array} + W_T \\
 &+ 1.87 (.25 [12.35 + 2.10 + 5.6 + 2.8 + 3.57 + 3.78 + .25 \\
 &+ 2.12 + 33.36])
 \end{aligned}$$

$$W_o = 126.7 \text{ K/ft}$$

$$F_b = \frac{W_u}{13.5} \left[1 - \frac{6e}{13.5} \right]$$

$$F_{bi} = \frac{126.7}{13.5} \left[1 + \frac{6 \times 1.55}{13.5} \right] = 15.85 \text{ KSF}$$

$$F_{bo} = \frac{126.7}{13.5} \left[1 - \frac{6 \times 1.55}{13.5} \right] = 2.92 \text{ KSF}$$

SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
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G-100

Bottom Reinforcing in Footing

$$\text{Toe, } M_{u_1} = 2.92 \times \frac{7^2}{2} + (9.62 - 2.92) \frac{7^2}{6} = 126.3 \text{ K-ft}$$

$$\text{Heal, } M_{u_2} = 12.5 \times \frac{3.5^2}{2} + (15.85 - 12.5) \frac{3.5^2}{3} = 90.2 \text{ K-ft}$$

$$\therefore M_{u_1} = 126.3$$

$$\bar{M} = \frac{M_{u_1}}{.9} = \frac{126.3}{.9} = 140.3 \text{ K-ft}$$

$$\bar{M} = \bar{R} b d^2$$

$$140.3 \times 12 = .783 \times 12 d^2$$

$$\therefore d = \sqrt{\frac{139.9}{.783}} = 13.39'' \text{ min.}$$

$$d = 24 - 3'' (\text{cover}) = 21'' > 13.39''$$

$$\text{assume } a = .378 d = .378 \times 21 = 7.94$$

$$jd = d - \frac{a}{j} = 21 - \frac{7.94}{2} = 17.03$$

$$\therefore A_s = \frac{\bar{M}}{f_y jd} = \frac{140.3 \times 12}{60 \times 17.03} = 1.65 \text{ in}^2/\text{ft}$$

$$\therefore a = \frac{A_s f_y}{.85 f'_c b} = \frac{1.65 \times 60}{.85 \times 3 \times 12} = 3.23''$$

$$jd = 21 - \frac{3.23}{2} = 19.38$$

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SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
	DATE	DATE		DATE	DATE	SHT. OF

G-101

$$A_s = \frac{140.3 \times 12}{60 \times 19.38} = 1.45 \text{ in}^2/\text{ft}$$

$$\therefore a = \frac{1.45 \times 60}{.85 \times 3 \times 12} = 2.84''$$

$$Jd = 21 - \frac{2.84}{2} = 19.58''$$

$$A_s = \frac{140.3 \times 12}{60 \times 19.58} = 1.43 \text{ in}^2/\text{ft} \text{ governs}$$

$$\text{Min. area of steel} = \frac{200 \text{ bd}}{f_y} = \frac{200 \times 12 \times 21}{60000} = 0.84 \text{ in}^2/\text{ft}$$

$$\text{Try \#9 bars @8'' c-c, } A_s = .994 \times \frac{12}{8} = 1.49 \text{ in}^2/\text{ft}$$

Check development length, L,

$$L = \frac{.04 A_b f_y}{\sqrt{f'_c}} = \frac{.04 \times .994 \times 60000}{\sqrt{3000}} = 43.6''$$

and L is not less than .0004 $d_b f_y$

$$L = .0004 \times 1 \frac{1}{8} \times 60000 = 27''$$

$$\text{Development length} = (7' - 0'') - 3'' (\text{cover}) = 6'9''$$

Use #9 bars at 8'' c-c.

40703-V

SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
	DATE	DATE		DATE	DATE	SHT. OF

G-102

Uplift Load, Pu

The heel and toe will be designed for the resisting weight of the soil and product.

Load on Toe --

$$P_{u1} = .75 [1.7 L + 1.4 D + 1.7 (1.1 E)]$$

$$= .75 [1.7 (0) + 1.4 (5.6) + 1.87 (5.6 \times .25)]$$

$$P_{u1} = 7.84 \text{ K}$$

$$M_{u1} = 7.84^{\text{K}} \times 3.5' = 27.5 \text{ K-ft}$$

Load on Heel --

$$P_{u2} = .75 [1.7 L + 1.4 D + 1.7 (1.1 E)]$$

$$= .75 [1.7 (20.9) + 1.4 (2.8 + .25) + 1.87 (20.9 + 2.8 + .25) .25]$$

$$P_{u2} = 38.25 \text{ K}$$

$$M_u = 38.25^{\text{K}} \times 1.75' = 66.9 \text{ K-ft governs.}$$

$$\frac{M}{M} = \frac{66.9}{.9} = 74.3 \text{ K-ft.}$$

$$\text{assume } a = .378 d = .378 \times 21 = 7.94''$$

$$Jd = d - \frac{a}{2} = 21 - \frac{7.94}{2} = 17.03''$$

40703-V

SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
	DATE	DATE		DATE	DATE	SHT. OF

G-103

$$A_s = \frac{\bar{M}}{f_y Jd} = \frac{74.3 \times 12}{60 \times 17.03} = 0.87 \text{ in}^2$$

$$a = \frac{A_s F_y}{.85 f'_{cb}} = \frac{0.87 \times 60}{.85 \times 3 \times 12} = 1.71 \text{ in}$$

$$Jd = 21 - \frac{1.71}{2} = 20.15 \text{ in}$$

$$A_s = \frac{74.3 \times 12}{60 \times 20.15} = .74 \text{ in}^2$$

$$a = \frac{.74 \times 60}{.85 \times 3 \times 12} = 1.45 \text{ in}$$

$$Jd = 21 - \frac{1.45}{2} = 20.27 \text{ in}$$

$$A_s = \frac{74.3 \times 12}{60 \times 20.27} = 0.73 \text{ in}^2$$

Try #8 bars at 12 c-c, $A_s = .785 \text{ in}^2/\text{ft.}$

Check development length L,

$$L = \frac{.04 A_b f_y}{\gamma f'_{c}} = \frac{.04 \times .785 \times 60000}{\sqrt{3000}} = 34.4''$$

L is not to be less than .0004 $d_b f_y$

$$L = .0004 \times 1 \times 60000 = 24''$$

Development length = (3'-6") - 3" (cover) = 3'-3"

Use #8 bars at 12" c-c. (3'-6")

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SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
	DATE	DATE		DATE	DATE	SHT. OF

G-104

Circumferential Steel in Footing (Ref. 7)

$$\begin{aligned}\text{Minimum steel required} &= .0018bd \\ &= .0018 \times 12 \times 21 \\ &= 0.45 \text{ in}^2/\text{lb}\end{aligned}$$

Use #5 bars @15" c-c top and bottom

$$A_s = 2 \times .31 \times \frac{12}{15} = 0.49 \text{ in}^2/\text{ft}$$

Hoop Steel in Ring of Footing (Ref. 7)

Lateral pressure from product,

$$P_1 = (5.97 \text{ KSF} \times 8.5' \times .3) = 15.2 \text{ K/ft}$$

Lateral pressure from soil,

$$P_2 = \frac{(.100 \text{ K/ft}^3 \times 8.5^2 \times .3)}{2} = 1.1 \text{ K/ft}$$

Lateral pressure from product due to vert. accel.

$$P_3 = (P_1 + P_2) \cdot 25 = 4.1 \text{ K/ft}$$

Ultimate pressure, P_T

$$P_{T1} = 1.7 (15.2) + 1.4 (1.1) = 27.4 \text{ K/ft}$$

$$P_{T2} = .75 [1.7 (15.2) + 1.4 (1.1) + 1.7 (1.1 \times 41)] = 26.3 \text{ K/ft}$$

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SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
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G-105

$$P_T = 27.4 \text{ K/ft}$$

$$\text{Hoop force, } Q = P_T R = 27.4 \times 30 = 822 \text{ K}$$

$$A_s = \frac{822}{60} = 13.7 \text{ in}^2 \text{ governs}$$

$$\begin{aligned} \text{Min. steel} &= .0018 b d = .0018 \times 36 \times 102 \\ &= 6.61 \text{ in}^2 \end{aligned}$$

$$\text{Use (19) \#8 bars, } A_s = 19 \times .785 = 14.9 \text{ in}^2$$

Vertical Steel in Ring (Ref. 7)

$$\begin{aligned} \text{Min. steel required} &= .0018 \times b d = .0018 \times 12 \times 36 \\ &= 0.78 \text{ in}^2/\text{ft} \end{aligned}$$

Use (2) #5 bars @ 9" c-c

$$A_s = 2 \times .31 \times \frac{12}{9} = 0.83 \text{ in}^2/\text{ft}$$

Shear Reinforcement (Ref. 7)

$$\text{Ultimate Shear Stress, } V_c = 2\sqrt{f'_c}$$

$$V_c = 2\sqrt{3000} = 110 \text{ PSI}$$

$$\text{Nominal Shear Stress, } V_u = \frac{V_u}{\phi b w d}$$

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SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
	DATE	DATE		DATE	DATE	SHT. OF

G-106

$$V_u = \frac{V_u}{.7 \times 12 \times 21} = \frac{V_u}{176.4}$$

Maximum shear load, V_u , is on the heel and is due to bearing pressure on soil.

$$V_u = 12.5 \times 3.5 + (15.85 - 12.5) \frac{3.5}{2} = 49.6 \text{ K}$$

$$V_u = \frac{49.6 \times 1000}{176.4} = 281 \text{ PSI} > 110 \text{ PSI}$$

∴ shear reinforcement is needed.

$$A_u = \frac{(V_u - V_c)}{f_y} \text{ bw S}$$

$$A_v = \frac{(281 - 110)}{60000} 12 \times 12 = 0.41 \text{ in}^2$$

Use #6 bars at 12" cc $A_s = .44 \text{ in}^2$ for heel and toe.

Anchor Bolt Embedment

Using (48) 2 1/2" Anchor Bolts, A36

$$T_u = .75 [1.7 L + 1.4 D + 1.7 (1.1 E)]$$

$$= .75 \left[1.7 \frac{(529.3 \text{ K})}{48} + 1.4 (0) + 1.87 \frac{(65380 \times 4)}{48 \times 60} \right]$$

1.3 PSI

M'_B from E. Q.

$$T_u = 141.4 \text{ K}$$

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SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
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G-107

Ultimate Bond Stress, $U_u = 4.2 f'_c$

$$U_u = \frac{4.2 \sqrt{3000}}{(2)} = 165 \text{ PSI}$$

Ref: AC1 318-63

$$\begin{aligned} \text{Ultimate Bearing Stress, } &= .85 \phi f'_c \sqrt{\frac{A_2}{A_1}} \\ &= .85 \times .7 \times 3000 \sqrt{\frac{A_2}{A_1}} \end{aligned}$$

1. Capacity of hook

$$\text{Length of hook} = 4 d_b = 4 \times 2 \frac{1}{2} = 10''$$

$$\therefore A_1 = 10'' \times 2 \frac{1}{2}'' = 25 \text{ in}^2$$

$$A_2 = \pi \frac{(31^2 - 28^2)}{48} \times 144 = 1668 \text{ in}^2$$

$$\sqrt{\frac{A_2}{A_1}} = \sqrt{\frac{1668}{25}} = 8.17 > 2 \quad \text{use } 2$$

$$\therefore = .85 \times .7 \times 3000 \times 2 = 3570 \text{ PSI}$$

Max. shear in anchor bolt at hook

$$T' = \frac{2.5^2}{4} \pi \times .3 \times 36 \times 1 \frac{1}{3} = 70.7 \text{ K}$$

Max. bearing load on hook

$$T_{U.B.R.} = 25 \times \frac{3570}{1000} = 89.3 \text{ K} \quad \text{use } 70.7 \text{ K max.}$$

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SUBJECT	MADE BY	CHKD BY	REV	MADE BY	CHKD BY	CONTRACT NO.
	DATE	DATE		DATE	DATE	
						SHT. OF

G-108

2. Balance of, T_u , must be taken in bond.

Required length of embedment, L

$$L = \frac{T_u - T'}{d_{B\pi} \times U_u} = \frac{141.4 - 70.7}{2.5_{\pi} \times .165} = 54.6'' \quad \text{use } 60''$$

Pad Design(Use 6" Minimum Depth)

Since load is uniform, pad does not see bending effects, and can be designed for minimum steel.

Area of steel required, A_s (Ref. 7)

$$A_s = .0018 b_w d = .0018 \times 12 \times 6'' = .13 \text{ in}^2/\text{ft}$$

use #4 bars at 12" c-c each way.

40703-V

SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
	DATE	DATE		DATE	DATE	SHT. OF

Figure G-11 Foundation

SUBJECT	MADE BY	CHKD BY	MADE BY	CHKD BY	CONTRACT NO.
	DATE	DATE	DATE	DATE	
			REV.		
					SHT. OF

G-110

DESIGN DRAWINGS

40703-V

D
C
G-115
B
A

DATA SHEET	
DESCRIPTION	114' OIL/ROCK TANK
NUMBER REQUIRED	1
CAPACITY	45,000 BBL ± 10% COMPACTED OIL
DESIGN PRESSURE	1.5 PSI EXCL. 1/2" 32' ETD CFT OIL EXCL. 3.5'
OPERATING PRESSURE	1.1 PSI
TEST PRESSURE	1.625 PSI - HYDROSTATIC HEAD
DESIGN TEMPERATURE	600°F WITH COOLDOWN TO 70°F
TEST TEMPERATURE	AMBIENT
JOINT EFFICIENCY	100% SHELL
CORROSION ALLOWANCE	NONE
CODE & STAMP	SEE NOTE #2
CUSTOMER SPECIFICATION	EXHIBIT A
MATERIALS	
SHELL & BOY W/KNUCKLE	A533 CLASS 2 GRADE A
TOP & BOTTOM KNUCKLE	A516-60
NOZZLE	NECK A 106
MANWAY	NECK A 516-60 FLANGE A 105
REINFORCING PADS	A516-60 FLANGE A 516-60 COVER A 516-60
COUPLINGS	A533 CLASS 2 GRADE A
STIFFENER RINGS	A533
INTERIORS	NONE
BOLTING	BOLTS A193-B7 NUTS A194-2H STUDS NONE
GASKETS	COMPRESSED ASBESTOS
STRUCTURAL ELECTRODES	F50A-D1 A533 CLASS 2 GRADE A
	F50A-D1 OR F50A-D2 A516-60
CONSTRUCTION	
STRESS RELIEF	REQUIRED EXH. PER ASME SEC. VIII DIV. 1
CLEANING	BROOM CLEAN AFTER ERECTION
SURFACE PREPARATION	NONE
INTERNAL PAINTING	NONE
EXTERNAL PAINTING	NONE
LINING	NONE
INSULATION	REQUIRED 9" OF FOAMGLASS ± ON ROOF
LANDERS & PLATFORMS	SHELL ± ANCHOR CHAIRS
CATHODIC PROTECTION	NONE
FOUNDATIONS	3000 PSI CONCRETE ± A615-60 RE-BAR PER DRAWING
QUALITY ASSURANCE	
QA MANUAL	NOT APPLICABLE
MILL CERTIFICATIONS	ALL PRESSURE RETAINING MATERIAL
WELDING	ALL WELDS TO BE QUALIFIED
NONDESTRUCTIVE TESTING	PER A.P.I. STD. 650 APP. D
SPECIAL TESTING	RADIOGRAPH SHELL ± BOTTOM KNUCKLE
	PER A.P.I. STD. 650 APP. D
TESTING	NONE
SHELL	HYDROTEST ± 1.625 PSI
BOTTOM	VACUUM BOX PER A.P.I. STD. 650
ROOF	

NOTES: 1. FLANGE BOLT HOLES STRADDLE TANK VERTICAL & RADIAL CENTER LINES - UNLESS OTHERWISE SPECIFIED.
2. A.P.I. STD. 650 APP. D, FOR FABRICATION, ERECTION, TESTING & EXAMINATION. A.P.I. STD. 650 APP. D, DESIGN MODIFIED FOR THERMAL LOADS.

Figure G-14. Main Storage - Commercial

PROJECT ENGINEER APPROVAL & DATE CHECKED BY & DATE DRAWN BY & DATE	NO. 2, 4, 4-77		REVISION	
	BROWN- MINNEAPOLIS TANK		THIS DRAWING IS THE PROPERTY OF BROWN-MINNEAPOLIS TANK AND IS TO BE USED ONLY IN CONNECTION WITH WORK PERFORMED BY BROWN-MINNEAPOLIS TANK. THE DRAWING IS NOT TO BE COPIED IN WHOLE OR IN PART AND MUST BE RETURNED UPON REQUEST.	
	DESCRIPTION 114' Ø x 48' HIGH OIL / ROCK TANK FOR HONEYWELL		PURCHASER'S NO.	
	DRAWING NUMBER 77-D441103		REVISION 1	

APPENDIX 1
COMPUTER PRINTOUT
1. 70°F Analysis Run
2. 600°F Analysis Run

G-118

*L

1:	2	2	0	1	0	0			
2:	0.0		90.		10	2	7	0	1
3:	0.0		336.		24.		1.0		
4:	29000000.		0.3						
5:	-.4375		.4375						
6:	0.0		84.		7	4	2	0	1
7:	0.0		360.		90.				
8:	29000000.		0.3						
9:	-.40625		.40625						
10:	0	0	0.0		0.0				
11:	1			3			6	-13398	7
12:	2			4			6		8
13:	0.0								
14:	53.470								1
15:	1								
16:	PRESS	7							
17:	0.0		53.470		15.0		51.955	30.	47.824
18:			42.198						45
19:	60.		36.572		75.		32.388	90.	30.641
20:	0.0								
21:	30.641								1
22:	1								
23:	PRESS	2							
24:	0.0		30.641		84.		25.768		

40703-V

DATA FILE:ZIRI

1

KSHELL-IBM FOR ANALYSIS OF AXISYMMETRIC SHELLS BY ARTURS KALNINS JANUARY 1 1974

0 RESPONSE ANALYSIS PARTS# 2 BRANCHES# 0 NUMBER OF SUBCASES# 1 OUTPUT TYPE 2 SUBCASE ADDITION 0

PART NO 1

OSI# .00000E+00 SX# .90000E+02 SEGMENTS# 10 OUTPUT POINTS# 2 STANDARD SURFACE NO. 7 NTP# 0 LAYERS MLY# 1
TOROIDAL SHELL NO. 7 K# .00000E+00 A# .33600E+03 B# .24000E+02 DIRECTION INDEX# 1.0
OLAYER NO 1 FROM Z# -.43750E+00 TO Z# .43750E+00

CONSISTS OF ISOTROPIC MATERIAL, YOUNGS MODULUS E# .29000E+08 POISSONS RATIO NU# .30000E+00
COEFFS OF THERMAL EXPANSION AFI# .00000E+00 ATHETA# .00000E+00 MASS DENSITY RHO# .00000E+00 COND# .10000E+01

PART NO 2

OSI# .00000E+00 SX# .84000E+02 SEGMENTS# 7 OUTPUT POINTS# 4 STANDARD SURFACE NO. 2 NTP# 0 LAYERS MLY# 1
CYLINDRICAL SHELL NO 2 K# .00000E+00 R# .36000E+03 PHI# 90.000 DEGREES
OLAYER NO 1 FROM Z# -.40625E+00 TO Z# .40625E+00

CONSISTS OF ISOTROPIC MATERIAL, YOUNGS MODULUS E# .29000E+08 POISSONS RATIO NU# .30000E+00
COEFFS OF THERMAL EXPANSION AFI# .00000E+00 ATHETA# .00000E+00 MASS DENSITY RHO# .00000E+00 COND# .10000E+01

1

KSHELL-IBM FOR ANALYSIS OF AXISYMMETRIC SHELLS BY ARTURS KALNINS JANUARY 1 1974

0

SUBCASE NO 1 FOR FOURIER HARMONIC COS 0 THETA

BOUND COND AT START EDGE	1#	.0000E+00	3#	.0000E+00	6#	-.1340E+05	7#	.0000E+00	ALFA#	.0000 DEG
BOUND COND AT FINAL EDGE	2#	.0000E+00	4#	.0000E+00	6#	.0000E+00	8#	.0000E+00	ALFA#	.0000 DEG

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LOADS FOR PART NO 1 SUBCASE NO 1
 SPRING LOADS AT END OF THIS PART ARE O= .00000E+00 NPHI# .00000E+00 NPHI# .00000E+00 N# .00000E+00
 SURFACE AND TEMP LOADS P# .53470E+02 PFI# .00000E+00 PTHETA# .00000E+00 TIN# .00000E+00 TOUT# .00000E+00
 0 CODE NUMBERS OF VARIABLE LOADS OVER THIS PART, GIVEN BY FORMS BELOW, ARE 1
 0 PRESS LINEAR FUNCTION GENERATOR NO. 1 FROM 7 POINTS
 OYS# .5347E+02 .596E+02 .4782E+02 .4220E+02 .3657E+02 .3239E+02 .3064E+02
 OXS# .0000E+00 .1500E+02 .3000E+02 .4500E+02 .6000E+02 .7500E+02 .9000E+02
 0 AT BEGINNING AND END OF PART 1 PARAMETERS ARE

RFI# .2400E+02 R# .3360E+03 FI# .0000E+00 RAD .0000E+00 DEGREES S# .0000E+00 C# .1000E+01 H# .8750E+00
 P OR PI# .5347E+02 PFI OR P2# .0000E+00 PTHETA# .0000E+00 TIN# .0000E+00 TOUT# .0000E+00 INORM# 0
 TEMPERATURE IN LAYER NO. 1 AT INSIDE IS .0000E+00 AT OUTSIDE IS .0000E+00 DEGREES

RFI# .2400E+02 R# .3600E+03 FI# .1571E+01 RAD .9000E+02 DEGREES S# .1000E+01 C# .1873E+00 H# .8750E+00
 P OR PI# .3064E+02 PFI OR P2# .0000E+00 PTHETA# .0000E+00 TIN# .0000E+00 TOUT# .0000E+00 INORM# 0
 TEMPERATURE IN LAYER NO. 1 AT INSIDE IS .0000E+00 AT OUTSIDE IS .0000E+00 DEGREES

LOADS FOR PART NO 2 SUBCASE NO 1
 SPRING LOADS AT END OF THIS PART ARE O= .00000E+00 NPHI# .00000E+00 NPHI# .00000E+00 N# .00000E+00
 SURFACE AND TEMP LOADS P# .3064E+02 PFI# .00000E+00 PTHETA# .00000E+00 TIN# .00000E+00 TOUT# .00000E+00
 0 CODE NUMBERS OF VARIABLE LOADS OVER THIS PART, GIVEN BY FORMS BELOW, ARE 1
 0 PRESS LINEAR FUNCTION GENERATOR NO. 2 FROM 2 POINTS
 OYS# .3064E+02 .2577E+02
 OXS# .0000E+00 .8400E+02
 0 AT BEGINNING AND END OF PART 2 PARAMETERS ARE

RFI# .9999E+10 R# .3600E+03 FI# .1571E+01 RAD .9000E+02 DEGREES S# .1000E+01 C# .0000E+00 H# .8125E+00
 P OR PI# .3064E+02 PFI OR P2# .0000E+00 PTHETA# .0000E+00 TIN# .0000E+00 TOUT# .0000E+00 INORM# 0
 TEMPERATURE IN LAYER NO. 1 AT INSIDE IS .0000E+00 AT OUTSIDE IS .0000E+00 DEGREES

RFI# .9999E+10 R# .3600E+03 FI# .1571E+01 RAD .9000E+02 DEGREES S# .1000E+01 C# .0000E+00 H# .8125E+00
 P OR PI# .2577E+02 PFI OR P2# .0000E+00 PTHETA# .0000E+00 TIN# .0000E+00 TOUT# .0000E+00 INORM# 0
 TEMPERATURE IN LAYER NO. 1 AT INSIDE IS .0000E+00 AT OUTSIDE IS .0000E+00 DEGREES

KSHL1-IBM FOR ANALYSIS OF AXISYMMETRIC SHELLS BY ARTURS KALNINS JANUARY 1 1974											
DEFLECTIONS AND STRESS		RESULTS		FOR SUBCASE NO. 1		N# 0		N		MTHETA	
X	W	Q	UPHI	NPHI	BPHI	MPHI	UTHETA	N	NTHETA	MTHETA	
0 MAIN SHELL PART NO											
.000	.0000E+00	.1137E+04	.0000E+00	.4601E+03	.4211E-01	-.1340E+05	.0000E+00	.0000E+00	.138E+03	-.382E+04	
4.500	-.6658E-01	.1063E+04	.2807E-02	.3717E+03	.2899E-01	-.1127E+05	.0000E+00	.0000E+00	-.706E+02	-.324E+04	
9.000	-.1101E+00	.9835E+03	.9915E-02	.2881E+03	.1807E-01	-.9305E+04	.0000E+00	.0000E+00	-.469E+03	-.271E+04	
9.000	-.1101E+00	.9835E+03	.9915E-02	.2881E+03	.1807E-01	-.9305E+04	.0000E+00	.0000E+00	-.469E+03	-.271E+04	
13.500	-.1343E+00	.8985E+03	.1966E-01	.2092E+03	.9159E-02	-.7498E+04	.0000E+00	.0000E+00	-.846E+03	-.221E+04	
18.000	-.1427E+00	.8086E+03	.3067E-01	.1360E+03	.2087E-02	-.5863E+04	.0000E+00	.0000E+00	-.106E+04	-.175E+04	
18.000	-.1427E+00	.8086E+03	.3067E-01	.1360E+03	.2087E-02	-.5863E+04	.0000E+00	.0000E+00	-.106E+04	-.175E+04	
22.500	-.1384E+00	.7155E+03	.4181E-01	.7015E+02	-.3337E-02	-.4408E+04	.0000E+00	.0000E+00	-.103E+04	-.134E+04	
27.000	-.1245E+00	.6205E+03	.5221E-01	.1300E+02	-.7309E-02	-.3136E+04	.0000E+00	.0000E+00	-.727E+03	-.971E+03	
27.000	-.1245E+00	.6205E+03	.5221E-01	.1300E+02	-.7309E-02	-.3136E+04	.0000E+00	.0000E+00	-.727E+03	-.971E+03	
31.500	-.1035E+00	.5252E+03	.6121E-01	-.3411E+02	-.1003E-01	-.2048E+04	.0000E+00	.0000E+00	-.147E+03	-.654E+03	
36.000	-.7777E-01	.4321E+03	.6835E-01	-.7036E+02	-.1169E-01	-.1141E+04	.0000E+00	.0000E+00	.673E+03	-.386E+03	
36.000	-.7777E-01	.4321E+03	.6835E-01	-.7036E+02	-.1169E-01	-.1141E+04	.0000E+00	.0000E+00	.673E+03	-.386E+03	
40.500	-.4930E-01	.3435E+03	.7332E-01	-.9554E+02	-.1248E-01	-.4093E+03	.0000E+00	.0000E+00	.168E+04	-.166E+03	
45.000	-.1971E-01	.2612E+03	.7597E-01	-.1100E+03	-.1258E-01	.1596E+03	.0000E+00	.0000E+00	.283E+04	.708E+01	
45.000	-.1971E-01	.2612E+03	.7597E-01	-.1100E+03	-.1258E-01	.1596E+03	.0000E+00	.0000E+00	.283E+04	.708E+01	
49.500	.9673E-02	.1870E+03	.7628E-01	-.1148E+03	-.1216E-01	.5796E+03	.0000E+00	.0000E+00	.404E+04	.138E+03	
54.000	.3783E-01	.1222E+03	.7429E-01	-.1112E+03	-.1137E-01	.8676E+03	.0000E+00	.0000E+00	.527E+04	.230E+03	
54.000	.3783E-01	.1222E+03	.7429E-01	-.1112E+03	-.1137E-01	.8676E+03	.0000E+00	.0000E+00	.527E+04	.230E+03	
58.500	.6401E-01	.6786E+02	.7013E-01	-.1011E+03	-.1034E-01	.1043E+04	.0000E+00	.0000E+00	.646E+04	.288E+03	
63.000	.8771E-01	.2420E+02	.6399E-01	-.8627E+02	-.9179E-02	.1126E+04	.0000E+00	.0000E+00	.759E+04	.319E+03	
63.000	.8771E-01	.2420E+02	.6399E-01	-.8627E+02	-.9179E-02	.1126E+04	.0000E+00	.0000E+00	.759E+04	.319E+03	
67.500	.1086E+00	-.9322E+01	.5608E-01	-.6877E+02	-.7969E-02	.1137E+04	.0000E+00	.0000E+00	.861E+04	.327E+03	
72.000	.1265E+00	-.3303E+02	.4662E-01	-.5046E+02	-.6779E-02	.1094E+04	.0000E+00	.0000E+00	.951E+04	.319E+03	
72.000	.1265E+00	-.3303E+02	.4662E-01	-.5046E+02	-.6779E-02	.1094E+04	.0000E+00	.0000E+00	.951E+04	.319E+03	
76.500	.1415E+00	-.4769E+02	.3585E-01	-.3308E+02	-.5656E-02	.1016E+04	.0000E+00	.0000E+00	.103E+05	.299E+03	
81.000	.1535E+00	-.5517E+02	.2401E-01	-.1811E+02	-.4630E-02	.9169E+03	.0000E+00	.0000E+00	.110E+05	.272E+03	
81.000	.1535E+00	-.5517E+02	.2401E-01	-.1811E+02	-.4630E-02	.9169E+03	.0000E+00	.0000E+00	.110E+05	.272E+03	
85.500	.1628E+00	-.5686E+02	.1132E-01	-.6776E+01	-.3714E-02	.8102E+03	.0000E+00	.0000E+00	.115E+05	.242E+03	
90.000	.1694E+00	-.5399E+02	-.2003E-02	-.1978E+03	-.2211E-02	.7049E+03	.0000E+00	.0000E+00	.119E+05	.211E+03	

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G MAIN SHELL PART NO 2

.000	.1694E+00	-.5395E+02	-.2004E-02	-.3553E-14	-.2911E-02	.7050E+03	.0000E+00	.0000E+00	.111E+05	.211E+03
3.000	.1762E+00	-.5128E+02	-.2437E-02	-.3553E-14	-.1595E-02	.5460E+03	.0000E+00	.0000E+00	.115E+05	.164E+03
6.000	.1793E+00	-.4539E+02	-.2882E-02	-.3553E-14	-.6017E-03	.4004E+03	.0000E+00	.0000E+00	.117E+05	.120E+03
9.000	.1799E+00	-.3790E+02	-.3331E-02	-.3553E-14	.1059E-03	.2752E+03	.0000E+00	.0000E+00	.118E+05	.826E+02
12.000	.1789E+00	-.3014E+02	-.3780E-02	-.3553E-14	.5738E-03	.1731E+03	.0000E+00	.0000E+00	.117E+05	.519E+02
12.000	.1789E+00	-.3013E+02	-.3780E-02	.4441E-15	.5741E-03	.1732E+03	.0000E+00	.0000E+00	.117E+05	.519E+02
15.000	.1767E+00	-.2271E+02	-.4225E-02	.4441E-15	.8516E-03	.9405E+02	.0000E+00	.0000E+00	.116E+05	.282E+02
18.000	.1739E+00	-.1614E+02	-.4663E-02	.4441E-15	.9851E-03	.3603E+02	.0000E+00	.0000E+00	.114E+05	.108E+02
21.000	.1709E+00	-.1064E+02	-.5094E-02	.4441E-15	.1016E-02	-.3865E+01	.0000E+00	.0000E+00	.112E+05	-.116E+01
24.000	.1679E+00	-.5280E+01	-.5517E-02	.4441E-15	.9792E-03	-.2897E+02	.0000E+00	.0000E+00	.110E+05	-.869E+01
24.000	.1679E+00	-.5273E+01	-.5517E-02	.5107E-14	.9794E-03	-.2891E+02	.0000E+00	.0000E+00	.110E+05	-.867E+01
27.000	.1650E+00	-.2985E+01	-.5933E-02	.5107E-14	.9025E-03	-.4254E+02	.0000E+00	.0000E+00	.108E+05	-.128E+02
30.000	.1625E+00	-.5482E+00	-.6343E-02	.5107E-14	.8062E-03	-.4777E+02	.0000E+00	.0000E+00	.106E+05	-.143E+02
33.000	.1602E+00	-.5918E+00	-.6746E-02	.5107E-14	.7053E-03	-.4722E+02	.0000E+00	.0000E+00	.105E+05	-.142E+02
36.000	.1582E+00	-.1799E+01	-.7144E-02	.5107E-14	.6098E-03	-.4305E+02	.0000E+00	.0000E+00	.104E+05	-.129E+02
36.000	.1582E+00	.1804E+01	-.7144E-02	.2900E-14	.6099E-03	-.4301E+02	.0000E+00	.0000E+00	.104E+05	-.129E+02
39.000	.1565E+00	.2233E+01	-.7537E-02	.2900E-14	.5256E-03	-.3685E+02	.0000E+00	.0000E+00	.102E+05	-.111E+02
42.000	.1551E+00	.2323E+01	-.7927E-02	.2900E-14	.4552E-03	-.2995E+02	.0000E+00	.0000E+00	.101E+05	-.398E+01
45.000	.1538E+00	.2138E+01	-.8313E-02	.2900E-14	.3993E-03	-.2314E+02	.0000E+00	.0000E+00	.101E+05	-.694E+01
48.000	.1526E+00	.1920E+01	-.8696E-02	.2900E-14	.3572E-03	-.1695E+02	.0000E+00	.0000E+00	.999E+04	-.509E+01
48.000	.1526E+00	.1925E+01	-.8696E-02	.3058E-14	.3574E-03	-.1691E+02	.0000E+00	.0000E+00	.999E+04	-.507E+01
51.000	.1516E+00	.1593E+01	-.9076E-02	.3058E-14	.3275E-03	-.1162E+02	.0000E+00	.0000E+00	.992E+04	-.349E+01
54.000	.1507E+00	.1245E+01	-.9454E-02	.3058E-14	.3077E-03	-.7363E+01	.0000E+00	.0000E+00	.986E+04	-.221E+01
57.000	.1498E+00	.9153E+00	-.9829E-02	.3058E-14	.2958E-03	-.4129E+01	.0000E+00	.0000E+00	.980E+04	-.124E+01
60.000	.1489E+00	.5225E+00	-.1020E-01	.3058E-14	.2897E-03	-.1833E+01	.0000E+00	.0000E+00	.975E+04	-.550E+00
60.000	.1489E+00	.5269E+00	-.1020E-01	.2554E-14	.2893E-03	-.1795E+01	.0000E+00	.0000E+00	.975E+04	-.539E+00
63.000	.1480E+00	.3615E+00	-.1057E-01	.2554E-14	.2877E-03	-.2950E+00	.0000E+00	.0000E+00	.969E+04	-.885E-01
66.000	.1472E+00	.1871E+00	-.1094E-01	.2554E-14	.2881E-03	.5452E+00	.0000E+00	.0000E+00	.963E+04	.164E+00
69.000	.1463E+00	-.4336E-01	-.1131E-01	.2554E-14	.2896E-03	.8786E+00	.0000E+00	.0000E+00	.958E+04	.264E+00
72.000	.1454E+00	-.5226E-01	-.1167E-01	.2554E-14	.2915E-03	.8536E+00	.0000E+00	.0000E+00	.952E+04	.256E+00
72.000	.1454E+00	-.4620E-01	-.1167E-01	.6332E-15	.2917E-03	.9142E+00	.0000E+00	.0000E+00	.952E+04	.274E+00
75.000	.1445E+00	-.9726E-01	-.1204E-01	.6332E-15	.2934E-03	.6881E+00	.0000E+00	.0000E+00	.946E+04	.208E+00
78.000	.1437E+00	-.1062E+00	-.1240E-01	.6332E-15	.2945E-03	.3727E+00	.0000E+00	.0000E+00	.940E+04	.112E+00
81.000	.1428E+00	-.7499E-01	-.1276E-01	.6332E-15	.2950E-03	.9088E-01	.0000E+00	.0000E+00	.935E+04	.273E-01
84.000	.1419E+00	-.4283E-02	-.1311E-01	.6332E-15	.50E-03	-.3786E-01	.0000E+00	.0000E+00	.929E+04	-.114E-01

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KSHLL-101 FOR ANALYSIS OF AXISYMMETRIC SHELLS BY ARTURS KALNINS JANUARY 1 1974										
FUNCTIONS AND STRESSES FOR SURFACE NO. 1 NR 0										
X	R	OPHI	DFITHETA	MFITHETA	SPHI IN	SPHI OUT	STHETA IN	STHETA OUT	SFITH IN	SFITH OT
IN SHELL PART NO	1									
.000	.0000E+00	.1137E+04	.0000E+00	.0000E+00	.1055E+06	-.1045E+06	.3007E+05	-.2975E+05	.000E+00	.000E+00
4.500	-.6658E-01	.1063E+04	.0000E+00	.0000E+00	.8678E+05	-.8793E+05	.2534E+05	-.2550E+05	.000E+00	.000E+00
9.000	-.1101E+00	.9835E+03	.0000E+00	.0000E+00	.7325E+05	-.7259E+05	.2067E+05	-.2174E+05	.000E+00	.000E+00
9.000	-.1101E+00	.9835E+03	.0000E+00	.0000E+00	.7325E+05	-.7259E+05	.2067E+05	-.2174E+05	.000E+00	.000E+00
3.500	-.1343E+00	.8985E+03	.0000E+00	.0000E+00	.5900E+05	-.5852E+05	.1633E+05	-.1826E+05	.000E+00	.000E+00
8.000	-.1427E+00	.8086E+03	.0000E+00	.0000E+00	.4611E+05	-.4579E+05	.1250E+05	-.1493E+05	.000E+00	.000E+00
8.000	-.1427E+00	.8086E+03	.0000E+00	.0000E+00	.4611E+05	-.4579E+05	.1250E+05	-.1493E+05	.000E+00	.000E+00
2.500	-.1384E+00	.7155E+03	.0000E+00	.0000E+00	.3463E+05	-.3447E+05	.9295E+04	-.1166E+05	.000E+00	.000E+00
7.000	-.1245E+00	.6205E+03	.0000E+00	.0000E+00	.2459E+05	-.2456E+05	.6780E+04	-.8441E+04	.000E+00	.000E+00
7.000	-.1245E+00	.6205E+03	.0000E+00	.0000E+00	.2459E+05	-.2456E+05	.6780E+04	-.8441E+04	.000E+00	.000E+00
1.500	-.1035E+00	.5252E+03	.0000E+00	.0000E+00	.1601E+05	-.1609E+05	.4958E+04	-.5294E+04	.000E+00	.000E+00
6.000	-.7777E-01	.4321E+03	.0000E+00	.0000E+00	.8365E+04	-.9026E+04	.3796E+04	-.2257E+04	.000E+00	.000E+00
6.000	-.7777E-01	.4321E+03	.0000E+00	.0000E+00	.8365E+04	-.9026E+04	.3796E+04	-.2257E+04	.000E+00	.000E+00
0.500	-.4930E-01	.3435E+03	.0000E+00	.0000E+00	.3098E+04	-.3317E+04	.3229E+04	.6202E+03	.000E+00	.000E+00
5.000	-.1971E-01	.2612E+03	.0000E+00	.0000E+00	.1377E+04	-.1125E+04	.3175E+04	.3286E+04	.000E+00	.000E+00
5.000	-.1971E-01	.2612E+03	.0000E+00	.0000E+00	.1377E+04	-.1125E+04	.3175E+04	.3286E+04	.000E+00	.000E+00
4.000	.3783E-01	.1222E+03	.0000E+00	.0000E+00	-.6927E+04	.6672E+04	.4221E+04	.7823E+04	.000E+00	.000E+00
4.000	.3783E-01	.1222E+03	.0000E+00	.0000E+00	-.6927E+04	.6672E+04	.4221E+04	.7823E+04	.000E+00	.000E+00
4.000	.3783E-01	.1222E+03	.0000E+00	.0000E+00	-.6927E+04	.6672E+04	.4221E+04	.7823E+04	.000E+00	.000E+00
1.500	.6401E-01	.6786E+02	.0000E+00	.0000E+00	-.8290E+04	.8059E+04	.5127E+04	.9647E+04	.000E+00	.000E+00
3.000	.8771E-01	.2418E+02	.0000E+00	.0000E+00	-.8924E+04	.8727E+04	.6170E+04	.1117E+05	.000E+00	.000E+00
3.000	.8771E-01	.2418E+02	.0000E+00	.0000E+00	-.8924E+04	.8727E+04	.6170E+04	.1117E+05	.000E+00	.000E+00
7.500	.1036E+00	-.9322E+01	.0000E+00	.0000E+00	-.8988E+04	.8830E+04	.7273E+04	.1240E+05	.000E+00	.000E+00
2.000	.1265E+00	-.3303E+02	.0000E+00	.0000E+00	-.8631E+04	.8515E+04	.9375E+04	.1337E+05	.000E+00	.000E+00
2.000	.1265E+00	-.3303E+02	.0000E+00	.0000E+00	-.8631E+04	.8515E+04	.9375E+04	.1337E+05	.000E+00	.000E+00
6.500	.1415E+00	-.4769E+02	.0000E+00	.0000E+00	-.7996E+04	.7921E+04	.9426E+04	.1411E+05	.000E+00	.000E+00
1.000	.1535E+00	-.5517E+02	.0000E+00	.0000E+00	-.7206E+04	.7165E+04	.1039E+05	.1455E+05	.000E+00	.000E+00
1.000	.1535E+00	-.5517E+02	.0000E+00	.0000E+00	-.7206E+04	.7165E+04	.1039E+05	.1455E+05	.000E+00	.000E+00
5.500	.1673E+00	-.5686E+02	.0000E+00	.0000E+00	-.6771E+04	.6341E+04	.1125E+05	.1504E+05	.000E+00	.000E+00
0.000	.1777E+00	-.5399E+02	.0000E+00	.0000E+00	-.6771E+04	.6341E+04	.1125E+05	.1504E+05	.000E+00	.000E+00

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0.000	.1654E+00	-.5399E+02	.0000E+00	.0000E+00	-.6407E+04	.6407E+04	.1172E+05	.1556E+05	.000E+00	.000E+00
3.000	.1700E+00	-.5126E+02	.0000E+00	.0000E+00	-.4963E+04	.4963E+04	.1269E+05	.1567E+05	.000E+00	.000E+00
6.000	.1753E+00	-.4539E+02	.0000E+00	.0000E+00	-.3640E+04	.3640E+04	.1355E+05	.1553E+05	.000E+00	.000E+00
9.000	.1799E+00	-.3796E+02	.0000E+00	.0000E+00	-.2501E+04	.2501E+04	.1374E+05	.1524E+05	.000E+00	.000E+00
12.000	.1782E+00	-.3014E+02	.0000E+00	.0000E+00	-.1573E+04	.1573E+04	.1394E+05	.1488E+05	.000E+00	.000E+00
12.000	.1789E+00	-.3013E+02	.0000E+00	.0000E+00	-.1574E+04	.1574E+04	.1394E+05	.1488E+05	.000E+00	.000E+00
15.000	.1787E+00	-.2271E+02	.0000E+00	.0000E+00	-.8548E+03	.8548E+03	.1393E+05	.1449E+05	.000E+00	.000E+00
16.000	.1739E+00	-.1614E+02	.0000E+00	.0000E+00	-.3274E+03	.3274E+03	.1391E+05	.1411E+05	.000E+00	.000E+00
21.000	.1709E+00	-.1064E+02	.0000E+00	.0000E+00	.3514E+02	-.3513E+02	.1377E+05	.1375E+05	.000E+00	.000E+00
24.000	.1679E+00	-.5280E+01	.0000E+00	.0000E+00	.2633E+03	-.2633E+03	.1360E+05	.1344E+05	.000E+00	.000E+00
24.000	.1679E+00	-.5273E+01	.0000E+00	.0000E+00	.2627E+03	-.2627E+03	.1360E+05	.1344E+05	.000E+00	.000E+00
27.000	.1650E+00	-.2985E+01	.0000E+00	.0000E+00	.3866E+03	-.3866E+03	.1341E+05	.1318E+05	.000E+00	.000E+00
30.000	.1625E+00	-.5482E+00	.0000E+00	.0000E+00	.4341E+03	-.4341E+03	.1322E+05	.1296E+05	.000E+00	.000E+00
33.000	.1602E+00	.3918E+00	.0000E+00	.0000E+00	.4292E+03	-.4292E+03	.1303E+05	.1278E+05	.000E+00	.000E+00
36.000	.1582E+00	.1795E+01	.0000E+00	.0000E+00	.3913E+03	-.3913E+03	.1286E+05	.1263E+05	.000E+00	.000E+00
36.000	.1582E+00	.1804E+01	.0000E+00	.0000E+00	.3909E+03	-.3909E+03	.1286E+05	.1263E+05	.000E+00	.000E+00
39.000	.1565E+00	.2233E+01	.0000E+00	.0000E+00	.3350E+03	-.3350E+03	.1271E+05	.1251E+05	.000E+00	.000E+00
42.000	.1551E+00	.2323E+01	.0000E+00	.0000E+00	.2722E+03	-.2722E+03	.1257E+05	.1241E+05	.000E+00	.000E+00
45.000	.1538E+00	.2188E+01	.0000E+00	.0000E+00	.2103E+03	-.2103E+03	.1245E+05	.1232E+05	.000E+00	.000E+00
48.000	.1525E+00	.1920E+01	.0000E+00	.0000E+00	.1541E+03	-.1541E+03	.1234E+05	.1225E+05	.000E+00	.000E+00
48.000	.1525E+00	.1925E+01	.0000E+00	.0000E+00	.1537E+03	-.1537E+03	.1234E+05	.1225E+05	.000E+00	.000E+00
51.000	.1516E+00	.1593E+01	.0000E+00	.0000E+00	.1056E+03	-.1056E+03	.1225E+05	.1218E+05	.000E+00	.000E+00
54.000	.1507E+00	.1245E+01	.0000E+00	.0000E+00	.6692E+02	-.6692E+02	.1216E+05	.1212E+05	.000E+00	.000E+00
57.000	.1493E+00	.9153E+00	.0000E+00	.0000E+00	.3753E+02	-.3753E+02	.1208E+05	.1205E+05	.000E+00	.000E+00
60.000	.1489E+00	.6225E+00	.0000E+00	.0000E+00	.1666E+02	-.1666E+02	.1200E+05	.1199E+05	.000E+00	.000E+00
60.000	.1489E+00	.6269E+00	.0000E+00	.0000E+00	.1632E+02	-.1632E+02	.1200E+05	.1199E+05	.000E+00	.000E+00
63.000	.1480E+00	.3815E+00	.0000E+00	.0000E+00	.2682E+01	-.2680E+01	.1193E+05	.1192E+05	.000E+00	.000E+00
66.000	.1472E+00	.1871E+00	.0000E+00	.0000E+00	-.4954E+01	.4950E+01	.1185E+05	.1186E+05	.000E+00	.000E+00
69.000	.1463E+00	.4336E-01	.0000E+00	.0000E+00	-.7984E+01	.7986E+01	.1178E+05	.1179E+05	.000E+00	.000E+00
72.000	.1454E+00	-.5226E-01	.0000E+00	.0000E+00	-.7757E+01	.7759E+01	.1171E+05	.1172E+05	.000E+00	.000E+00
72.000	.1454E+00	-.4620E-01	.0000E+00	.0000E+00	-.8308E+01	.8310E+01	.1171E+05	.1172E+05	.000E+00	.000E+00
75.000	.1445E+00	-.9726E-01	.0000E+00	.0000E+00	-.6253E+01	.6255E+01	.1154E+05	.1165E+05	.000E+00	.000E+00
78.000	.1437E+00	-.1062E+00	.0000E+00	.0000E+00	-.6386E+01	.6388E+01	.1157E+05	.1157E+05	.000E+00	.000E+00
81.000	.1428E+00	-.7499E-01	.0000E+00	.0000E+00	-.8250E+00	.8269E+00	.1150E+05	.1150E+05	.000E+00	.000E+00
84.000	.1419E+00	-.4288E-02	.0000E+00	.0000E+00	.3477E+00	-.3430E+00	.1143E+05	.1143E+05	.000E+00	.000E+00

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1:	2	2	0	1	0	0			
2:	0.0		90.		10	2	7	0	1
3:	0.0		336.		24.		1.0		
4:	25700000.		0.3					.00000723	.00000723
5:	-.4375		.4375						
6:	0.0		84.		7	4	2	0	1
7:	0.0		360.		90.				
8:	25700000.		0.3					.00000723	.00000723
9:	-.40625		.40625						
10:	0	0	0.0		0.0				
11:	1			3			6	-11255	7
12:	2			4			6		8
13:	0.0								
14:	41.167						530.	530.	1
15:	1								
16:	PRESS	7							
17:	0.0		41.167		15.0		40.279	30.	36.636
18:		31.678							45
19:	60.		26.732		75.		23.188	90.	21.593
20:	0.0								
21:	21.593						530.	530.	1
22:	1								
23:	PRESS	2							
24:	0.		21.593		84.		18.666		

KSHELL-IBM FOR ANALYSIS OF AXISYMMETRIC SHELLS BY ARTURS KALNINS JANUARY 1 1974

0 RESPONSE ANALYSIS PARTS# 2 BRANCHES# 0 NUMBER OF SUBCASES# 1 OUTPUT TYPE 2 SUBCASE ADDITION 0

PART NO 1
 OSI# .00000E+00 SX# .90000E+02 SEGMENTS# 10 OUTPUT POINTS# 2 STANDARD SURFACE NO. 7 NTP# 0 LAYERS MLY# 1
 TOROIDAL SHELL NO. 7 K# .00000E+00 A# .33600E+03 B# .24000E+02 DIRECTION INDEX# 1.0
 LAYER NO 1 FROM Z# -.43750E+00 TO Z# .43750E+00
 CONSISTS OF ISOTROPIC MATERIAL, YOUNGS MODULUS E# .25700E+08 POISSONS RATIO NU# .30000E+00
 COEFFS OF THERMAL EXPANSION AFI# .72300E-05 ATHTA# .72300E-05 MASS DENSITY RHO# .00000E+00 COND# .10000E+01

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PART NO 2
 OSI# .00000E+00 SX# .84000E+02 SEGMENTS# 7 OUTPUT POINTS# 4 STANDARD SURFACE NO. 2 NTP# 0 LAYERS MLY# 1
 CYLINDRICAL SHELL NO 2 K# .00000E+00 R# .36000E+03 PHI# 90.000 DEGREES
 LAYER NO 1 FROM Z# -.40525E+00 TO Z# .40625E+00
 CONSISTS OF ISOTROPIC MATERIAL, YOUNGS MODULUS E# .25700E+08 POISSONS RATIO NU# .30000E+00
 COEFFS OF THERMAL EXPANSION AFI# .72300E-05 ATHTA# .72300E-05 MASS DENSITY RHO# .00000E+00 COND# .10000E+01

1 KSHELL-IBM FOR ANALYSIS OF AXISYMMETRIC SHELLS BY ARTURS KALNINS JANUARY 1 1974
 0 SUBCASE NO 1 FOR FOURIER HARMONIC COS 0 THETA

GROUND COND AT START EDGE	1#	.0000E+00	3#	.1039E+01	6#	-.1126E+05	7#	.0000E+00	ALFA#	.0000 DEG
GROUND COND AT FINAL EDGE	2#	.0000E+00	4#	.0000E+00	6#	.0000E+00	8#	.0000E+00	ALFA#	.0000 DEG

LOADS FOR PART NO 1 SUBCASE NO 1
 ORING LOADS AT END OF THIS PART ARE Q= .00000E+00 NPHI# .00000E+00 MPHI# .00000E+00 N# .00000E+00
 OSURFACE AND TEMP LOADS P# .41167E+02 PFI# .00000E+00 PTHETA# .00000E+00 TIN# .53000E+03 TOUT# .53000E+03
 0 CODE NUMBERS OF VARIABLE LOADS OVER THIS PART, GIVEN BY FGENS BELOW, ARE 1
 0 PRESS LINEAR FUNCTION GENERATOR NO. 1 FROM 7 POINTS
 OYS# .4117E+02 .4028E+02 .3664E+02 .3168E+02 .2673E+02 .2319E+02 .2159E+02
 OXS# .0000E+00 .1500E+02 .3000E+02 .4500E+02 .6000E+02 .7500E+02 .9000E+02
 0 AT BEGINNING AND END OF PART 1 PARAMETERS ARE
 RFI# .2400E+02 R# .3360E+03 FI# .0000E+00 RAD .0000E+00 DEGREES S# .0000E+00 C# .1000E+01 H# .8750E+00
 P OR PI# .4117E+02 PFI OR P2# .0000E+00 PTHETA# .0000E+00 TIN# .5300E+03 TOUT# .5300E+03 INORM# 0
 TEMPERATURE IN LAYER NO. 1 AT INSIDE IS .5300E+03 AT OUTSIDE IS .5300E+03 DEGREES
 RFI# .2400E+02 R# .3600E+03 FI# .1571E+01 RAD .9000E+02 DEGREES S# .1000E+01 C# .1873E-06 H# .8750E+00
 P OR PI# .2159E+02 PFI OR P2# .0000E+00 PTHETA# .0000E+00 TIN# .5300E+03 TOUT# .5300E+03 INORM# 0
 TEMPERATURE IN LAYER NO. 1 AT INSIDE IS .5300E+03 AT OUTSIDE IS .5300E+03 DEGREES

LOADS FOR PART NO 2 SUBCASE NO 1
 ORING LOADS AT END OF THIS PART ARE Q= .00000E+00 NPHI# .00000E+00 MPHI# .00000E+00 N# .00000E+00
 OSURFACE AND TEMP LOADS P# .21593E+02 PFI# .00000E+00 PTHETA# .00000E+00 TIN# .53000E+03 TOUT# .53000E+03
 0 CODE NUMBERS OF VARIABLE LOADS OVER THIS PART, GIVEN BY FGENS BELOW, ARE 1
 0 PRESS LINEAR FUNCTION GENERATOR NO. 2 FROM 2 POINTS
 OYS# .2159E+02 .1867E+02
 OXS# .0000E+00 .8400E+02
 0 AT BEGINNING AND END OF PART 2 PARAMETERS ARE
 RFI# .9999E+10 R# .3600E+03 FI# .1571E+01 RAD .9000E+02 DEGREES S# .1000E+01 C# .0000E+00 H# .8125E+00
 P OR PI# .2159E+02 PFI OR P2# .0000E+00 PTHETA# .0000E+00 TIN# .5300E+03 TOUT# .5300E+03 INORM# 0
 TEMPERATURE IN LAYER NO. 1 AT INSIDE IS .5300E+03 AT OUTSIDE IS .5300E+03 DEGREES
 RFI# .9999E+10 R# .3600E+03 FI# .1571E+01 RAD .9000E+02 DEGREES S# .1000E+01 C# .0000E+00 H# .8125E+00
 OR ! .1867E+02 PFI OR P2# .0000E+00 PTH # .0000E+00 TIN# .5300E+03 TOUT# .5300E+03 INORM# 0
 TEMPERATURE IN LAYER NO. 1 AT INSIDE IS .5300E+03 AT OUTSIDE IS .5300E+03 DEGREES

KSHL1-IBM FOR ANALYSIS OF AXISYMMETRIC SHELLS BY ARTURS KALNINS JANUARY 1 1974											
CDEFLECTIONS AND STRESS RESULTANTS			FOR SUBCASE NO. 1		N# 0						
X	W	O	UPHI	NPHI	BPHI	MPHI	UTHETA	N	NTHETA	MIHETA	
G MAIN SHELL PART NO 1											
.000	.0000E+00	.8539E+03	.1039E-01	.1204E+04	.2252E-01	-.1126E-05	.0000E+00	.0000E+00	-.163E+05	-.328E+04	
4.500	.5149E-01	.8661E+03	.1045E+01	.1038E+04	.1004E-01	-.9580E-04	.0000E+00	.0000E+00	-.163E+05	-.283E+04	
9.000	.1249E+00	.8491E+03	.1046E-01	.8759E+03	-.4312E-03	-.7927E-04	.0000E+00	.0000E+00	-.162E+05	-.238E+04	
9.000	.1249E+00	.8491E+03	.1046E+01	.8759E+03	-.4312E-03	-.7927E+04	.0000E+00	.0000E+00	-.162E+05	-.238E+04	
13.500	.2160E+00	.8133E+03	.1040E+01	.7184E+03	-.8938E-02	-.6330E+04	.0000E+00	.0000E+00	-.161E+05	-.194E+04	
18.000	.3206E+00	.7605E+03	.1027E+01	.5692E+03	-.1558E-01	-.4824E+04	.0000E+00	.0000E+00	-.156E+05	-.151E+04	
18.000	.3206E+00	.7605E+03	.1027E+01	.5692E+03	-.1558E-01	-.4824E+04	.0000E+00	.0000E+00	-.156E+05	-.151E+04	
22.500	.4347E+00	.6938E+03	.1005E+01	.4316E+03	-.2047E-01	-.3437E+04	.0000E+00	.0000E+00	-.147E+05	-.111E+04	
27.000	.5544E+00	.6158E+03	.9737E+00	.3082E+03	-.2379E-01	-.2192E+04	.0000E+00	.0000E+00	-.135E+05	-.745E+03	
31.500	.6752E+00	.5299E+03	.9329E+00	.2015E+03	-.2571E-01	-.1106E+04	.0000E+00	.0000E+00	-.120E+05	-.422E+03	
36.000	.7959E+00	.4399E+03	.8826E+00	.1129E+03	-.2643E-01	-.1901E+03	.0000E+00	.0000E+00	-.102E+05	-.145E+03	
36.000	.7959E+00	.4399E+03	.8826E+00	.1129E+03	-.2643E-01	-.1901E+03	.0000E+00	.0000E+00	-.102E+05	-.145E+03	
40.500	.9136E+00	.3498E+03	.8228E+00	.4269E+02	-.2616E-01	.5531E+03	.0000E+00	.0000E+00	-.819E+04	.847E+02	
45.000	.1024E+01	.2628E+03	.7541E+00	-.9477E+01	-.2511E-01	.1127E+04	.0000E+00	.0000E+00	-.607E+04	.266E+03	
45.000	.1024E+01	.2628E+03	.7541E+00	-.9477E+01	-.2511E-01	.1127E+04	.0000E+00	.0000E+00	-.607E+04	.266E+03	
49.500	.1126E+01	.1820E+03	.6770E+00	-.4491E+02	-.2347E-01	.1541E+04	.0000E+00	.0000E+00	-.392E+04	.401E+03	
54.000	.1218E+01	.1097E+03	.5921E+00	-.6554E+02	-.2143E-01	.1811E+04	.0000E+00	.0000E+00	-.180E+04	.492E+03	
58.500	.1300E+01	.4778E+02	.5004E+00	-.7382E+02	-.1915E-01	.1953E+04	.0000E+00	.0000E+00	.208E+03	.546E+03	
63.000	.1369E+01	-.2833E+01	.4027E+00	-.7241E+02	-.1677E-01	.1990E+04	.0000E+00	.0000E+00	.206E+04	.567E+03	
63.000	.1369E+01	-.2833E+01	.4027E+00	-.7240E+02	-.1677E-01	.1990E+04	.0000E+00	.0000E+00	.206E+04	.567E+03	
67.500	.1426E+01	-.4225E+02	.3000E+00	-.6403E+02	-.1440E-01	.1943E+04	.0000E+00	.0000E+00	.373E+04	.561E+03	
72.000	.1470E+01	-.7061E+02	.1933E+00	-.5131E+02	-.1213E-01	.1833E+04	.0000E+00	.0000E+00	.520E+04	.535E+03	
72.000	.1470E+01	-.7058E+02	.1932E+00	-.5130E+02	-.1213E-01	.1833E+04	.0000E+00	.0000E+00	.520E+04	.535E+03	
76.500	.1502E+01	-.8853E+02	.8350E-01	-.3664E+02	-.1002E-01	.1679E+04	.0000E+00	.0000E+00	.645E+04	.494E+03	
81.000	.1521E+01	-.9778E+02	-.2827E-01	-.2214E+02	-.8118E-02	.1501E+04	.0000E+00	.0000E+00	.749E+04	.445E+03	
81.000	.1521E+01	-.9773E+02	-.2828E-01	-.2213E+02	-.8117E-02	.1502E+04	.0000E+00	.0000E+00	.749E+04	.445E+03	
85.00	.1528E+01	-.9971E+02	-.1411E+00	-.5474E-01	-.132E-02	.1314E+04	.0000E+00	.0000E+00	.33E+01	.392E+03	

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.000	.1524E+01	-.9572E+02	-.2540E+00	.7105E-13	-.4970E-02	.1129E+04	.0000E+00	.0000E+00	.836E+04	.339E+03
3.000	.1535E+01	-.8767E+02	-.2429E+00	.7105E-13	-.2622E-02	.8521E+03	.0000E+00	.0000E+00	.901E+04	.256E+03
6.000	.1540E+01	-.7543E+02	-.2318E+00	.7105E-13	-.8952E-03	.6068E+03	.0000E+00	.0000E+00	.931E+04	.182E+03
9.000	.1541E+01	-.6152E+02	-.2207E+00	.7105E-13	.2943E-03	.4012E+03	.0000E+00	.0000E+00	.935E+04	.120E+03
12.000	.1539E+01	-.4766E+02	-.2096E+00	.7105E-13	.1045E-02	.2376E+03	.0000E+00	.0000E+00	.923E+04	.713E+02
12.000	.1539E+01	-.4762E+02	-.2096E+00	.1310E-13	.1047E-02	.2381E+03	.0000E+00	.0000E+00	.923E+04	.714E+02
15.000	.1535E+01	-.3493E+02	-.1985E+00	.1310E-13	.1459E-02	.1146E+03	.0000E+00	.0000E+00	.901E+04	.344E+02
18.000	.1530E+01	-.2401E+02	-.1874E+00	.1310E-13	.1620E-02	.2670E+02	.0000E+00	.0000E+00	.874E+04	.801E+01
21.000	.1525E+01	-.1510E+02	-.1763E+00	.1310E-13	.1609E-02	-.3145E+02	.0000E+00	.0000E+00	.846E+04	-.944E+01
24.000	.1521E+01	-.8206E+01	-.1652E+00	.1310E-13	.1489E-02	-.8593E+02	.0000E+00	.0000E+00	.819E+04	-.198E+02
24.000	.1521E+01	-.8213E+01	-.1652E+00	.1554E-13	.1489E-02	-.6600E+02	.0000E+00	.0000E+00	.819E+04	-.198E+02
27.000	.1516E+01	-.3153E+01	-.1540E+00	.1554E-13	.1309E-02	-.8262E+02	.0000E+00	.0000E+00	.794E+04	-.248E+02
30.000	.1513E+01	.3234E+00	-.1429E+00	.1554E-13	.1106E-02	-.8651E+02	.0000E+00	.0000E+00	.773E+04	-.260E+02
33.000	.1510E+01	.2509E+01	-.1317E+00	.1554E-13	.9048E-03	-.8197E+02	.0000E+00	.0000E+00	.756E+04	-.246E+02
36.000	.1507E+01	.3694E+01	-.1205E+00	.1554E-13	.7206E-03	-.7245E+02	.0000E+00	.0000E+00	.741E+04	-.217E+02
36.000	.1507E+01	.3707E+01	-.1205E+00	.6370E-14	.7209E-03	-.7234E+02	.0000E+00	.0000E+00	.741E+04	-.217E+02
39.000	.1505E+01	.4157E+01	-.1093E+00	.6370E-14	.5629E-03	-.6039E+02	.0000E+00	.0000E+00	.730E+04	-.181E+02
42.000	.1504E+01	.4101E+01	-.9815E-01	.6370E-14	.4343E-03	-.4790E+02	.0000E+00	.0000E+00	.722E+04	-.144E+02
45.000	.1503E+01	.3725E+01	-.8697E-01	.6370E-14	.3347E-03	-.3610E+02	.0000E+00	.0000E+00	.715E+04	-.108E+02
48.000	.1502E+01	.3175E+01	-.7578E-01	.6370E-14	.2615E-03	-.2572E+02	.0000E+00	.0000E+00	.710E+04	-.772E+01
48.000	.1502E+01	.3189E+01	-.7578E-01	-.9294E-14	.2620E-03	-.2559E+02	.0000E+00	.0000E+00	.710E+04	-.768E+01
51.000	.1501E+01	.2568E+01	-.6459E-01	-.9294E-14	.2118E-03	-.1695E+02	.0000E+00	.0000E+00	.706E+04	-.508E+01
54.000	.1501E+01	.1952E+01	-.5340E-01	-.9294E-14	.1800E-03	-.1018E+02	.0000E+00	.0000E+00	.702E+04	-.305E+01
57.000	.1500E+01	.1387E+01	-.4220E-01	-.9294E-14	.1621E-03	-.5183E+01	.0000E+00	.0000E+00	.699E+04	-.156E+01
60.000	.1500E+01	.8991E+00	-.3101E-01	-.9294E-14	.1541E-03	-.1776E+01	.0000E+00	.0000E+00	.697E+04	-.533E+00
60.000	.1500E+01	.9187E+00	-.3101E-01	-.1543E-13	.1548E-03	-.1585E+01	.0000E+00	.0000E+00	.697E+04	-.475E+00
63.000	.1499E+01	.5187E+00	-.1981E-01	-.1543E-13	.1538E-03	.5488E+00	.0000E+00	.0000E+00	.694E+04	.165E+00
66.000	.1499E+01	.2088E+00	-.8614E-02	-.1543E-13	.1566E-03	.1618E+01	.0000E+00	.0000E+00	.691E+04	.485E+00
69.000	.1498E+01	-.1473E-01	.2585E-02	-.1543E-13	.1609E-03	.1888E+01	.0000E+00	.0000E+00	.689E+04	.566E+00
72.000	.1498E+01	-.1579E+00	.1378E-01	-.1543E-13	.1651E-03	.1610E+01	.0000E+00	.0000E+00	.686E+04	.483E+00
72.000	.1498E+01	-.1370E+00	.1378E-01	-.1746E-13	.1658E-03	.1804E+01	.0000E+00	.0000E+00	.686E+04	.541E+00
75.000	.1497E+01	-.2074E+00	.2498E-01	-.1746E-13	.1695E-03	.1270E+01	.0000E+00	.0000E+00	.683E+04	.381E+00
78.000	.1497E+01	-.2097E+00	.3619E-01	-.1746E-13	.1717E-03	.6278E+00	.0000E+00	.0000E+00	.680E+04	.188E+00
81.000	.1496E+01	-.1473E+00	.4739E-01	-.1746E-13	.1725E-03	.7637E-01	.0000E+00	.0000E+00	.677E+04	.229E-01
84.000	.1496E+01	-.2125E-01	.5859E-01	-.1746E-13	.173E-03	-.1923E+00	.0000E+00	.0000E+00	.674E+04	-.577E-01

ESHEL1-IBM FOR ANALYSIS OF AXISYMMETRIC SHELLS BY ARTURS KALNINS JANUARY 1 1974											
DEFLECTIONS AND STRESSES FOR SUBCASE NO. 1 N# 0											
Q	X	W	OPHI	NFITHETA	MFITHETA	SPHI IN	SPHI OUT	STHETA IN	STHETA OUT	SFITH IN	SFITH OUT
Q	MAIN SHELL PART NO 1										
	.000	.0000E+00	.8639E+03	.0000E+00	.0000E+00	.8958E+05	-.8683E+05	.7111E+04	-.4430E+05	.000E+00	.000E+00
	4.500	.5149E+01	.8661E+03	.0000E+00	.0000E+00	.7626E+05	-.7389E+05	.3603E+04	-.4078E+05	.000E+00	.000E+00
	9.000	.1249E+00	.8491E+03	.0000E+00	.0000E+00	.6312E+05	-.6112E+05	.7594E+02	-.3722E+05	.000E+00	.000E+00
	9.000	.1249E+00	.8491E+03	.0000E+00	.0000E+00	.6312E+05	-.6112E+05	.7594E+02	-.3722E+05	.000E+00	.000E+00
	13.500	.2160E+00	.8133E+03	.0000E+00	.0000E+00	.5043E+05	-.4879E+05	-.3177E+04	-.3351E+05	.000E+00	.000E+00
	18.000	.3206E+00	.7605E+03	.0000E+00	.0000E+00	.3846E+05	-.3715E+05	-.5959E+04	-.2961E+05	.000E+00	.000E+00
	18.000	.3206E+00	.7605E+03	.0000E+00	.0000E+00	.3846E+05	-.3715E+05	-.5959E+04	-.2961E+05	.000E+00	.000E+00
	22.500	.4347E+00	.6938E+03	.0000E+00	.0000E+00	.2743E+05	-.2644E+05	-.8128E+04	-.2552E+05	.000E+00	.000E+00
	27.000	.5544E+00	.6158E+03	.0000E+00	.0000E+00	.1753E+05	-.1682E+05	-.9613E+04	-.2129E+05	.000E+00	.000E+00
	27.000	.5544E+00	.6158E+03	.0000E+00	.0000E+00	.1753E+05	-.1682E+05	-.9613E+04	-.2129E+05	.000E+00	.000E+00
	31.500	.6762E+00	.5299E+03	.0000E+00	.0000E+00	.8898E+04	-.8437E+04	-.1040E+05	-.1701E+05	.000E+00	.000E+00
	36.000	.7569E+00	.4399E+03	.0000E+00	.0000E+00	.1619E+04	-.1361E+04	-.1051E+05	-.1278E+05	.000E+00	.000E+00
	36.000	.7569E+00	.4399E+03	.0000E+00	.0000E+00	.1618E+04	-.1361E+04	-.1051E+05	-.1278E+05	.000E+00	.000E+00
	40.500	.9136E+00	.3498E+03	.0000E+00	.0000E+00	-.4286E+04	.4383E+04	-.1002E+05	-.8693E+04	.000E+00	.000E+00
	45.000	.1024E+01	.2628E+03	.0000E+00	.0000E+00	-.8843E+04	.8821E+04	-.9020E+04	-.4852E+04	.000E+00	.000E+00
	45.000	.1024E+01	.2628E+03	.0000E+00	.0000E+00	-.8844E+04	.8822E+04	-.9020E+04	-.4852E+04	.000E+00	.000E+00
	49.500	.1126E+01	.1820E+03	.0000E+00	.0000E+00	-.1213E+05	.1203E+05	-.7615E+04	-.1335E+04	.000E+00	.000E+00
	54.000	.1218E+01	.1097E+03	.0000E+00	.0000E+00	-.1427E+05	.1412E+05	-.5918E+04	.1799E+04	.000E+00	.000E+00
	54.000	.1218E+01	.1097E+03	.0000E+00	.0000E+00	-.1427E+05	.1412E+05	-.5918E+04	.1800E+04	.000E+00	.000E+00
	58.500	.1300E+01	.4778E+02	.0000E+00	.0000E+00	-.1539E+05	.1522E+05	-.1040E+04	.4515E+04	.000E+00	.000E+00
	63.000	.1369E+01	-.2833E+01	.0000E+00	.0000E+00	-.1568E+05	.1552E+05	-.2081E+04	.6799E+04	.000E+00	.000E+00
	63.000	.1369E+01	-.2823E+01	.0000E+00	.0000E+00	-.1568E+05	.1552E+05	-.2080E+04	.6800E+04	.000E+00	.000E+00
	67.500	.1426E+01	-.4225E+02	.0000E+00	.0000E+00	-.1530E+05	.1515E+05	-.1276E+03	.8663E+04	.000E+00	.000E+00
	72.000	.1470E+01	-.7061E+02	.0000E+00	.0000E+00	-.1442E+05	.1430E+05	.1748E+04	.1013E+05	.000E+00	.000E+00
	72.000	.1470E+01	-.7058E+02	.0000E+00	.0000E+00	-.1442E+05	.1430E+05	.1749E+04	.1013E+05	.000E+00	.000E+00
	76.500	.1502E+01	-.8853E+02	.0000E+00	.0000E+00	-.1320E+05	.1312E+05	.3493E+04	.1124E+05	.000E+00	.000E+00
	81.000	.1521E+01	-.9773E+02	.0000E+00	.0000E+00	-.1179E+05	.1174E+05	.5068E+04	.1205E+05	.000E+00	.000E+00
	81.000	.1521E+01	-.9773E+02	.0000E+00	.0000E+00	-.1179E+05	.1174E+05	.5068E+04	.1205E+05	.000E+00	.000E+00
	85.500	.1528E+01	-.9971E+02	.0000E+00	.0000E+00	-.1131E+05	.1029E+05	.6452E+04	.1260E+05	.000E+00	.000E+00

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O MAIN SHELL PART NO 2

.000	.1524E+01	-.9572E+02	.0000E+00	.0000E+00	-.1026E+05	.1026E+05	.7213E+04	.1337E+05	.000E+00	.000E+00
3.000	.1535E+01	-.8767E+02	.0000E+00	.0000E+00	-.7745E+04	.7745E+04	.8768E+04	.1342E+05	.000E+00	.000E+00
6.000	.1540E+01	-.7543E+02	.0000E+00	.0000E+00	-.5515E+04	.5515E+04	.9803E+04	.1311E+05	.000E+00	.000E+00
9.000	.1541E+01	-.6152E+02	.0000E+00	.0000E+00	-.3646E+04	.3646E+04	.1042E+05	.1261E+05	.000E+00	.000E+00
12.000	.1539E+01	-.4766E+02	.0000E+00	.0000E+00	-.2159E+04	.2159E+04	.1072E+05	.1201E+05	.000E+00	.000E+00
12.000	.1539E+01	-.4762E+02	.0000E+00	.0000E+00	-.2164E+04	.2163E+04	.1071E+05	.1201E+05	.000E+00	.000E+00
15.000	.1535E+01	-.3493E+02	.0000E+00	.0000E+00	-.1042E+04	.1042E+04	.1078E+05	.1140E+05	.000E+00	.000E+00
18.000	.1530E+01	-.2401E+02	.0000E+00	.0000E+00	-.2428E+03	.2426E+03	.1068E+05	.1083E+05	.000E+00	.000E+00
21.000	.1525E+01	-.1510E+02	.0000E+00	.0000E+00	.2858E+03	-.2860E+03	.1049E+05	.1032E+05	.000E+00	.000E+00
24.000	.1521E+01	-.8206E+01	.0000E+00	.0000E+00	.5991E+03	-.5994E+03	.1025E+05	.9894E+04	.000E+00	.000E+00
24.000	.1521E+01	-.8213E+01	.0000E+00	.0000E+00	.5998E+03	-.5999E+03	.1025E+05	.9894E+04	.000E+00	.000E+00
27.000	.1516E+01	-.3153E+01	.0000E+00	.0000E+00	.7509E+03	-.7510E+03	.9999E+04	.9549E+04	.000E+00	.000E+00
30.000	.1513E+01	.3234E+00	.0000E+00	.0000E+00	.7861E+03	-.7864E+03	.9751E+04	.9279E+04	.000E+00	.000E+00
33.000	.1510E+01	.2509E+01	.0000E+00	.0000E+00	.7448E+03	-.7452E+03	.9523E+04	.9076E+04	.000E+00	.000E+00
36.000	.1507E+01	.3694E+01	.0000E+00	.0000E+00	.6583E+03	-.6587E+03	.9324E+04	.8929E+04	.000E+00	.000E+00
36.000	.1507E+01	.3707E+01	.0000E+00	.0000E+00	.6574E+03	-.6577E+03	.9323E+04	.8929E+04	.000E+00	.000E+00
39.000	.1505E+01	.4157E+01	.0000E+00	.0000E+00	.5488E+03	-.5489E+03	.9154E+04	.8824E+04	.000E+00	.000E+00
42.000	.1504E+01	.4101E+01	.0000E+00	.0000E+00	.4352E+03	-.4355E+03	.9014E+04	.8752E+04	.000E+00	.000E+00
45.000	.1503E+01	.3725E+01	.0000E+00	.0000E+00	.3280E+03	-.3283E+03	.8899E+04	.8703E+04	.000E+00	.000E+00
48.000	.1502E+01	.3175E+01	.0000E+00	.0000E+00	.2337E+03	-.2338E+03	.8808E+04	.8667E+04	.000E+00	.000E+00
48.000	.1502E+01	.3189E+01	.0000E+00	.0000E+00	.2325E+03	-.2327E+03	.8807E+04	.8668E+04	.000E+00	.000E+00
51.000	.1501E+01	.2568E+01	.0000E+00	.0000E+00	.1539E+03	-.1541E+03	.8733E+04	.8641E+04	.000E+00	.000E+00
54.000	.1501E+01	.1952E+01	.0000E+00	.0000E+00	.9225E+02	-.9269E+02	.8673E+04	.8618E+04	.000E+00	.000E+00
57.000	.1500E+01	.1387E+01	.0000E+00	.0000E+00	.4688E+02	-.4725E+02	.8623E+04	.8595E+04	.000E+00	.000E+00
60.000	.1500E+01	.8991E+00	.0000E+00	.0000E+00	.1600E+02	-.1625E+02	.8580E+04	.8570E+04	.000E+00	.000E+00
60.000	.1500E+01	.9187E+00	.0000E+00	.0000E+00	.1425E+02	-.1450E+02	.8580E+04	.8571E+04	.000E+00	.000E+00
63.000	.1499E+01	.5187E+00	.0000E+00	.0000E+00	-.5125E+01	.4813E+01	.8541E+04	.8544E+04	.000E+00	.000E+00
66.000	.1499E+01	.2088E+00	.0000E+00	.0000E+00	-.1488E+02	.1456E+02	.8505E+04	.8513E+04	.000E+00	.000E+00
69.000	.1498E+01	-.1473E-01	.0000E+00	.0000E+00	-.1731E+02	.1700E+02	.8470E+04	.8480E+04	.000E+00	.000E+00
72.000	.1498E+01	-.1579E+00	.0000E+00	.0000E+00	-.1475E+02	.1450E+02	.8436E+04	.8445E+04	.000E+00	.000E+00
72.000	.1498E+01	-.1370E+00	.0000E+00	.0000E+00	-.1650E+02	.1625E+02	.8435E+04	.8445E+04	.000E+00	.000E+00
75.000	.1497E+01	-.2074E+00	.0000E+00	.0000E+00	-.1163E+02	.1150E+02	.8401E+04	.8408E+04	.000E+00	.000E+00
78.000	.1497E+01	-.2097E+00	.0000E+00	.0000E+00	-.5875E+01	.5563E+01	.8366E+04	.8369E+04	.000E+00	.000E+00
81.000	.1496E+01	-.1473E+00	.0000E+00	.0000E+00	-.8750E+00	.5625E+00	.8330E+04	.8331E+04	.000E+00	.000E+00
84.000	.1496E+01	-.2125E-01	.0000E+00	.0000E+00	-.125E+01	-.1875E+01	.8294E+04	.8293E+04	.000E+00	.000E+00

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APPENDIX 2

EAR 738

**Pittsburgh Corning Corporation
800 Presque Isle Drive
Pittsburgh, Pennsylvania 15239
Area Code (412) 327-6100**

March 17, 1977

Mr. John Wirt
Brown-Minneapolis Tank Company
P. O. Box 3670
St. Paul, Minnesota 55165

Dear Mr. Wirt:

On March 14, I spoke to you about the insulation of a cylindrical tank containing heat transfer oil and rocks. The tank, operating at 600°F, is to be used as storage for a solar energy collection system.

I asked our Energy Analysis Department to compute the heat losses through various thicknesses of FOAMGLAS® insulation. The results are given in Energy Analysis Report (EAR) No. 738. I then calculated the surface area of the sidewalls and dome roof of the tank insulation to be approximately 13,500 square feet. To keep the total heat losses through the tank sidewalls and dome roof (base not considered) below 474,000 Btu/hr, an insulation thickness of nine (9) inches is required.

Because of the temperature involved, the FOAMGLAS® insulation should be fabricated in laminate form (see the enclosed brochure). I don't recommend the composite of FOAMGLAS® and TEMP-MAT® insulation for this application, because the TEMP-MAT® blanket will absorb any heat transfer fluid spill.

I trust this information is to your satisfaction. If I may be of further assistance, please do not hesitate to contact me.

Very truly yours,

James S. Carr

James S. Carr
Technical Services Engineer

JSC:mah

Enc.

cc: T. J. Bennett
R. E. Fuhs

RECEIVED

MAR 21 1977

BMT ENGINEERING DEPT.

PITTSBURGH CORNING CORPORATION
ENERGY ANALYSIS DEPT.
ENERGY ANALYSIS REPORT NO. 738

03/14/77
OUTPUT GENERATED FOR JOHN WIRT, BROWN MINNE. TANK CO.
REQUESTED BY JIM CARR

PROBLEM SPECIFICATIONS

PURPOSE

CALCULATION OF THE THERMAL PERFORMANCE OF A SERIES OF SINGLE
LAYER INSULATION SYSTEMS. PIPES MAY BE HOT OR COLD.
THE OUTPUT CAN BE DISPLAYED IN ENGLISH, METRIC, OR SI UNITS.

THE RESULTS FOR ONE PIPE SIZE, ONE AMBIENT TEMPERATURE, ONE
WIND VELOCITY, ONE EMITTANCE, UP TO FOUR PIPE TEMPERATURES,
AND UP TO FIFTEEN THICKNESSES CAN BE DISPLAYED ON ONE PAGE.
FOR COLD PIPES NO INFORMATION IS DISPLAYED PERTAINING TO THE
CONDENSATION OF MOISTURE. THIS TYPE OF INFORMATION CAN BE
FOUND BY THE USE OF PIPE PROGRAM 3.

THE VALUE OF THE THERMAL CONDUCTIVITY USED IN THE CALCULATION
IS DETERMINED BY EVALUATING A POLYNOMIAL AT THE MEAN INSULATION
TEMPERATURE. THIS POLYNOMIAL HAS BEEN DETERMINED FROM A
REGRESSION ANALYSIS OF DATA OBTAINED BY COMMERCIAL LABORATORIES
OTHER THAN PITTSBURGH CORNING. A TABLE OF CONDUCTIVITIES AS A
FUNCTION OF TEMPERATURE IS DISPLAYED ON PAGE 1. THE TEMPERATURE
RANGE AND TEMPERATURE STEPS CAN BE CONTROLLED BY THE INPUT DATA.

*** HEAT LOSS CALCULATION ***

INPUT DATA

AMBIENT TEMPERATURE..... 43.5 DEG F
WIND VELOCITY..... 9.0 MPH
EMITTANCES..... 0.4, 0.9
TANK SIZE..... 60.0 FEET (DIAMETER)
OPERATING TEMPERATURE..... 600.0 DEG F
INSULATION MATERIAL..... FOAMGLAS

PIPE PROGRAM USED - PP 2

FOR ADDITIONAL INFORMATION CONTACT
DR E K HALTEMAN OR I TRAUGUT (412) 327-6100

RECEIVED

MAR 21 1977

BMT ENGINEERING DEPT.

PREPARED BY

APPROVED BY

DATE 3/15/77

DATE 3/15/77

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TEMPERATURE DEG F	FOAMGLAS CONDUCTIVITY BTU-IN/HR/SQFT/DEG F	KCAL/HR/M/DEG C	DEG CENTIGRADE
0.00	0.34	0.042	-17.78
50.00	0.37	0.046	10.00
100.00	0.40	0.049	37.78
150.00	0.43	0.053	65.56
200.00	0.46	0.057	93.33
250.00	0.50	0.062	121.11
300.00	0.54	0.067	148.89
350.00	0.58	0.072	176.67
400.00	0.63	0.078	204.44
450.00	0.69	0.085	232.22
500.00	0.75	0.092	260.00
550.00	0.81	0.101	287.78
600.00	0.88	0.109	315.56

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OUTPUT DATA
PROGRAM PP 2, LAST REVISION 10/10/73

ENGLISH UNITS

INSULATION MATERIAL - FOAMGLAS

NOMINAL PIPE SIZE = 720.00 INCHES

ACTUAL DIAMETER = 720.000 INCHES

AMBIENT TEMPERATURE = 48.50 DEG F

WIND VELOCITY = 2.0 MILES/HOUR

EMITTANCE = 0.90

INSULATION THICKNESS		PIPE TEMP = 550.00 DEG F				PIPE TEMP = 575.00 DEG F				PIPE TEMP = 600.00 DEG F				PIPE TEMP = 625.00 DEG F			
INCHES		SURFACE		BTU		SURFACE		BTU		SURFACE		BTU		SURFACE		BTU	
NOM	EQUIV	TEMP	HR SQFT	HR FT	TEMP	HR SQFT	HR FT	TEMP	HR SQFT	HR FT	TEMP	HR SQFT	HR FT	TEMP	HR SQFT	HR FT	
3.0	3.01	83.82	-87.98	-16722.94	86.01	-94.57	-17974.23	88.25	-101.44	-19279.74	90.56	-108.60	-20641.76				
3.5	3.52	79.70	-75.82	-14429.85	81.64	-81.48	-15508.63	83.63	-87.40	-16634.01	85.68	-93.57	-17808.11				
4.0	4.02	76.50	-66.60	-12693.02	79.24	-71.57	-13641.30	80.03	-76.76	-14630.51	81.87	-82.18	-15662.49				
4.5	4.53	73.93	-59.37	-11331.75	75.51	-63.81	-12177.87	77.14	-68.43	-13060.47	78.82	-73.26	-13981.21				
5.0	5.03	71.32	-53.56	-10236.18	73.27	-57.56	-11000.14	74.77	-61.73	-11797.03	76.31	-66.08	-12628.33				
6.0	6.05	68.55	-44.78	-8531.07	69.80	-48.12	-9221.07	71.10	-51.60	-9888.61	72.43	-55.23	-10534.76				
7.0	7.07	66.12	-38.46	-7390.43	67.22	-41.33	-7941.37	68.37	-44.32	-8515.61	69.55	-47.43	-9114.97				
8.0	8.09	64.24	-33.69	-6492.21	65.24	-36.20	-6975.99	66.26	-38.82	-7480.57	67.32	-41.55	-8006.54				
9.0	9.11	62.75	-29.97	-5790.61	63.65	-32.20	-6221.97	64.58	-34.53	-6671.88	65.53	-36.96	-7141.16				
10.0	10.14	61.53	-26.98	-5227.35	62.35	-28.99	-5616.66	63.20	-31.09	-6022.69	64.08	-33.77	-6446.21				
12.0	12.20	59.65	-22.48	-4379.16	60.35	-24.16	-4705.18	61.08	-25.90	-5045.18	61.83	-27.72	-5399.83				
14.0	14.27	58.26	-19.26	-3770.79	58.88	-20.69	-4051.43	59.52	-22.18	-4344.11	60.18	-23.74	-4649.39				
16.0	16.35	57.19	-16.83	-3313.09	57.74	-18.08	-3559.61	58.32	-19.39	-3816.71	58.90	-20.75	-4084.87				
18.0	18.44	56.34	-14.94	-2956.24	56.84	-16.05	-3176.17	57.36	-17.21	-3405.53	57.89	-18.42	-3644.76				
20.0	20.55	55.65	-13.42	-2670.18	56.10	-14.42	-2868.81	56.58	-15.46	-3075.95	57.06	-16.55	-3291.99				

Note:
Emittance factor of 0.90 is for black or dark gray, rough non-metallic weather barrier.

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SUBROUTINE CS 169

PURPOSE: To find the surface temperature of pipe insulation for a given pipe temperature and ambient air temperature.

METHOD OF SOLUTION: The transfer of heat between an insulated pipe and its surroundings is controlled by the thermal conductance of the insulation and the ability of the insulation surface to transfer heat to the local environment. The heat transferred within the cylindrical insulation is governed by the equation

$$Q/L = 2\pi k(T_1 - T_2)/\ln(R_2/R_1)$$

where Q is the energy flow per hour or the power, L is the length, k is the thermal conductivity, and $R_1, T_1; R_2, T_2$ the radius and temperature at the inside and outside surface of the cylindrical insulation. For this problem the total temperature difference from the source of the energy to the energy sink is given, i.e., the absolute value of the expression (pipe temperature - ambient temperature).

The surface conductance and hence the flux are not known as the surface conductance is a function of the insulation surface temperature.

The surface conductance is given by the ratio of the flux through the surface to the temperature difference between the surface and the environment.

The contribution to the heat flow per unit area through the insulation surface due to radiation is calculated by using the Stephan-Boltzmann equation

$Q(\text{rad}) = \epsilon \sigma (T_3^4 - T_2^4)$ where σ is Stephan-Boltzmann constant with a value of 0.1714×10^{-8} BTU/hr.sq.ft.deg. R^4 ; ϵ is the emittance of the surface, T_2 is the surface temperature in degrees Rankine and T_3 is the ambient temperature in degrees Rankine.

The contribution to the energy flux through the insulation surface due to convective transfer from the surface to the ambient temperature is given by Malloy.¹ Thus for horizontal cylinders

$$Q(\text{conv}) = 1.016 \cdot (1/d)^{0.2} \cdot (0.5(T_2 + T_3))^{-0.181} \cdot (T_2 - T_3)^{1.266} \cdot ((V + 68.9)/68.9)^{0.5}$$

where d is the cylinder diameter in inches and V is the air velocity in ft/min. The total energy flux is given by the sum of the radiation and convective contributions, thus $Q = Q(\text{rad}) + Q(\text{conv})$.

The calculation of the surface temperature requires an iterative procedure as it is not possible to write an explicit equation for T_2 , the surface temperature in terms of the input parameters. The initial iteration is started by assuming the surface temperature is the average of the pipe and ambient temperature. One calculates the thermal conductivity k from the conductivity polynomial, the thermal resistance of the insulation from k and the known insulation geometry, the surface conductance from the ratio of the surface flux due to radiation and convection to the temperature difference between the surface and ambient. One now has an estimate of the total thermal resistance between the pipe and the ambient. Using this resistance, the surface conductance and the surface flux, one can find the surface temperature. Using this new surface temperature the process is repeated until the surface temperature changes less than a predetermined amount, usually 0.1 degree F.

¹ J. F. Malloy, "Thermal Insulation," Van Nostrand Reinhold Co. (1969).

Successful employment of FOAMGLAS^R insulation at high temperatures is contingent on proper specifications and attention to system details. In particular, provision should be made for the thermal stress cracking of FOAMGLAS^R ware due to rapid heating or cooling. There are effective, proven ways of handling these situations and we would suggest you contact us for any applications employing FOAMGLAS^R insulation above 250°F.

REFERENCE:

1. API-650, Fifth edition up to & including Supplement No.3.
2. API-620, Fifth edition up to & including Supplement No. 3.
3. API-2000, Second edition.
4. ASME Section III, Division I, 1974 Edition up to & including Summer of 1976 addenda.
5. ASME Section VIII, Division I, 1974 Edition up to & including Summer of 1976 addenda.
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7. ACI Standard 318-71.
8. ACI Standard 318-63.
9. AISC, Seventh Edition.
10. "Design of Plate Structures", Steel Plate Engineering Data, Volume 2.
11. "Plate Formulas", William Griffel, Frederick, Ungar Publishing Co., Inc.
12. USAEC Regulatory Guide, NRC 1.60.
13. "Nuclear Reactor & Earthquakes", TID-7024 USAEC, Division of Technical Information.
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SUBJECT	MADE BY	CHKD BY	REV.	MADE BY	CHKD BY	CONTRACT NO.
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APPENDIX H

OIL MAINTENANCE REQUIREMENTS (see Section 3)

OIL MAINTENANCE UNIT

Equipment Design and Specification

The degraded products are separated from the usable oil in a vacuum distillation column. To remove the degraded oil at the rate at which they could be formed the column must be able to process 18.9 m^3 (5000 gallons) of the fluid per day. This corresponds to a feed flow rate of 760 liters per hour (200 gph). Up to 75.7 liters/hr (20 gph) of each of the high and low boiler waste could be removed. The remaining usable oil 606 liter/hr (160 gph) is returned to the oil tankage system. The 151 liters per hour (40 gph) that are removed as waste are replaced with fresh Caloria HT-43 (see Section 6 for discussion of the oil).

The storage tankage required consists of separate storage for the low and high boiler products and a third tank to store fresh Caloria HT-43 for make up. Based on a capacity to store 1 month's supply the make up tank holds 120,000 liters and the high and low boiler tanks hold 60,000 liters each.

The vacuum separation tower required to recover the usable Caloria HT-43 will be 15.1 meters tall 0.76 meters (2.5 feet) in diameter in the pilot plant. The commercial tower will be 1.52 meters (5 feet) in diameter and approximately the same height.

Schematically, the column can be thought of in three sections. The first is the flash zone where High Boilers are removed. The second is the Caloria reflux section where the reusable Caloria is recovered. And, the third is

the Low Boilers reflux section where the light hydrocarbons are condensed and removed from the column. The system is shown in Figure H-1.

The feed to the column is preheated to 357°C (675°F), a high enough temperature so that the reusable oil and the light boilers will flash vaporize when fed to the fractionating column. The High Boilers do not vaporize and are cooled to (300°F) 149°C and pumped from the column to storage at this point. The vapors pass up the column through 0.91 m (3 ft) of distillation grid in contact with liquid from the Caloria refluxing section. The vapors that are not condensed by the cooler liquid will enter the Caloria refluxing section through a chimney tray.

The Caloria refluxing section consists of 1.83 meters (6 feet) of distillation grid. A reflux stream is withdrawn from one of the chimney tray, is cooled, and then readmitted into the column just above the top tray. This flow of cooler oil down the column condenses the reusable oil from the vapor in the column. The reusable product stream is drawn off the reflux stream just before the cooler so that the product is recovered at as high a temperature as possible. The product is recovered at 177°C (350°F).

The vapors that pass through this portion of the column enter another chimney tray rise into the Low Boiler reflux section. In this portion of the column, oil is being refluxed at 66°C (150°F). At this temperature all Low Boiling products will be condensed. The Low Boiling products will be removed from this recycle stream after cooling to 38°C (100°F) and pumped to storage.

The noncondensables in the system will be passed through a wire mesh mist eliminator and then will be removed by a three-stage vacuum steam ejector. The condensed steam from the steam ejectors is cooled in water coolers and then further cooled with a small refrigeration unit to prevent emission of water vapor.

The operation of the column is continuous due to the nature of the distillation processes. Shutdowns will be scheduled once a year for boiler inspections. The heat loads and utility requirements are given in the following tables.

Heat Loads in the Units of the Oil Maintenance Unit

Unit	Function	Heat Load	Commercial
H241	Main Furnace	187 kW	750 kW
E213	HB Cooler	20kW	81.47 kW
E212	Caloria Cooler	188 kW	753 kW
E211	LB Cooler	20 kW	81.2 kW
E214	Steam Ejector Coolers	370 kW	1483 kW
M372	Steam Ejector Refrigeration	9 kW	35.8 kW

Utilities Required for Operation of Oil Maintenance Unit

Utility	Pilot	Commercial
Fuel Consumption (equivalent)	222 kW	285 kW
Electricity	10 kW	10 kW
Skam at 1034 kPa	544 kg/hr	2041 kg/hr
Cooling Water at 29C	0.79 m ³ /min	2.20 m ³ /min
Instrument Air	0.57 m ³ /min	0.57 m ³ /min

The control of column operation will be accomplished with the following instrumentation. The feed to the column will be controlled with a setpoint flow controller (C-14). The feed is heated in the furnace to a set temperature. This temperature controls the fuel rate to the furnace to keep the temperature constant. The pressure in the flash zone is monitored and used to control the operation of the steam ejectors and hence column pressure.

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Figure H-1. Oil Maintenance Flow Design

If the pressure in the column drops below the set point a valve will open to allow vapors from the third stage discharge to spill back into the first stage suction placing extra load on the ejectors and allowing the column pressure to rise.

The rate of reflux in the Caloria and low boiler sections of the column will be controlled manually to maintain the proper temperature on the draw off of the chimney trays for the products desired.

OIL MAINTENANCE UNIT - EQUIPMENT LIST

V-111	Vacuum Tower
V-181	Steam Separator
E-211	Low Boilers Reflux Cooler
E-212	Caloria Reflux Cooler
E-213	High Boilers Cooler
E-214 A, B, C	1st, 2nd, 3rd Stage Ejector Condensers
H-241	Charge Heater
P-311 A and B	Charge Pumps
P-312 A and B	Low Boilers Pumps
P-313 A and B	Caloria Pumps
P-314 A and B	Heavy Boilers Pumps
P-315 A and B	Sump Pumps
M-371 A, B, C	Steam Jet Ejectors
M-372 A and B	Refrigeration Unit