Solar Controlled Environment Agriculture Project

FINAL REPORT

Volume 1 Project Summary

Published for the
United States - Saudi Arabian Joint Program
for Cooperation in the Field of Solar Energy
SOLERAS

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FOREWORD

THE SOLERAS PROGRAM: A UNIQUE EFFORT IN COOPERATIVE SOLAR ENERGY RESEARCH

In October 1977, Saudi Arabia and the United States signed a Program Agreement for Cooperation in the Field of Solar Energy. The Program, named SOLERAS, is the first of its kind in purpose, funding, organization, and results. It is based on the respective commitments of the United States and Saudi Arabia to advance the development of solar energy as a viable cost-competitive energy alternative, by combining the technical and other unique resources of each country. SOLERAS has made significant progress in demonstrating the effectiveness of solar energy—progress that would have been difficult for either country to achieve on its own.

SOLERAS is sponsored by the government agencies responsible for energy research and development in each country: the Saudi Arabian National Center for Science and Technology (SANCST) and the United States Department of Energy. The Program is under the auspices of the United States-Saudi Arabian Joint Commission on Economic Cooperation, formed in 1974 by the Saudi Arabian Ministry of Finance and National Economy and the United States Department of the Treasury.

Although SOLERAS is only one of more than 30 such projects under the direction of the Joint Commission, it is the only one that is funded by both countries. All other projects are funded completely by Saudi Arabia. This jointly funded program is evidence, therefore, that both countries recognize the mutually beneficial results expected to be generated by the cooperative research projects undertaken by SOLERAS.

The administration of SOLERAS also reflects the philosophy of cooperation underlying this unique Program. Senior officials from SANCST, the Ministry of Finance and National Economy, the U.S. Department of Energy, and the U.S. Department of the Treasury comprise an eight-member Executive Board which governs all aspects of the SOLERAS Program. The Board establishes the goals, objectives, and policies of SOLERAS and oversees the technical and financial management of the projects undertaken to implement those goals and objectives.

A four-member Project Selection Committee, with two members from each government, assists the Executive Board in selecting and evaluating projects. Its members combine their technical expertise and experience in renewable energy technologies and demonstration projects to review proposals, designs, plans, reports, operations, and data for the various projects.

The daily technical and administrative management of the SOLERAS projects is the responsibility of Midwest Research Institute, an independent, not-for-profit research organization, which has been designated as the SOLERAS Operating Agent. MRI utilizes technical and managerial personnel from both countries in fulfilling its responsibility for implementing the decisions of the Executive Board and in managing the individual technical projects. This includes contracting with various companies and research organizations in both countries to design and install state-of-the-art solar systems. SOLERAS program offices are located at MRI's Kansas City, Missouri, headquarters, and in Riyadh and Yanbu, Saudi Arabia.

SOLERAS has initiated several major research projects: converting solar energy into electricity for everyday use by the inhabitants of several rural villages; testing solar energy as a source for space cooling and water treatment; developing agricultural systems using solar energy to control the entire growing environment; undertaking fundamental photovoltaic and solar thermal research; establishing high technology laboratories for advanced solar research at Saudi Arabian universities; and sponsoring basic solar energy research in universities in the United States.

In addition, SOLERAS has contributed to the dissemination of scientific and technical solar information through its sponsorship of technology workshops, short courses, and the publication of technical reports. These have provided an important means of informing the scientific research community about the solar energy technologies developed under SOLERAS and other relevant projects throughout the world.

تقديم

«البرنامج السعودي الأمريكي المشترك» للتعاون في ميدان أبحاث الطاقة الشمسية

وقعت المملكة العربية السعودية والولايات المتحدة الأمريكية في عام ١٩٧٧م اتفاقية برنامج التعاون في ميدان أبحاث الطاقة الشمسية . وكان هذا البرنامج الذي سُمي «سوليراس» الأول من نوعه من حيث الغرض والتمويل والتنظيم والنتائج . وهو معتمد على الالتزام المتبادل بين الولايات المتحدة الأمريكية والمملكة العربية السعودية بالعمل على تنمية الطاقة الشمسية ، بوصفها طاقة بديلة متجددة وذات كلفة منافسة ، عن طريق الجمع للموارد الفنية وغيرها من المصادر الطبيعية لكل من البلدين . ولقد حقق برنامج «سوليراس» تقدماً ملحوظاً ببيان فعالية الطاقة الشمسية ، وهو تقدم قد يكون من الصعب تحقيقه على أي من البلدين منفرداً .

يتم انجاز برنامج «سوليراس» تحت رعاية الهيئات الحكومية المسؤولة عن أبحاث وتنمية الطاقة في كل من البلدين ، أي المركز الوطني السعودي للعلوم والتكنولوجيا ووزارة الطاقة الأمريكية . وتشرف على البرنامج اللجنة الأمريكية السعودية المشتركة للتعاون الاقتصادي المكونة عام ١٩٧٤م من قبل وزارة المالية والاقتصاد الوطني في المملكة العربية السعودية ووزارة المالية في الولايات المتحدة الأمريكية .

بالرغم من أن برنامج «سوليراس» هو واحد من بين ما يزيد عن ٣٠ مشروعاً تديرها اللجنة المشتركة فإنه البرنامج الوحيد الذي يموله البلدان ، في حين أن جميع البرامج الأخرى تمولها المملكة العربية السعودية كلياً . فيبرهن هذا البرنامج ، المشترك التمويل ، على أن كلا البلدين يعترفان بالفوائد المتبادلة المتوقعة تحقيقها من خلال مشاريع البحث التعاوني التي يتداولها برنامج «سوليراس» .

وتعكس إدارة «سوليراس» أيضاً فلسفة التعاون التي يستند عليها هذا البرنامج . فيشكل مسؤولون من المركز الوطني السعودي للعلوم والتكنولوجيا ومن وزارة المالية والاقتصاد الوطني ومن وزارة الطاقة الأمريكية ووزارة المالية الأمريكية مجلساً تنفيذياً يضم ثمانية أعضاء ويدير جميع جوانب برنامج «سوليراس» . فيحدد هذا المجلس أهداف وغايات وسياسة «سوليراس» كما يشرف على الإدارة الفنية والمالية للمشاريع المباشرة لتحقيق هذه الأهداف والغايات .

تقوم لجنة اختيار المشاريع المكونة من أربعة أعضاء ، اثنان من كل جانب بمساعدة المجلس التنفيذي في اختيار وتقييم المشاريع . فيجمع أعضاء هذه اللجنة خبرتهم الفنية وتجربتهم في مجال تكنولوجيا الطاقة المتجددة والمشاريع النموذجية لمراجعة المقترحات والتصاميم والمخططات والتقارير والعمليات والبيانات المتعلقة بالمشاريع المتنوعة .

أما الإدارة الفنية والإدارية اليومية لمشاريع «سوليراس» فهي تحت مسؤولية «مدوست ريسيرتش انستيتوت» (معهد «مدوست» للأبحاث) . وهو معهد أبحاث مستقل ليس ذا صبغة تجارية ، تم تعيينه كوكيل تشغيل لبرنامج «سوليراس» . ويستخدم معهد «مدوست للأبحاث» فنيين وإداريين من كلا البلدين للقيام بمسؤولية تنفيذ قرارات المجلس التنفيذي وإدارة المشاريع الفنية الفردية . ويشمل ذلك التعاقد مع مختلف الشركات ومعاهد الأبحاث في كلا البلدين لتصميم وتركيب أنظمة طاقة شمسية من أحدث تكنولوجيا . وتقع مكاتب برنامج «سوليراس» في المقر الرئيسي لمعهد «مدوست للأبحاث» بمدينة كنساس سيتي بولاية ميزوري وكذلك في الرياض وينبع بالمملكة العربية السعودية .

انبعث من برنامج «سوليراس» العديد من مشاريع الأبحاث الكبرى ، منها تحويل الطاقة الشمسية الى كهرباء للاستعمال اليومي لسكان العديد من القرى الريفية واختبار الطاقة الشمسية كمصدر طاقة للتبريد والتدفئة وتحلية المياه وتطوير أنظمة زراعية باستعمال الطاقة الشمسية للتحكم في كامل بيئة الانماء ، والقيام بأبحاث نظرية حول الخلايا الكهروضوئية والحرارة الشمسية وانشاء مختبرات تكنولوجيا عالية للأبحاث الشمسية المتقدمة في الجامعات السعودية ورعاية أبحاث أساسية في الطاقة الشمسية في جامعات بالولايات المتحدة الأمريكية .

كما أن برنامج «سوليراس» ساهم في نشر المعلومات العلمية والفنية المتعلقة بالطاقة الشمسية من خلال رعايته للندوات العلمية والدورات القصيرة ونشر التقارير الفنية . ولقد كان ذلك وسيلة لنقل معلومات هامة لمجموعة الباحثين العلميين حول تكنولوجيا الطاقة الشمسية المطورة من خلال برنامج «سوليراس» والمشاريع الأخرى المرتبطة به عبر بلدان العالم .

PREFACE

SOLERAS, the United States-Saudi Arabian Joint Program for co-operation in the field of solar energy, is pleased to release this final Phase I report covering the entire Solar Controlled Environment Agriculture Project. While additional efforts were originally planned that are beyond the scope of the studies included in this report, the efforts completed by the project contractor teams represent state-of-the-art system analyses which are outstanding achievements. The contractor teams were headed by:

Battelle Columbus Laboratories,
Saudi Engineering Solar Energy Applications, and
Science Applications Incorporated.

SOLERAS wishes to thank these contractors for their cooperation and for the company commitments to these studies that went beyond the contractual relationships. Also, SOLERAS would like to recognize the technical reviewers, including Dr. James Brownell, Dr. Theodore Bond, Richard DeBlasio, Larry Haugseth, William Kolar, Dr. Hedayat Gari, Dr. Mohammed Mandura, Dr. Ali El-Saif, Dr. Abdu Mashhadi, Dr. Attala Abu-Hassan, and many others. Major contributions to the success of the project were also made by Dr. Joe Froechtenigt, Dr. Ghassan Hamad, Werner Luft, and Mohammed Al-Mubarak in the definition of the project scope and assistance in technical management.

This final report includes nine volumes. Volume 1 describes the project efforts, summarizes each project team's concepts, and notes outstanding technical concerns. Executive Summaries of each contractor's design study are also included in Volume 1. Volumes 2 through 9 provide in-depth discussion of each project team's accomplishments. A detailed table of contents for each volume is included as an appendix to Volume 1 to assist readers in locating specific information. The volumes are:

1. Project Summary
2. Battelle Columbus Laboratories
System Requirements Definition and
System Analysis
3. Battelle Columbus Laboratories
Pilot Plant Preliminary Design and
Phase 2 Definition Study
4. Saudi Engineering Solar Energy Applications
System Design Study
5. Science Applications Incorporated
Executive Summary and System Requirements Definition
6. Science Applications Incorporated
System Analysis
7. Science Applications Incorporated
Field Test Facility Preliminary Design
8. Science Applications Incorporated
Specifications for Engineering Field Test
Facility Preliminary Design
9. Science Applications Incorporated
Phase 2 - Definition Study

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SECTION 1.0

INTRODUCTION

1.1 Background

SOLERAS is the acronym for the United States-Saudi Arabian Joint Program for cooperation in the field of solar energy. The program was started in October 1977 by a Project Agreement signed by the two countries under the auspices of the United States-Saudi Arabian Joint Commission on Economic Cooperation. The objectives of the Agreement are:

- to cooperate in the field of solar energy for the mutual benefit of the two countries, including the development and stimulation of solar industries within the two countries;
- to advance the development of solar energy technology in the two countries; and
- to facilitate the transfer between the two countries of technology developed under the agreement.

One project area of the SOLERAS technical program is called Rural/Agricultural Solar Applications. The objective of this project area is to enhance the quality of rural life in hot, arid climates without negatively affecting the environment, by providing systems using renewable energy sources for domestic, communal, agricultural, and local industrial applications.

The Solar Controlled Environment Agriculture Project is one of several SOLERAS projects. The goal of this project is to integrate controlled environment agriculture greenhouses with solar energy to demonstrate the technical and economic feasibility of commercially viable solar controlled environment agriculture facilities in arid zones.

Other projects conducted by SOLERAS include a 350-kW photovoltaic power station to supply electricity to three villages near Riyadh, Saudi Arabia; four solar cooling engineering field tests to supply air conditioning to buildings in Phoenix, Arizona; a 200-m³/day solar-powered seawater desalination pilot plant in Yanbu, Saudi Arabia; solar air conditioning laboratories at four major Saudi universities; and joint educational solar short courses and technology workshops in the two countries.

Anticipated future demand for food production, coupled with rapidly depleting fossil fuel reserves, points to the need for food production concepts that utilize renewable energy sources. Many regions of the world

have large areas of land available for agricultural use, but the lack of irrigation water is a major constraint. Such conditions exist in most of Saudi Arabia and in portions of the southwestern United States. Even in some areas of the United States where water is available for irrigation, the cost of fossil fuel used for pumping makes the cost of irrigation farming prohibitive. In such regions, controlled environment agriculture is an attractive option. The benefits of controlled environment agriculture include reduced fresh water consumption, protection from harmful external conditions (e.g., insects, sandstorms, cold weather), and higher quality and larger yields of produce. Energy systems for controlled environment agriculture in hot, arid climates must be able to provide power for water desalination, for pumping irrigation water, and for cooling the controlled environment so that it is possible to grow selected fruit and vegetable crops.

Conventionally powered controlled environment agriculture facilities are in operation worldwide. In the United States, commercial controlled environment agriculture facilities in Tucson, Arizona, and Cleveland, Ohio, have been successfully operating for many years. In 1977, there were approximately 92,000 ha of controlled environment agriculture facilities throughout the world powered by electric grid and/or fossil fuel.

As demonstrated at some of the controlled environment agriculture facilities in the Middle East and southwestern United States, the ratio of yield per hectare of controlled environment agriculture to the yield in open field agriculture may range from 4:1 to 21:1, depending on the type of crop grown. Since 1972, controlled environment agriculture pilot plants have been established in Saudi Arabia, Kuwait, Abu Dhabi, Iran, and other arid areas, and high agricultural yields have been achieved. In some of these projects, seawater is used for evaporative cooling and desalinated seawater is used for irrigation.

Much effort has been exerted by the United States in the use of solar energy in support of agriculture; however, the objectives of these efforts have been directed toward one specific aspect of farming, such as crop drying, heating of greenhouses or livestock shelters, or providing solar energy to power irrigation pumps. Although conventionally powered controlled environment agriculture activity is worldwide, no significant effort is being made to replace these facilities with completely integrated, solar-powered controlled environment agriculture systems. It is in this context that SOLERAS undertook the Solar Controlled Environment Agriculture Project.

1.2 Project Description

SOLERAS adopted a two-phased activity to accomplish the goals of the Solar Controlled Environment Agriculture Project.

Phase 1 - System study, incorporating preliminary design and cost analysis.

Phase 2 - Engineering field test, including first the detailed design and construction of a test facility; and second, operation, maintenance, evaluation, and training.

Three contractors completed Phase 1 studies in 1982. In these studies system concepts were developed which utilized solar energy technologies to provide power for water desalination, for pumping irrigation water, and for cooling the controlled environment space so that selected crops could be grown. A baseline commercial-sized facility of 5 ha of growing area was first conceptualized. Then an engineering field test of between 0.4 and 1.0 ha was designed to prove the system concepts of the larger facility.

At the end of Phase 1, contractors also provided a detailed proposal for Phase 2. The project was interrupted at the end of Phase 1, however, because of insufficient funds to complete Phase 2. Additionally, it was felt that the technical issues involved with each of the design concepts would have increased the cost of Phase 2 beyond the actual contractor proposals. These issues are summarized in Section 2.5. Also, it was felt that reducing the scope of the field test significantly below 0.4 ha would introduce some technical questions of scaling.

The three contractors' Phase 1 final reports are assembled in this overall project documentation effort as Volumes 2 through 9. The appendix of Volume 1 provides the table of contents for the contractors' reports to assist the user in locating specific information.

It will be apparent to the reader that the intent of the individual contractors was the construction of an engineering field test in Phase 2. Utilization of the Phase 1 results should not be impaired by this documentation direction, however. The Phase 1 preliminary design and system studies demonstrate the engineering feasibility of a solar-powered controlled environment agriculture facility for a hot, arid climate. Operational confidence and economic competitiveness are research goals which remain unproven but have been furthered by the Phase 1 results.

1.3 Summary

The Phase 1 research system concepts and the research teams were:

Photovoltaic energy subsystem with solar thermal collectors to provide thermal energy for cooling and heating and a shade control roof on the greenhouse

Project Manager - Battelle Columbus Laboratories

Team Members - U. S. Agro Systems
Kellam & Associates

Solar pond for combined wastewater disposal, energy delivery, and energy storage with combined shading and radiation selective reflection material for the greenhouse

Project Manager - Saudi Engineering Solar Energy Applications (SESEA)

Team Members - KTI, Incorporated

Photovoltaic and wind turbine energy subsystems with fluid roof/roof filter concept for greenhouse

Project Manager - Science Applications, Inc. (SAI)

Team Members - Texas A&M Agriculture Experiment Station
Geiger Berger & Associates
University of Texas at Dallas/McCormack Corp.
Robert E. McKee, Inc.

The team project managers were responsible to SOLERAS for overall project coordination and development of the final reports.

While SOLERAS is not continuing financial support of the concept development through the engineering field test stage, the contractor team members are pursuing further research.

SECTION 2.0

PROJECT SUMMARIES

2.1 The Research Problem

In many regions where large areas of land are available for agricultural use, a major constraint is the lack of irrigation water. These conditions exist in most of Saudi Arabia and in portions of the southwestern United States. Even in some areas of the United States where water is available for irrigation, the rising cost of fossil fuel for pumping this water is making the cost of irrigation in farming prohibitive. In such regions, controlled environment agriculture facilities afford an attractive means of increasing food production by controlling adverse environmental conditions with minimum water input.

The areas that countries have under controlled environment cultivation are small compared to the land areas used for conventional agriculture. Only high priced selected crops can be grown economically in conventionally powered, controlled environment facilities. Common greenhouse vegetable crops are tomatoes, cucumbers, squash, lettuce, peppers, cabbage, eggplant, radishes, turnips, and okra.

The advantages of controlled environment agriculture are increased yield, high quality produce, conservation of water and nutrients, flexibility of location, protection from external stresses, reliable continuous production, reduced agricultural pollution, reduced storage and transportation needs, and potential integration with other systems.

Insect pests and disease must be well controlled in greenhouses. Insects such as aphids, leaf miners, spider mites, and white flies are generally controlled with insecticides. Diseases such as tomato mosaic virus, leaf mold, and gray mold are controlled by chemicals, use of disease-resistant varieties, and careful sanitation.

The high yields achievable with controlled environment agriculture, as compared to high yield field growth, are illustrated in Table 2.1. The yields at a controlled environment facility at Khark Island in Iran are compared to a single crop per year, high yield, open field production in the United States.

Table 2.1

COMPARISON OF CONTROLLED ENVIRONMENT AND
OPEN FIELD YIELDS

<u>Crop</u>	<u>Controlled Environment (tons/ha/yr)</u>	<u>Open Field (tons/ha/yr)</u>	<u>Ratio</u>
Cucumber	570	27	21
Tomato	318	67	4.7
Lettuce	168	24	7
Cabbage	172	27	6.4

Source: L. H. de Bivort et al. An assessment of Controlled Environment Agriculture Technology. Final report.
Feb. 1978. NTIS PB 279211.

The water requirements of closed, controlled environment systems for vegetable production have been reported to be about one-third of those for open field production in the same locality, and fertilizer needs to be about two-thirds. The water requirements of a closed, controlled environment system for vegetable production in central Chile for example, are, 5,000 m³/ha/yr (14 m³/ha/day) compared to 10,000 to 15,000 m³/ha/yr of water (27 to 41 m³/ha/day) for open field production. On the other hand, the amount of labor required for greenhouse cultivation is relatively high, ranging from 11 persons per hectare (7 for cultivation, 2 for packing, and 2 for support/maintenance) to 30 persons per hectare, depending on the crop.

The power and water requirements for controlled environment agriculture vary with location. Estimates for greenhouses in the Middle East are:

- 110 to 120 kW/ha of electric power for pumps, fans, and light;
- 47 to 74 m³/ha/day of desalted water for irrigation; and
- 28 m³/ha/day of brackish water for year-round evaporative cooling.

Key factors for plant growth are mean leaf temperature, amount of insolation, carbon dioxide concentration and humidity in the air, and amount of water and nutrients available to the roots.

For greenhouses, one problem is to control the plant leaf temperatures. Leaf temperature is a function of the relative humidity in the greenhouse, air temperature in the greenhouse, amount of insolation, soil surface temperature, and the greenhouse roof temperature. A number of greenhouse designs that reduce the inside temperature by essentially passive means have been proposed for hot climates. However, passive design features alone often are insufficient to maintain an adequately low temperature regime; active cooling is generally required.

Among the potential design features that can be considered are (1) selective reflective coatings applied to the greenhouse roof to reduce insolation on the plants, (2) heat-absorbing water filter in the roof, (3) heat-absorbing fluid of variable absorptance in the roof, (4) cool aquifer water, and (5) variable shading.

General design principles for controlled environment agriculture to minimize capital and operation costs include design of the greenhouse structure for tension loads; no pressurizing of the growing area because this makes carbon dioxide enrichment expensive; use of uncontaminated carbon dioxide for enrichment; year-round operation as a closed cycle system; use of local sand as a growth medium; recycling of any residues; and use of plant transpiration as the primary cooling means, thereby minimizing the need for active cooling.

The use of evaporative cooling to avoid or minimize refrigeration requirements will reduce capital and operational costs. However, such cooling is effective only in hot, dry climates, not in high humidity climates. Furthermore, evaporative cooling uses large amounts of water. Although brackish water can be used, such supplies may be scarce and there might be objection even to the use of brackish water for cooling purposes.

Figure 2.1 shows a schematic design for brackish water evaporation for space cooling and simultaneous fresh water production. The water vapor condenses against the transparent roof, and the condensate is collected. Such a system, however, results in high humidity levels within the greenhouse that might cause problems with certain crops.

The design in Figure 2.2 reduces the amount of sunlight that enters the greenhouse. It uses latent heat stored in rocks to reduce the daytime to nighttime temperature variations. Evaporative cooling of the roof is used for daytime temperature reduction in the greenhouse. The drainage from the water sprayed on the roof is used for fresh water production in a freestanding solar still. The light is distributed uniformly within the greenhouse by means of reflective foil on the walls and ceiling. Convective air flow assists in maintaining low temperature in the greenhouse.

Other design concepts make use of the fact that only 48% of the solar spectrum is usable for photosynthesis, namely the spectrum from 0.39 to 0.72 μm wavelength (see Figure 2.3).

Figure 2.1. Schematic Design of Greenhouse for Hot Climates Using Simple Evaporative Cooling and Solar Still

Figure 2.2. Greenhouse Design with Evaporative Cooling and Rock Bed Cooling for Hot Climates

Figure 2.3. Photosynthetically Active Solar Radiation

Examples of design concepts using spectrum cutoffs are shown in Figures 2.4 and 2.5. Figure 2.4 shows a design using an absorption filter in the transparent roof to reduce the amount of heat entering the greenhouse and to evaporate seawater. Seawater trickling down over the warm surface incorporating the absorption filter is evaporated and condenses against the upper transparent layer. The condensate is collected and used for irrigation. The second design, shown in Figure 2.5, uses an absorbing liquid in the roof to reduce the amount of heat entering the controlled environment. The absorbing liquid could be a 2.5% copper chloride and water mixture. The heat absorbed in the fluid could be stored for nighttime heating of the greenhouse or could be used for fresh water production.

Some examples of conventionally powered, controlled environment horticulture systems are described in Table 2.2.

2.2 Project Approach

The plan for the SOLERAS project was for two phases of activity, a Phase 1 system study and a Phase 2 engineering field test. The rationale was to select the baseline system model on the basis of minimum levelized produce cost for the commercial-sized system. Levelized produce cost means the total cost (capital, operation, and maintenance) of the system over its lifetime divided by the total production output over the same time span.

Figure 2.4. Greenhouse Design for Hot Climates with Asorbing Filter and Solar Still to Reduce Temperature

Figure 2.5. Greenhouse Design for Hot Climates with Double Glazing and Absorbing Fluid

Table 2.2

PERFORMANCE DATA OF SELECTED SYSTEMS

	<u>Puerto Penasco, Mexico</u>	<u>Khark Island, Iran</u>	<u>Sadiyat Island, Abu Dhabi</u>	<u>Tucson, Arizona, USA</u>
System Completion Date	-	1974	1972	-
Greenhouse Area (m ²)	1,700	8,000	20,000	37,000
Vegetable Yield (ton/ha/yr)	-	307	270 ^a	368 ^a
Fresh Water Production (m ³ /ha/day)	53	-	133	-
Maximum Fresh Water Consumption (m ³ /ha/day)	32	57	-	740
Active Evaporative Cooling	Yes	Yes	Yes	-
Diesel Motor Generator	Yes	-	Yes	No
Power (kW)	180	-	866	-
Power Consumption (kW/ha)				
Electric	1,059	-	433	325
Thermal	-	-	-	3,000
Maximum Greenhouse Temperature (°C)	35	-	24	29
Labor (persons/ha)	-	15	-	15

^a Tomatoes

A pilot plant was then to be built to prove the principles and the operational aspects of the baseline commercial-sized system. The construction costs for the pilot plant were to be factored into the baseline system model, along with the performance results of the pilot plant operation. Thus, the initial projected performance and cost data would be verified with information acquired from the pilot plant.

Phase 1 of the project was completed in 1982. Each subcontractor team analyzed different system concepts. System analyses and economic analyses were performed for solar powered, controlled environment systems with growing area of 5.0 ha to establish a baseline system for each concept. The systems were optimized to minimize produce cost and technological risk. Each system was designed for a specific site and application, but the site, application, and technology will have broad applicability to needs in both the United States and Saudi Arabia. It was the intent of the project to encourage innovation without unduly affecting performance and reliability. Crop yield data were gathered and cost projections were made for a number of different crops. A development plan for Phase 2 was generated including detailed cost estimates for the design and construction of an integrated, solar powered, controlled environment agriculture pilot plant using the technology of the baseline system (growing area from 0.8 to 1.0 ha).

The activities of each project team were organized into five tasks. The contractor reports reference these tasks in Volumes 2 through 9.

The contract statement of work for each task was as follows:

Task 1 - Program Management and Control: The contractor shall provide the necessary management direction and control to ensure the effectiveness of the technical effort, implementation of program plans, and timely completion of the subcontract deliverables.

Task 2 - System Requirement Definition: The three main items under this task are:

- collection of climatic data,
- generation of engineering field test system performance specification(s), and
- generation of integrated system design criteria.

All climatic data required for the design shall be compiled by the subcontractor.

The subcontractor shall generate system specifications and design criteria to ensure that the integrated system will meet the design requirements.

The outputs from this task shall be:

- climatic data for the proposed site,
- system performance specification(s), and
- integrated system design criteria.

Task 3 - System Analysis: A system analysis of the proposed concept for an engineering field test of an integrated solar controlled environment agriculture system shall be performed. The size of the growing area shall be determined by the subcontractor to minimize levelized produce cost for a commercially viable facility. The system must meet the specifications generated in Task 2.

The objective of this analysis shall be to identify the major design trade-offs and to arrive at the most cost-effective design consistent with performance and reliability requirements. The analysis shall include all components of the integrated system and their interactions. Since reliability and maintainability are significant design considerations, the subcontractor shall document the reliability and maintainability characteristics of the proposed system. The daily operating period of the system shall be one of the parameters considered in the analysis. Other critical parameters shall be identified and sensitivity studies performed. The economic analyses shall be in constant dollars and shall show levelized produce cost for a 20 yr system life. The analyses shall be performed using the methodology described in Doane et al.¹ All measurement values shall be expressed in the International System of Units (SI) in all Phase 1 documentation.

The output from this task shall be:

- commercial-sized detailed system definition for costing purposes,
- performance analyses of commercial-sized system, and
- recommendation on engineering field test size.

Task 4 - Preliminary Design of Pilot Plant of an Engineering Field Test: The main items under this task are:

- generation of engineering field test performance specification;
- development of functional requirements for components of integrated system;

¹ J. W. Doane, R. P. O'Toole, R. G. Chamberlain, P. B. Bos, and P. D. Maycock. The Cost of Energy from Utility-Owned Solar Electric Systems --A Required Review Methodology for ERDA/EPRI Evaluations. ERDA/JPL-5040-29. Pasadena, California: Jet Propulsion Laboratory. June 1976. NTIS No. N76-28647.

- development of component performance specifications;
- development of integration/interface specification;
- identification of instrumentation requirements;
- performance of simulation tests and analyses to confirm and ensure system performance; and
- conducting preliminary design review.

Based upon the detailed system definition resulting from Task 3, the subcontractor shall prepare a preliminary design for an engineering field test project of a solar controlled environment agriculture system sized in the range of 0.4 to 1.0 ha of growing area.

Specifications for items to be manufactured shall include, as a minimum, interface and performance specifications, top assembly drawings, and fabrication schedules. For those items that are commercially available, performance specifications and test data should already be available. In addition, for purchased components, interface specifications, parts lists, and drawings are required.

The subcontractor shall perform all analyses that may be required to ensure the expected performance of all components of the integrated system. Also, the subcontractor shall accomplish the necessary analysis, simulation, and tests to demonstrate that the proposed integrated system and its associated components are capable of meeting the required system performance specification.

The subcontractor shall subdivide the integrated system into logical elements for analytical consideration and cost analyses.

The design must be in compliance with local codes and ordinances of the selected site.

The outputs from this task shall be a preliminary system design review package including:

- top level drawings,
- drawing list,
- instrumentation and control diagrams,
- support requirements analysis,
- engineering field test performance analysis,
- test plans, and
- acceptance test plan.

Task 5 - Phase 2 Definition Study: The main items under this task are:

- development of detailed plans for Phase 2--the detailed design and construction of an engineering field test;
- definition of all essential subtasks;
- establishment of project coordination requirements;
- establishment of project controls such as performance measurement criteria, phasing, milestones, go/no-go points, and scheduling;
- definition of operation and maintenance plan objectives;
- definition of test plan objectives;
- establishment of cost estimates and schedule for complete system (include long lead time list, as well as discussion of potential impediments to timely accomplishment of the work plan); and
- plans for environmental assessment for the engineering field test (if system is to be constructed in the United States).

The subcontractor shall prepare detailed cost and schedule estimates for the detailed design and the construction and operation of the engineering field test at the proposed site. These estimates shall be for the designs resulting from Task 4. Based on these cost estimates, the leveled costs for produce (e.g., \$/kg of tomatoes) shall again be determined.

The subcontractor shall also perform cost analyses for systems according to the system design resulting from Task 3 and as modified by the analyses of Task 4. These cost analyses shall be for engineering field tests ranging in size from 0.4 to 1.0 ha of growing area. These analyses shall be made for engineering field tests installed in the United States and in Saudi Arabia.

The outputs from this task shall be:

- cost analyses, and
- organization and management plan (includes schedules and milestones, project management controls, and design controls).

The contractor shall provide for the operation and maintenance of the system from the operation date until the end of the contract. Operation and maintenance manuals, as required, shall be supplied 30 days prior to the initiation of formal acceptance testing. The manuals shall include detailed procedures for all system and subsystem operation and maintenance.

The contractor shall provide a training course in the operation and maintenance of the system for operating personnel.

The engineering field test system is to be totally energy self-sufficient and designed to economize on water because of its scarcity in arid areas. The systems shall be designed to dispose the waste from the desalination of brackish or seawater (if this is required). Some means of proper usage or disposal of agricultural waste materials (vines, leaves, etc.) must be provided.

All power required to operate the system shall normally be provided by solar energy. Solar energy is understood to include both direct and indirect solar energy sources. A backup power generation system shall be provided to protect the overall system and crop during emergencies, engineering repair, and maintenance activities.

Since the irrigation pumps may be operated at periodic intervals for 24 h and the growing area may require 12 to 24 h of cooling during high solar conditions, some means of storing energy (thermal, electrical, etc.) shall be provided to maintain operation of the system during periods when insolation is poor.

The systems shall be capable of maintaining temperature, humidity, and carbon dioxide concentration in the growing area at optimum levels for crop growth.

The integrated system shall be designed to operate with minimal operator attention. Automatic controls shall be designed to protect all parts of the system (including crops) from damage due to malfunction or power failure. A central control room for instrumentation for normal operation and monitoring as well as collection of evaluation data, such as irrigation flow rates, electrical usage, temperature, carbon dioxide levels, etc., shall be provided.

In order to evaluate the engineering field test system, data shall be collected for the entire system. Automatic data recording shall be provided in addition to any manually kept log sheets. Data for evaluation shall include but not be limited to:

- derived energy production rates;
- irrigation water parameters (salinity flow rate, storage levels, etc.);
- energy storage parameters;
- ambient conditions--temperature, wind speed and direction, relative humidity, insolation, etc.; and
- comments as to problems, repairs made, reasons for units off line, etc.

The entire engineering field test facility shall be enclosed by a fence to prevent damage by stray animals and to prevent unauthorized persons from wandering into the area. Access roads will be made available for delivery of equipment and for transporting produce from the site.

The design life of the engineering field test system shall be 20 yr. Simplicity of design, high operational reliability, and minimum maintenance are to be emphasized. Design requirements are as follows:

- 5 ha for the commercial-sized greenhouse (0.4 to 1.0 ha for the engineering test facility)
- System design life of 20 years
- Reliable and safe operation
- Environmentally acceptable waste disposal facilities
- Stand-alone solar power/energy system
- Fossil fuel backup for emergency only
- Fuel storage for backup power system (7 days)
- Desalinated brackish water with total dissolved solids less than 500 mg/L
- Irrigation water purity (500 mg/L)
- Irrigation water storage 20 days (minimum)
- Support facilities for personnel, storage of supplies, equipment, and produce

2.3 Concept Descriptions

All three systems developed for the Solar Controlled Environment Agriculture Project are designed for operation in a hot, dry climate and use brackish well water for irrigation and cooling water. The main features of the systems are summarized in Table 2.3 and shown in Figures 2.6, 2.7, and 2.8. A detailed description of each follows.

The Battelle Columbus Laboratories system includes a 5-ha greenhouse which uses brackish well water desalinated by a reverse osmosis unit. The power required to operate the greenhouse, desalination unit, and other support facilities is provided by a photovoltaic subsystem and a thermal collector and energy conversion subsystem.

The greenhouse roof is transparent and has channels for a fluid of variable opacity. This roof design has been developed by Ramada Energy Systems. The fluid provides partial shading of the greenhouse and is under operator control. The heat absorbed by the fluid is rejected via a heat exchanger located in the exhaust air stream from the greenhouse. The greenhouse consists of a 59,076-m² growing area divided into six production areas and one seedling area.

The temperature is controlled through a combination of evaporative cooling and active cooling using 12 absorption chillers. The cooling system maintains the leaf temperature below 25°C for maximum growth. The growing media in the greenhouse production areas are nutrient film and sand.

Table 2.3

SUMMARY OF SYSTEMS

<u>Parameter</u>	<u>Battelle</u>	<u>SESEA</u>	<u>SAI</u>
Site	Saudi Arabia	Saudi Arabia	United States
Greenhouse Design	Transparent roof with channels for fluid of variable opacity	Double-pane extruded acrylic, aluminized mylar shade, and diffuser	Single glazing with air-supported film roof; fluid flowing on inner tinted pane
Growth Medium	Sand and hydroponics	Sand and hydroponics	Sand and hydroponics
Cooling Method	Absorption chiller, evaporative cooling, and shading	Evaporative cooling and shading	Ground water and shading
18 Solar Energy Collectors	Photovoltaic and flat-plate thermal	Solar pond	Photovoltaics
Thermal-to-Electric Energy Conversion	None	Organic Rankine cycle turbine	None
Energy Storage	Electric storage battery	Solar pond and electric storage battery	Electric storage battery
Backup Power	Diesel generator	Diesel generator	Diesel generator
Desalination Process	Reverse osmosis	Reverse osmosis	Reverse osmosis
Feed Water Pre-treatment	Yes	Yes	Yes
Brine Disposal	Evaporation pond	Solar pond	Evaporation pond

Figure 2.6 - Block Diagram for Battelle System

Figure 2.7. Block Diagram for SESEA System

Figure 2.8. Block Diagram for SAI System

The desalination subsystem consists of pretreatment and reverse osmosis units. The water flowing into the pretreatment unit contains approximately 2,200 mg/L total dissolved solids. The reverse osmosis membranes are the cellulose type and the units are designed for 75% water recovery. The fresh water produced by this subsystem will have total dissolved solids of less than 500 mg/L. The capacity of the reverse osmosis unit is 1,530 m³/day. The brackish water is stored in tanks having 2,500-m³ capacity and the freshwater storage has a tank capacity of 7,500 m³. The brine from the reverse osmosis is directed to two asphalt-lined evaporation ponds of 4,800-m² surface area.

The energy subsystem for this design consists of 19,440 m² of flat-plate photovoltaic collectors and 30,000 m² of flat-plate Ramada thermal collectors, and 5,200 kWh of electric battery storage. Two 400-kW diesel generators provide backup power for the system in case of failure or during emergency maintenance. The power system output is 700 kW under normal insolation conditions.

The Saudi Engineering Solar Energy Applications (SESEA) system also includes a 5-ha greenhouse which uses brackish well water desalinated by a reverse osmosis unit. The power necessary to operate the greenhouse, desalination unit, and other support facilities is provided by solar ponds with a total area of 60,000 m².

The greenhouse uses a double-pane extruded acrylic layer, a retractable aluminized mylar shade, and a 1-mm fiberglass diffuser. The greenhouse has a net growing area of 50,000 m² divided into 20 growing sections of 2,500 m² each. The growing media are sand and nutrient film. The greenhouse is cooled by evaporative means. Additional temperature control is achieved by shading the growing areas. Greenhouse heating can be achieved by circulating greenhouse air across the condenser from the organic Rankine cycle turbine.

The desalination subsystem consists of pretreatment and a reverse osmosis unit. The reverse osmosis uses hollow-fiber membranes and has a water recovery of 65%. The fresh water produced by the subsystem will have total dissolved solids of less than 500 mg/L and will be stored. The brine from the reverse osmosis, as well as the waste water from the greenhouse, is directed to evaporating ponds associated with the solar ponds.

The energy subsystem is driven by the two solar ponds. The energy conversion from thermal to electric energy is obtained with an organic Rankine cycle turbine using freon as the heat transfer medium. In addition, the energy subsystem contains electric battery storage, a dc battery regulator, and a diesel generator to provide backup power.

The Science Applications, Incorporated (SAI) system includes a 5-ha greenhouse which utilizes brackish well water desalinated by a reverse osmosis unit. The power necessary to operate the greenhouse, desalination unit, and other support facilities is provided by a photovoltaic subsystem having a peak output of 850 kW.

The greenhouse uses an innovative filter/fluid roof design in which the inner roof glazing selectively passes sunlight in the 400 to 700-nm range but strongly absorbs sunlight in the infrared region. The heat produced by the absorbed infrared radiation is removed by water flowing over the upper layer of the inner glazing. The heated water passes through a heat exchanger utilizing 18°C aquifer water before returning to the roof. The infrared radiation is thus prevented from entering the greenhouse and being absorbed by the plant foliage. Thus, the plant foliage and greenhouse air temperatures are approximately the same, and the plant foliage is closer to its optimum temperature for growth. Since fresh water is scarce in many hot, arid parts of the world, a greenhouse dehumidification system is employed which uses aquifer water for cooling. This system allows both humidity control in the greenhouse and water recovery from the greenhouse air during daylight hours. The greenhouse is designed as essentially a closed system, meaning air exchange with the outdoor environment is near zero. (Open systems have continued air exchange.) Carbon dioxide enrichment (600 to 1,000 mg/L) will be used to increase the productivity of the crops. The 5-ha greenhouse has 4.75 ha of net growing space (sand medium) divided into four sections, and crops will be rotated on an alternate year basis.

The desalination subsystem consists of pretreatment and reverse osmosis units. The water flowing to the pretreatment unit contains approximately 3,500 mg/L total dissolved solids. After pretreatment, the water directed to the reverse osmosis unit will be preheated to a maximum of 40°C to increase membrane flux rates. The membranes are the spiral-wound type and the subsystem is designed for 75% water recovery. The fresh water produced by this system will contain total dissolved solids of less than 500 mg/L and will be stored in a 300-m³ tank. The waste water produced by the reverse osmosis unit will be sent to a holding pond of 100-m² surface area and 2 m deep. The water from the holding pond will then be blended with ground water in such a manner that the water reinjected into the aquifer will be less than 20 mg/L above the total dissolved solids level of the supply well water.

The energy subsystem for this design consists of 344 kW (peak) of photovoltaic modules, 2,700 kWh of battery storage capacity, a 350-kW dc battery regulator, and a 250-kW ac power conditioning unit. Two 200-kW diesel units provide backup power for the facility.

2.4 System Comparison

2.4.1 Performance: System performance is measured by such parameters as produce output, brackish and fresh water consumption, and electric energy consumption. Table 2.4 shows the annual output and consumption for the three systems.

Comparison of the parameters of Table 2.4 shows that the SAI system has a higher output of produce, less water consumption (both brackish and fresh), and lower energy consumption than do either the Battelle or SESEA systems. The design of SAI, for a southwestern U.S. site, is a

closed, passive cooling system that (1) utilizes carbon dioxide enrichment, which has been proven to increase crop production; (2) eliminates the need for evaporation pads for cooling, which consume large amounts of brackish water; (3) uses dehumidification that recovers fresh water by condensation; (4) has lower energy consumption through elimination of the many ventilating fans and circulating pumps needed for active cooling; and (5) has a less stringent requirement on leaf temperature control, allowing less energy and water to be consumed. The produce output by SAI is 1.4 to 1.8 times greater than that for the open systems, mainly because of carbon dioxide enrichment.

Table 2.4

PROJECTED SYSTEM PERFORMANCE

<u>Parameter</u>	<u>Battelle</u>	<u>SESEA</u>	<u>SAI</u>
Produce Output kg/m ² /yr	44.2	55.0	78.6
Brackish Water Consumption m ³ /ha/yr	48,200	76,386	5,940
L/kg produce	109	139	7.6
Fresh Water Consumption m ³ /ha/yr	26,600	14,600	2,460
14,600 L/kg produce	60	27	5.7
Electric Energy Consumption MWh/ha/yr	351	245	87
Wh/kg produce	790	445	111
Leaf Temperature (°C)	25 max.	15-35	35 max.
Labor (persons/ha)	10	5	8

Battelle and SESEA, with a specific site in Saudi Arabia, have open greenhouse designs (continual air exchange with the outdoors) with active cooling systems that use evaporative pads as their main means of cooling. The SESEA system also consumes more brackish water because of evaporation from the solar pond. The open, active cooling system consumes 16 to 18 times more brackish water than does the closed, passive cooling system. The fresh water consumed is also correspondingly lower for the closed, passive cooling system.

The largest single difference between the two types of systems (open versus closed) is that at the specific Saudi Arabian site, the well water temperature is too high (29 to 30°C) to permit humidity control and water recovery with a groundwater condenser as can be done at the specific United States site. Because of the higher well water temperature, an active cooling subsystem is necessary for the Saudi site, which requires much more energy to cool the greenhouse sufficiently to provide leaf temperature control. Although leaf temperature higher than 25°C can be tolerated, a suitable variety selection for each type of crop is required. With appropriate variety selection, occasional temperature extremes of 35°C maximum can be tolerated for short periods of time. The energy savings achieved by the use of cold groundwater ranges from 75 to 86%.

2.4.2 Cost: The primary criterion by which the various controlled environment agriculture systems are judged is the levelized cost of the vegetables produced. The levelized produce cost is the levelized annual system cost in 1981 dollars divided by the annual output measured as weight. The levelized annual system cost consists of the capital investment (including replacement of capital equipment during the 20-yr life of the system) and operation and maintenance costs, including such items as labor, nutrients, water, carbon dioxide, and maintenance and repair. The levelized costs are calculated by the methodology described in Doane et al.¹ The significant factors in the cost model are cost of capital = 8.6%, general inflation = 6%, a 20-yr lifetime, and start of commercial operation in 1986. The specified parameters yield an annualized fixed charge rate of 0.1437 and a capital recovery factor of 0.1064. The significant cost projections for the three systems are shown in Table 2.5.

Table 2.5

COST PROJECTIONS FOR THREE 5-HA SYSTEMS

<u>Parameter</u>	<u>Battelle</u>	<u>SESEA</u>	<u>SAI</u>
Actual Capital Investment (K\$)	64,082	13,890	17,932
20-Yr Operation and Maintenance Costs (K\$)	102,501	19,447	13,952
Levelized Annual Cost Capital (K\$)	9,203	2,016	2,580
Operation and Maintenance (K\$)	8,641	1,496	1,560
Total (K\$)	17,844	3,512	4,140
Levelized Cost of Output (\$/kg)	8.07	1.28	1.14

¹ J. W. Doane et al. The Cost of Energy from Utility-Owned solar Electric Systems.

The costs of the open and closed systems cannot be compared directly because of the large differences not only in the systems but also in the site locations. Comparison of the two open systems (Battelle and SESEA) shows that the actual capital investment for Battelle is about 4.6 times higher than that for SESEA. To aid in analyzing this large difference in capital investment, a breakdown of the capital costs of the major subsystems is made in Table 2.6.

Table 2.6

CAPITAL COST DISTRIBUTION AMONG MAJOR SUBSYSTEMS

<u>Subsystem</u>	<u>Battelle</u>		<u>SESEA</u>		<u>SAI</u>	
	<u>K\$</u>	<u>%</u>	<u>K\$</u>	<u>%</u>	<u>K\$</u>	<u>%</u>
Greenhouse	23,451	37	6,566	77	13,809	77
Energy Generation and Distribution	13,258	21	5,772	8	1,463	8
Cooling	10,179	16	-	-	-	-
Desalination and Water Storage	1,544	2	405	3	1,385	8
Controls	5,325	8	472	4	550	3
Balance of System	10,325	16	725	4	675	5
Total	64,082	100	13,890	100	17,932	100

The table shows that the cost of the greenhouse for the Battelle system is about 3.5 times higher than that for SESEA and that the energy generation and distribution subsystem costs are similarly higher for Battelle. The capital costs for these two systems would have been expected to be approximately equal because they are both for open systems that are designed for the same site in Saudi Arabia. Some of the higher costs for the greenhouse and for the cooling can be attributed to the fact that the Battelle system maintains a maximum leaf temperature of 25°C as compared to a 35°C maximum for the SESEA system. Consequently, the Battelle system requires a chiller in addition to the evaporative cooling.

The higher costs for the energy generation and distribution subsystem may be attributed to the fact that solar ponds provide energy more cost-efficiently than do either photovoltaics or flat-plate thermal collectors. However, these differences alone do not seem to justify the wide cost disparity between the two systems.

It can only be speculated that an additional reason may be undercosting of portions of the SESEA system. Analysis of the costs for replacement items that are included in the capital costs enhances the likelihood of undercosting. The Battelle costs include replacement for items such as desalination membranes, evaporative pads, batteries, and fan drives, whereas SESEA includes only replacement of desalination membranes.

The operation and maintenance costs over the 20-yr life of the systems are also higher by a factor of five for Battelle. These higher recurrent costs are attributed partly to the higher amount for labor estimated for the Battelle system as compared to the SESEA system.

The SAI system eliminates the need for active cooling by using cold aquifer water to cool the water that runs through the greenhouse roof. This is possible because of the location selected in the United States for the SAI system. This fact explains partially the lower costs for the SAI system as compared to the Battelle system.

It appears from the Phase 1 data gathered that the capital costs for solar energy controlled environment agriculture are lower in closed, passive cooling systems than in corresponding open, active cooling systems. Furthermore, system designs that are more complex, for reasons such as maintaining low temperatures, are more costly than simpler systems not having the same temperature control ability. This appears to be true even considering the difference in productivity, that is, comparing per unit produce costs. The site location and the ability to use cold ground water for cooling are also significant factors in system costs.

2.5 Outstanding Issues

During Phase 1, the contractor efforts were continuously reviewed and assessed for technical merit. A number of issues and considerations remained unresolved at the end of Phase 1 which were expected to be addressed during Phase 2. These issues are listed here for completeness and to assist other researchers who may utilize the concepts presented. The issues are not listed in any particular order.

2.5.1 Battelle Columbus Laboratories:

- The relative complexity to conventional systems is a major concern. The numerous subsystems are complicated, interactive, and interdependent, so the environmental control system must also be complex, requiring numerous computers and stored programs. The control system will require highly trained personnel to make it function properly.

- The greenhouse roof panels have several material concerns. Several absorbing roof panel configurations were suggested by Battelle. The decision on the roof panel material configuration will dictate much of the resulting greenhouse environment and operation of other subsystems. It is anticipated that accelerated material testing will be required.

- The growing system which will be used in the greenhouse is a new multi-crop tray-bench hydraulic system. The system appears to have several advantages from both the growing and operations standpoint, but these advantages are only for low growing crops such as lettuce. Growing taller and/or vining crops, such as tomatoes or cucumbers, requires adjustments in the system which have not been demonstrated structurally.

- Dust accumulation on and ingress into the photovoltaic modules, solar thermal collectors, and the greenhouse roof may be a serious problem.

- The water consumption rate for evaporation pads may be a problem if the system will be located in Saudi Arabia, since water is scarce.

2.5.2 Saudi Engineering Solar Energy Applications:

- Nutrient film technique is the proposed growing system. This is a new growing technique, and some technology advancements may be required before commercial acceptance.

- The use of a solar pond for combined waste water disposal, energy delivery, and energy storage is a good concept, but adequacy of current solar pond techniques for withdrawal and injection of different temperature water layers to enable the system to operate as planned without problems and interruptions are serious concerns. The small sizing of the evaporation pond is also an unresolved issue.

- The organic Rankine cycle turbine generator used in conjunction with a solar pond is quite experimental.

- The water consumption rate for the system is very high for arid climates.

- Dust accumulation may be a problem needing additional field data to quantify cleaning requirements before large systems are installed.

2.5.3 Science Applications, Incorporated:

- The possibility of water condensing on the inside of the Tefzel plastic roof panel may be a problem in reducing the transmission of visible light to the crops still a major concern.

- One of the weak points of the SAI system is its dependency on an ample supply of cool ground water. The system design is very site-dependent but might be capable of modification for other sites.

SECTION 3.0

BATTELLE COLUMBUS LABORATORIES EXECUTIVE SUMMARY

3.1 Overview

The solar controlled environment agricultural system designed by Battelle Columbus Laboratories is a facility capable of growing high yields of practically any crop, even temperature-sensitive vegetables such as lettuce. A commercial-sized (5 ha) system and an experimental-sized (0.37 ha) system were developed which contain a great deal of flexibility, an important factor in a stressful climatic environment such as the hot, arid zones of Saudi Arabia and the southwestern United States. The system is designed to conserve water in a cost-effective manner. In order to obtain optimum growing conditions, the system is designed to maintain year-round temperature, humidity, and solar insolation at desired levels. The energy for such control is lower than could be provided by conventional cooling/heating systems. The recirculation and ventilating system provides a great deal of flexibility in controlling temperature and humidity and in reducing water consumption. An efficient, highly productive growing system has been designed that not only increases growing rates but lends itself to being highly automated, thereby reducing significantly the need for skilled labor.

3.2 Description of Concept

The solar controlled environment agriculture system conceived by Battelle includes a greenhouse which uses brackish well water desalinated by a reverse osmosis unit. The power required to operate the greenhouse and desalination unit is provided by a photovoltaic subsystem and thermal collectors and energy conversion subsystem. The basic system used for both the commercial-sized facility and the experimental test facility is illustrated by the schematic in Figure 3.1.

Solar insolation is controlled by the greenhouse roof, which is transparent with channels for fluid of variable opacity. This roof design is a modification of the thermal collectors developed by Ramada Energy Systems. The fluid provides a partial shading of the greenhouse which is under operator control. The heat absorbed by the fluid is rejected by means of a heat exchanger located in the exhaust air stream from the greenhouse. The greenhouse serves as the growing area for the production of lettuce, tomatoes, and cucumbers.

The temperature is controlled through a combination of evaporative cooling and active cooling using an absorption chiller. The cooling

Figure 3.1. SCEAS Schematic

system maintains the leaf temperature at between 25° and 27°C for maximum growth.

The desalination subsystem consists of pretreatment and reverse osmosis units. The water flowing into the pretreatment unit contains approximately 2,200 mg/L total dissolved solids. The reverse osmosis membranes are of the cellulose acetate type, and the units are designed for 75% water recovery. The fresh water produced by this subsystem will have total dissolved solids of less than 500 mg/L. The brackish water and the fresh water are stored in tanks. The brine from the reverse osmosis unit is directed to two evaporation ponds.

The energy subsystem for this design consists of flat-plate photovoltaic collectors and flat-plate Ramada thermal collectors, electric battery storage capacity, and a power conditioning unit. Two diesel generators provide backup power for the system in case of failure or need for emergency maintenance. Batteries charged by the photovoltaic system during the day supply all the electric needs at night and occasionally at peak periods during the day.

The overall water system consists of two basic subsystems: brackish water and fresh process water. The brackish water is used directly for the reverse osmosis system, evaporation pads, service lines in support buildings, etc. The fresh water is used for crop watering, the fogging system, and vegetable rinsing.

Support facilities are included in the agriculture complex to make it self-sufficient. A central controller monitors all critical functions and provides automatic control of the system interactions. The controller also allows the operator to control any system manually. The support building also includes refrigerated crop storage, loading, cleaning, and processing areas; office facilities; a laboratory; a warehouse; and maintenance areas.

Figure 3.2 shows in schematic form the major functional components directly involved in and supporting the growing system. The cluster at the lower left represents the water system, the cluster at the upper left represents the electrical system, and the elements at the lower right represent the thermal system. Table 3.1 lists the subsystems specifications for the commercial-sized and experimental-sized test facility.

A layout of the site, including buildings and other support facilities, is shown in Figure 3.3 for the commercial-sized system and Figure 3.4 for the experimental-sized test facility.

Figure 3.2. Functional Components of Solar Controlled Environment Agriculture System

Table 3.1

SUBSYSTEM SPECIFICATIONS

	<u>Commercial Facility</u>	<u>Experimental Test Facility</u>
Size of system	28 ha	4 ha
Subsystem:		
Greenhouse		
Size	5 ha	0.37 ha
Growing area	59,076 m ²	3,700 m ²
Variable shading/filtering roof panels providing 5-70% incident solar radiation	63,000 m ²	4,500 m ²
Evaporator pads surface	2,000 m ²	178 m ²
Energy		
Flat-plate photovoltaic array	19,440 m ²	4,600 m ²
Battery storage capacity	5,100 kWh	1,000 kWh
Diesel generator (2) backup power	400 kW	60 kW
Power system output (normal insolation)	1,300 kW	230 kW
Cooling		
Ramada thermal collectors	30,000 m ²	3,000 m ²
Absorption chiller (nominal capacity)	1,500 tons (5,250 kJ/s)	120 tons (422 kJ/s)
Recirculation heat exchanger surface	400 m ²	311 m ²
Rejection heat exchanger surface	2,000 m ²	100 m ²
Hot thermal water storage	2,500 m ³	200 m ³
Chilled water storage	2,500 m ³	200 m ³
Desalination (reverse osmosis)		
Capacity per day	1,530 m ³	95 m ³
Brackish water storage	2,500 m ³	700 m ³
Fresh water storage	7,500 m ³	500 m ³
Evaporation Ponds (2) Surface Area	2,400 m ²	730 m ²

Figure 3.3. Commercial-Sized (5-ha) Site Layout

Figure 3.4. Experimental-Sized (0.37-ha) Site Layout

To summarize, the functions of the various subsystems are as follows:

<u>Subsystem</u>	<u>Function</u>
Shade control roof	Control heat loads and light levels
Photovoltaic array	Provide electrical energy
Solar thermal collectors	Provide thermal energy for cooling and heating
Desalination system	Provide water for growing and other people or system needs
Recirculation/ventilation	Control temperature and humidity
Evaporator pads	Provide cooling
Absorption chiller	Provide supplemental cooling
Battery storage	Provide electricity for night and low light situations
Diesel generator	Provide backup electrical power

In general terms, this solar controlled agriculture installation uses solar energy in three ways:

- Directly for vegetable growth,
- Converted into electricity in a photovoltaic array for use throughout the installation, and
- Converted into heat for powering the absorption chiller and for heating needs.

3.3 Findings

3.3.1 Design Criteria: During the preliminary analysis of Task 2, it was determined that there were many unknowns regarding the effects of the singular and combined variables of temperature, humidity, carbon dioxide levels, and light levels on plant growth. Based on the best available data, optimum conditions were estimated for maximum plant growth. The overall system design criteria (Table 3.2) were derived from this information. The design criteria were selected to allow optimum growth conditions for a wide variety of crops.

Table 3.2

DESIGN CRITERIA FOR SOLAR CONTROLLED
ENVIRONMENT AGRICULTURE SYSTEM

<u>Growing Parameter</u>	<u>Lower Design Limit</u>	<u>Upper Design Limit</u>
Daytime Temperature	19°C	25°C
Nighttime Temperature	15°C	25°C
Relative Humidity	50%	85%
Carbon Dioxide	300 ppm	-
Insolation	500 W/m ² (nominal)*	-
Fresh Water	27 m ³ /day	-

* Depends on crop selected and grower requirements; insolation is variable.

Considerable uncertainty exists in the published data on plant growth. The proposed greenhouse will allow controlled research on the effects of these variables to a degree not possible with previous designs. Use of the variable shading roof will also allow experiments on the spectral response of plants, since the shading liquid can be varied to pass different portions of the visible, ultraviolet, and infrared spectrum.

It was planned that several different crops can be simultaneously grown under separate environmental conditions. It is anticipated that tomatoes, cucumbers, and lettuce would be grown during Phase 3, the evaluation period, although many other crops could be grown if desired. This will permit a full evaluation of the controlled environment concept.

3.3.2 Systems Analysis: A detailed analysis and evaluation of both the commercial-sized controlled environment agriculture system and an experimental field test facility coupled with a solar energy system was conducted using an engineering model of the system which included all of the important subsystems and their interactions. Based on the design criteria established in Task 2 (Table 3.2), a number of trade-off studies were conducted in order to determine the most appropriate components, and the best relative sizing of components which meet the performance goals. Trade-off studies were conducted for several shade control roof designs, for the Ramada-type thermal collectors versus the evacuated tube collector, the potential for increasing the size of the photovoltaic system, and of a wet cooling tower versus a dry heat exchanger. Sensitivity analyses were also conducted to verify the selected design parameters and to gain a better understanding of design sensitivities.

The long-term performance of the proposed system and the ability of the system to maintain growing conditions year-round were determined by continuous computer simulation.

The overall system performance for the solar controlled environment agriculture system was evaluated using Battelle's SOLGEM computer code. SOLGEM is a numerical engineering model which solves the mass energy balance equations for the air flowing through a growing environment, assuming quasi-steady-state conditions within the system. The temperature and flow conditions are determined on an hour-by-hour basis using the typical meteorological year weather data suitably modified for the specific site as input. The growing space is divided into a number of isothermal nodes, and the energy balance is computed to determine the temperature rise of the air flowing through the growing space. The model determines the airflow requirements and energy requirements for maintaining the temperature and humidity of the greenhouse within the desired (specific) growing conditions.

The results of the system performance analysis were used as input to the evaluation of the cost-effectiveness of the system, as an aid in sizing the individual components under the given system constraints, and as input to the reliability and maintainability considerations. The development of the preferred system for a specific application and site required considerable interaction between the performance analysis, the cost evaluation, the physical constraints, and the reliability and maintainability analysis.

The proposed crop growing system evolved from a conventional sandbag hydroponic culture system or trough hydroponic culture system to an energy-conserving, state-of-the-art multi-crop tray-bench hydroponic system.

The significant advantages of this crop growing system are as follows:

- Energy efficient
- Automated
- Will hold crop safely during extended power failure periods
- Can grow most crop varieties
- Convertible from small to large plant crop
- Nutrient supply maintains maximum plant growth
- Simple to operate
- Equipment designed to last
- Only growing is done in greenhouse
- Control of plant predators more effective

- All handling, picking, pruning, cleaning, spraying, and seeding of the crop done in the support building
- All work done in comfort and under sanitary conditions
- Worker productivity increased
- Minimum labor input needed
- Unskilled labor used for most operations

The long-term advantages of the tray-bench system lend themselves both to experimental research and full-scale commercial production.

The three crops specified for this greenhouse are tomatoes, lettuce, and cucumbers, although numerous other vegetables, flowers, and tropical plants could also be grown. This system flexibility could have important impact on the overall applications of the technology by providing optimum conditions for crops that might be in demand in the food industry, for protein supplements, or for pharmaceutical uses.

The ability to grow all three crops in the same greenhouse complex throughout the year will allow significant research data to be developed. The beneficial results of such data will be important in determining operating characteristics and will yield information necessary for construction of multi-hectare, full-scale production facilities which can be used for year-round growing of desirable crops in regions where it is currently difficult or impossible during much of the year.

The weather in Yuma, Arizona, is similar to that of Riyadh in that both are characteristic of hot, dry desert climates. Several differences, however, may affect the performance of the proposed growing environment. First, the average dry bulb temperature is approximately 3°C cooler in Yuma than in Riyadh. Thus, all other conditions being equal, the proposed growing system would experience lower average growing temperatures.

The second difference concerns the daily solar radiation, which is as much as 20% greater in Yuma than in Riyadh. As with the average daily temperature, this is also a beneficial difference since the output of the thermal collectors and the photovoltaic array will be greater in Yuma. However, an increase in the shading level will be required to prevent an increase in the thermal load on the ventilating system, due to the high radiation levels. For the Yuma site, the roof shading level will be increased to the point where the radiative intensity on the plant canopy is the same as the radiative intensity for the Riyadh system.

Finally, the relative humidity in Yuma is somewhat higher than in Riyadh during July, August, and September. The higher humidities limit the effectiveness of the evaporative coolers. This will result in higher temperature air entering the growing environment under certain conditions and reduces the cooling capacity of the ventilating system. The reduced cooling capacity can be partially compensated for by increasing the ventilation

rate. The remainder of the cooling requirement can be met by an increase in the recirculation air chilling. These two modifications (shading and ventilation rate) were found to be sufficient to control the growing environment temperatures to within a degree of the system performance predicted using the Riyadh weather data.

Early in the project it was anticipated that a need would exist to generate or supplement the carbon dioxide (CO₂) levels within the greenhouse to maintain levels at or above ambient (300 ppm). As the system analysis progressed, it was determined that there would be only a few times during the year when CO₂ generation would be practical, and at no time would the airflow through the greenhouse be low enough to cause measurable depletion below ambient CO₂ levels.

The concept of a closed greenhouse, where most of the air is recirculated and CO₂ levels are increased to about 1,500 ppm, has many attractions since there is a direct relationship to crop yield when the CO₂ level can be increased. A CO₂ generation system has been specified for the solar controlled environment agriculture system design, but is only regarded as being appropriate in the system for experimental use, as the cost to run the system cannot be equated with enough increase in crop yield to make the system economically viable. It is believed that due to the close control of environmental conditions possible with the Battelle design, experimentation on CO₂ enhancement would be of significant value to the research community. Although the cost could not be justified on the basis of crop yield, the information obtained would be valuable for greenhouses in other areas where CO₂ enhancement would be viable.

Utilizing a 0.37-ha system for commercial production does not appear economically attractive. This is not surprising considering that the cost for this test unit is higher than one which would be built after the demonstration has been completed. Also, as with any system, economy of scale results. For example, the support building for the 0.37-ha site could accommodate more than six times the growing area which is available in the solar controlled environment agriculture system test unit. This is because a certain minimum amount of space is needed for each operation but, for the test unit, will not be utilized at all times of the day.

3.3.3 System Advantages and Features: The production facility is capable of growing high yields of lettuce (one of the more temperature-sensitive crops) on a year-round basis. Flexibility has been designed into the system as a required advantage in the highly stressful climate of Saudi Arabia. The flexibility of the design would enable the product to survive and grow during periods even more stressful than the design days and respond to market fluctuations in supply and demand.

Every attempt has been made to develop a highly cost-effective and water-conserving system. However, the desires to be cost-effective and to conserve water frequently are opposing goals. Therefore, trade-offs are mandatory. The system concept is not the most water-conserving design; this would be an entirely recirculating system, but also a very expensive system in terms of chiller and electric output capacity. Nor is the system

the least expensive; this would be an entirely ventilated design but would also be unable to achieve proper environmental conditions for year-round production of lettuce and other vegetables. The design resulting from trade-off analyses is one that has appropriate chilling capacity to achieve year-round crop growth but ventilates at most other times. In terms of water consumption, the design will use approximately 30% less water than more traditional greenhouse operations. The system includes several features that conserve water and enhance cost-effectiveness:

- A rejection heat exchanger (frequently termed a dry cooling tower) that saves considerable water from evaporation as compared with water evaporation for a conventional wet cooling tower;
- A roof design that filters infrared light and permits variable degrees of shading;
- An adaptable and logical environmental control sequence, allowing the grower to selectively conserve water and/or energy; and
- An efficient, highly productive hydroponic growing system.

SECTION 4.0

SAUDI ENGINEERING SOLAR ENERGY APPLICATIONS EXECUTIVE SUMMARY

4.1 Overview

Saudi Engineering Solar Energy Applications (SESEA), a registered Saudi Arabian company, incorporated a team of international firms who contributed to the preparation of this study. SESEA applied extensive methods of system engineering and economic analysis to select the best of the technologies involved. To arrive at the optimum system configuration, the full range of candidate agriculture, desalination, and electricity generation technologies were evaluated, both separately and in combination, within the limitations set in the subcontract. The selected system uses the solar pond as the prime source of solar energy collection and storage.

Solar energy is one of the most abundant sources of energy available. Despite its abundance, the problems associated with harnessing it have restricted its widespread use. The principal difficulties with solar radiation involve its variability over time, direction, and intensity, as well as finding an adequate method of storage. As a result, considerable effort has been devoted to solar collectors and energy storage facilities, such as flat-plate collectors and fluid or solid heat reservoirs. Even where radiation levels are sufficient for the successful application of such technology, costs have been high and the power delivered has been suitable only for domestic or minor industrial use.

For the proposed controlled environment agriculture system, the solar pond has been selected as the ideal method for both the collection and storage of solar energy in the form of thermal energy. The thermal energy is converted into electrical energy by means of an organic Rankine cycle to power fans, pumps, instrumentation, controls, and lighting. Not only does the solar pond overcome the difficulties mentioned, but it does so simply and economically. A viable solar pond can be established with minimum effort on any impermeable site (even without a liner) given sufficient salt, water, and radiation.

Where electricity is the desired output, the organic Rankine cycle coupled to a generator represents a minor capital investment to the user. This combination was selected for its high efficiency in this application.

The greenhouse uses a double-pane extruded acrylic layer, a retractable mylac shade, and a 1-mm fiberglass diffuser. The greenhouse is cooled by evaporative means. Additional temperature control is achieved by shading the growing areas. The greenhouse is heated by circulating greenhouse air across the condenser from the organic Rankine cycle turbine.

The greenhouse growing medium is a hydroponic system based on the nutrient film technique and sand culture.

Desalination of brackish water is accomplished by a reverse osmosis system.

The system design study of Phase I had the following tasks:

Task 1 - Program Management and Control: In this task, SESEA built a team of management and technical personnel to begin the implementation of the project plans and to ensure on-time completion of this phase of the project.

Task 2 - System Requirement Definition: Efforts under this task produced the following information:

- Climatic data for the proposed site
- System performance specifications
- Integrated system design criteria

Task 3 - System Analysis: The object of this task was to identify the major design trade-offs and to arrive at the most cost-effective design consistent with performance and reliability requirements. This task produced the following information:

- Detailed system definition for costing of a commercial-sized unit;
- Performance analysis of a commercial-sized unit; and
- Recommendation on the size of an engineering field test.

Task 4 - Preliminary Design of Pilot Plant of an Engineering Field Test: Based upon the detailed system definition resulting from Task 3, SESEA prepared a preliminary design for an engineering field test (EFT) of a solar controlled environment agriculture system that would have a growing area in the range of 0.4 to 1.0 ha. Under this task the following information was prepared:

- Preliminary process engineering design of an integrated system
- Process flow diagrams
- Heat and material balance
- Piping and instrumentation diagrams
- Equipment specifications
- Pilot plans

- Preliminary piping designs and studies
- Preliminary civil engineering design and drawings
- Preliminary electrical design and drawings
- Preliminary instrumentation design and control diagram
- Performance analysis
- Test plans

Task 5 - Phase 2 - Definition Study: Based on the preliminary design made in Task 4, SESEA prepared detailed cost and schedule estimates for the detailed design, construction, and operation of an engineering field test at the proposed site. Task 5 produced the following information:

- Detailed plans for design and construction of an EFT
- Definition of all subtasks
- Definition of project coordination requirements
- Definition of project controls such as performance criteria, phasing, milestones, and scheduling
- Definition of operation and maintenance objectives
- Definition of test plan objectives
- Definition of cost estimates and schedule for complete system

Table 4.1 summarizes the results of this study by comparing key data obtained on the commercial-sized and EFT facilities.

Table 4.1

SUBSYSTEM SPECIFICATIONS

	<u>Commercial</u> (5 ha)	<u>EFT</u> (0.4 ha)
Solar Pond Size (m ²)	60,000	8,100
Crop Production (tons/yr) ^a	2,750	250
Well Water Supply (m ³ /day)		
Average	990	143
July	1,720	254
December	418	61
Pond Water Make-up m ³ /day)		
Average	542	107
July	1,063	201
December	211	44
Cooling Pad Evaporation (m ³ /day)		
Average	241	19
July	450	36
December	0	0
Fresh Water Consumption (m ³ /day)	207	26.5
Electrical Energy Requirement, Average (kWh)	200	25
Desalination Energy Requirement (kWh/m ³ of sweet water)	1.5	1.5
Thermal Energy Output, Average (kW _{th})	2,175	350
Electrical Energy Output (kW _e)	200	28.6

^a Depending upon type of crop, yields of 100 to 1,000 tons/ha/yr can be expected.

The results of each task of the project study are summarized in the following subsections. This system schematic diagram is shown in Figure 4.1.

Figure 4.1. System Schematic

4.2 System Requirements Definition

The system requirements definition task involved two major efforts: environmental data assessment, and design requirements definition. Based on the identification of the engineering field test site on the experimental farm of the College of Agriculture of the University of Riyadh, Saudi Arabia, environmental data were collected from the College of Agriculture, University of Riyadh; the Ministry of Agriculture and Water; and the University of Petroleum and Minerals in Dhahran.

The environmental conditions of the selected site were evaluated to assess the suitability of the site within the design parameters (hot, dry climate) and to determine the actual design parameters to be used in order to optimize the design and, at the same time, protect the natural environment.

Since this is a controlled environment agriculture (CEA) greenhouse which uses hydroponic growing techniques with desalted water, many environmental restrictions controlling conventional agricultural development are eliminated. However, the type of design selected for the CEA greenhouse imposes certain conditions on the environment of the selected site. The main concerns for the CEA greenhouse are:

- Availability of sufficient solar radiation in the photosynthetically active radiation (PAR) frequency range;
- Atmospheric temperature versus relative humidity conditions that may be modified to acceptable levels required for best crop conditions within the CEA greenhouse. This condition may require additional cooling or heating of the atmospheric air entering the CEA greenhouse for ventilation purposes; and
- Availability of sufficient water from the aquifer to provide the CEA irrigation and cooling system.

The PAR frequencies are those that are within the range of solar radiation required for the photosynthetic process to take place in the plants grown within the CEA greenhouse. The frequency range is 400 to 700 nm. The percentage of PAR of the available radiation accounts for only about 42% of the total solar energy. The limiting factor for design of a CEA greenhouse is a minimum average PAR radiation of 19 to 25 W/m². This factor has been established as the optimum condition for plant development. More radiation will result not in greater crop production but an increase in the heat load on the greenhouse and should therefore be prevented.

The CEA greenhouse climate should be controlled within the limits of temperature and humidity shown in Table 4.2 to achieve the optimum agricultural production.

Table 4.2

GREENHOUSE ENVIRONMENTAL LIMITSTemperature:

	Dry Bulb °C	
	<u>Range</u>	<u>Extreme</u>
Day	21-25	29
Night	19-16	14

Humidity:

	Percent Relative		
	<u>Minimum</u>	<u>Range</u>	<u>Maximum</u>
24-hour cycle	60	70-80	90

Reviewing the absolute maximum and absolute minimum atmospheric temperatures recorded, it is clear that both heating and cooling of the CEA greenhouse are required to reach the set criteria for optimum CEA climate. The cooling of the atmospheric air used for ventilation of the CEA greenhouse during the hot summer conditions is critical. Since the cooling is based on an evaporative system and the maximum humidity in the CEA greenhouse should be kept below 90%, the combination of maximum atmospheric temperature and relative humidity should be evaluated.

As a design parameter, a wet bulb temperature limit of 24°C was selected. If at any time the atmospheric wet bulb temperature exceeds this limit, it is impossible to cool the air by evaporative cooling to a temperature within the set range of operation.

Water is one of the basic needs for a CEA system. Although the hydroponic techniques selected ensure a minimum of water consumption and the recirculation of all unused water, the crops need a considerable amount of water for production of the vegetables (most vegetables consist of 80 to 90% water by weight) and for leaf cooling through evapotranspiration. In addition to the irrigation water, a certain amount of water is needed for the evaporative cooling in the summer and to increase humidity in the winter heating cycle.

It is of little value to attempt to calculate the exact water consumption at the different growing stages of a crop under the different climatic conditions because there are so many variables. Therefore, certain maximum limits are set for design, against which the water supply may be measured. Table 4.3 gives the estimated consumption of water at maximum design conditions for the planned project site of 1 ha.

Table 4.3

ESTIMATED CONSUMPTION OF WATER
FOR ENGINEERING TEST FACILITY

	<u>Water Consumed (m³/day)</u>
Irrigation	40 ^a
Cooling Pads	90
Pond Make-up	<u>214</u>
Total Raw Water Consumption	344

^a 75% recovery from reverse osmosis.

For a cost-effective solar pond, certain criteria have to be satisfied. The main site criteria for the solar pond are:

- Availability of sufficient solar radiation and a minimum of cloud cover;
- Sufficient area of a suitable geological character (ease of excavation to the desired depth, form of the pond, and absence of heat-dissipating soil structures or ground water);
- Availability of water in sufficient quantities to meet the pond requirements;
- Availability of salt to stock and maintain the pond; and
- Minimum pollution hazard in the event of pond leakage.

The climatic parameters of key importance to the thermal performance of the solar pond are radiation and temperature. Table 4.4 shows the monthly radiation averages calculated from the data collected for the selected locality. Table 4.5 shows calculated average atmospheric temperatures. The average data collected for these climatic parameters are suitable for the assessment since the solar pond due to its large thermal inertia does not react to extreme conditions of short duration. Assessment of the data reveals that radiation levels are high and average temperatures are high, indicating a suitable climatic location for a solar pond. In addition, the design parameter of an average of 2.5 cloudy days is in accordance with the collected data for 50 to 100% sky cloud cover. Furthermore, the cloud cover effect has been considered in the radiation level calculation.

Table 4.4

MONTHLY AVERAGE CLIMATIC DATA FOR RIYADH

<u>Month</u>	<u>J</u>	<u>F</u>	<u>M</u>	<u>A</u>	<u>M</u>	<u>J</u>	<u>J</u>	<u>A</u>	<u>S</u>	<u>O</u>	<u>N</u>	<u>D</u>
<u>Atmospheric Temperature °C</u>												
Maximum Daily Average	19.9	24.1	28.2	33.3	38.5	41.6	42.4	42.4	39.9	34.4	27.7	21.3
Minimum Daily Average	7.8	10.2	14.3	19.2	23.9	25.7	26.7	26.4	23.7	18.6	13.5	9.1
Daily Mean	13.5	16.9	21.1	26.3	31.5	34.1	35.0	34.8	32.1	26.5	20.4	14.9
<u>Relative Humidity %</u>												
67 Maximum Daily Average	72	61	56	48	36	22	22	22	25	35	52	70
Minimum Daily Average	29	22	20	16	12	8	8	8	9	12	20	30
Daily Mean	29	39	36	30	22	14	14	14	16	22	35	49
<u>Wind Speed km/hr</u>												
Maximum Daily Average	15	16	18	18	18	19	20	17	14	13	13	14
Daily Mean	7	7	8	8	7	8	9	7	6	5	5	6

Table 4.5

AVERAGE DAILY RADIATION IN
W/m²

<u>Year</u>	<u>Jan</u>	<u>Feb</u>	<u>Mar</u>	<u>Apr</u>	<u>May</u>	<u>June</u>	<u>July</u>	<u>Aug</u>	<u>Sept</u>	<u>Oct</u>	<u>Nov</u>	<u>Dec</u>	<u>Source</u>
1978	174	208	271	260	346	334	323	328	307	261	249	191	MAW
1976	145	178	192	242	262	287	279	282	247	208	190	194	MAW
1975	146	175	216	186	223	238	251	234	206	223	171	105	MAW
1974	128	158	155	235	231	235	248	243	246	206	181	117	MAW
1973	181	197	226	223	233	263	247	222	215	213	194	N/A	MAW
MFAN	162	199	227	238	264	287	285	272	257	226	184	161	UPM
P.A.R.	68	83	95	100	111	121	120	114	108	95	77	67	

MAW: Ministry of Agriculture and Water - data measured at 24°34' N.LAT, 46°43' E.LONG.

UPM: University of Petroleum and Minerals - average calculated from daily values recorded 1965 - 1978.

The crop production targets shown in Table 4.6 are well within the range of amounts produced by CEA greenhouses with nutrient film technique and sand culture systems.

Table 4.6

CROP PRODUCTION TARGETS OF
ENGINEERING FIELD TEST

<u>Crop</u>	<u>Production Target</u> <u>(kg/ha/day)</u>	<u>Proven Performance</u> <u>of Growing System</u> <u>(kg/ha/day)</u>
Cucumber	1,900 ^a	2,800
Eggplant	1,300	1,300
Lettuce	1,500	1,500
Okra	300 ^a	400
Tomato	900 ^a	1,200

^a Yields for varieties suitable for Saudi Arabian markets are lower than yields suitable for North American markets.

The crop costs for the engineering field test are based on crop costs of CEA greenhouses in similar geographic areas. The crop costs, calculated on the basis of the annualized system resultant cost formula for 1983 and expressed in 1980 prices, are shown in Table 4.7. This calculation was selected in order to measure the realistic viability of the project compared to that of non-solar-operated CEA systems.

Table 4.7

CROP COSTS FOR ENGINEERING
FIELD TEST

<u>Crop</u>	<u>Cost</u> <u>(U.S.\$/kg)</u>
Cucumber	0.78
Eggplant	1.23
Lettuce	1.05
Okra	4.91
Tomato	1.71

Because the performance of the CEA greenhouse is one of the most critical functions in the field test, it needs to be carefully evaluated. The basic function of the CEA greenhouse is to provide a constant, ideal growing environment for the crops being produced. Such an environment is created when its growing area is enclosed and when the major factors of the environment such as light, temperature, humidity, and wind, are controlled. Table 4.8 gives the environmental performance specifications for the CEA greenhouse.

Table 4.8

CEA PERFORMANCE SPECIFICATIONS

		<u>Day</u>	<u>Night</u>
Dry Bulb Temperature (°C)	- Maximum	29	25
	Mean	23	17
	Minimum	16	14
Relative Humidity (%)	- Maximum	85	
	Mean	75	
	- Minimum	60	
Air Velocity (m/sec)	- Maximum	1.0	
	Mean	.3	
	- Minimum	0 (Night)	
Radiation Level (PAR) (W/m ²)	- Maximum	73	
	Mean	22	
	- Minimum	0 (Night)	

The desalination subsystem, consisting of a reverse osmosis unit, supplies the water requirements of the CEA greenhouse. Water from the subsystem also partially feeds the solar pond to replace evaporated water. The feedwater is drawn from a well to be drilled on the selected site. The performance specifications for the product water are given in the following tabulation:

Purity of Product Water	< 500 ppm total dissolved solids
Amount of Product Water Produced Per Day	40 m ² per day
Amount of Reject Flow Produced Per Day	13.7 m ³

The solar energy subsystem consists of two major parts: energy collection (solar pond) and energy transformation (organic Rankine cycle). Incorporated in this subsystem is also the required energy storage to fully operate the field test system.

Solar ponds are bodies of salt concentration, i.e., stratified brine. The salt concentration increases with depth, rendering the fluid anticonvective against thermally induced convection. Although there is a net upward flux of salt induced by the salt concentration gradient, techniques have been established to concentrate the bottom by the addition of salt and to dilute the top by the addition of fresh water to nullify the flux.

Having become anticonvective, the pond becomes a heat trap. In this situation, the pond quickly rises in temperature, which induces heat losses. The incident radiation less surface-reflected losses penetrates the pond and is absorbed at various depths. Heat losses to the surroundings begin when a temperature differential appears.

Losses through the gradient non convective zone coupled with surface effects, like wind, induce a surface upper convective zone through which heat escapes to the atmosphere. Where increased thermal storage is desired, a homogeneous lower convective zone is induced below the nonconvective zone. As radiation attenuation causes a temperature increase, heat is lost from the pond by conduction through the nonconvective zone and to the side and bottom.

Solar ponds behave principally as first order systems. Their time constants are strongly dependent on depth due to the amount of radiation absorption versus depth and decreased mass. The forcing radiation function resembles a sine wave.

The specifications governing the solar pond must ensure that the pond meets the anticipated power requirements. The following data are used as basis for specifications.

- Power Delivery: The solar pond should provide an estimated maximum continuous power in December and January of 1,342 kW thermal and a minimum during the summer of 767 kW thermal.

Pond Efficiency: The overall annual efficiency delivered energy/incident radiation energy should be equal to or greater than 10%.

- Energy Storage: The pond should provide the required power at all times considering 50 to 100% cloud cover during 2.5 days (typical for Riyadh).
- Operating Temperatures: The pond should deliver to the organic Rankine cycle sufficient flow of brine at the following temperatures:

Summer	- 85°C
Fall	- 80°C
Winter	- 65°C
Spring	- 70°C

The organic Rankine cycle (ORC) and generator package convert heat energy to electrical energy through a closed heat transfer loop. The electrical energy generated by the ORC-generator package is supplied to the central control panel from where it is distributed to ventilators, pumps, instruments, controls, and the battery storage.

The total electrical power requirement has been calculated and is used to set the ORC-generator specifications, which varies seasonally as follows:

Summer	-	40.5	kW
Fall	-	36	kW
Winter	-	28	kW
Spring	-	36	kW

The well water pumped to the surface for use in the system performs a number of critical functions in the following sequence:

- Provides cooling for the CEA greenhouse
- Supplies the reverse osmosis system, with resultant production of water for irrigation and humidification, plus partial solar pond make-up
- Provides make-up water for the solar pond

The performance of the system should be carefully matched with the interdependent functions and the required storage capacity of the system. The performance specifications with regard to water storage and flow are as follows:

- Raw water storage: 7 days' supply.
- Raw water flow: Maximum 130 m³/day plus solar pond evaporation loss.
- Cooling water flow: 90 m³/day maximum consumption.
- Irrigation water flow: 40 m³/day maximum consumption.

The design criteria may be identified as the general criteria for the system design and the specific criteria for each subsystem. Design criteria controlling all systems are as follows:

- The environmental data for the site.
- 20-year service life.
- Maximum automation to reduce human labor (target: for operation of field test, eight employees).

- Simplicity of design (target: maximum repair time for any failure, 3 days).
- Represent accurate system performance to allow evaluation on a full commercial scale of 4 to 5 ha.
- Material and equipment selection based on proven performance and availability within 6 mo from the date of contract in order to meet contract schedule.

A summary of the design criteria for the CEA greenhouse is as follows:

- Provide sufficient insulation, heating, and cooling to maintain the specified environment.
- Provide shading for photosynthetically active radiation to reach specified levels at all times.
- Maintain leaf temperatures between 15° and 35°C.
- Provide suitable support for crop system.
- Provide a total growing area of 9,000 m².
- Provide a seedling area and test area of 1,000 m².
- Provide clear overhead height of 2m.
- Have 20-day water storage incorporated in main foundation design.

4.3 System Analysis

Task 3 involved the use of detailed performance and cost analyses to identify the optimum controlled environment agriculture project design. The task started with a 5-ha design and culminated in the recommendation of a 0.4-ha experimental size unit.

The first step was to define the criteria for system evaluation. The prime evaluation criteria involve system cost--both initial and recurring life-cycle cost. The factors of reliability and maintainability, which, in turn, affect the system availability, were incorporated into the life-cycle cost analysis in the form of recurring costs and in determining the quantity of product over which the plant capital is amortized.

Most of the effort in Task 3 was devoted to the system analysis, which involved the detailed configuration of several different solar, desalting, and growing culture concepts. Included was the application of performance and economic models to evaluate both the technical and economic merit of each configuration. Key analyses included sizing the collection

area in the solar technology and establishing the operating temperature of the organic Rankine cycle and the greenhouse and the specific control modes to be utilized in the various anticipated operating scenarios. The growing area of the greenhouse was analyzed as a function of heating, cooling, and ventilation load to determine the optimum size of the CEA greenhouse.

In optimizing the desalination plant, for a given water quality, the recovery rate was one of the key parameters to be examined. Recovery rate influences the power requirements of the solar power subsystem since the power requirement of the reverse osmosis unit directly affects this rate. Configurations involving a range of recovery rates were therefore simulated and evaluated to identify the optimum unit.

SESEA's approach to the system analysis was to use the performance requirements generated in Task 2 as guidelines. A parametric analysis of each subsystem was performed which led to cost and performance estimates and to component configuration selection. This yielded a commercial assessment, which was then fed back to both the parametric analysis and cost and performance estimates to yield an optimum system selection.

As a result of the system evaluation, selection of components, trade-offs, and optimization, the following subsystems were selected.

A CEA subsystem applying nutrient film techniques along with sand culture was selected, as it satisfies all conditions for a reliable commercial enterprise. The greenhouse will have an acrylic covering and an acrolon dropped ceiling to provide proper radiation characteristics, while optimizing on heating and cooling requirements.

Reverse osmosis was chosen over all competitors to be the desalination technique. The selection of hollow fine fiber over the spiral-wound technique received thorough attention.

The solar pond size for the CEA system was defined and data are provided on the composition and gradient control as well as construction details.

The electrical subsystem has been simplified with the utilization of battery storage for short-term load fluctuations and backup by diesel generator.

The control and instrumentation subsystem was analyzed to yield a recommendation of a HP-85 desktop computer. With the required data base and number of sensors, this unit is adequate for both data acquisition and control and is both reliable and inexpensive.

SESEA developed a computer model based on the EPRI* technique to define a parameter labeled leveled farm crop cost. The cost estimates for the 5-ha system exclude transportation and distribution.

* Doane, J. W. et al. The Cost of Energy from Utility-Owned Solar Electric Systems--A Required Revenue Methodology for ERDA/EPRI Evaluations. ERDA/JPL-1012-76-3. Pasadena, CA: Jet Propulsion Laboratory; June 1976. Available from NTIS.

For these figures the levelized farm crop cost technique yielded costs per kilogram produced based on the predicted annual crops. These economic projections are encouraging and confirm the assumption that the optimization of all operating parameters during the experimental test will yield a solid economic enterprise. This justifies the SESEA position that this technical approach is ready for immediate commercialization.

An iterative approach was used in conjunction with detailed performance and cost models to analyze and optimize the CEA system. This approach involved identifying system level trade-offs for a finite number of alternative system configurations which were optimized over a range of operating conditions. The product of this optimization was a thorough analysis of the capital and life-cycle costs of each configuration which allowed the selection of the most cost-effective solar, desalination, and agricultural units.

In the optimization of the total system, the solar power, feed-water pretreatment, desalination, waste evaporation ponding, and greenhouse were characterized in terms of capital cost over a range of capacities. This can be translated into capital costs as a function of the crop yield. These various components were then integrated in an optimization algorithm to identify the total system configuration. This provided minimum life-cycle costs for the produce.

After one specific configuration had been optimized, the process was repeated for alternative configurations until all configurations were optimized. The product of this task was the identification of the CEA system which provided the lowest life-cycle cost per unit of produce delivered.

A full range of agriculture, desalination, and solar energy performance and cost parameters were evaluated to select the most reliable and cost-effective approach. The commercial system finally selected is comprised of the following six units:

Unit 100	Controlled Environment Agriculture Subsystem
Unit 200	Overall Water Flow Subsystem
Unit 300	Organic Rankine Cycle Subsystem
Unit 400	Solar Pond
Unit 500	Electrical Subsystem
Unit 600	Instrumentation Subsystem

4.4 Preliminary Design of an Engineering Field Test

Task 4 of the Solar Controlled Environment Agricultural System design consisted of a preliminary design of an engineering field test (EFT) located at Derab in Saudi Arabia.

The main purpose of the EFT is to verify the predicted performance of the commercial unit as analyzed in Task 3 and to provide real experimental data for scale-up and design of a future 5 ha commercial unit.

Fully computerized data logging, together with the extensive instrumentation, provide all the data required for practical system and subsystem performance verification.

The size of the system described is 0.4 ha. A further size reduction of approximately 10% is possible for all the subsystems without losing the possibility of scale-up. This is especially true for the Freon expander, which at present is at the lower limits of its performance potential.

4.4.1 Preliminary Design of CEA Subsystem, Unit 100: The CEA greenhouse provides the controlled conditions required for the optimum production of crop throughout the year.

The CEA greenhouse consists of a structural steel frame, the roof and side walls of which are covered with double acrylic sheets. The sheets are 16 mm thick, provide excellent thermal insulation ($U = 2.9 \text{ W/m}^2/\text{°C}$), and were selected for their low transmission of light with frequencies above 1,100 nm. A special treatment eliminates light with frequencies below 400 nm.

A suspended ceiling of flat fiberglass, 40-mil thick provides for additional filtration and diffusion of the light while creating a duct in the top part of the greenhouse for return of the ventilation air.

In the center of the greenhouse is a service corridor. The corridor forms an airlock to reduce the loss of cool air when entering the greenhouse. On the opposite ends of the shelter an air filter-louver-cooling pad combination allows control of the air temperature and humidity. The ventilation air is passed over this combined package by exhaust fans that remove air from the house at a maximum rate of about 0.5 m/s.

Exhaust fans are installed in the ceiling of the greenhouse 4 m apart. The air exhausted by the fans from the house is passed through the ceiling duct, providing additional cooling, and is exhausted at the end of the greenhouse.

The mixture of return air and outside air is lower in temperature due to the evaporative cooling effect of water passing over the cooling pads. A bypass louver allows further control of humidity and temperature.

When the outside temperature is cooler than the temperatures set for the CEA greenhouse climate, the ventilating air is heated with the reject heat from the organic Rankine cycle and recycled in the greenhouse in order to keep the temperature at the required level.

The foundation of the CEA greenhouse incorporates also the raw and sweet water storage. This large volume of water assists in stabilizing the temperatures in the shelter.

On the outside of the roof an electrically driven shading system is provided. This system reduces the radiation in the greenhouse by 50%

and, as such, reduces the cooling requirement of the greenhouse. The drive motors for the system are of the tubular geared type and are suitable for outdoor installation.

The EFT greenhouse is also equipped with exhaust louvers to allow the condenser cooling air to be exhausted directly to the outside without passing through the duct.

The growing area size is 4,000 m². The size selection considered the ability to obtain accurate growing results for scaling up of the engineering field test to a 5-ha commercial facility and the available area for the EFT.

The requirement to produce different crops and to include both nutrient film technique (NFT) and sand culture called for a further subdivision of the CEA area into the following growing sections:

2,000 m² NFT Crop 1, Tomatoes, Cucumbers

1,000 m² NFT Crop 2, Lettuce, Strawberries

500 m² Sand Culture, Multiple Crops

500 M² Seeding Area

A larger area is assigned to NFT culture because it promises to be the better system for future CEA development and the data will be better suited for scale-up. The sand culture area will allow comparative measurement against other systems of field crop production in Saudi Arabia.

4.4.2 Preliminary Design of Water Subsystem, Unit 200: The storage of raw water is based on the requirement that there be a 7-day supply of water to satisfy the evaporative loss from the cooling pads. This gives an approximate capacity of 250 m³, which is divided into two equal sections running the full length of the greenhouse in the form of a concrete trench 80 m long x 2.5 m wide, and 1.15 m deep. In the middle section of this trench, support footings for the cooling pads are provided. From this storage, the reverse osmosis system and the make-up water to the solar pond are fed. The raw water is treated periodically with sodium hypochlorite in order to control algae growth.

Raw water flows first through a 5 µm cartridge filter, then through the first stage and second stage permeators of the reverse osmosis unit. Reject, high salinity water (average 8.9 m³/day) from the osmosis unit, is flow controlled and sent to the solar ponds for partial make-up. Sweet, low salinity water (average 16.6 m³/day) is sent to the sweet water storage. The conductivity and pH of the raw water are continuously analyzed, and the pH analyzer automatically controls the dosing of sulfuric acid.

The storage of sweet water is based on the requirement that there will be 20 days' supply based on the normal consumption rate. This gives a

storage capacity of approximately 350 m³ which is provided in the central section of the greenhouse, under the central service corridor in two sections of concrete trench.

4.4.3 Preliminary Design of Organic Rankine Cycle Subsystem

Unit 300: The essential function of the organic Rankine cycle is to convert the energy accumulated in the solar pond into the energy needed for the CEA subsystem. This is achieved by applying the heat pump principle whereby an organic fluid (in this case Freon 114) is pumped and heated in the liquid state to the vaporization temperature, vaporized at constant pressure and temperature, expanded isentropically to condenser pressure, and condensed at essentially constant pressure. About 87% of the theoretical enthalpy drop in isentropic expansion is recovered as work in the expander. Coupled with mechanical losses in the expander, gear reducer, and generator, the net overall efficiency is about 75 to 85% of the theoretical enthalpy drop.

Freon 114 from the Freon storage vessel, at a temperature of 84°C and pressure of 2.96 kg/cm², is pumped to the Freon vaporizer, operating at a pressure of 20.3 kg/cm², this being the saturation pressure of Freon 114 at 84°C. This temperature and pressure correspond to the highest values that can be achieved by using brine from the solar pond as a heating medium estimated to have a maximum summer temperature of 89°C. Allowing 5°C approach for design, 84°C was taken to be the maximum vaporization temperature. The corresponding brine and Freon vaporization temperatures for winter are 68°C and 63°C, respectively.

Saturated Freon vapors at a pressure of 10.1 kg/cm² and 84°C enter the expander and are exhausted as superheated vapors at a pressure of 3 kg/cm² and 53°C. Pressure and temperature of the exhaust Freon is continuously monitored. The expansion of the Freon drives the rotar at a speed of 23,000 rpm, which is then reduced in a gearbox to 3,600 rpm for the ac generator. The selected expander from Rotoflow Corporation is a nominal 100 kW ocean thermal energy conversion single stage turbine coupled to a gearbox and an ac generator with a generator output of 28.6 kW. The expander, gearbox, and generator unit are mounted on a 2 m x 1.2 m skid.

Superheated vapors from the expander exhaust flow to finned tubes of Freon condenser located in the CEA subsystem. The condenser tubes are designed integrally with the cooling fans of the CEA subsystem and consist of forty 1-in. tubes of 2,200 mm length and 1,270 mm total bundle width. There are 40 condenser bundles each designed for a duty of 6,710 kcal/h. The fan and the tube bundle are located in a horizontal position with a slope to the tubes for gravity drainage into the liquid header. For ease of piping arrangement, 2 x 6 in. carbon steel headers are provided for vapor flow, one on either side of the central corridor. Each vapor header is provided with a vertically located vent drum to purge out noncondensable vapors. Likewise, 2 x 3 in. liquid headers carry the condensed Freon back to the Freon storage vessel. A gradient is given to the liquid pipe for natural drainage to the storage vessel. Additionally, the liquid pipe is kept at condensation temperature by providing the 3-in. pipe with a 4-in. concentric pipe jacket, through the annulus of which the solar pond make-up water flows. Each condenser bundle can be blocked off from vapor and liquid sides.

4.4.4 Preliminary Design of Solar Pond Subsystem, Unit 400: The purpose of a solar pond is to collect and store thermal energy from solar radiation. This is achieved by a salt-concentration gradient increasing from low salinity near the pond surface to high salinity at approximately 1.5 m below the surface. As a result of this gradient, the deeper water has a greater density than the water above it. Thermal buoyancy convection is thereby suppressed, impeding upward movement of warmed water, which is the principal mechanism of heat loss in an ordinary pond. The SESEA solar pond has three layers, described as follows from top to bottom:

- A thin layer of low salinity water (0.2 to 2.0%), the upper convective zone, depth 0.25 m.
- A layer of water with in-depth increasing salinity (2 to 23%), the nonconvective zone, depth 1.25 m.
- A storage layer of water of uniformly high salinity (23%), the lower convective zone, depth usually 1.5 to 2 m.

In the lower convective zone, the thermal energy is stored in the form of high temperature brine. Operating static solar ponds have shown temperatures in the lower convective zone as high as the boiling point of saline water. The solar pond envisaged will feed hot brine (68 to 89°C) from the lower convective zone to the organic Rankine cycle (Unit 300), which will power the electric generator. The thermal capacity of the lower convective zone is sufficiently large to overcome seasonal changes. If because of mechanical failure or extreme weather conditions a shortage of electricity should occur, the required extra power would be automatically taken from the grid. To make up for evaporation of water from the solar pond (approximately 3.05 m³/m²/yr), raw, low salinity (0.2%) make-up water will be supplied. An amount of salt is added with this water to the pond.

Based on the results obtained from the University of Petroleum and Minerals Research Institute simulations, a surface area of 8,100 m has been incorporated. This figure slightly exceeds the simulation results, because a safety factor must be included for the following reasons:

- Variations in annual radiation values
- Optimistic soil thermal properties assumed in the modeling
- Modeling inaccuracy
- Variations in the ORC thermal load

The solar pond system consists of two adjacent symmetric ponds each 45 x 90 m. The ponds are divided equally to allow for duplication of experiments and as a safety measure in case of leakage. Each pond's freeboard is 4 m. The solar ponds are located due north of the CEA facility. The evaporation pond system consists of two evaporation pans 40 x 20 m in size and a brine concentration pond 40 x 50 m in size. The evaporation pond is located north of the solar ponds. The freeboard of the evaporation pans and the brine concentration pond are 0.5 m and 2.0 m, respectively.

The solar ponds are separated by a concrete wall on which a 1-m-wide walkway is provided to facilitate pond maintenance. All edges of the ponds are constructed for ease of maintenance. An asphalt road runs around the entire subsystem.

4.4.5 Preliminary Design of Electrical Subsystem, Unit 500: The layout of the electrical subsystem is based upon the requirements of the other subsystems. The basis for the electrical design and installation of the solar controlled environmental agriculture system is in accordance with the U.S. electrical and engineering standards and with SESEA electrical requirements. In case of conflict the more stringent regulations apply. These standards are applied fully to all parts of the electrical design, including packaged units which form part of the plant.

The electrical energy must be supplied continuously without interruption. In general, the organic Rankine cycle expander-generator system supplies the electrical energy. In emergency cases, however, battery power supplies the energy required for critical functions for up to 5 kW for 5 h. If after 4.5 h the organic Rankine cycle expander is not in operation, the local grid provides the required electrical energy to ensure continued operation.

To equalize the peak power consumption, a battery system is provided. It is connected to the grid via a rectifier (380/220V 60 Hz to 110V dc) and a converter (100V input and 380/220V 60 Hz output). The 110V dc battery is sufficient for 412 Ah or a capacity of 102 A during 5 h energy demand.

The system is designed so that at maximum power demand the batteries supply electricity at 5 kW maximum power for 5 h, i.e., the power demand of three electric motors consuming 1.7 kW each. The changeover from generator supply to battery supply has a built-in time delay of 100 ms. No synchronization is required and there is no risk of damage to the dc/ac converter. This converter is designed so that motors are to be started one at a time. It is therefore important that a proper start sequence is ensured. During the night, when energy demand is low, the batteries are recharged.

The battery set consists of 64 cells, type tublar plate traction batteries and have the following specifications:

- Nominal voltage - 120V dc
- Nominal capacity - 490 Ah for 5 h.
- Maximum load - 5 h, 98 amps, to 105V lowest voltage limit.
- Efficiencies - batteries 90%
- converter 78%
- rectifier 88%

By a charging time of maximum 19 h from 50 to 98% of the battery capacity, and a discharge time of 5 h (98 to 30%), these batteries have a lifetime of 3 to 4 yr. The maximum operating temperature is 25°C (conditioned room is required).

For emergency supply of electricity to instruments, control valves, and data logging system, a battery unit is provided with a power of 2 kVA for 5 h. In the event of grid supply failure, battery power is made available for as long as it lasts or until the resumption of grid supply.

4.4.6 Preliminary Design of Instrumentation Subsystem, Unit 600: Instrumentation is required to enable safe, reliable, consistent, and economic operation of the various systems required for the operation of the greenhouse. Additional equipment is required for optimization, evaluation, and fault finding within the systems.

The main control is effected from a control room which houses all controlling, data logging, shutdown and alarm, indication, and computing equipment. Transmission to the remote mounted transmitters and actuating devices is electronic. All instrument power for actuators is electrical.

The master control subsystem integrates microprocessor-based analog control systems in each major subsystem of the CEA facility. The objective of the master control subsystem integration and design work is the automatic production and distribution of electricity and product water in a safe and economic manner. The subsystem integrates control of all subsystems and provides full operator control and override of automatic functions from a central location. Existing control technology is incorporated wherever possible and implemented using graphic consoles, human engineered for rapid operator response and understanding. Design conventions, including standard color codes, rationalized control locations, operational procedures, and modifications of different manufacturers' control templates is used to ensure consistency of operating patterns and appearance.

In general, the design approach is to integrate microprocessor-based analog control systems in each major subsystem with the main power plant computer. Microprocessors, as currently used by the process industry, provide both flexibility for control system design and interface capability required for new designs. Hence, the proven performance of a conventional power plant computer serves as the basic process data acquisition and plant monitoring function. The ancillary data acquisition and, in particular, subsystem operational requirements are fulfilled by highly versatile and expandable (in both software and hardware) microprocessors.

The data acquisition subsystem provides input in real time to the master control subsystem for plant operation and to the archived data base for diagnostics, analysis of performance, and reporting. The data acquisition subsystem senses and records data from the solar power subsystem, the water treatment subsystem, product water storage, and the organic Rankine cycle subsystems. The data acquisition subsystem time-shares components and information with the master control subsystem and includes the various interface buses, all sensors, wiring, and all signal conditioning equipment and required input/output units such as printers, terminals, and disk and tape drives.

The essential element for the proper coordination and transfer of data throughout the entire plant is the data bus system.

Each microcomputer location has a data acquisition module to accommodate its set of data channels. Each module is composed of an analog-to-digital converter, a buffer, an address register, and the supporting decommutators, gates, and line drivers. Each decentralized data module is supplied with an adjustable address switch so that a discrete address may be established for each measurement within the data acquisition system. The central processor computer will sequentially address each decentralized data module with an 11-bit parallel digital address. The addressed module then samples the parameter of interest, converts it from an analog voltage to digital readout, and transmits the data upon receiving a strobe pulse from the computer.

Capability to perform tabulation of daily and hourly performance, graphic output of stored data, and graphical integration of color charts is provided as needed. The plant master computer has storage capability for replay of diagnostics of unplanned outages.

The data acquisition subsystem functions in which data are stored for future reference, projections, and diagnostics is performed by the separate subsystem computer and storage equipment. This allows a separate plant control and data acquisition function. Thus, the plant operation never has to be interrupted because of subsystem failures.

4.5 Phase 2 - Definition Study

The objective of Task 5 was to supply a comprehensive Phase 2 implementation plan, developed under Task 4. This plan includes management and cost analysis which would form the basis of proceeding into Phase 2 with a high degree of confidence and assurance of success. In order to accomplish the above, a detailed work breakdown and management plan were developed. The main activities for Phase 2 were characterized by the preparation of subtasks identified in the work breakdown structure. The organizational and management practices SESEA will employ in the execution of Phase 2 will conform to current professional engineering practice. The organizational and management plan are tailored to complete the work required in a systematic and efficient way.

The SESEA management organization chart and the detailed work breakdown were included in their final report (Volume 4). The information and forecasts in the final report are the best estimates based on available data. These will become more exact upon determination of the start of Phase 2. The final report was prepared with respect to the Derab Site in Saudi Arabia and may be readily modified to suit the U.S.A. site.

SECTION 5.0

SCIENCE APPLICATIONS, INCORPORATED EXECUTIVE SUMMARY

5.1 Overview

The commercial solar controlled agricultural environment system conceived by Science Applications, Inc., (SAI) uses a novel filter/fluid roof concept for the greenhouse and is generally configured and designed for an environment comparable to that in the El Paso, Texas, area. The corresponding engineering test facility would be located on a 40 ha experimental farm located in El Paso. All the water requirements for this system would be provided by a brackish water well on the farm. A reverse osmosis desalination subsystem would be used to produce fresh water for irrigation and deionized water for cooling the greenhouse. The original concept was to have photovoltaics and wind turbines in combination with batteries and diesel backup power providing all the energy requirements of the proposed system including controls and support facilities. The system analysis effort resulting in the definition of the commercial facility, however, eliminates the wind turbines for the El Paso site analyzed. Carbon dioxide enrichment would be provided to enhance crop growth. Crop residue would be tilled into the land surrounding the greenhouse and offer the possibility of growing limited outside crops. Heating or cooling (depending upon the season) of the greenhouse would be provided by means of heat exchange with the well water and with thermal storage tanks. The effluents from this system would be appropriately discharged if environmentally acceptable; otherwise, they would be stored in a lined evaporation pond.

The work on this project was divided into one management and four technical tasks. The first task dealt with management, operational, and reporting activities. In Task 2, the requirements were defined for the 5-ha commercial unit and the engineering field test system of 0.4 to 1.0 ha. Systems analyses of a commercial-sized system, carried out under Task 3, included detailed subsystem trade-off studies and optimization of the integrated system. Based upon the results of that task, the size of an engineering field test for El Paso, Texas, was recommended. Preliminary design of an engineering test facility with process flow diagrams and top level drawings was completed in Task 4. Work plans to carry out the detailed design, construction, operation, and training of personnel were developed in Task 5. Levelized produce costs for sites in the United States and the Kingdom of Saudi Arabia were estimated in Task 5 taking into account the changes in system design and cost that resulted from accomplishment of Task 4.

Section 5.2 describes the system as it evolved, and Section 5.3 summarizes the work performed under Tasks 2 through 5.

5.2 Description of Concept

This section summarizes briefly the features of the solar controlled agricultural environment system concept as it evolved during the Phase 1 effort. It changed little from the originally proposed concept. The changes that were made will be summarized later in this section.

5.2.1 General Description: The greenhouse complex is based on a novel roof concept, a photovoltaic power system, and carbon dioxide enrichment, all designed to enhance the growth of vegetables. The fresh water needs of the facility are provided by a reverse osmosis desalination system using brackish aquifer water with 3,500 mg/L total dissolved solids. All power needs of the greenhouse and desalination facility are provided by solar energy.

The greenhouse employs an innovative filter/fluid roof concept that utilizes an inner roof glazing which selectively allows sunlight in the 400- to 700-nm range to pass into the greenhouse but strongly absorbs sunlight outside this range. The absorbed infrared radiation heats the inner glazing. This heat is removed by water flowing along the upper portion of the glazing and collected by a gutter system at its lower edges. The heated roof water is returned to an underground storage tank. In the summertime, when the roof must be cooled, water from the storage tanks is pumped through heat exchangers where its temperature is reduced by 18°C groundwater. In wintertime, the excess energy is collected in the storage tanks and is used to provide nighttime heating of the greenhouse, if required. The 18°C groundwater source can be used to augment the heating requirement.

The primary function of the filter/fluid roof is to prevent harmful infrared radiation from entering the greenhouse and being absorbed by the plant foliage. In this manner plant foliage and greenhouse air temperatures are nearly identical, plant evapotranspiration losses are minimized, and plant foliage is more nearly at its optimum growth temperature. Because of the lower evapotranspiration losses, fan power requirements to control humidity are significantly reduced.

The layout of the commercial greenhouse complex is shown in Figure 5.1. The greenhouse itself is basically square, and it has four square growing compartments separated by two corridors, one running north-south and the other running east-west. Outside the east and west sides of the greenhouse are large storage tanks which contain the roof cooling/heating water. This water must be purified by a demineralizer to no more than 5 ppm total dissolved solids to prevent scale buildup on the glass. The main corridor is used for access to all growing sections and houses materials needed for direct support of the growing operations and other growing area mechanical and electrical equipment. A support facility housing such items as fertilizer, fresh produce, reverse osmosis system, office space, control room, and batteries is located at the north end of the greenhouse.

The greenhouse growing medium is a 30-cm layer of porous sand spread on top of a sloped floor, covered with a plastic liner. Embedded in

Figure 5.1. Overall Facility Layout

the sand are drainage pipes which allow fertigation water to reach the plant roots and which are used for periodic purging of the soil to prevent salt buildup. The leachate is collected in a holding pond along with a portion of the rainwater and is subsequently used to irrigate outside vegetation. Crop residue is taken outside, tilled into the soil, and allowed to compost, thereby improving the quality of the soil and allowing for the possibility of growing marketable products outside the greenhouse.

The desalination system consists of pretreatment and reverse osmosis subsystems. Fresh water produced by the reverse osmosis system has total dissolved solids of less than 250 ppm and is stored in a fresh water tank. During plant startup, water from the fresh water tanks is sent through a demineralizer reducing the total dissolved solids to no more than 5 ppm before entering roof water storage. During greenhouse operation, the demineralizer is used to maintain the roof water at less than 5 ppm purity. Wastewater from the reverse osmosis and demineralizer systems is sent to an evaporation pond.

The energy system consists of photovoltaic modules, electric battery storage, and a power conditioning unit. Backup power is provided by diesel generators.

A fully automatic control system, with the capability for manual override, monitors the entire facility from a centrally located point in the support building. Several individual subsystems, however, have their own integral controls, in which case the central control system is used only to monitor these subsystems, to sound alarms, and to activate or deactivate the system. An uninterruptible power supply system has been included to serve all control functions.

Each of the four growing areas is operated and controlled individually. This procedure provides for increased facility reliability and for maintaining separate environmental conditions.

The support building is a typical prefabricated structure that houses equipment and facilities required to operate the greenhouse.

5.2.2 The Commercial Facility: The subsystem sizes and characteristics of the commercial system, the result of comprehensive analyses performed under Task 3, are summarized as follows:

Energy Subsystem

Photovoltaic Array

- Sized at 340 kWp (modules at 28°C, 1 kW/m²)
- Block V module specs
- Modules tilted at 20°
- Electrical protection (diodes, lightning protection, breakers, etc.)

Array Regulator

- Buck boost dc to dc converter, 94% efficiency
- Peak power tracking
- Multiple parallel units

Battery Storage

- Rated capacity 2,700 kWh, 256 kW
- Lead-calcium grid for 10-yr life
- Allowable depth of discharge 80% of rated capacity

Wind Energy Conversion

- Not included in optimized El Paso design

Power Conditioning Unit

- 250 kVA dc to ac inverter, over 90% efficient
- Multiple parallel units for high part load efficiency and high reliability
- Built-in protection (overload, overvoltage, under voltage, etc.)

Backup Power

- Two 200-kW diesel generators
- Uninterruptible power supply for key control functions

Greenhouse Subsystem

- 4.7-ha growing area in four compartments
- Filter/fluid roof cooling, ridge and furrow configuration
- Carbon dioxide enrichment
- Central access corridor
- Sand growing medium

Desalination Subsystem

- Pretreatment
- Reverse osmosis desalination
 - 75% recovery ratio
 - 3.04 m³/h (73 m³/day) capacity
 - spiral-wound membrane
 - automatic operation
- Product water storage
- Demineralizer and storage tanks for fluid roof circulating water
- Evaporation pond (7,320 m³) for brine discharge

Control Subsystem

- Leaf temperature control
- Direct control from central control station (CCS)
 - roof water circulation subsystem
 - greenhouse ventilation
 - greenhouse dehumidification
 - Carbon dioxide supplementation
 - independent controls for each growing compartment
- Integral control modules
 - fertigation
 - groundwater pumps
 - desalination and demineralization
 - fresh water distribution
 - brackish water low-volume distribution
 - photovoltaic subsystem
 - support facility environmental control
 - enable-inhibit from CCS status and alarms to CCS

5.2.3 The Engineering Test Facility: The purpose of the engineering test facility is to demonstrate the feasibility of the system analyzed in Task 3 by constructing and operating a smaller version. The engineering test facility must meet the same basic requirements and design criteria as the commercial system and must be representative in the most fundamental way, especially the stand-alone power requirement. It must be sized in such a way that results obtained with it can be reliably extrapolated to a larger facility. It must be constructed, furthermore, at the lowest possible cost to the SOLERAS program.

The principal equipment sizes and capacities for the engineering test facility are given in Table 5.1. To be responsive to the cost consideration stated above, slight differences were introduced between the commercial facility and the engineering test facility, none of which impacting in any way the satisfaction of the basic system requirements. These differences can be summarized as follows:

- No evaporation pond--Wastes are retained in a holding pond.
- No diesel generators--Local electric utility backup is used instead.
- Not all electric loads met by photovoltaic systems--The support facility uses entirely local electric utility power in order to limit the cost of the system (the support facility loads do not scale readily with the size of the greenhouse, therefore distorting the load profiles severely when reducing greenhouse size).
- East-west corridor eliminated but four growing compartments retained--The removal of the corridor provided additional growing area and more readily approximated the fraction of roof covered area not actively used for growing.

Table 5.1

MAJOR ENGINEERING TEST FACILITY
SUBSYSTEM SIZES

<u>Subsystem</u>	<u>Rating</u>
Photovoltaic Array	38 kWp
Array Regulator	37 kW
Battery	89 kWh
Power Conditioner	37 kVA
Desalination	10 m ³ /day
Well Pumps	Two 25-hp, One 5-hp
Greenhouse	0.36 ha total area, 0.32 ha growing area

5.2.4 Changes from Original Concept: The original proposed concept was slightly different from the final one in only a few respects. A comparison of the before and after concepts is summarized in Table 5.2. The most important difference is the elimination of wind machines from the power production subsystem. Because wind machines contributed only marginally for the El Paso, Texas, site, it was decided to eliminate it from the concept for reasons of simplicity. This is not to say that a combined photovoltaic-wind energy system is not economical, but rather that the El Paso, Texas, meteorological environment was not suited for inclusion of wind power.

5.3 Approach to Tasks

This section restates briefly the purpose of each task and summarizes either the context of the appropriate task report or gives certain relevant facts of the effort concluded under each task. These summaries provide only highlights of the effort that was conducted. Details on each of the task results are reported in Volumes 5-9.

5.3.1 Task 2 - System Requirements Definition: The purpose of Task 2 was threefold:

1. To define the requirements relevant to the configuration and sizing of equipments for the design of the solar controlled environment agriculture system,
2. To define design criteria based on these requirements, and
3. To determine environmental impacts.

The system requirements pertain to the overall objectives and goals of the project and are generally specified in the contract. They deal with aspects of system performance, site constraints, and economic factors. The key system requirements are summarized in Table 5.3.

Table 5.2

SYSTEM CONCEPT DEVELOPMENT

<u>System Feature</u>	<u>Original Proposed Concept^a</u>	<u>Final Proposed Concept^a</u>
Size of Greenhouse	4 ha/0.96 ha	5 ha/0.36 ha
Number of Compartments	4	4
Filter/Fluid Roof	Yes	Yes
Roof Structure	Double glazing	Single glazing and film
Photovoltaic Power	Yes	Yes
Wind Power	Yes	No
Evaporation Pond	Yes/No	Yes/No
Crop Residue Drying and Burning	Yes	No
Carbon Dioxide Enrichment	Yes	Yes
Humidity Control	Cooled inside air mixed with outside air	Inside air cooled and reheated
Backup Diesel Generator	Yes/No	Yes/No
Reverse Osmosis Desalination	Yes	Yes
Water Storage Tanks	Yes	Yes
Electric Storage Batteries	Yes	Yes
Central Control System	Yes	Yes
Aquifer Water	Yes	Yes
Support Facilities	Yes	Yes
Location in El Paso, Texas	Yes	Yes

^a When two items are separated by a slash (/), first item refers to the commercial system and the second to the engineering test facility. A single answer applies to both.

Table 5.3

SYSTEM REQUIREMENTS

- 5 ha for the commercial-sized greenhouse (0.4 to 1 ha for the engineering test facility)
- Stand-alone solar power/energy system
- Fossil fuel backup for emergency only
- Desalinated brackish water with total dissolved solids less than 500 mg/L
- Irrigation water storage for 20 days
- Backup power system fuel storage for 7 days
- Support facilities for personnel, storage of supplies, equipment, and produce
- Environmentally acceptable waste disposal facilities
- Reliable and safe operation
- Design life for 20 years

The El Paso, Texas, site was proposed for the location of the solar controlled environment agriculture system because it met the climatic requirements. These requirements can be summarized as follows:

- Abundance of sunshine (typical of the southwestern United States and the Kingdom of Saudi Arabia),
- Low humidity,
- Little rainfall (mostly July through September),
- Mild winter season (virtually no snowfall), and
- Dust storms (greatest frequency March and April).

In defining the economies of the system, the economic analysis methodology and values of basic economic factors were specified as a requirement.

Design criteria resulting from these requirements provide guidelines and limits that the overall system and the various subsystems must satisfy. The design criteria as met by SAI are summarized in Table 5.4. The design criteria for the major subsystems are reported in supporting

Table 5.4

DESIGN CRITERIA

SYSTEM DESIGN CRITERIA

- . Lowest possible energy consumption
- . Lowest possible water use rate
- . Suitable working environment for personnel
- . Use of commercially available equipment
- . Maximum possible technology transfer functions

SITE DESIGN CRITERIA

- . SOLMET TMY hourly meteorological data for El Paso, Texas
 - direct normal radiation
 - total radiation on horizontal surface
 - wind speed
 - wind direction
 - dry bulb temperature
 - wet bulb temperature
 - barometric pressure
- . Maximum solar intensity of 1,050 W/m²
- . Maximum wind speed of 35.8 m/s (at 10 m above ground)
- . Water from aquifer
 - Rio Grande alluvium aquifer
 - on the average the aquifer is full
 - water level averages 3 to 6 m below land level
 - water temperature is virtually constant at 18°C
 - total dissolved solids in water is approximately 3,500 ppm
- . Seismic zone no. 1

ECONOMIC DESIGN CRITERIA

- . Minimum levelized life-cycle cost per kilogram of produce based on the requirements that
 - methodology used is "the cost of energy from utility-owned solar electric systems - a required revenue methodology for ERDA/EPRI evaluations," ERDA/JPL-11012-76-3, June 1976
 - basic economic factors be used that are specified in the contract
- . 1986 U.S. Department of Energy cost goals for solar energy sub-systems

volumes of this report in the following format: identification/name, scope, design philosophy, features, technical constraints, environmental constraints, and operation and maintenance requirements.

5.3.2 Task 3 - Systems Analysis: The purpose of this task was to define a viable 5-ha commercial greenhouse system that satisfies the requirements and criteria defined and developed under Task 2. This included trade-off studies and the determination of the sizes and/or capacities of all of the major subsystems, and to evaluate overall system performance from both a technical and cost point of view. Once the commercial system was defined, scaling criteria were to be derived to define a smaller scale engineering field test for which the preliminary design was to be developed during the next task.

The approach taken by SAI in Task 3 is best summarized by Figure 5.2. It shows the basic steps that were taken starting with a refinement of the original proposed concept, using additional information gathered since the original submittal of the idea and preliminary comments from reviewers. As a result, the following key system features were defined:

- . Five-hectare greenhouse providing leaf temperature control via an energy-efficient filter/fluid roof concept, carbon dioxide enrichment for increased plant productivity, and loads closely matched to the solar energy resource.
- . Stand-alone solar power system incorporating a photovoltaic array, wind machines, battery storage, a dc-ac inverter and power conditioning unit, and diesel generator backup for emergency conditions.
- . Self-contained fresh water supply provided by a reverse osmosis desalination unit with 75% recovery ratio and an evaporation pond for brine disposal.
- . Automatic control system with redundant alarms and provision for manual control.
- . Energy-efficient support facility providing necessary work areas, produce storage, equipment storage, and office space.
- . Supplementary crop area with enrichment using crop residues and irrigation using leachate and excess desalinated water.

Following this, subsystem trade-off studies were conducted to determine the most appropriate form of the subsystem. The next three steps were concerned with analytical work that defined the optimum system configuration from model development to detailed performance analyses and optimization to sensitivity studies. Lastly, the engineering field test scaling was performed. All of these individual steps were highly interactive, as shown by the dotted lines in Figure 5.2. Detailed subsystem trade-off studies were conducted on the greenhouse roof structure, the fluid-roof filter, greenhouse dehumidification, greenhouse cooling, carbon dioxide supply, and water desalination.

Figure 5.2. System Analysis Approach

Following the definition of all of the major subsystem types, mathematical models were derived for each subsystem compatible with the optimization methodology used in this project. System optimization was based on the following criteria: minimum levelized produce cost, economic assumptions specified by the contract, and U.S. Department of Energy cost goal projections for 1986 for the energy subsystems.

The optimization methodology used was based on a linear programming formulation of the hourly performance characteristics of the subsystems. Hourly weather data for a year was analyzed and reduced to a representative week from each of the four seasons. Unit greenhouse electrical and water loads and energy system electrical output were determined from hourly simulations. Models were derived for all other pertinent subsystems and made part of the simulation computer program (SYSOPT). The SYSOPT program generated the appropriate equations which were subsequently solved with the commercially available APEX III LP solver. The results from the latter program were then processed and cast into a form more suitable for analysis and evaluation. The system schematic diagram for optimization is shown in Figure 5.3, where nodes define the balance of dc power, ac power, brackish water flow, fresh water flow, thermal energy, and carbon dioxide. Of particular importance in this methodology is the model for the greenhouse. The loads imposed by the greenhouse on the system were determined from detailed simulations.

The results of these analyses are summarized in Table 5.5. These results are described and discussed in detail in volumes of this report.

Table 5.5

SUBSYSTEM OPTIMIZATION RESULTS

<u>Subsystem</u>	<u>Rated Capacity</u>	<u>Annual Performance</u>
Photovoltaic System ^a	344 kWp	723 MWh dc
Wind subsystem	0 kW	0 MWh
Battery Charging	256 kW, 2,740 kWh ^b	291 MWh dc
Battery Discharging	256 kW, 2,740 kWh ^b	232 MWh dc
Power Conditioner	250 kVA	437 MWh ac
Reverse Osmosis Desalination	3.04 m ³ /h	22,300 m ³
Total ac Loads	250 kVA	437 MWh ac

^a Includes array regulator.

^b Nominal capacity (usable capacity is 2,190 kWh at 80% allowable depth of discharge).

Figure 5.3. SCEAS Optimization Schematic

5.3.3 Task 4 - Preliminary System Design and Cost Analysis: The purpose of Task 4 was to develop a preliminary design of an engineering test facility to be located on the Texas A&M Agricultural Experiment Station farm in El Paso, Texas. The preliminary design was to consist of top-level drawings and component specifications. This information would be used to determine the cost of construction and operation of the engineering test facility.

The objective of the SAI design was the faithful scaling of the commercial facility to ensure that the engineering test facility results could be extrapolated to a commercial facility of any size. Therefore, all major features, including the photovoltaic power system, an integral water desalination system, and even the basic structural module, have been retained. A computer simulation of the performance of the engineering test facility in El Paso, Texas, was made to verify the adequacy of the design.

The Task 4 results represent an effort substantially greater than a typical preliminary engineering design study would provide. The added effort was deemed necessary in order to develop realistic implementation schedules and high confidence cost estimates.

The engineering test facility design emulates the commercial-sized facility in all important aspects except size. The enclosed greenhouse area is 3,600 m² with 3,150 m² of growing area. There are four equal size growing compartments and a 7.5-m wide corridor through the center that provides access to the compartments and work space. The size and compartmentation are adequate for all experimental objectives.

The only significant departure from the commercial system design is the powering of nonagricultural loads from the local utility. The housekeeping functions for the engineering test facility do not scale linearly, and their inclusion in the power requirement for the photovoltaic system would have resulted in a substantial cost increase without any experimental purpose. The utility is also used as a backup power source for the agricultural loads in lieu of diesel generators.

The performance analysis indicates a remarkably small energy requirement for operation of the facility. Prudent design dictates a slight oversizing of the solar energy system to account for reduced efficiencies resulting from smaller motors and a 4:1 increase in the ratio of unfiltered side walls to filter glass roof.

5.3.4 Task 5 - Phase 2 Definition: The purpose of Task 5 was to develop a plan for implementing the engineering test facility developed under Task 4. Task 5 was also to determine the cost of Phase 2 based on the preliminary drawings and specifications for the El Paso, Texas, site and prepare an estimate for an equivalent facility in Saudi Arabia. An additional item to be considered under Task 5 was the estimation of the cost of operation during Phase 3.

In order to accomplish the above, SAI developed a detailed work breakdown structure accounting for all activities required under Phase 2. This information was used to determine the project design and management costs and the overall implementation schedule. The preliminary drawings and specifications were used to generate material take-offs to determine equipment, material, and construction costs. Cost quotations were solicited for all items to be purchased or constructed and tallied to obtain the total system construction cost.

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SOLAR CONTROLLED ENVIRONMENT AGRICULTURE

FINAL REPORT VOLUME 2

**BATTELLE COLUMBUS LABORATORIES
SYSTEM REQUIREMENTS DEFINITION
AND SYSTEM ANALYSIS**

United States - Saudi Arabian Joint Program
for Cooperation in the Field of Solar Energy

Midwest Research Institute

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SOLAR CONTROLLED ENVIRONMENT AGRICULTURE

FINAL REPORT VOLUME 3

**BATTELLE COLUMBUS LABORATORIES
PILOT PLANT PRELIMINARY DESIGN AND
PHASE 2 DEFINITION STUDY**

United States - Saudi Arabian Joint Program
for Cooperation in the Field of Solar Energy

Midwest Research Institute

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SOLAR CONTROLLED ENVIRONMENT AGRICULTURE

FINAL REPORT VOLUME 4

SAUDI ENGINEERING SOLAR ENERGY APPLICATIONS SYSTEM DESIGN STUDY

United States - Saudi Arabian Joint Program
for Cooperation in the Field of Solar Energy

Midwest Research Institute

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SOLAR CONTROLLED ENVIRONMENT AGRICULTURE

FINAL REPORT VOLUME 5

SCIENCE APPLICATIONS INCORPORATED EXECUTIVE SUMMARY AND SYSTEM REQUIREMENTS DEFINITION

United States - Saudi Arabian Joint Program
for Cooperation in the Field of Solar Energy

Midwest Research Institute

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FINAL REPORT VOLUME 6

**SCIENCE APPLICATIONS INCORPORATED
SYSTEMS ANALYSIS**

United States - Saudi Arabian Joint Program
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FINAL REPORT VOLUME 7

SCIENCE APPLICATIONS INCORPORATED
FIELD TEST FACILITY PRELIMINARY DESIGN

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SOLAR CONTROLLED ENVIRONMENT AGRICULTURE

FINAL REPORT VOLUME 8

**SCIENCE APPLICATIONS INCORPORATED
SPECIFICATIONS FOR ENGINEERING FIELD
TEST FACILITY PRELIMINARY DESIGN**

United States - Saudi Arabian Joint Program
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THE FOLLOWING ELEMENTS OF THE SOLAR CON-
TROLLED ENVIRONMENT AGRICULTURE SYSTEM:

- 1 Site Preparation and Construction
- 2 Mechanical and Plumbing
- 3 Electrical, General
- 4 Power Conditioning Subsystem
- 5 Display and Control Panels
- 6 Control System Equipment
- 7 Water Desalination System
- 8 Meteorological Station

SOLAR CONTROLLED ENVIRONMENT AGRICULTURE

FINAL REPORT VOLUME 9

**SCIENCE APPLICATIONS INCORPORATED
PHASE 2 - DEFINITION STUDY**

United States - Saudi Arabian Joint Program
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