PN-AAA-130

RENEWABLE ENERGY RESOURCES
FIELD TESTING

PN-AAA-126-7

APPLICATIONS REVIEW AND CONCEPTUAL DESIGN FOR FIELD TEST #3

PV-POWERED DESALINATION PLANT AT EL KASR

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FINAL

Prepared for

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FOREWORD
APPLICATIONS REVIEW AND CONCEPTUAL DESIGN

The Egyptian Electricity Authority (EEA), the United States Agency for International Development (USAID/Cairo), and a group of U.S. consultants form a team responsible for conducting field test demonstration projects for 11 renewable energy applications in Egypt. These demonstration projects include the use of photovoltaic (pV), wind, and solar thermal systems for water pumping, ice making, desalination, industrial process heat, small village electrification, and grid connected electricity generation applications. The specific objectives of the 4-year program are to: (1) demonstrate the viability of renewable energy technologies in Egypt; (2) comprehensively strengthen Egyptian technical and institutional capabilities in the full spectrum of renewable energy planning and decision-making; and (3) establish the infrastructure necessary to ensure that renewable energy technologies that have been proven successful are available for widespread use in Egypt.

Each field test demonstration project contains seven generic tasks: technology review, application review, conceptual design, preparation of a statement-of-work for a tender document, proposal evaluation, supervision of hardware installation, and performance evaluation. Two of these tasks, the application review and the conceptual design for a photovoltaic-powered brackish water desalination plant and a diesel powered seawater desalination plant are presented in this document. This report is subtask 3.8.1 and 3.8.3 to the field test requirements under Contract AID 263-0123C-00-4069-00, Task Area 3.

TABLE OF CONTENTS

		Page
1.0	EXECUTIVE SUMMARY	1
	1.1 Purpose of Field Test	2
	1.2 Site Selection	3
	1.3 Conceptual Design	5
	1.4 Additional Data Needs	6
2.0	FIELD TEST OBJECTIVES AND DESCRIPTION	10
	2.1 Objectives	10
	2.2 Description of Field Test	10
	2.2.1 General El Kasr Area & Feedwater Sources	12
	2.2.2 Possible Sites for Desalination Plant	12
	2.2.3 Scope of Field Test Hardware	17
	2.2.4 Feedwater Quality	21
	2.3 Requirement for Product Water Quality	22
3.0	SITE LOCATION CONSIDERATIONS AND RECOMMENDATION	23
	3.1 Mowah	23
	3.2 El Kasr Central	24
	3.3 El Kasr #3	24
	3.4 Seawater Desalination Plant Location	25
	3.5 Recommendation	25
4.0	TECHNOLOGY REVIEW SUMMARY	28
5.0	CONCEPTUAL DESIGN	31
	5.1 Background	31
	5.2 Engineering Approach	31
	5.2.1 Choose Desalination Technology (Reverse Osmosis) or Electrodialysis)	32
	5.2.2 Choose Operating Procedures for Desalination Equipment	34
	5.2.3 Design the Desalination Equipment	36
	5.2.4 Choose Type of Photovoltaics Technology	38
	5.2.5 Choose Power Subsystems Protocol, i.e. all-PV, PV-battery, PV-Diesel Hybrid or a combination	41
	5.2.6 Design the Photovoltaics Array, Battery Storage System and Specify Diesel Engine (if appropriate)	43
	5.2.7 Design the Storage Tank	58
	5.2.8 Specify Brine Rejection System	58
	5.2.9 Specify Site Layout of Entire Installation	60
	5.2.10 Specify Instrumentation	60
	5.3 Conceptual Design Summary	64
6.0	FT #8 ESTIMATED CAPITAL COST	66

APPENDICES
(Separately Bound)

		Page
Appendix A.	Available Ground Water Quality Analyses for El Kasr Extension #3 Wells....	A-1
Appendix B.	Eastern Mediterranean Water Quality Analysis.....	B-1
Appendix C.	Comments and Direction Received by Meridian Resulting from EEA/USAID Review of the Draft-for-Comment AR/CD FT #8.....	C-1
Appendix D.	Trip Reports Resulting from Site Visit to Mersa Matruh and El Kasr, Mr. James Hoelscher and Mr. Bruce Watson.....	D-1
Appendix E.	Report on Conceptual Design for Field Test Site #8 - Photovoltaic Brackish Desalination System, May 26, 1986.....	E-1
Appendix F.	Field Test #8 at El Kasr Reverse Osmosis Redesign, February 23, 1987.....	F-1
Appendix G.	Derivation of Array Power Formula.....	G-1
Appendix H.	PV F-Chart Printouts.....	

LIST OF EXHIBITS

		Page
ES-1	Sketch of Water Distribution System near El Kasr	7
ES-2	Sketch of Layout - Field Test #8	8
2-1	Field Test #8 Location	13
2-2	Schematic Illustrating Water Flow to Roman Wells	14
2-3	Schematic Illustrating Water Flow to Roman Well Collection Point	15
2-4	Photo of Beach Area where Roman Wells are Located	16
2-5	Mowah Candidate Field Test Site	18
2-6	El Kasr Central Candidate Field Test Site	19
2-7	El Kasr Extension #3 Candidate Field Test Site	20
3-1	Site Location Factors	26
4-1	Comparison of Reverse Osmosis and Electrodialysis Feature	30
5-1	Comparison of Electrodialysis and Reverse Osmosis Power Consumption	33
5-2	Summary of Various Desalination Options	35
5-3	Seawater Desalination Plant Flow Diagram	39
5-4	Brackish Water Plant Flow Diagram	40
5-5	Insolation as a Function of Various Tilt Angles	42
5-6	Percent of Annual Load as a Function of PV Array Size	48
5-7	Hours of Operation of Annual Load as a Function of PV Array Size	50
5-8	Percent of Load Furnished by PV/Battery Storage-Monthly Basis	51
5-9	Typical Module Electrical Schematic	55
5-10	Typical Branch Circuit Schematic	56
5-11	Sketch of Suggested Water Storage Tank for Product Water	59
5-12	Sketch of Water Distribution System near El Kasr	61

LIST OF EXHIBITS (Cont.)

		Page
5-13	Sketch of Layout - Field Test #8	62
5-14	Data Element Requirements	65

1.0 EXECUTIVE SUMMARY

The Renewable Energy Field Testing (REFT) Project has broad objectives to investigate selected renewable energy option:

- o Comprehensively strengthen Egyptian technical and institutional capabilities in the full spectrum of renewable energy planning and decision-making for technologies and applications;
- o Develop and sustain an Egyptian renewable energy infrastructure through the establishment of data bases, information systems and organizations that effectively serve both the public and private sectors;
- o Design, install, operate and evaluate a series of renewable energy field tests which utilize commercially available technologies in applications having potential for widespread use in Egypt; and
- o conduct a formal; management and technical training program, both on-the-job and specialized, and establish an intensive information dissemination program.

The proposed field test for PV-powered desalination systems near Mersa Matruh is based on three observations; (1) the belief that future regional growth and the potential for dispersed development throughout Egypt can be strengthened by the satisfaction of basic potable water needs, (2) a review of the solar resource in Egypt, which suggests that the country has a substantial resource for the widespread deployment of photovoltaic power systems, and (3) the value of a PV-powered desalination demonstration to be sited where strengthening of Egyptian technical and institutional capabilities for widespread development of this technology can be maximized.

An assessment of the contribution of this specific field test to the REFT Project objectives is the main purpose of the Application Review. Activities

completed during the review address the criteria necessary for a successful demonstration of any stand-alone PV-power system application.

These criteria are listed below, although not necessarily in order of importance.

- Current and future user requirements
- Evidence of a viable solar resource
- Appropriate site characteristics and infrastructure for installation
- Capability of the host organization (or local village personnel) for successful operation and maintenance of the system.

The system Conceptual Design activities are focused to size the power system, to provide instruction and information sufficient to direct bidding contractors in proposal preparation, and to support EEA/USAID in proposal evaluation and contractor selection.

Specifically, the Conceptual Design will:

- Develop site specific energy source profiles and application specific load demand profiles.
- Define hardware performance and environmental specifications.
- Conduct system sizing and perform trade-off analyses.
- Specify performance monitoring instrumentation requirements.
- Identify critical additional data needs that must be addressed before a competitive request for proposal (RFP) can be issued.
- Recommend a specific site for the location of the PV-powered desalination plant

1.1 Purpose of the Field Test

The field test is primarily a demonstration project in the Matruh governorate that, if successful, could be replicated in other remote areas in Egypt.

The specific objectives of Field Test #8 are to:

- Demonstrate, in a remote Egyptian environment, the viability of a PV-powered, stand-alone desalination system that can desalt brackish water with variable salinity to potable water with salinity no more than 500 parts per million (ppm) total dissolved solids (TDS). This field test uses ground water which may vary from approximately 1000 to 12,000 ppm TDS

- Demonstrate that such a system can be maintained in a remote location

- Determine start-up and operation and maintenance costs of the system

- Develop, through training, a working capability in Egypt to design, procure, install, maintain, and analyze the performance of a PV powered desalination plant

- Identify modifications that should be made in replicated systems in other locations in Egypt.

1.2 Site Selection

Three sites were selected by the EEA after an extensive survey by them of potential sites throughout Egypt. These sites were evaluated by the project field test engineers during a visit in November 1985. The three site, located in the Matruh Governorate are Mowah, El Kasr Central and El Kasr Extension #3.

From a technical standpoint, each of the sites is acceptable. Each has different assets and liabilities that affect the installation of a PV-power desalination system. None of the sites had a significant enough liability to rule it out as a possible location for the field test demonstration. Trade-off analyses were completed to select the best location considering not only technical issues, but also social and political issues.

El Kasr Extension #3 was selected as the site for the field test demonstration because it satisfied the broadest range of the site selection criteria. An important factor in its selection was that the site included strict environmental constraints which encompass those that would be encountered elsewhere in Egypt. The major liability of the site was the fact that beach sand and potential salt air corrosion problems would be encountered if the hardware were sited at the original location evaluated during the site

visit in November 1985. Therefore, to alleviate this potential problem and to make the location more representative of others throughout Egypt, the U.S. engineers recommend that the location of the PV-desalination system at El Kasr Extension #3 be moved approximately 200 meters inland.

The brackish groundwater source at El Kasr Extension #3 is Roman wells near the beach. The seawater source is the Mediterranean Sea. Groundwater samples taken during the site visit made in November, and at later times over the past year, indicate that the water has a TDS of 359 - 737 ppm to 13,397 ppm TDS. However there is a strong indication that the extremely low TDS levels and perhaps the high TDS level are in error. The salinity of the groundwater is expected to decrease during the rainy winter months and increase during the summer. Water yield is also uncertain, but the yield is expected to be greatest during the rainy winter months. Therefore, the conceptual system design in this document for the brackish groundwater system assumed a variable salinity of 1,000 ppm to 12,000 ppm TDS as originally specified in the USAID RFP for the REFT Project.

A water quality analysis was not available for the Mediterranean Sea at the selected location for this field test. Therefore, the seawater desalination system conceptual design assumes an average salinity of 38,400 ppm TDS, representative of the eastern Mediterranean region.

The other two key site specific parameters that influence the conceptual design for this field test are solar insolation and ambient temperature. Insolation on a horizontal surface at the site ranges from a high of 8.4 kWh/m2 in July to a low of 2.90 kWh/m2 in December. Ambient temperature varies from a high of 25.5 degrees Centigrade in August to a low of 12.8 degrees Centigrade in January. Both of these measured values are representative of what can be found throughout Egypt.

1.3 Conceptual Design

A step-by-step procedure was used to develop the conceptual design for this field test:

- Choose the desalination technology (reverse-osmosis or electrodialysis)
- Choose the operating procedures for the desalination equipment
- Design the desalination equipment
- Choose the photovoltaics technology
- Choose the power system protocol, i.e. all-PV, PV-battery, PV-diesel hybrid or a combination
- Design the PV array, battery storage system and specify the diesel engine
- Design the water storage tank
- Specify the brine disposal system
- Specify the site layout for the entire installation
- Specify the performance monitoring instrumentation requirements

These procedures are detailed in this document. The conceptual design for the desalination and power systems is briefly described below. The results of the other steps and the rational for them are presented also.

- The desalination technology selected was reverse-osmosis (RO) because electrodialysis is not appropriate for salinity levels above a few thousand ppm TDS.
- The selection of RO as the desalination technology drives the selection of an operating procedure. RO systems require constant power and steady-state operation. It is important to minimize the number of starts and stops for this equipment. Therefore, the system will be operated continuously 24-hours per day.
- The desalination equipment design is summarized in Section 5.2.3 and detailed in Appendix F. Separate seawater and brackish water systems are recommended. Each plant operates continuously and produces 25 cubic meters of potable water per day. The brackish water plant requires an average power of 2.1 kilowatts. The seawater plant requires an average power of 5.8 kilowatts.

  Since the Mediterranean Sea is an alternate supply of feedwater for this field test, it would be inconsistent to power the seawater

system with a PV-array that is nearly three times as large as the primary PV power system for the brackish water unit (see Section 5.2.6 for design details). Therefore, the brackish water plant is PV-powered and the alternate feedwater supply, i.e. the seawater plant is powered by a conventional diesel generator.

- In keeping with a goal of simplicity of operation, a fixed, flat-plate PV array composed of crystalline (single or poly) silicon solar cell modules is recommended. However, the tender document should allow for contractors to bid thin film (amorphous silicon) arrays, but they should be required to prove the stability and reliability of the modules and the business stability of their manufacturing facility.

- Three different power options are considered for the brackish water system:

  - PV and battery storage only. The diesel generator is for back-up.

  - PV with one day of battery storage for operation 8-hours per day with the diesel operating 16-hours per day.

  - PV and diesel with no battery storage.

  The PV and diesel with no battery storage is not recommended because the unpredictability of the solar resource will cause an unacceptable number of diesel start/stops. F-Chart analyses and cost-effectiveness trade-offs of the other two options results in a recommended PV-powered system consisting of a 12 kilowatt PV array and 500 amp-hours of battery storage backed up by a 5 kilowatt diesel generator operating as a hybrid power system.

- Two 25 cubic meter water storage tanks are recommended, one for each of the desalination plants. These tanks should be similar to those currently at El Kasr Central.

- Brine disposal should be directly to the sea.

A schematic of the site layout for the installation is shown in Exhibits ES-1 and ES-2. Performance monitoring instrumentation requirements are specified in Section 5.2.10.

1.4 Additional Data Needs

There are some significant data needs that must be resolved before a procurement is initiated. The most pressing need is data on the variation in ground water quality as a function of time at the El Kasr Extension #3 site. The following activities must be completed as input to hardware design

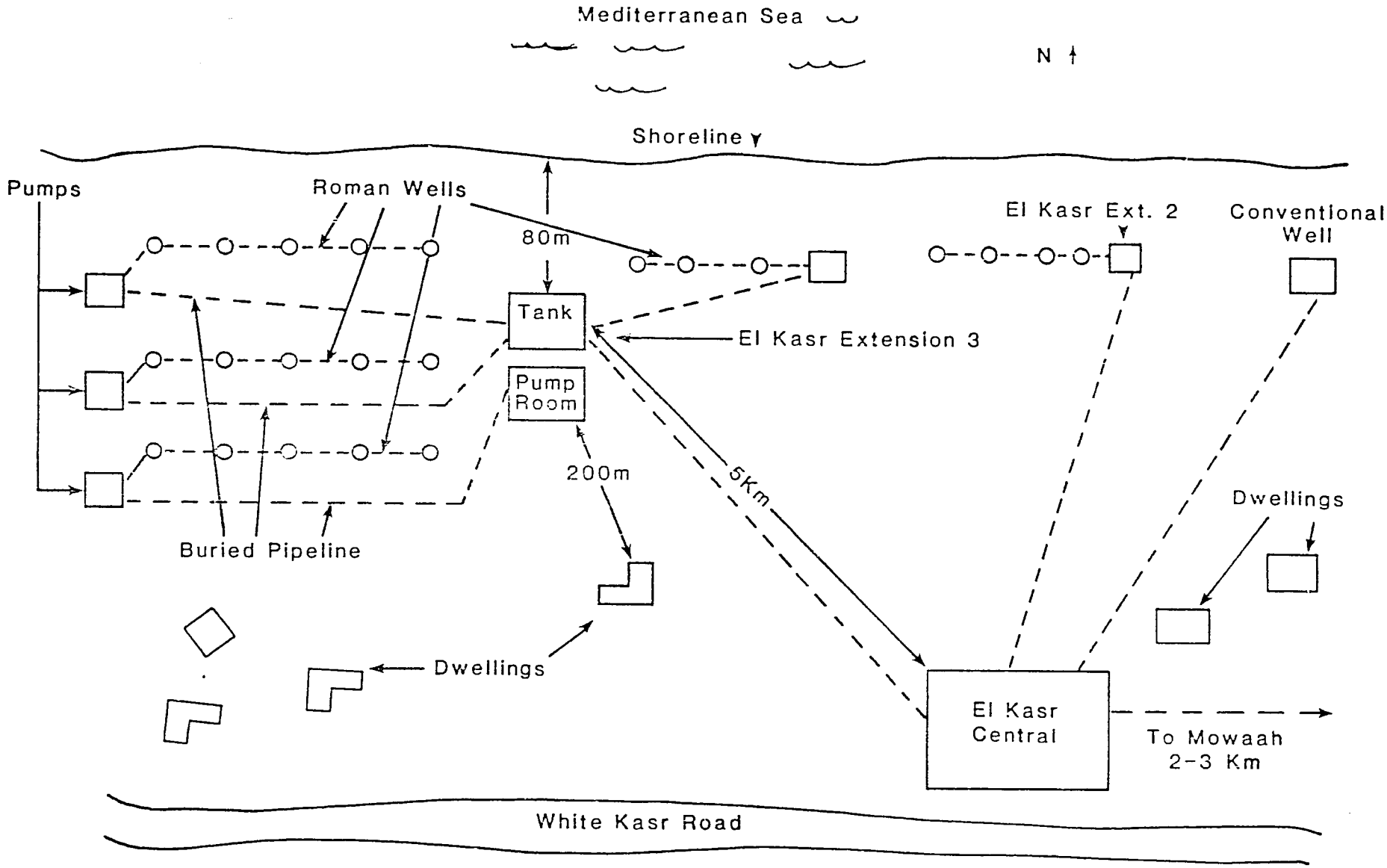

Exhibit E3-1

SKETCH OF WATER DISTRIBUTION SYSTEM NEAR EL KASR

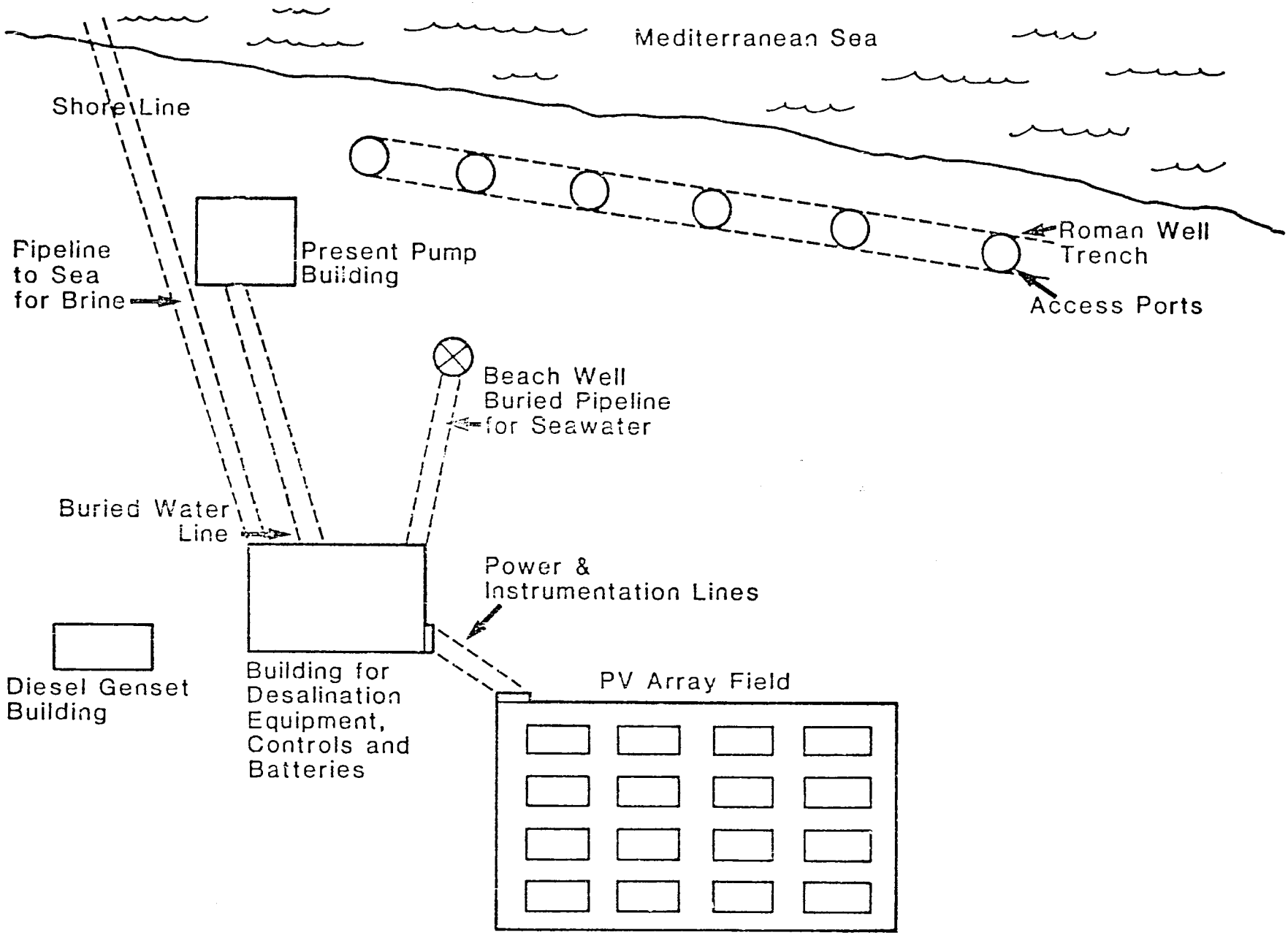

Exhibit ES-2

SKETCH OF LAYOUT FIELD TEST 8

specifications for a statement-of-work:

- As many periodic water quality analyses of the groundwater as possible must be completed between now and the release of a tender document, including measurement of Silicon ion and Hydrogen Sulfide

- An analysis of the Mediterranean Sea must be made at the seawater intake location at the same time as groundwater measurements are made of the Hydrogen Sulfide (inexpensive measurement kits are available). Also, a measurement of PH should be made (portable PH-meters are available)

- Data must be collected to determine a silt density index

- Water temperature should be measured when the groundwater sample is taken

- Water availability as a function of time should be estimated

- Biological activity of the groundwater sample should be measured

In addition, there should be data collected on the load bearing qualities of the land where the plant will be sited. We strongly recommend that a data collection program to accomplish these critical activities be implemented immediately so that adequate data will be available for inclusion in the tender document.

2.0 FIELD TEST OBJECTIVES AND DESCRIPTION

2.1 Objectives

The general objective of this field test is to demonstrate the use of photovoltaic (PV) powered desalination systems that can provide significant amounts of potable water to open up new areas for development throughout Egypt and to improve the quality of life in existing communities, particularly those in remote areas.

The specific objectives of Field Test #8 are to :

- Demonstrate, in a remote Egyptian environment, the viability of a PV-powered, stand-alone desalination system that can desalt brackish water with variable salinity to potable water of less than 500 ppm TDS. This field test uses groundwater which may vary from approximately 1,000 to 12,000 ppm TDS
- Demonstrate, in a remote Egyptian environment, the viability of a diesel-powered stand-alone seawater desalination system that can desalt Mediterranean seawater at approximately 38,600 ppm TDS to potable water of less than 500 ppm TDS
- Demonstrate if these systems can be maintained in a remote location
- Determine start-up and operation and maintenance costs of the systems
- Develop, through training, a working capability in Egypt to design, procure, install, maintain, and analyze the performance of a PV powered desalination plant
- Identify modifications that should be made in replicated systems in other locations in Egypt.

2.2 Description of the Field Test

The Governorate of Mersa Matruh, which includes the entire north coast of Egypt west of Alexandria, has no natural source of fresh water. The wells in the area are brackish, but in the rainy season rain water drains into the wells producing a stratified layer of fresh water. For this reason, the salinity of the wells depends upon the season and the amount of water taken from a particular well in proportion to its inflow.

The water demand of Matruh (population 70,000), the largest city of the

Governorate (Population 140,000), is over 2000 m3/day. This demand is only partially met by a small waterline from Alexandria with intermittent flow, two water trains per week (500 m3 each) from Alexandria, and a 3-inch brackish waterline from the village of El Kasr, 15 kilometers west of Matruh. A multistage flash distillation unit in Mersa Matruh, rated at 2000 m3/day, is old, inefficient, and unreliable. Potable water for the people who live in El Kasr must be transported to the area. This problem will be lessened when two 200 m3/ day capacity electrodialysis units are commissioned in the near future at Mowah under a USAID funded project.

The main thrust of this field test is to demonstrate the viability of a PV-powered desalination system. The recommended PV-powered desalination system at El Kasr Extension #3 is a stand-alone system to produce 25 cubic meters of product water of less than 500 ppm TDS daily from brackish groundwater. The method of desalination is reverse osmosis (RO).

Because of the uncertain groundwater supply at the El Kasr Roman wells, the field test also requires the consideration of the Mediterranean Sea as an alternate feedwater source. The use of a seawater to brackish water desalination system to supplement the Roman well feedwater supply was not cost-effective since, (1) the system might not be used at all during the year since it is unclear as to the extent of the reduction of groundwater at El Kasr, (2) the system would certainly be idle for long periods of time during the rainy winter months, and (3) RO desalination systems cannot be run intermittently and should not be stopped for long periods of time without a significant level of maintenance to protect the membranes. Therefore, a diesel powered RO seawater desalination system that can produce 25 cubic meters of potable water per day is designed as the alternate feedwater source for the PV-powered system. The seawater system can provide additional potable water for the El Kasr area when

it is run. It can also provide a supplemental brackish water supply for the PV-powered plant demonstration, if necessary, by tapping off some of the seawater flow before it is completely processed to potable water by the entire desalination plant.

2.2.1 General El Kasr Area and Feedwater Sources

El Kasr, (see Exhibit 2-1) is located in a farming region about 15 kilometers west of Mersa Matruh. As mentioned previously, groundwater is not potable and is used only for washing and irrigation. Potable water is periodically received from the pipeline and water trains from Alexandria.

Feedwater for the proposed PV-powered desalination system will be taken from the already existing brackish water sources in the El Kasr area, i.e. from "Roman wells" near the beach. Roman wells (so named because they were built in the days of the Roman Empire) are trenches dug into the bedrock near the shore. Rainwater filters through the sand and runs over the bedrock until it is caught in one of the trenchs (Exhibit 2-2). The trenchs run parallel to the shoreline and are inclined so that the water gravitates to a collection area, where it is pumped to an above-ground reservoir (Exhibit 2-3). There are two Roman well areas on the beach a few tens of meters from the Mediterranean shoreline; Exhibit 2.4 is a photograph of one of them. In addition, some brackish water is collected from conventional wells in the El Kasr area.

2.2.2 Possible Sites for Desalination Plant

During a visit to the El Kasr area in November 1985, three sites chosen by the EEA as potential sites for the demonstration of a PV-powered desalination plant were shown to the REFT project team. These sites were:

- Mowah. This site, located on an Army installation, is the present site for distribution of brackish water. It is also the site where two diesel-powered 200 cubic meters per day electrodialysis units are being installed in another USAID project. The units were not yet

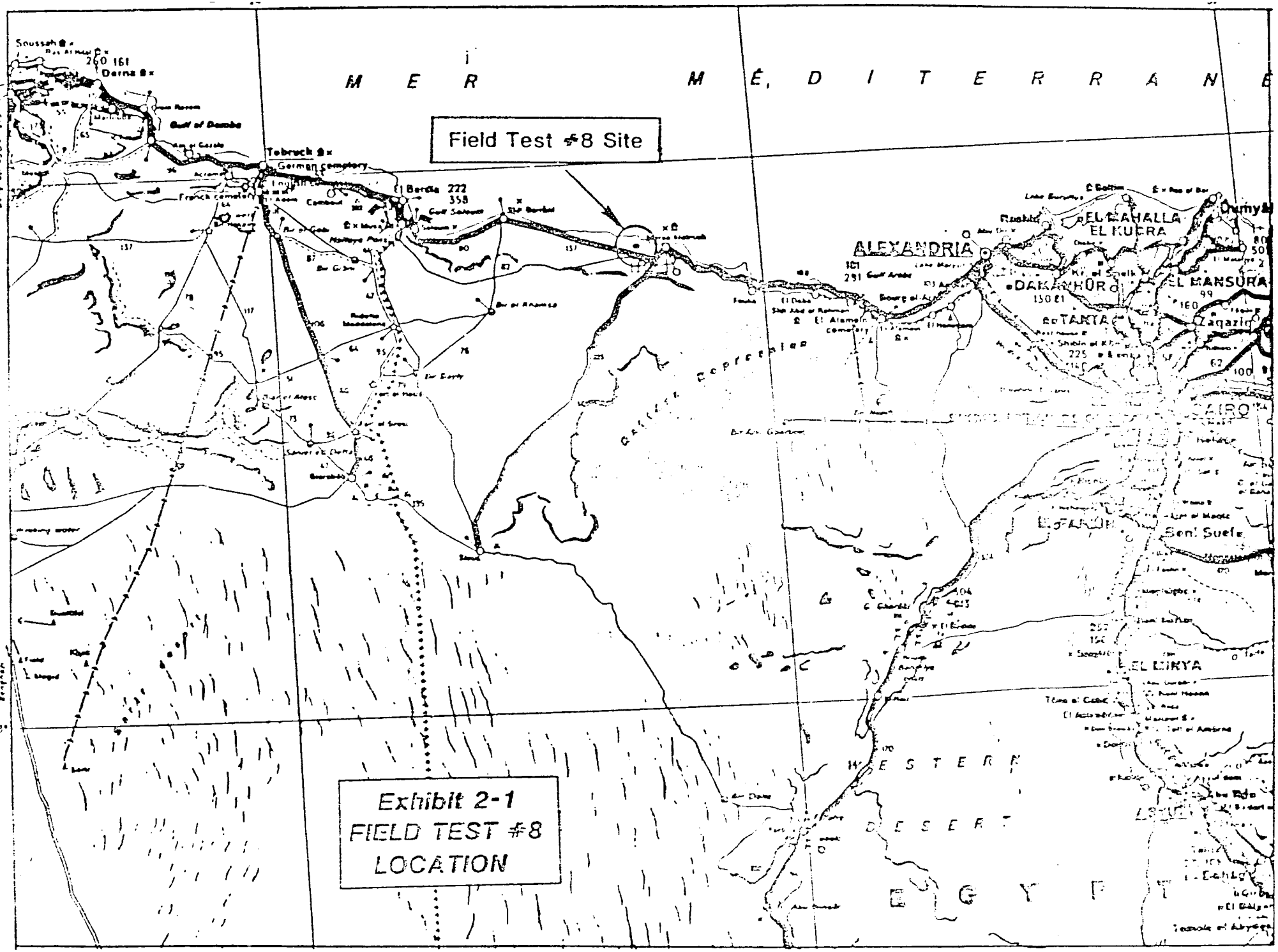

Exhibit 2-1
FIELD TEST #8
LOCATION

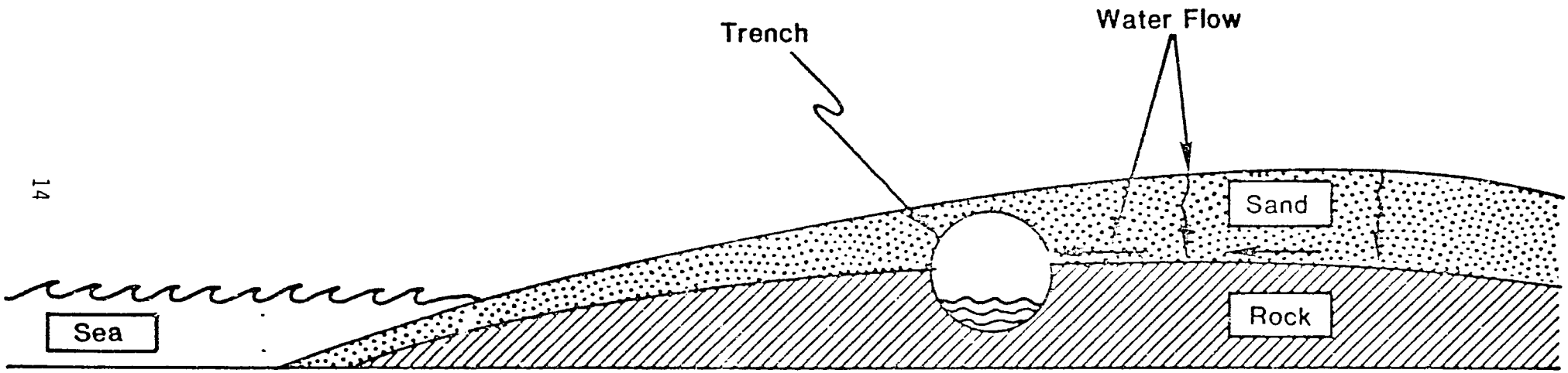

Exhibit 2-2
SCHEMATIC ILLUSTRATING WATER FLOW TO ROMAN WELLS

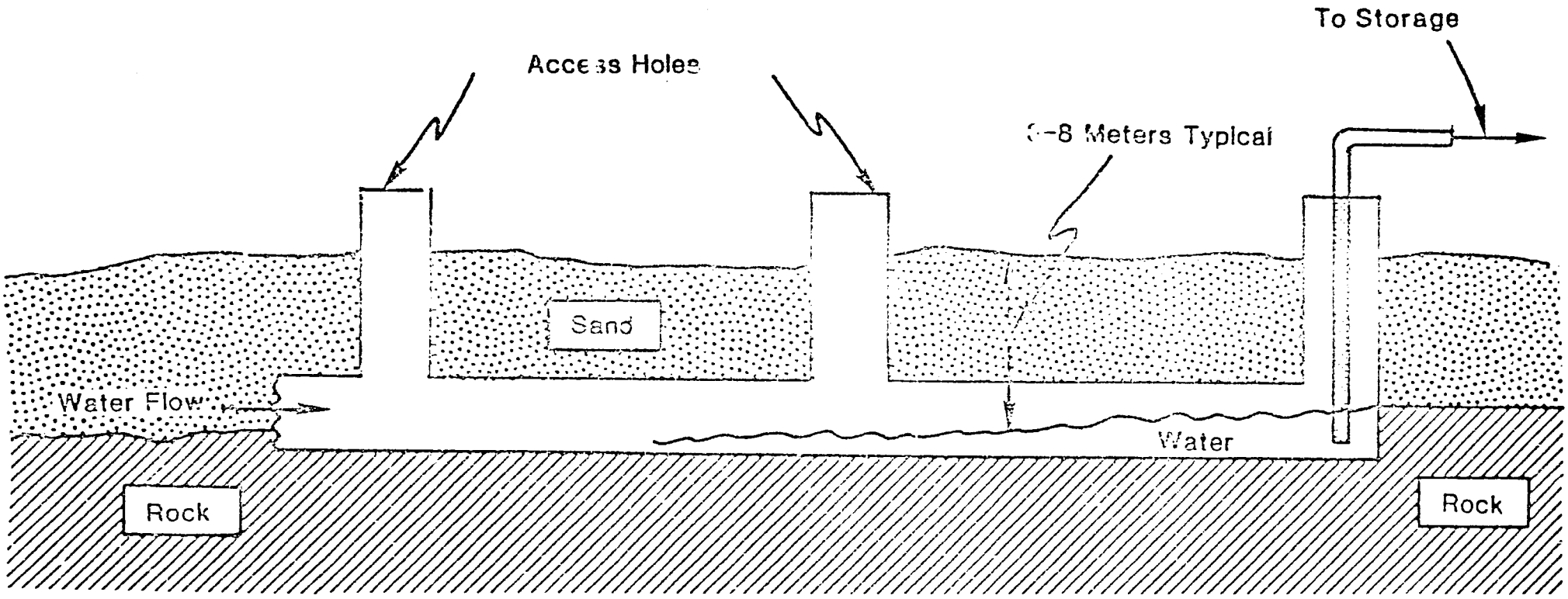

Exhibit 2-3
SCHEMATIC ILLUSTRATING WATER FLOW TO ROMAN WELL COLLECTION POINT

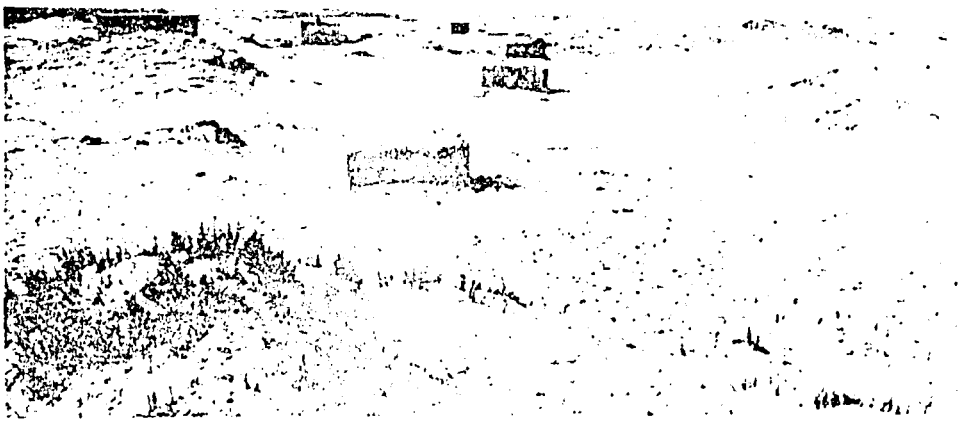

Exhibit 2-4
PHOTO OF BEACH AREA
WHERE ROMAN WELLS ARE LOCATED

View Looking West. Blocks in Middle of Photo are Access Ports for Roman Wells. Building on Left Is Pump House.

operational during the team's visit in November 1985. It is understood that since that time the units have been turned over to the governorate; however, no performance data are available. (See Exhibit 2-5.)

- El Kasr Central. At this site, water from two different Roman well collection areas and a conventional well is mixed and pumped either to vehicles or to Mowah via a pipeline. (See Exhibit 2-6.)

- El Kasr Extension #3. This is the site near the beach where water is collected in Roman wells. The team was told by Mersa Matruh officials that there was a similar site (El Kasr Extension #2) located nearby that had similar site characteristics. (See Exhibit 2-7.)

2.2.3 Scope of Field Test Hardware

The field test hardware will include:

- A reverse-osmosis desalination system capable of desalting brackish groundwater of varing salinity level and delivering 25 cubic meters of 500 ppm TDS or less product water per day

- A reverse-osmosis desalination system capable of desalting Mediterranean seawater and delivering 25 cubic meters of 500 ppm TDS or less product water per day

- Pump(s) and plumbing to transport product water from the Roman wells collection point or the Mediterranean Sea to the respective desalination systems

- Pump(s) and plumbing to transport product water to a holding tank and to interconnect the two desalination systems if required

- Photovoltaic array and associated structure and wiring

- Power conditioning system

- Battery bank for storage of energy from the PV array

- Auxiliary diesel generators

- Fence around PV array

- Building(s) to house the diesel engines, power conditioning systems, and desalination systems

- An evaporation reservoir or plumbing for reject brine.

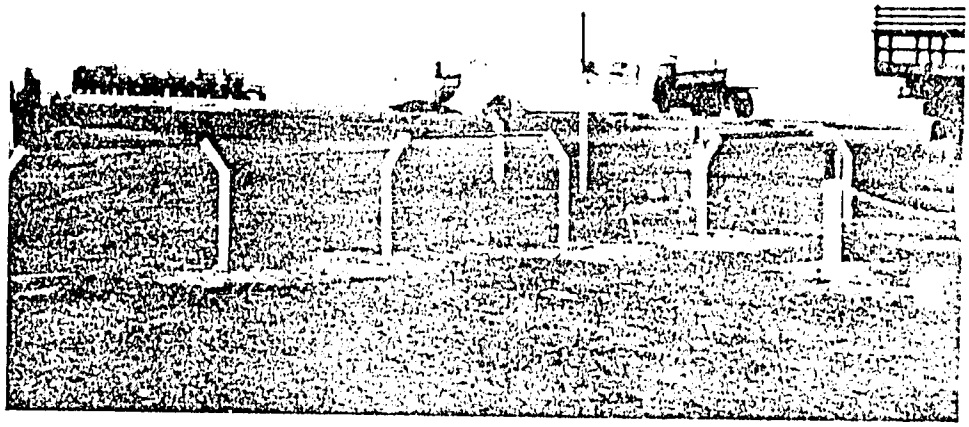

Exhibit 2-5
MOWAH CANDIDATE FIELD TEST SITE

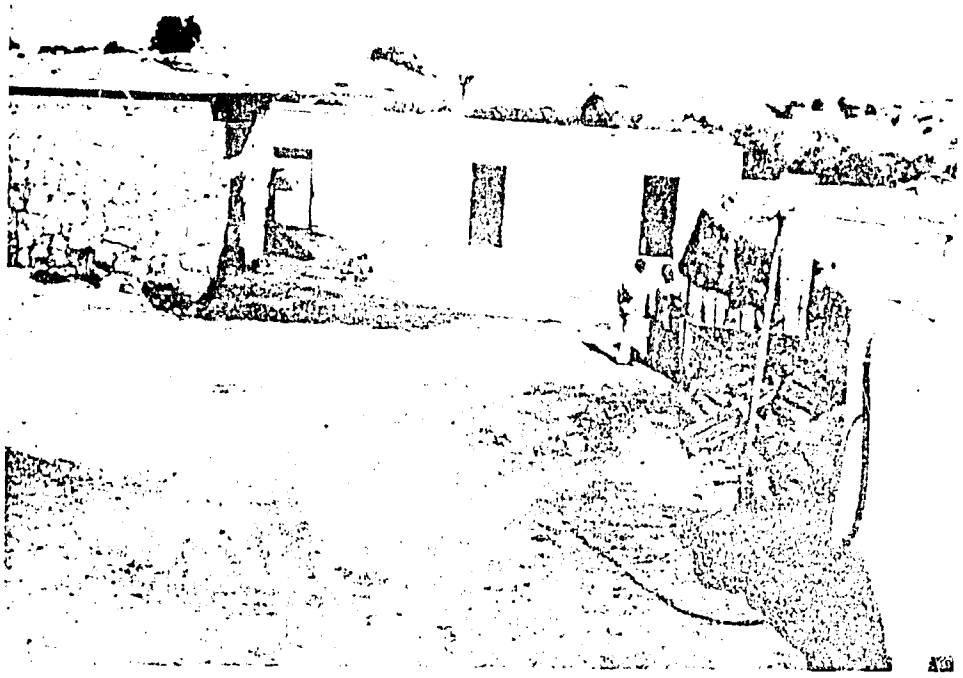

Exhibit 2-6
EL KASR CENTRAL FARM CANDIDATE
FIELD TEST SITE

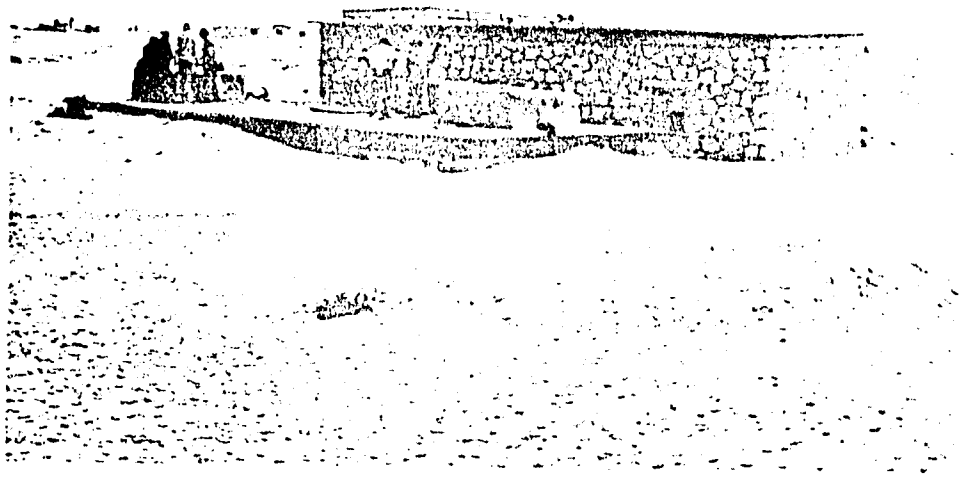

Exhibit 2-7
EL KASR EXTENSION #3 CANDIDATE
FIELD TEST SITE

2.2.4 Feedwater Quality

During the project team's visit in November 1985, groundwater samples were taken from each of the three sites visited. Additional groundwater samples were taken periodically over the following 10 months. Results of these analyses, completed by an EEA laboratory in Cairo, are presented in Appendix A.

These groundwater samples indicate a wide variability in salinity from a low of 359 ppm TDS on September 1, 1986 to a high of 13,397 ppm TDS on September 8, 1986. This large a difference in salinity in only one week from the same groundwater source is highly unlikely and therefore the accuracy of these data must be suspect. A similar conclusion can be made with respect to the low salinity level of 737 ppm TDS in June 1986, down from a level of 10,093 ppm TDS approximately two months earlier.

For the conceptual design in this document, the assumption was made that these three data points are in error. The resulting water quality data still suggests a highly variable salinity level for the groundwater from the Roman wells, i.e. a low of 6,380 in March 1986 to a high of 12,840 in September 1986. In fact, the USAID Project Paper that led to the Renewable Energy Field Testing Project mentions TDS levels in the El Kasr region as high as 12,000 ppm and as low as 1,000 ppm.[1] This variability has a significant effect on the desalination system design. An RO membrane must be chosen that can accommodate the operating pressures required to desalt 12,000ppm TDS feedwater while still performing in an efficient manner at the lower salinity levels. As shown in Section 5.2, point designs were developed for four salinity levels between the extremes documented in the USAID report and verified by the on-site EEA measurements.

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1 Egypt: Project 263-0123.2 Energy Policy Planning, Renewable Energy Field Testing and Utility Management Grant, 1983.

The requirement to accommodate a seawater feedwater source for this field test was specified in December 1986 (Appendix C). A sample of the Mediterranean Sea in the area of the Roman wells has not yet been obtained. In lieu of any measured data, the water quality analysis specified in the USAID Desalination Manual, August 1980 for an eastern Mediterranean location was used. Data from this analysis is presented in Appendix B. These data indicate a total salinity of 38,600 ppm TDS.

2.3. Requirement for Product Water Quality

The World Health Organization Guidelines for drinking water[2] are as follows:

Hardness (as $CaCO_3$) 500 mg/l

Hydrogen Sulfide - not detectable

pH - 6.5 - 8.5

Total Dissolved Solids - 500 mg/l

Taste and Odor - inoffensive to most consumers.

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2 Guidelines for Drinking Water Quality, Vol. 1, Recommendations, World Health Organization.

3.0 SITE LOCATION CONSIDERATIONS AND RECOMMENDATIONS

To arrive at a recommendation for the best site (of the three considered) for demonstration of a PV-powered brackish water desalination plant and a diesel powered seawater desalination plant, the following factors were considered although not necessarily in this order:

- Recommendation of Matruh governorate officials
- Terrain
- Accessibility
- Surroundings
- Proximity to sea
- Distance from Mersa Matruh
- Sociological factors.

3.1 Mowah

Mowah is located on an Army installation and already has an existing road network, water filling stations (for brackish water), and plumbing infrastructure. It is situated on the coastal desert plain approximately 1-2 kilometers from the sea. Land area is available to site a photovoltaic array, but it is not known if the array would infringe on other Army prerogatives. Mowah is the closest of the three sites to Mersa Matruh. Presumably, Mowah has personnel trained to maintain the two new diesel-powered electrodialysis units currently on the installation who would be able to maintain the PV-powered unit if it were located here.

There is a question at the Mowah site about the ability to objectively evaluate a PV-powered installation. If the PV-powered system were placed here, it would be difficult to objectively evaluate its sociological impact because the PV-powered reverse osmosis system would be located nearby two conventionally powered electrodialysis units with a capability to provide 20 to

40 times more product water than the PV system. It is also possible that the water provided by the system would be mixed with the water from the conventionally powered units, eliminating any opportunity to objectively evaluate the performance of the PV-powered unit.

3.2 El Kasr Central

El Kasr Central has seven 200 cubic meter concrete water storage reservoirs. These reservoirs and some equipment buildings are located within an area enclosed by a stone fence. There is provision to fill water trucks at this location. East of the stone enclosure is an area large enough to install a photovoltaic array; however, should the array be located here, some rearrangement of the truck access routes to the storage area might have to be made. El Kasr Central is located on a gently sloping hill (approximately 2-3 percent grade) from south to north, approximately 1 kilometer from the sea. the site is on desert terrain rather than a sandy beach. A gravelbed road runs east and west just to the south of the property.

Small farms and some houses surround the property. The officials from the Matruh governorate felt that the people from the surrounding village would not particularly welcome a PV array and there might be damage by vandalism.

3.3 El Kasr Extension #3

This site although not without some potential problems, is technically acceptable for the PV installation and is supported by the Matruh governorate officials. The reasoning behind this support is that El Kasr Extension #3 would provide a rigorous test for the system; therefore, if a PV-powered system works at El Kasr Extension #3, a replicated system would most likely work in other locations to the west and south of Mersa Matruh.

The proposed El Kasr Extension #3 site is located near the Roman wells.

Presently, the pumping station is powered by diesel engines located in stone-walled buildings. The terrain is near-white beach sand with outcroppings of rock. Access to the site with heavy construction equipment or delivery trucks will be difficult. The building that houses the pumps is approximately 50 meters from the shore of the Mediterranean. At this location, salt air corrosion would definitely be a problem.

There is currently no provision for dispensing water directly to a consumer. If this site is chosen, either a pipeline would have to be installed from the desalination equipment inland or a better road would have to be built for access by water trucks.

3.4 Seawater Desalination Plant Location

The seawater desalination plant should be co-located with the brackish water plant for ease of operation and maintenance. The plants can be physically located in the same building and perhaps share some operating instrumentation. The diesel generator for the seawater desalination plant will be sized to supply enough power to pump seawater approximately 200 meters from either a beach well near the Mediterranean shoreline or from the sea itself.

3.5 Recommendation

Exhibit 3-I summarizes the evaluation factors analyzed during the site selection process. Each of the three sites would be acceptable from a technical standpoint. There is sufficient unobstructed open space and a reasonably adequate feedwater supply. Since the three sites are generally equally acceptable and the Matruh governorate officials stated a preference for El Kasr extension #3, for purposes of the conceptual design, El Kasr Extension #3 will be considered the location of Field Test #8.

One variation to the site at El Kasr Extension #3 is recommended. The site of the desalination plant and photovoltaics array should be moved inland

EXHIBIT 3-1: SITE LOCATION FACTORS

Criteria	Mowah	El Kasr Central	El Kasr #3	Seawater Plant Location
Matruh governorate Officials Support	No	No	Yes	Yes
Terrain	Desert-Flat	Desert, rocky, slightly sloping south to north	Sandy beach	Sandy beach
Accessibility	Good	Good	Difficult	Difficult
Surroundings	Army Installation	Farms	Beach	Beach
Proximity to Sea	1-2 kilometers	1 kilometer	50 meters	200 meters
Remoteness	About 10 km from Mersa Matruh on Army Installation	About 15 km from Mersa Matruh	About 20 km from Matruh; Scattered Houses inland	About 20 km from Matruh; Scattered Houses inland
Sociological Factors	On Army Base with existing Water Infrastructure	Population around site may be opposed to having a PV-array located here	Loose population group that can form bases for a community	Loose population group that can form bases for a community
Water Supply Availability	Yes	Yes	Uncertain during dry season	Unlimited
Water Quality (ppm TDS)	5,520 (Based on 1 Data Point)	7,080 (Based on 1 Data Point)	6,380-13,397 (Based on Data Set in Appendix B)	38,600 (Based on data in Appendix B)

approximately 200 meters so that it is no longer located on the beach sand.

This relocation would accomplish the following:

- The base for the buildings and the PV array would be more stable.
- Access to the building site for construction equipment would be less of a problem.
- There would be less of a problem with salt air corrosion and blowing beach sand.
- It would be easier to set up a system for access by the villagers or water distribution trucks to the product water after the plant is operational.

4.0 TECHNOLOGY REVIEW SUMMARY

Field Test #8 is composed of commercially available subsystems that have been in operation worldwide. These subsystems include:

- o Desalination (either electrodialysis or reverse osmosis). Both of these technologies have been proven effective when the systems are designed correctly and when proper maintenance is performed. For a detailed description of the principles of operation, see the Technology Review (Section 5).[3]

- o Photovoltaics. Photovoltaics have repeatedly been shown to be the least troublesome part of a remotely located PV-powered application.

- o Diesel gensets. Diesel generators are considered the standard standalone power source. Their performance is well documented and predictable.

- o Controllers. Controllers for battery charging and power conditioning to the loads are available from a number of vendors. They are considered proven components.

- o Batteries. Batteries designed for photovoltaic applications are available from several sources, many of which have outlets in Egypt or the Middle East.

- o Inverters. Inverters have had a less-than-perfect performance record in stand-alone applications. If possible, the loads should be D.C. to avoid inverter use.

To date, there has been limited experience with PV-powered desalination systems. Mobil Solar has sponsored two reverse osmosis installations in the Middle East: one in Jeddah, Saudi Arabia, and one in Doha, Qatar, United Arab Emirates. In addition to these projects, the EEA has a functioning reverse osmosis PV-powered experiment at the High-Tension Laboratory north of Cairo. There are currently no PV-powered electrodialysis installations in operation. The principal conclusions that come from the FT #8 Technology Review are:

- o Either reverse osmosis or electrodialysis technologies are appropriate for this application.

- o Although there is limited experience with PV-powered desalination equipment, there is extensive experience with all of the component

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[3] Technology Review for Field Test #8, Meridian Corporation, April 1986.

technologies. There appears to be no technical reason why these technologies cannot be combined into a successful system.

- Monitoring and maintenance of the desalination subsystem is mandatory.

- There are significant differences in the hardware, principles of operation, and power requirements between reverse osmosis and electrodialysis systems. Exhibit 4-1 summarizes these features.

EXHIBIT 4-1

Comparison of Reverse Osmosis and Electrodialysis Features

Factor	Reverse Osmosis	Electrodialysis
Scientific Principle	High pressure on feedwater side of membrane; reverse osmotic pressure passes product water, brine stays behind	Ions of dissolved impurities are attracted to positive or negatively charged electrodes leaving product water behind
Technology Maturity	Many large plants in operation with conventional power	Less mature technology; mostly in brackish water; smaller applications
Typical Salinity Range Applications	All salinities	Lower salinities are found in brackish water
Tolerance to Change in Salinity from Design Case?	Yes, at a cost of higher power consumption and lower flow rates	Yes, at a cost of higher power consumption and lower flow rates
Tolerance to Change in Power Supply	No, decreased performance in product water quality	Yes, flow rate and power to electrodes are automatically adjusted
Primary Electrical Load	High pressure pumps	Current flow to electrodes
Specific Power Consumption (KW-HR/m^3 of Product Water)	For 1000 TDS - 0.90 For 12000 TDS - 1.81	For 1000 TDS - 0.61 For 12000 TDS - 6.67
Capital Costs - Estimated ($ per m^3 per day capacity)	Large Municipal - 200 Industrial - 260 Small (<200m^3/day) - 530 Seawater 790 - 1060	Industrial - 260 Small (<200m^3/day) - 530

5.0 CONCEPTUAL DESIGN

5.1 Background

The following application requirements and/or data were stated in the preliminary conceptual design in the original RFP for the REFT Project, developed from the November 1985 site visit, or requested in various documents in Appendix C.

- Output is to be 25 cubic meters of potable water (500 ppm TDS or less) per day.
- Feedwater is to be taken from one of the three water sources: Mowah, El Kasr Central, or El Kasr #3. A backup source of water is the Mediterranean Sea.
- The desalination method is to be either reverse osmosis or electrodialysis.
- Five different water quality samples were analyzed. Details are in Appendix A. The TDS ranged from a low of 359 ppm to a high of 13,397 ppm. (The low and perhaps the high TDS values are suspect.)
- The power is to be supplied by a photovoltaic array.

On November 14, 1985, the potential plant sites were visited and the Matruh governorate officials were interviewed about their recommendations. Details of this visit are provided in trip reports by Mr. James Hoelscher and Mr. Bruce Watson. (Appendix D).

5.2 Engineering Approach

A step-by-step procedure was used to develop the conceptual design. These steps are:

1. Choose Desalination Technology (Reverse Osmosis or Electrodialysis)
2. Choose Operating Procedures for Desalination Equipment
3. Design the Desalination Equipment.
4. Choose Type of Photovoltaics Technology
5. Choose Power Subsystems Protocol, i.e. all-PV, PV-battery, PV-Diesel Hybrid or a combination.
6. Design the Photovoltaics Array, Battery Storage System and Specify Diesel Engine (if appropriate).

7. Design the Storage Tank

8. Specify Brine Rejection System

9. Specify Site Layout of Entire Installation

10. Specify Instrumentation.

5.2.1 Step 1. Choose Desalination Technology (Reverse Osmosis or Electrodialysis)

Several analyses were done to determine the power required to do desalination at various TDS levels using both reverse osmosis and electrodialysis units. The basic assumptions for each case were:

- o Feedwater of about 1,000, 7,000, and 12,000 ppm TDS. Components were scaled from one El Kasr Extension #3 water quality analysis of about 7,000 ppm TDS.
- o Product Water is to be less than 500 ppm TDS. Note: Two different flow rates of product water were used - 15 cubic meters per day for electrodialysis and 25 cubic meters per day for reverse osmosis; however the figure of merit (Cubic meters of product water per day per kWhr) are not materially affected by the absolute flow rate).

Three different options were considered:

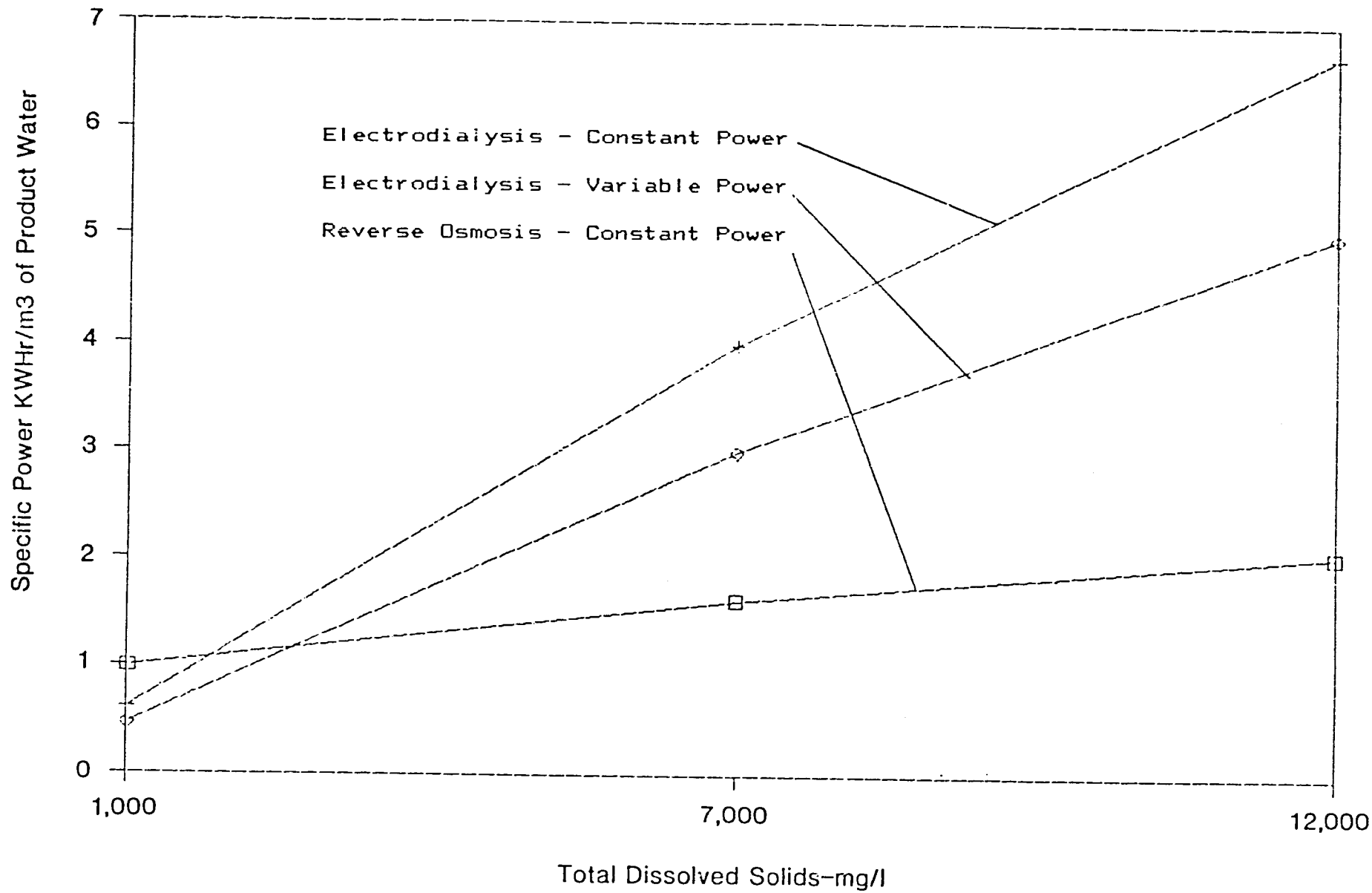
- o Reverse Osmosis only - constant power to equipment
- o Electrodialysis only - constant power to equipment
- o Electrodialysis - variable power - this option takes into account the fact that electrodialysis is more compatible with a variable DC power source such as Photovoltaics or a battery.

Details of the designs are in Appendix E. The results are:

	Specific Energy (kWh/m^3)		
TDS (mg/l)	1000	7000	12000
Reverse Osmosis	0.99	1.62	2.06
Electrodialysis	0.61	4.00	6.70
Electrodialysis-Variable Power	0.46	3.00	5.03

The results are displayed graphically in Exhibit 5-1.

Exhibit 5-1
Comparison of Electro dialysis and Reverse Osmosis
Specific Power Consumption



It can be seen by examining Exhibit 5-1 that while all specific power figures increase with increasing salinity, the Reverse Osmosis specific power figures increase at a slower rate than either of the Electrodialysis options. If one extrapolates the specific power required to the higher salinity of 13,397, the highest figure measured, then the specific energy would be:

Electrodialysis	-	8.02 $kWhr/m^3$
Electrodialysis (Variable Power)	-	6.02 $kWhr/m^3$
Reverse Osmosis	-	2.30 $kWhr/m^3$

Based on this analysis and the fact that there are two water quality analyses which show that salinity is above 12,000 TDS, we recommend that the unit be reverse osmosis. The fact that sea water from the Mediterranean is to be used as a backup feedwater source (with a TDS of 36,000+) makes this an even clearer choice.

5.2.2 Step 2. Choose Operating Procedure for Desalination Equipment.

The next choice to be made is the operating procedure of the desalination system. We want to make a choice on whether to operate the desalination unit continuously over 24 hours or perhaps some variation in which the duty cycle would approximate the insolation pattern.

From a point of view of the desalination equipment, reverse osmosis units like to be operated on a steady state basis. During September, 1986, the FT #8 trainees toured three different reverse osmosis plants in Florida which were fed by feed water from brackish wells. All the plants worked very efficiently and continuously. In discussions with the operators of those plants, the point was made that while the plants were capable of being started again after shutdowns because of power outages or other reasons, it clearly is not a good mode of operation. The seasonal variation at El Kasr in salinity will cause

Option & Description	#1 Brackish Water Only	#2 Seawater Only	#3 Integrated System	#4 More Efficient Integrated System
Feedwater Salinity TDS (mg/l)	1000-12000	38,404	38,404	38,404
Input Flow Rate m^3/hr	1.9	2.6	2.6	2.6
Pump Pressure Kg/cm^2	13-32	62	60	60
Recovery (Percent)	55	40	1st Stage 50 2nd Stage 55	1st Stage 50 2nd Stage 80
Specific Energy $kWhrs/m^3$ product water	0.99-2.06	5.57	7.51	6.00
Estimated Capital Cost ($) Desalination System (Does not include Power system)	26,800	35,200	87,600	101,800

EXHIBIT 5-2

Summary of Various Desalination Options

enough problems without designing in a daily start/stop complication. This Field Test also has the advantage of the equipment being designed for a comparatively low flow rate (about 1 m^3/hour or 17.4 liters/minute) and thereby allowing the use of small membranes, plumbing, etc. On the other hand, there is no room for expansion should there be a need for it. The limit of the capacity is 25 m^3/day.

We recommend that the reverse osmosis units be operated on a steady cycle for 24 hours

5.2.3 Step 3. Design the Desalination Equipment

There are two main complicating factors that must be addressed in the design of the desalination equipment for this Field Test:

- o Variable Salinity in the brackish water supply.
- o Alternate feedwater source being seawater which requires a totally different design and equipment.

Several different options were considered to address this.

- o Option 1 addresses only the variably brackish feedwater.
- o Option 2 addresses only the seawater feedwater.
- o Options 3 and 4 are integrated systems in which the effluent from the seawater stage is the feedwater for the brackish system.

The results of the three investigations are summarized in Exhibit 5-2 and detailed in Appendix F.

By looking at the various options in Exhibit 5-2 one can conclude that it is less expensive (from a desalination hardware standpoint) to build separate seawater and brackish water desalination systems rather than an integrated system. It is also less complex and therefore more reliable to do this. Our recommendation is therefore to build separate seawater and brackish water desalination units. The method of powering each unit will be determined in

subsequent steps. It should be stressed that even though there are two separate desalination units, both the units can be housed in the same building side-by-side. The outer appearance of the two units will be very similar. The desalination unit fed by seawater will have the following characteristics:

- Single Stage System
- 40% Recovery
- Two powered vessels which each contain six elements (membranes)
- Product flow = $25m^3$/day
- Product TDS = 407 mg/l
- Maximum pressure = 62 kg/cm^2
- Recommended membrane - Film Tech SWHR4040
- Brine Flow = 36 m^3/day
- Brine TDS = 63,731 mg/l
- Powered by Diesel Engine genset
- Energy required for $25m^3$ of product water = 139.5 Kwh

The desalination unit fed by brackish water from the Roman wells will have the following characteristics:

- Single Stage System
- 55% Recovery
- One vessel which contains 6 elements (membranes)
- Product Flow = 25 m^3
- Product TDS = 475 mg/l
- Maximum Pressure = 32 kg/cm^2
- Recommended Membrane-Film Tech Model BW 4040
- Brine Flow = $19.2m^3$/day
- Brine TDS = 25,613 mg/l
- Powered by PV or PV/hybrid
- Energy required for $25m^3$ of Product Water = 51.57 kWhr.

Exhibits 5.3 and 5.4 are schematics of the two desalination units.

5.2.4 Step 4. Choose Type of Photovoltaics Technology

Several design choices must be made regarding the photovoltaic array. These choices are:

- Stationary vs. one- or two-axis tracking
- Thin film (amorphous silicon) vs. crystalline silicon
- Concentrator vs. flat plate
- Fixed tilt vs. movable tilt.

In keeping with the goal of using uncomplicated project hardware and minimizing complex equipment that may suffer breakdowns because of over-sophistication, we recommend that neither one- nor two-axis tracking systems be used. Though these arrays offer some gain in effective energy efficiency (more energy collected per unit time), the danger of having a long downtime because of a mechanical or control system breakdown is not considered worth the risk.

During the last year or so, thin-film power modules (modules of about 1000 cm^2 in area) have been introduced by several U.S. companies. There are predictions that within a short time these modules may become less expensive ($/watt) than crystalline silicon modules and may approach crystalline modules in reliability and stability. These predictions have not yet been proven in service. Therefore, the request for proposal should not disallow thin-film power modules, but, if they are proposed, the evaluation committee should require assurance of the stability and reliability of these modules and assurance of the business stability of the manufacturer of the module. Single crystal or poly-crystalline silicon modules are considered the industry standard.

Concentrator modules have not achieved wide acceptance and, therefore,

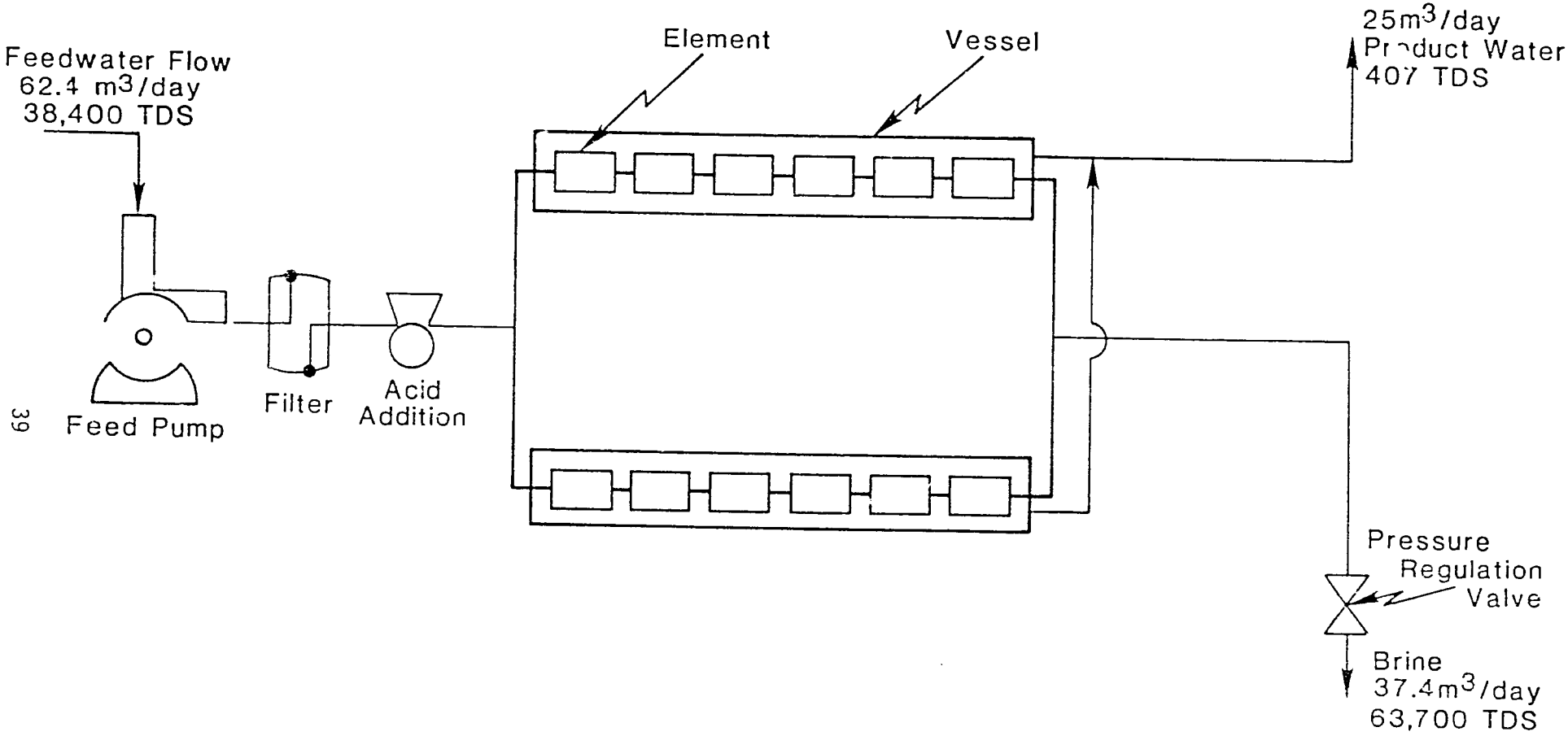


Exhibit 5-3
SEAWATER DESALINATION PLANT FLOW DIAGRAM

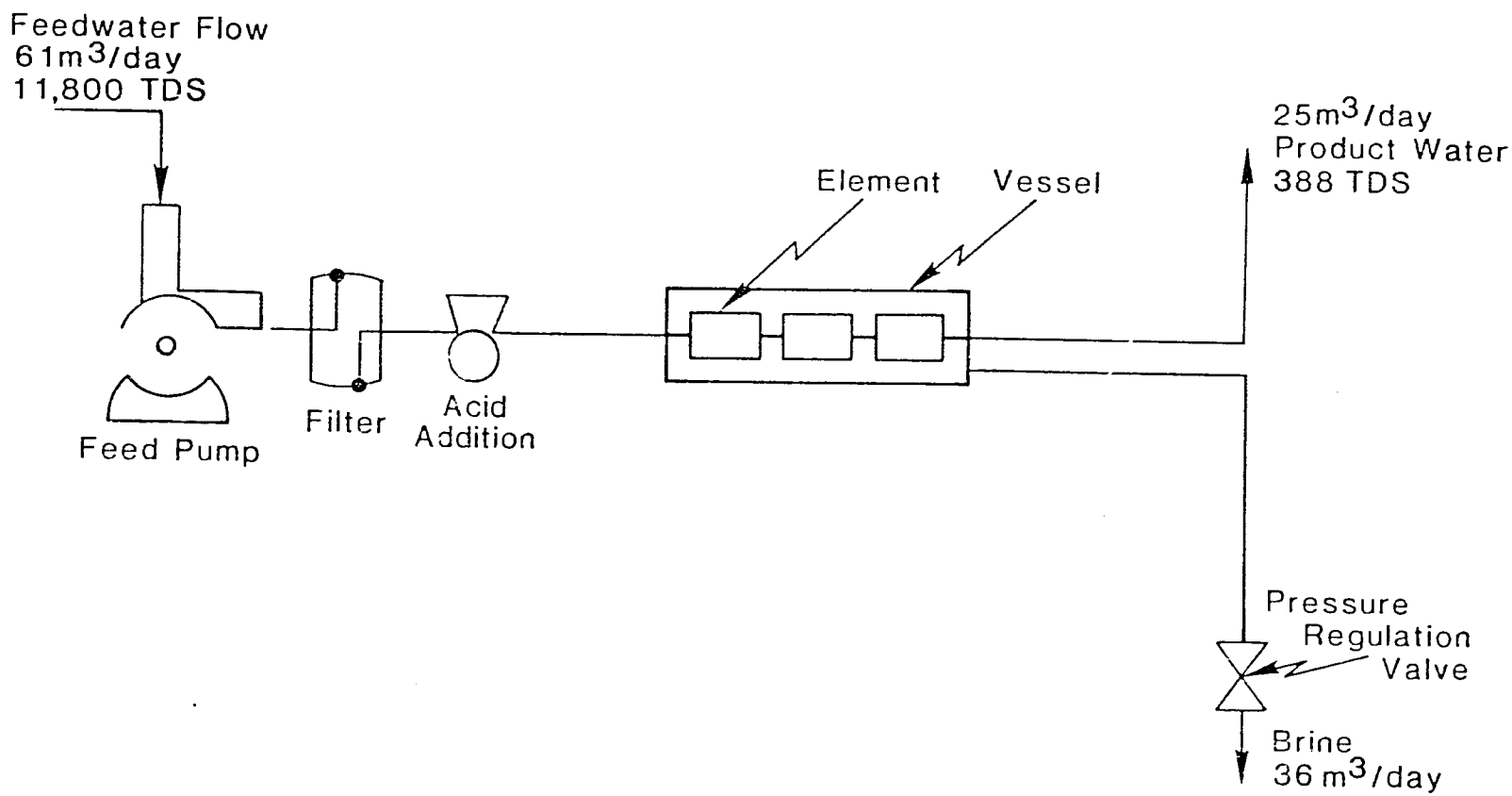


Exhibit 5-4
BRACKISH WATER PLANT FLOW DIAGRAM

their industrial base is not very broad. Pointing accuracy must be controlled to within one degree or so. This requires an electrical control system and mechanical hardware which may be overly complex and not easily maintained or repaired in a remote area such as El Kasr.

In keeping with the spirit of design simplicity, a variable tilt array is not recommended. Not using a variable tilt array results in a slightly simpler (and hopefully less expensive) structure. Exhibit 5-5 illustrates the effect of using differing tilt angles for the array. One can see that during the May-August time period, a flatter tilt would result in more solar energy being intercepted by the array. But (as will be developed in Step 5) we are designing for the worst case month, December. Having a flatter inclination would worsen the December insolation and result in a larger PV array to provide a given power output. We therefore recommend that the tilt of the array be consistent with usual design practice equal to the latitude which is about 32°.

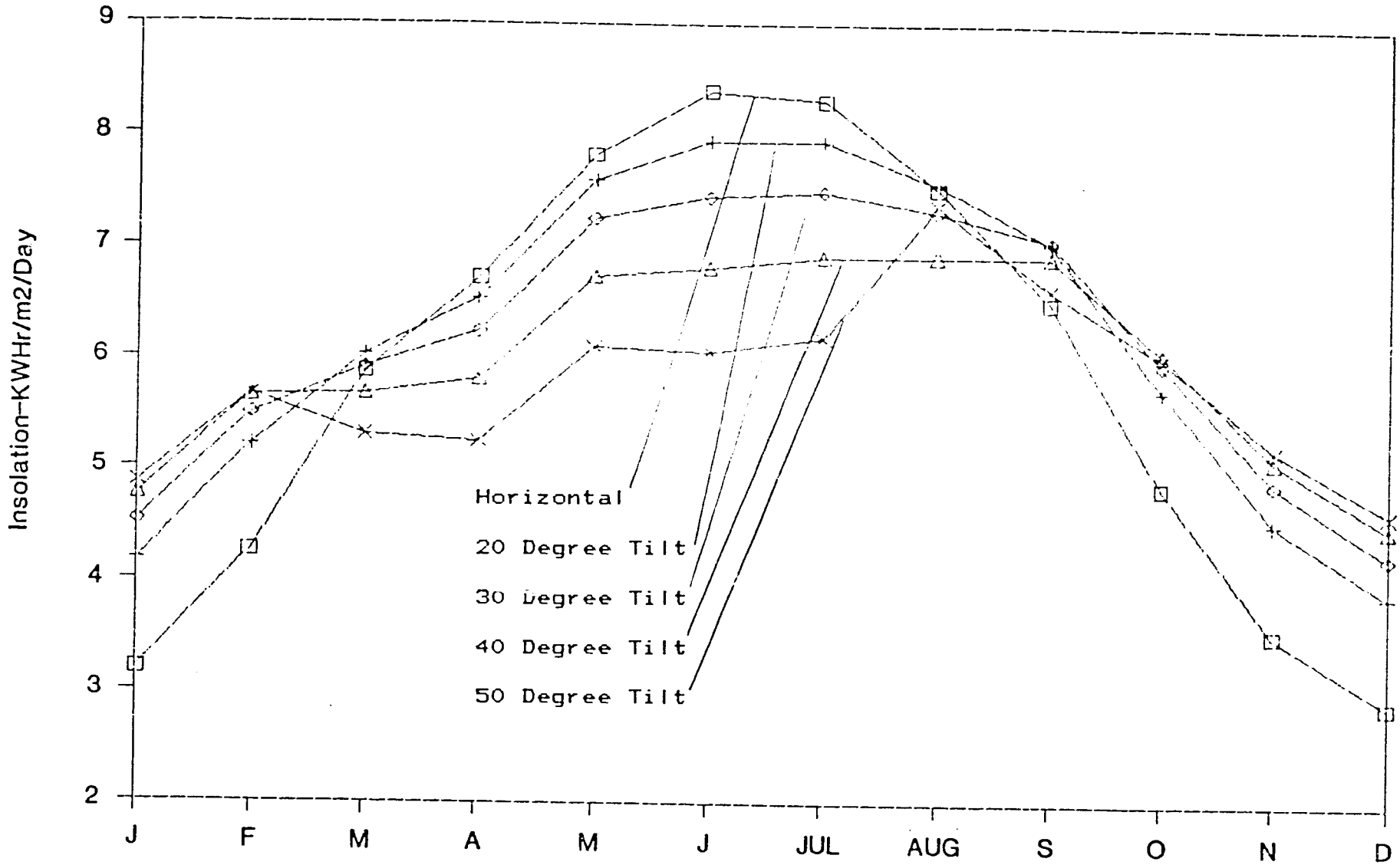
In summary, we recommend that the <u>PV array be a fixed, flat-plate array (with a 32° tilt) composed of crystalline (single or poly) silicon solar cell modules.</u>

5.2.5 Step 5. Choose Power Systems Protocol

Based on recommendations from Step 3, these are to be two separate reverse osmosis plants, one for seawater and one for the brackish water supply. The energy requirement for the seawater plant is 139.5kWh/day and the brackish water plant is 51.57 kWhrs per day. In accordance with the directions contained in Appendix C, three different power options will initially be considered for powering the desalination equipment.

- PV and battery storage only, diesel generator for backup only.
- PV (with one day battery storage) for 8 hours operation and 16 hours of diesel operation.

Exhibit 5-5
Insolation as a Function of Various Tilt Angles



o PV and Diesel with no battery storage.

The choice of the best option must be determined from the information developed in the next step.

5.2.6 Step 6. Design the Photovoltaics Array, Battery Storage System and Specify Diesel Engine

The requirements of the design are that 25 m^3 of product water be produced daily. There is no mention of seasonal variation, so the PV array sizing must be designed for the worst case insolation month. Data[6] are as follows:

Month	Daily Solar Insolation on a 32^0 Surface KW-Hrs/m^2 at Mersa Matruh	Mersa Matruh Ambient Temp ^oC
JAN	4.56	12.8
FEB	5.52	13.0
MAR	5.88	15.1
APR	6.16	17.4
MAY	7.17	20.1
JUN	7.35	23.3
JUL	7.41	24.9
AUG	7.26	25.5
SEP	7.04	24.3
OCT	5.98	21.6
NOV	4.92	18.1
DEC	4.28	14.4

The worst month from an insolation standpoint is December with an insolation of 4.28 kWhrs/m^2.

The first option to consider is the one in which the PV array and battery bank provide all the energy for the array. (A diesel is there for backup only).

A first approximation of the PV array size is provided by the following formula (See Appendix G for derivation).

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6 Irene Sakr, Masters Thesis, Modelling of Photovoltaic Generators. Aim Shams University, 1984

$$\text{PV Array Size} = \frac{\text{Load} + \text{Losses}}{(\text{Time})\ (\text{Operating})\ (\text{P.C.})}$$

Where:

PV Array Size	=	Rated Power at Standard Conditions at a given tilt angle (watts)
Time	=	No. of full sun hours equivalent (Hours)
Operating	=	Efficiency factor that takes into account a derating because of temperature effects and wiring losses in the array field (dimensionless)
P.C.	=	Efficiency that takes into account the losses associated with channeling power through the power conditioning equipment (dimensionless)
Load	=	Load (kW) times duration (Hr) yielding kW-Hr

First the power system for the brackish water system will be examined.

The "Load" term from Step 5 is 51.57 kWhr/day.

The "Losses" term is primarily from the conversion of electrical energy to chemical energy (and back) from battery storage. We assign that value 20% of the load.

The "Time" (Previously determined) is 4.28 hours.

The " Operating" Term is 0.88 from temperature effects and wiring losses

The " P.C. = 0.90 (from manufacturer's data)

Substituting these values:

$$\text{PV Array Size} = \frac{51.57 + (0.20)\ (51.57)}{(4.28)\ (.88)\ (.80)}$$

$$= 20.53 \text{ kW}$$

This value will be used as a starting point for using the PV-f Chart.

Using the same analytical approach, the amount of PV required for the seawater plant would require 55.55 kW of PV (peak power).

The second option is to provide PV with one day of battery storage for 8

hours of operation only. During the remaining 16 hours, a diesel will provide the energy for the desalination equipment.

Using the same general formula as before:

$$\text{PV Array Size} = \frac{\text{Load} + \text{Losses}}{(\text{Time})\ (\eta\ \text{Operating})\ (\eta\ \text{P.C.})}$$

Where:

PV Array Size	=	Rated Power at Standard Conditions at a given tilt angle (watts)
Time	=	No. of full sun hours equivalent (Hours)
η Operating	=	Efficiency factor that takes into account a derating because of temperature effects and wiring losses in the array field (dimensionless)
η P.C.	=	Efficiency that takes into account the losses associated with channeling power through the power conditioning equipment (dimensionless)
Load	=	Load (kW) times duration (Hr) yielding kW-Hr

In this case, the Load is for 8 hours or 1/3 day. The other terms will remain the same. Substituting numbers in the formula yields:

$$\text{PV Array Size} = \frac{(51.57) + (0.20)(51.57)}{(4.28)(.88)(.80)}$$

$$= 6.85 \text{ kW}$$

This value will again be refined by use of the PV-f-chart.

Using the same analytical approach, the amount of PV required for the seawater plant would require 18.53 kW of PV (peak power).

The third option is to use a PV-diesel option only with no battery storage.

We do not recommend this option because it causes problems with the desalination equipment, unpredictability of product water quality, and probable shortening of the diesel engine's lifetime due to frequent starts and stops. For instance, during a day in which there are scattered clouds in the sky, as soon as a minimum value of insolation occurs the pumps will stop until the diesel engine gets up to speed and engine temperature. If the sun then returns, the engine will be turned off, perhaps to be repeated many times per day. Diesel engines do not tolerate this type of stop/start well and it will affect the lifetime and operations and maintenance costs negatively.

Summarizing, the primary features of the two requested (in Appendix C) options are:

Option	PV Array Size Required-KW	
	Brackish Water	Seawater
PV/Battery Bank Only-Diesel for Backup	20.53	55.53
PV/Battery Bank for 8 hours Diesel for 16 hours	6.85	18.53
PV/Diesel Hybrid with no Battery	Not Analyzed	

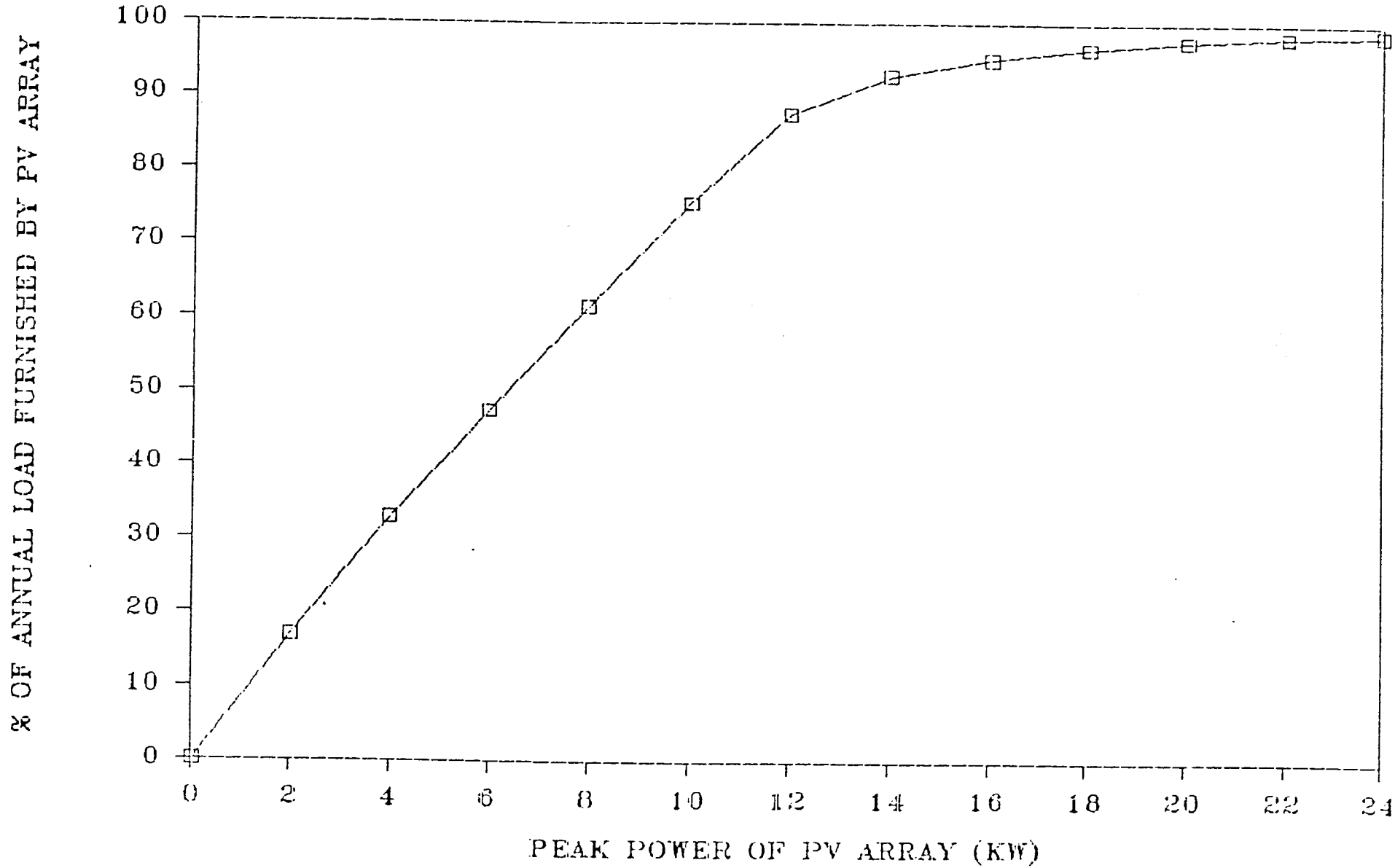
At this point, the designer must make some basic recommendations which involve the philosophy of this particular Field Test, economics, and technical

considerations.

The Mediterranean seawater source is an alternate supply (Ref. 3) for feedwater. As such, depending on the philosophy of the operation, it may not be used but a few weeks or months per year. This Field Test is designed for brackish feedwater. It would not be consistent with the objectives of the project for an "alternate" feedwater source, (in this case the Mediterranean) to use a PV array nearly three times as large (55 desalination plants. Accordingly, we recommend that the desalination equipment designed for seawater be powered by a diesel genset and that the renewable energy (PV) objectives be demonstrated using only the brackish water equipment.

The tentative PV array size previously determined is a point design based on the worst insolation month of the year (December). In order to look at the effect during the entire year, a series of runs were made using the PV-f-Chart. The input parameters of the runs are contained in Appendix H. Loads are a constant 2.145 kW (51.57 kW-Hr per 24 Hours) which was calculated in Step 3. Other input data were based on commonly accepted performance data or conditions determined in earlier steps. Only the array power was varied from 0 to 24 kW. The output parameter which is of most interest is the "F" term which in the summary table is the percent of annual or monthly power which the PV array or the battery furnish the load. A graph was constructed in which the independent variable is the array peak power (at standard conditions) and the dependent variable is the "F" factor. This graph (Exhibit 5-6) shows that when the array is about 24 kW, the percent of annual load furnished by the array and battery is about 98.6%. However, upon closer examination, it can be seen that an array about half that size (about 12 kW) furnishes about 87.7% of the load. Another way of looking at this result is that increasing the array by 12 kW only contributes to (98.6 - 87.7 percent) an increase of 10.9 percent of the load.

Exhibit 5 - 6
PERCENT OF ANNUAL LOAD AS A FUNCTION OF PV ARRAY SIZE



To get a clearer picture of this, a second graph (Exhibit 5-7) was constructed. Instead of plotting the load factor on the y-axis, the number of PV annual average daily hours of operation are plotted. One can see that the curve is essentially a straight line until about 12 kW. After that point, the marginal return for increase in performance is much less for each peak watt of PV array increase.

To examine the situation further, one more plot (Exhibit 5-8) was constructed which illustrates the average PV-battery duty cycle during each month using an array of 12 kW of power.

From this exhibit it can be seen that even with the smaller (12 kW) array, 100% of the load is furnished by the PV array/battery storage during the summer months. It should be stressed that this gives an average picture based on sparse data. On any given day the diesel genset may run many more or fewer hours than indicated on the graph.

This situation is excellent for consideration of a PV diesel hybrid system.

We recommend that the PV array be about 12 kW (peak power) and that there be a diesel genset controlled by a controller which will turn the genset on when the battery voltage is below the minimum charge level (a PV-diesel hybrid system).

The cost breakout of the various options is shown below. The following assumptions were used to calculate the costs:

Array Cost	=	$10,250/kW
Battery Cost	=	$ 182/kWh
BOS Cost	=	$ 500/kW
Diesel Engine Cost	=	$ 800/kW
Array Lifetime	=	$ 20 years
Battery Life	=	10 years
Discount Rate	=	10%
Array Efficiency	=	9%
Fuel Cost	=	$ .21/liter
Fuel Efficiency	=	1.5 kWh/liter

Exhibit 5 - 7

HOURS OF OPERATION OF ANNUAL LOAD AS A FUNCTION OF PV ARRAY SIZE

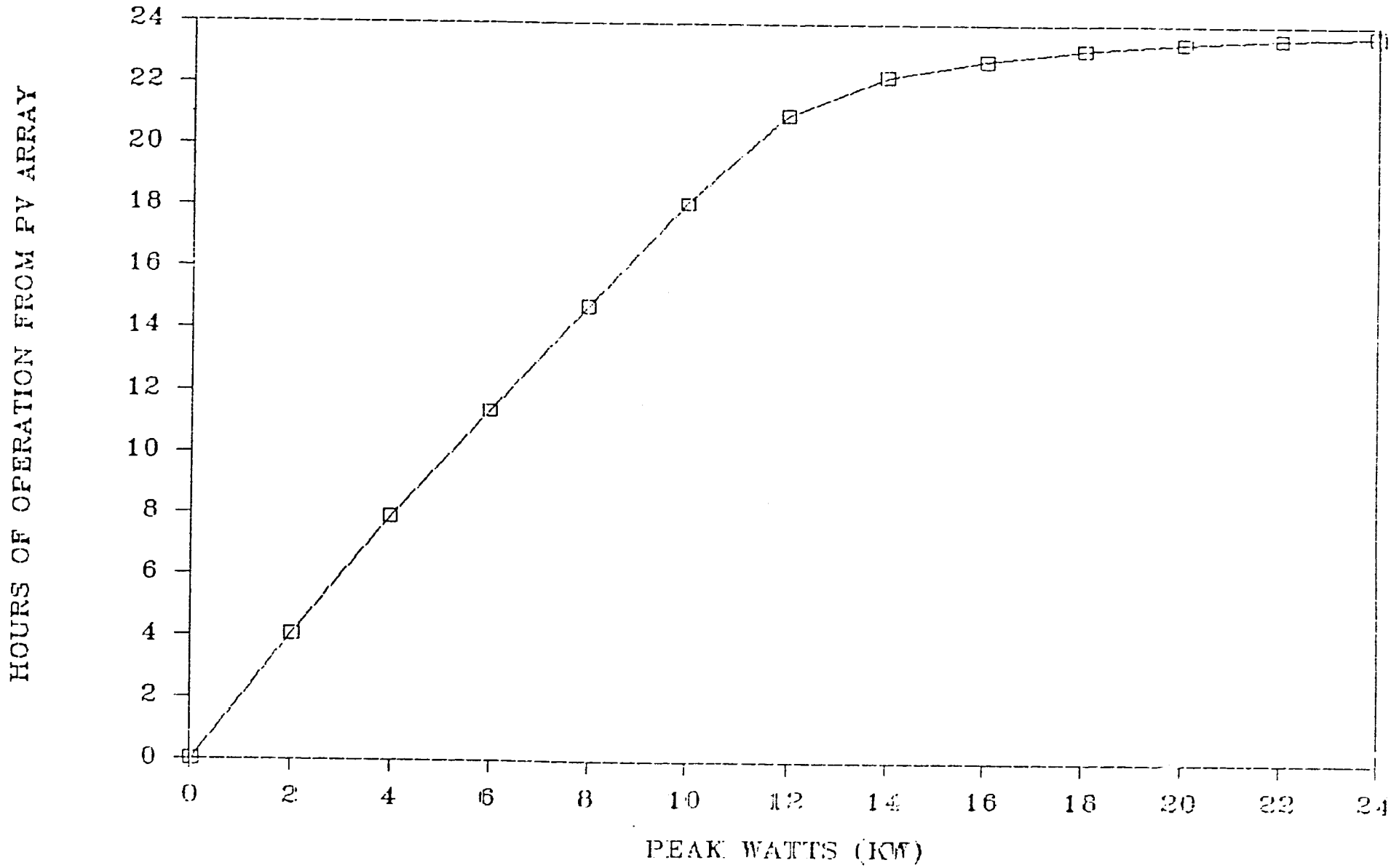
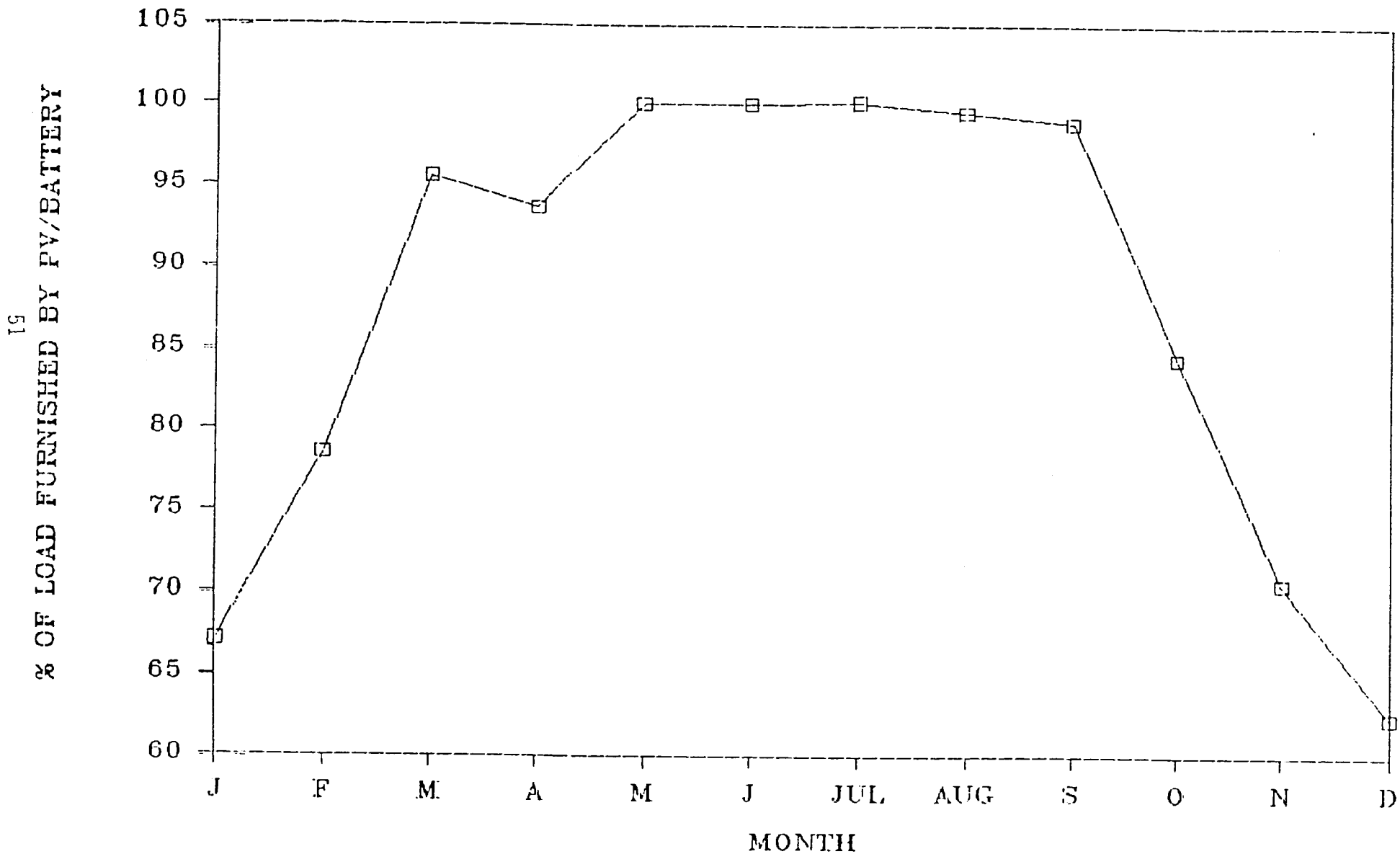


Exhibit 5 - 8

PERCENT OF LOAD FURNISHED BY PV/BATTERY STORAGE (MONTHLY BASIS)



From these assumptions we can determine the following matrix:

	Option 1 PV/Battery Bank Only Diesel for Backup	Option 2 PV/Battery Bank for 8 Hours Diesel for 16 Hours	Hybrid Option 12 kW Array
PV Capital Cost	245,385	81,795	123,000
Battery Cost (One Day)	10,938	3,646	10,938
BOS Cost	11,970	3,990	6,000
Diesel Engine Capital Cost	4,000	4,000	4,000
Diesel Fuel Cost over 20 years (Present Value)	---	34,802	6,421
Diesel O&M Cost for 20 years (Present Value)	---	5,108	5,108
Total (Power System)	271,740	132,621	155,467

We recommend the hybrid option. It is consistent with the principles of the Renewable Energy Field Test project and will provide an excellent side-by-side cost and technical performance comparison to the conventionally powered seawater plant.

To get an acceptable input voltage and current to the pump motor, decisions must now be made regarding the series-parallel arrangement of the PV modules. Assume that the nominal voltage of the battery bank is 240 V (chosen because the industrial standard DC motor voltage is 240 V) output when the battery bank state of charge is 50 percent. The output voltage will be approximately 1.70 volts per cell. When the battery bank is 100 percent charged, its voltage per cell will be approximately 1.9V/cell.[7] To provide an efficient charging voltage at all parts of the operating range, the voltage of the photovoltaic array would have to be approximately 2.3 volts per (battery) cell. Using this data, the number of battery cells in series can be calculated as follows:

$$\text{Number of Battery Cells in Series} = \frac{\text{System Voltage}}{\text{Volts per cell at lowest state of charge}}$$

$$= 240 \text{ Volts}/1.75 \text{ Volts/Cell} = 126 \text{ cells}$$

At near 100 percent state of charge, PV array voltage must be 2.3 volts per cell or 315 volts.

To assure that the PV array will be effective even at the hottest temperature encountered, the voltage degradation due to temperature must be taken into account. A typical value for crystalline silicon is -2.4×10^{-3} V/^{o}C per cell in series.[8] This means that if a 50°C operating temperature for the array is assumed, then, to deliver 315 volts, an array capable of delivering 359 volts at 25°C is needed. This is equivalent to approximately 741 cells in series assuming an operating voltage of 0.485 volts per cell.

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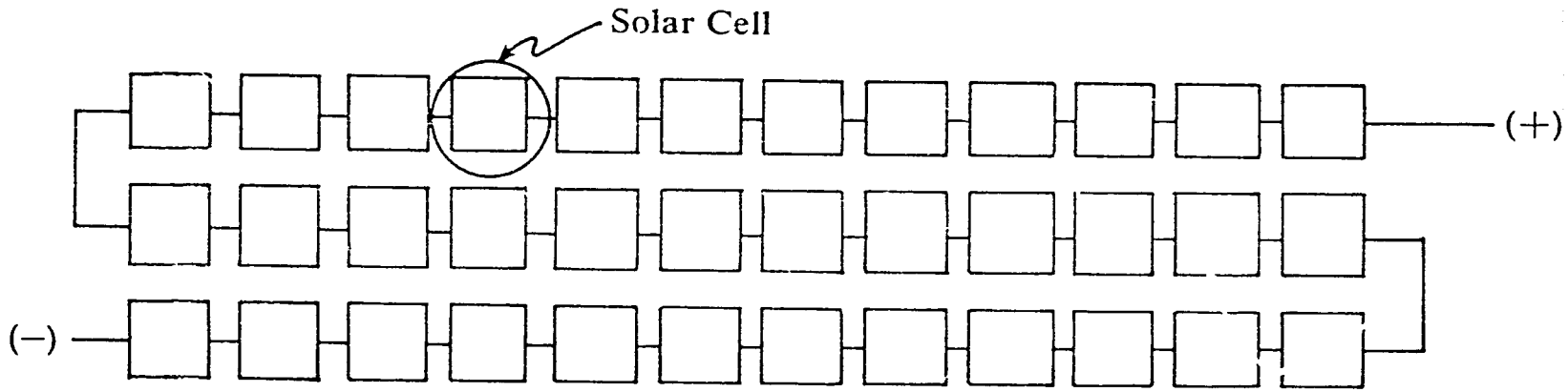
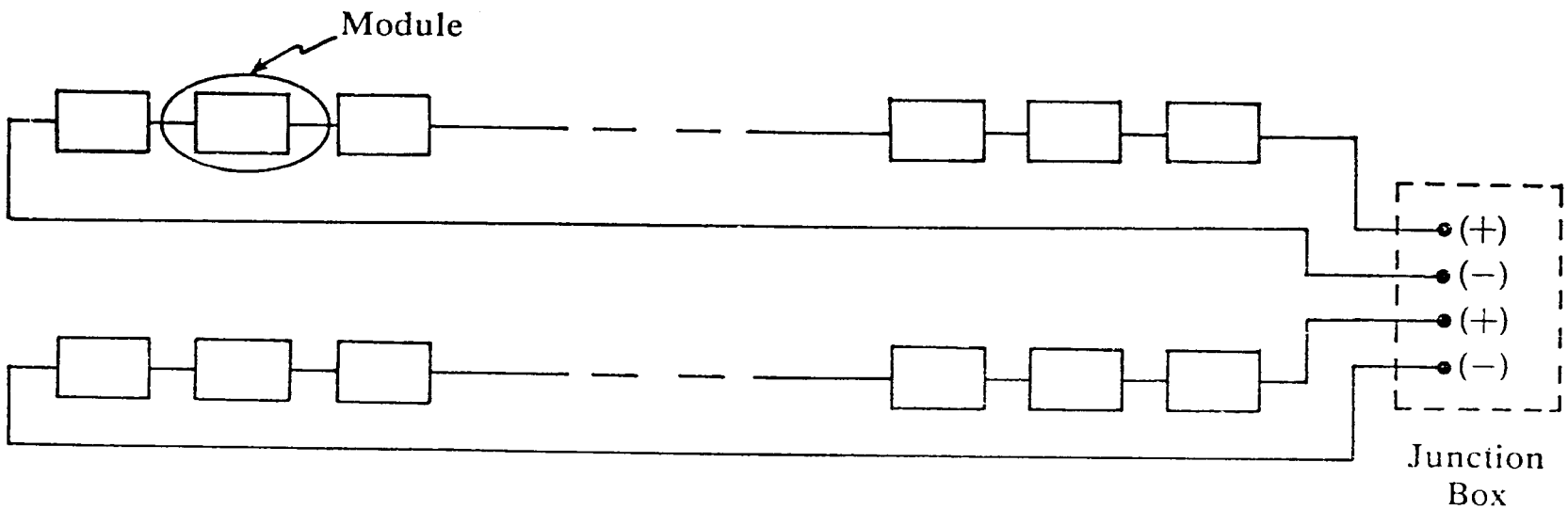
7 Handbook for Battery Energy Storage in Photovoltaic Power Systems Final Report, Sandia Report SAND80-7022, Bechtel National, May 1980.

8 User Handbook for Block V Silicon Solar Cell Modules, Jet Propulsion Laboratory document No 5101-262, May 15, 1985.



36 Cells in Module
36 Cells in Series

Exhibit 5-9
TYPICAL MODULE ELECTRICAL SCHEMATIC



TWO BRANCH CIRCUITS ARE ILLUSTRATED:

At Standard Conditions Each Branch Circuit Delivers:
903 Watts
363 Volts
2.49 Amps

Exhibit 5-10
TYPICAL BRANCH CIRCUIT SCHEMATIC

Battery Storage ·

To illustrate the method of sizing the battery bank, consider using the GNB Absolyte battery. (Literature was provided in the Appendix to TR #6). The Absolyte battery is a good candidate for use at El Kasr because it is a no maintenance battery. The electrolyte is suspended in a sponge-like material which prevents stratification. During the Field Test #8 trainee visit to the United States in September, 1986, several people in companies which have used the Absolyte battery commented favorably on them. From previous work, the following has been calculated:

- One (24-hour day) Energy Consumption = 51.57 kWh
- Battery Cells in Series Required = 126 cells
- Voltage Output = 240 volts
- Depth of Discharge Limit = 50 percent

To calculate the number of amp-hours required, divide the storage kW-hrs by system voltage.

51,570 Watt Hr. ÷ 240 Volts = 215 Amp-Hr.

This is effective amp-hours. To get the required amp-hours capacity, this figure must be divided by the depth of discharge which is 50%.

215 Amp-Hr. ÷ 0.50 = 430 Amp Hr.

By consulting the specification sheet, it can be seen that the 3-55A17 battery which produces 450 amp-hours per cell for a 10 hour discharge is appropriate; 42 batteries (i.e., 126 ÷ 3) are required. Summarizing, the recommended battery storage is as follows:

Number of Batteries Required	42
Battery Type	GNB Absolyte 3-55A17
Battery Dimensions	68.0 x 21.8 x 50.0
Battery Weight (Unpackaged)	109 kg

Battery Weight (Export Pack)	144 kg
Total Weight of Batteries	6048 kg

The power conditioning unit's functions are to:

- o Provide a max power tracking function for the PV array
- o Monitor and control the state-of-charge of the battery
- o Provide the startup and shutdown signals to the diesel genset and desalination equipment.

There are no off-the-shelf controllers available for this function, though there are a number of models which can be used with little development.

The diesel engine in the hybrid system is an integral part of the power system. We recommend that it be about 5 kW and that it be equipped with a battery charger.

5.2.7 Step 7. Design the Storage Tank

We recommend that there be two 25 m^3 tanks, one for each of the proposed desalination systems. We further recommend that these tanks be made of concrete of the same construction style as those at El Kasr Central. One possible configuration is that shown in Exhibit 5-11.

5.2.8 Step 8. Specify Brine Disposal System

There are two commonly used methods to dispose of brine from desalination plants: evaporation ponds and piping the brine to the sea. We recommend piping the brine to the sea for both the plants. In the case of the brackish water system which presumably will be run most of the time, the TDS of the brine is about 20,000 mg/liter which is less salty than the seawater. In the case of the seawater plant brine, the TDS is about 64,000 mg/liter, but it is a comparatively small amount (36m^3/day) which should have no appreciable effect on the sea.

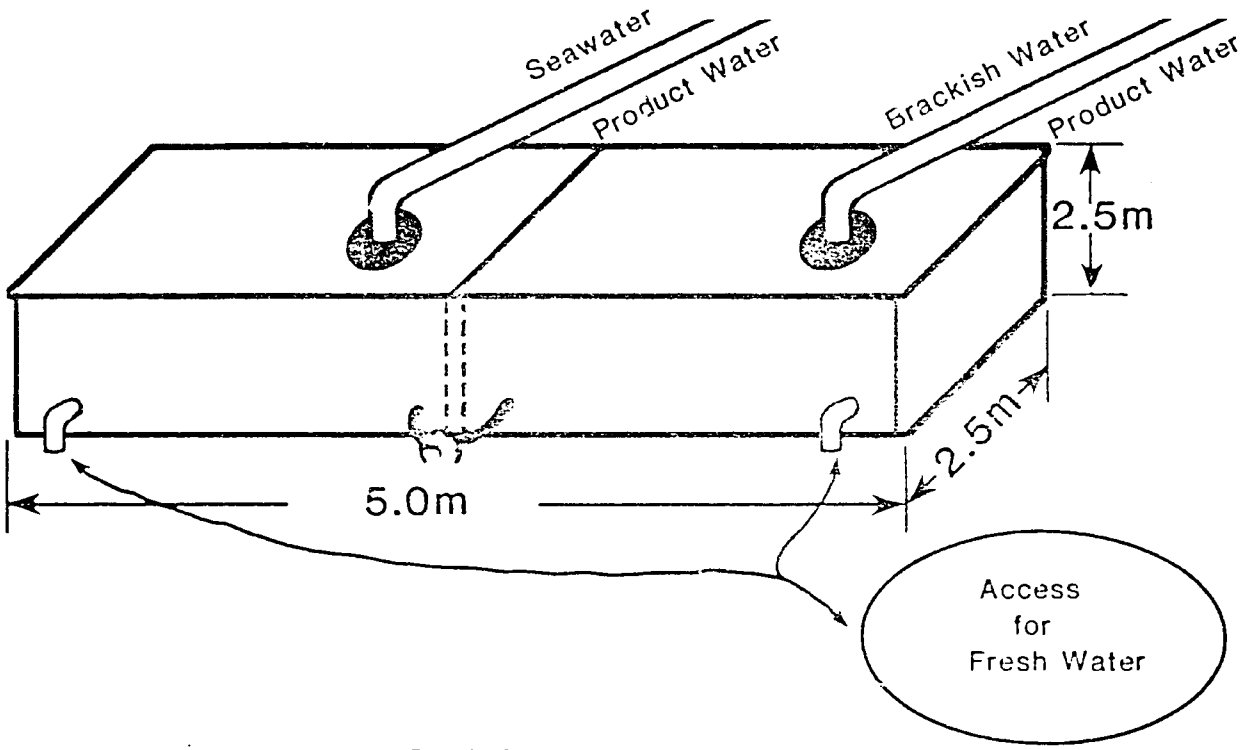


Exhibit 5-11
Sketch of Suggested Water Storage Tank for Product Water

There will be no problem with scaling inside the pipes carrying the brine because enough acid will be added as part of the pretreatment to prevent this from happening.

There will not be a need for any auxiliary pressure pumps since the pressure of the brine as it leaves the desalination equipment is well above 10 kg/cm^2.

5.2.9 Step 9. Specify Site Layout of Entire Installation

Exhibit 5-12 is a sketch of the layout of the desalination plant, the PV array, storage tank, and its distance relationship to the sea presently. Exhibit 5-13 is a suggested layout of the desalination plant.

5.2.10 Step 10. Specify Instrumentation

An on-site data acquisition system (ODAS) will be required for monitoring the performance of hardware installed for this field test. This requirement is in addition to any other requirement for system instrumentation necessary for routine test and maintenance procedures. Exact specifications of the ODAS will be detailed in the statement-of-work.

The ODAS must be a stand-alone system. Failure of the system must not affect the performance of the field test system that is being monitored. The ODAS must have an on-site data storage system that is non-volatile and capable of easy physical removal and transport to another location for data removal and long-term storage. One form of the non-volatile storage system must be a microchip/ EPROM or CMOSRAM - Type system that can be "milked" on-site easily and without danger of a loss of data.

The ODAS must be a microcomputer based data logger with programmable input channels and output formats, both analog and digital. The user must have

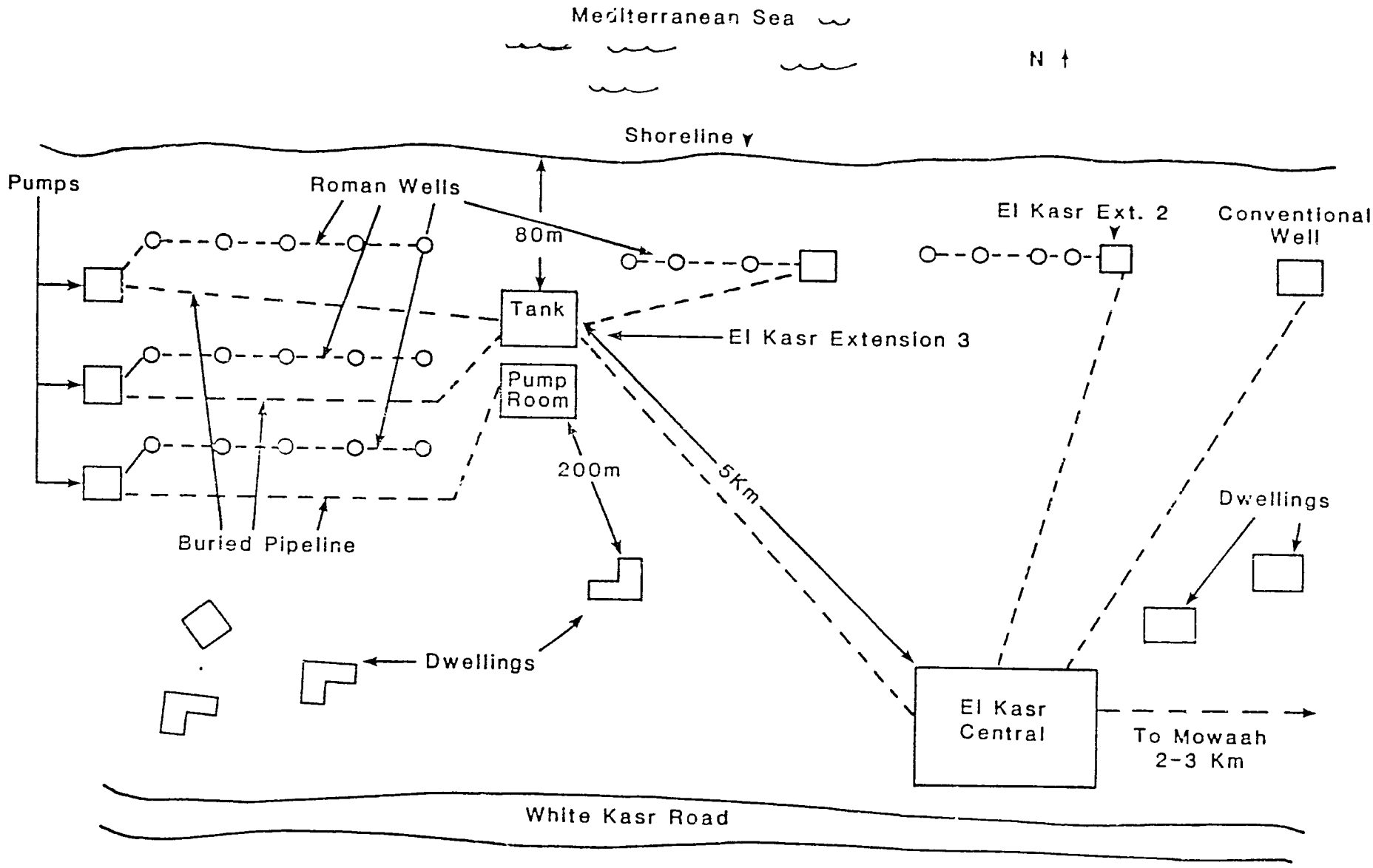


Exhibit 5-12
SKETCH OF WATER DISTRIBUTION SYSTEM NEAR EL KASR

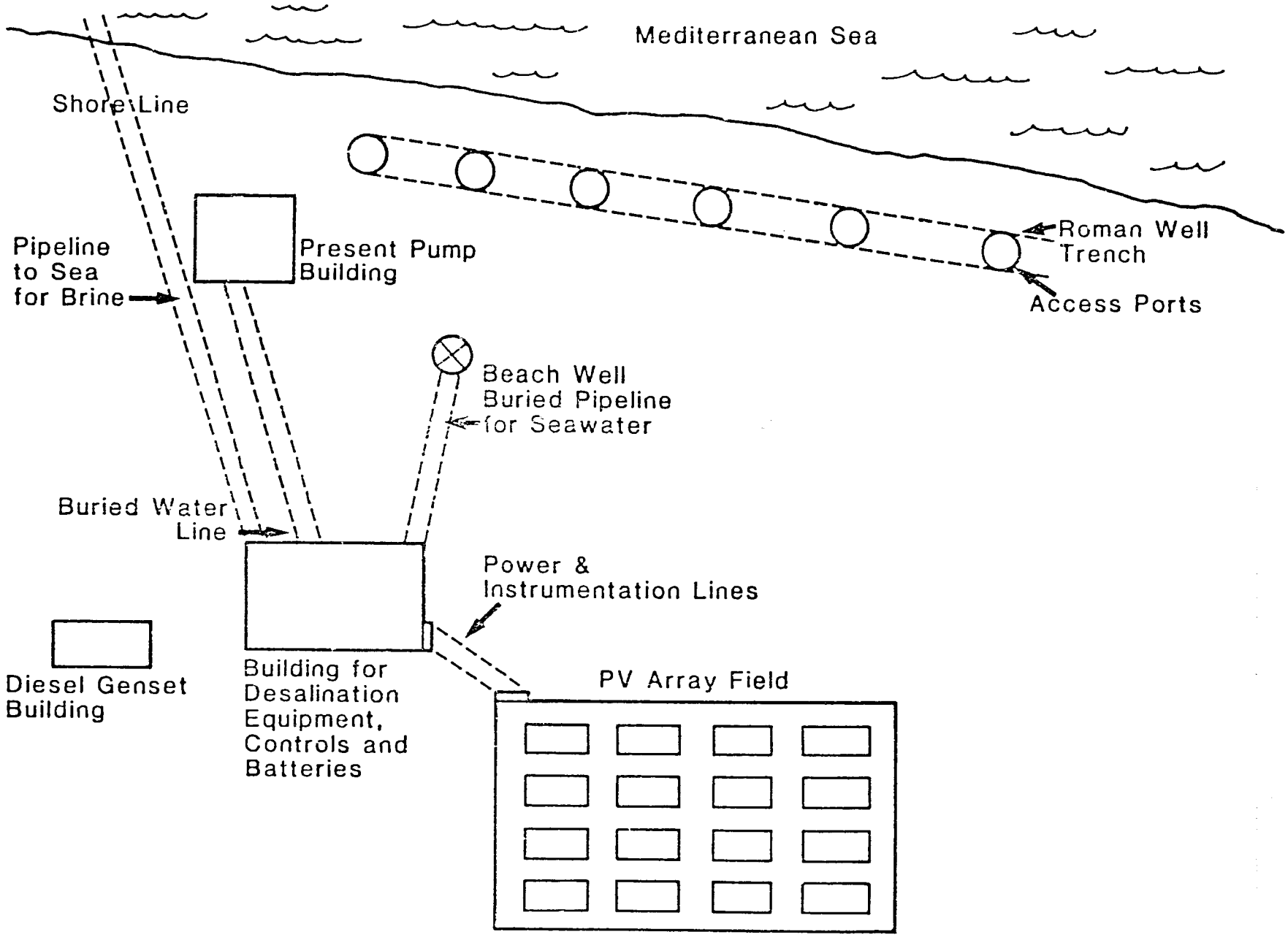


Exhibit 5-13
SKETCH OF LAYOUT FIELD TEST 8

control over sampling frequency and output period for each channel. The capability to multiplex some of the channels is also required. Primary design objectives for the ODAS should be reliability, simplicity, small size, low power and the ability to operate in environmental extremes (especially high temperature, sand/dust and tropical/sea coast). The unit must be capable of stand-alone battery operation for a period of at least one month, preferably for two months.

The following minimum specifications are required for the ODAS:

Physical Specifications

- o Small, stand-alone, self-contained system in an environmental enclosure
- o Desired weight: less than 10 pounds
- o Desired size: less than 10 inches x 10 inches x 6 inches

System Power Requirements

- o Capable of operation using self-contained batteries
- o Capability for these use of an external power source to allow continued data collection while changing batteries is desirable
- o Capable of transient protection from spurious electrical charges or lightning

Environmental Specifications

- o Ambient Temperature: -25 deg. C to +50 deg. C
- o Relative Humidity: 0 to 90 percent non-condensing
- o Impervious to a tropical, oceanside environment with occasional high airborne sand/dust and/or sulphur levels

Analog Inputs

Voltage Measurement Types: Differential or single-ended

Accuracy of Measurements: at least ± 0.5 percent

Range and Resolution: Selectable for any input channel from microvolts to several volts full scale

Multiplex capability: at least four channels

Pulse Inputs

Analog and Digital Control Outputs: a total of three resettable channels is desired with a range of 0 to ± 5 volts with a 0.5 volt resolution

Multiplex capability: at least three channels

Output Signal Interface

Memory: Capable of storing at least 3000 data points per day for a period of one month (two months desirable)

Display: A visual display of stored data is required on-site for data verification before data removal

Peripheral Interface: Downloading of data at the site should be by physical removal of the data storage device or simple, reliable data downloading to a non-volatile storage device. Storage data files shall be IBM-PC compatible on floppy disc either directly from the data logger or through a simple, fast, reformatting technique.

Specific parameters to be monitored for Field Test #8 are shown in Exhibit 5-14.

5.3 Conceptual Design Summary

- We recommend two separate desalination systems, both reverse osmosis, each capable of producing 25 cubic meters per day. One of the systems uses feedwater from the brackish water in the Roman wells and the other uses feedwater from the Mediterranean.

- We further recommend that the seawater plant be powered by a diesel engine generator set and that the brackish water plant be powered by photovoltaics.

- Of the three options considered for the power system for the brackish system, all-PV/battery, 8 hour PV/Battery-16 Hour Diesel and all-PV and diesel, we found that all three options had assets and liabilities. We recommend that the system be a PV-Hybrid with about 12 kW (peak) of PV with a 5 kW diesel engine providing the power when the PV or battery storage is unable to do so.

- We recommend that the brine from both systems be piped to the sea.

Item	Channel Type	Sampling Frequency	Output Interval	Priority Want	Priority Must
Array Power	P	1 sec.	10 min.		x
Array Current	A		10 min.	x	
Array Voltage	A		" "	x	
Insolation	A		" "		x
Load (kilowatts)	A		" "		x
Load Voltage	A		" "	x	
Load Current	A		" "	x	
Battery Charge Current	A		" "		x
Battery Discharge Current	A		" "		x
Battery Voltage	A		" "	x	
Ambient Temp.	A		" "		x
Ref. Cell Temp.	A		" "		x
Battery Temp.	A		" "		x
Diesel Power	P		10 min.		x
Feedwater Conductivity	P		30 min.		x
Product Conductivity	P		30 min.		x
pH Feedwater	?		30 min.		x
Feedwater Temp.	A		30 min.		x
Feedwater Pressure	A		10 min.		x
Product Water Flow	P		10 min.		x
Product Water Flow	P	(Totalized)	daily		x
Brine Outlet Pressure	A		10 min.		x

12 ("musts") x 6 samples x 24 hours = 1728
4 ("musts") x 2 samples x 24 hours = 192
1 ("must") x 1 day = 1
Time mark (6 x 24) = 144

Total = 2065 data points per day

17 channels
- o 6 pulse
- o 11 analog

EXHIBIT 5-14

Data Element Requirements

6.0 FT #8 ESTIMATED CAPITAL COST

We estimate the capital cost of the recommended PV-hybrid system described in Section 5.0 as follows (all figures in U.S. Dollars):

Conventionally powered seawater desalination plant		
Desalination Equipment	35,200	
Diesel Engine	4,000	
		39,200
PV-Hybrid Plant		
Desalination Equipment	26,800	
Photovoltaics and Balance of Systems	120,000	
Battery Storage	11,175	
Diesel Engine	4,000	
Total		161,975
Subtotal		201,175
Spares at 20%		40,235
		241,410

It should be emphasized that this cost does not take into account other cost factors such as:

- Well Drilling for the seawater feed
- Training
- Contingency Costs for Working Overseas
- Tanks for product water and excavation work for pipelines.