THE
PACIFIC INTERNATIONAL
CENTER FOR
HIGH TECHNOLOGY
RESEARCH

Enerpy and Resources Division

Design of an Open-Cycle Ocean Thermal Energy Conversion (OTEC) Experimental Facility

There are, basically, two approaches to the extraction of thermal energy from the oceans, one referred to as "closed-cycle" and the other as "open-cycle." In the closed-cycle, warm surface seawater and cold deep seawater are used to vaporize and condense a working fluid, such as ammonia, which drives a turbine-generator in a closed loop, producing electricity. In the open-cycle, surface seawater is flash-evaporated in a vacuum chamber at pressures of approximately 3% atmospheric. The resulting low-pressure steam is used to drive a turbine-generator. Cold seawater is used to condense the steam after it has passed through the turbine. The open-cycle can, therefore, be configured to produce fresh water as well as electricity.

Several small proof-of-concept facilities have been operated for up to six months, but unfortunately minimal operational data has been obtained. These projects demonstrated that both cycles are technically feasible and only limited by the large diameters required for the cold water pipes, to sizes of no more than about 100 MW gross. In the case of the open-cycle, due to the low-pressure steam, the turbine is presently limited to sizes of no more than 3 MW gross.

As the next step, realizable with the minimal funding available, towards answering some of the questions related to the operation of OTEC plants, a land-based small experimental facility will be installed and operated for 24 months at the Natural Energy Laboratory of Hawaii (NELH), Kailua-Kona, Hawaii. The offshore and inland seawater piping system, already installed at NELH, will be utilized. The power block will be built around a single, vertical-axis, mixed-flow turbine, rated at 210 kW-gross, supported by a concrete vacuum vessel, 25 feet (7.6 m) in diameter and 31 feet (9.5 m) high. The electrical generator will be located above the turbine assembly and outside the vacuum enclosure, adding 12 feet (3.7 m) to the overall height of the apparatus. Steam will be produced in an annular flash evaporator at the periphery of the vacuum vessel. The steam will flow up from the evaporator and enter the turbine radially inward. The steam will exit the turbine axially in the center of the vessel. A conical exhaust diffuser will be used for pressure recovery. A dired-contad, structured-packing condenser composed of two coaxial stages will be utilized. The noncondensible gases liberated from the seawater streams, at pressures of 2% to 3% atmospheric, and a small amount of uncondensed steam will be compressed and exhausted using a multiple-stage vacuum compression system. All subsystems will be instrumented to measure the parameters required to assess performance.

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TESTING

The 210 kW OC-OTEC system will demonstrate the feasibility of the low pressure open-cycle turbine and the high efficiency vacuum compression subsystems. Additionally, the production of net power will be demonstrated; therefore, the system is also referred to as the Net Power Producing Experiment or NPPE.

Data will be gathered to assess the performance of the 210 kW-gross OC-OTEC system. Subsystem as well as system tests will be performed for the :

Evaporator

1) Confirm the design by determining the values of thermal effectiveness and steam generation rate.

2) Confirm the relationships previously established between: thermal effectiveness and degree of flashdown (i.e., difference between inlet temperature and saturation temperature of warm seawater); and warm seawater mass flow rate.

Direct Contact Condenser

3) Confirm the design by determining the values of fraction of steam condensed in the first stage.

4) Confirm the relationships previously established between fraction of steam condensed in the first stage (F) and steam mass flow rate; cold seawater flow rate; and, mass flow rate of non-condensible gases.

Vacuum Compression System

5) Confirm the design by determining the overall power consumption at the design point.

6) Establish the relationships between overall power consumption and mass flow rate of non-condensible gases; and; inlet pressure.

Turbine-Diffuser-Generator System

7) Confirm the design by determining the power production at the design point.

8) Establish the relationships between power production and mass flow rate of steam; and, inlet pressure.

9) Confirm the design by determining the system net power, i.e., the difference between power production and power consumption, at the design point.

10) Establish the relationship between system net power and control parameters, i.e., warm water flow rate, cold water flow rate, and vacuum compressor setting (e.g., inlet pressure).

11) Evaluate the capability to optimally adjust the system to varying environmental conditions (seawater temperatures) expected throughout the year.

12) Establish the transient behavior of the system during startup, shutdown, emergency shutdown and variation of electrical load.

13) Determine the system availability and power produced over an extended period (e.g., six to twelve months).

TEST ARRANGEMENT

The overall tests can be considered as encompassing two parts to be tested simultaneously:

(1) Subsystem Tests. Subsystem Tests include the performance measurements on (a) spout evaporator, @) direct-contact condenser, (c) turbine-generator, and (d) vacuum compression system. In the future, a surface condenser subsystem will be added, and its performance tests will also be developed and conducted separately.

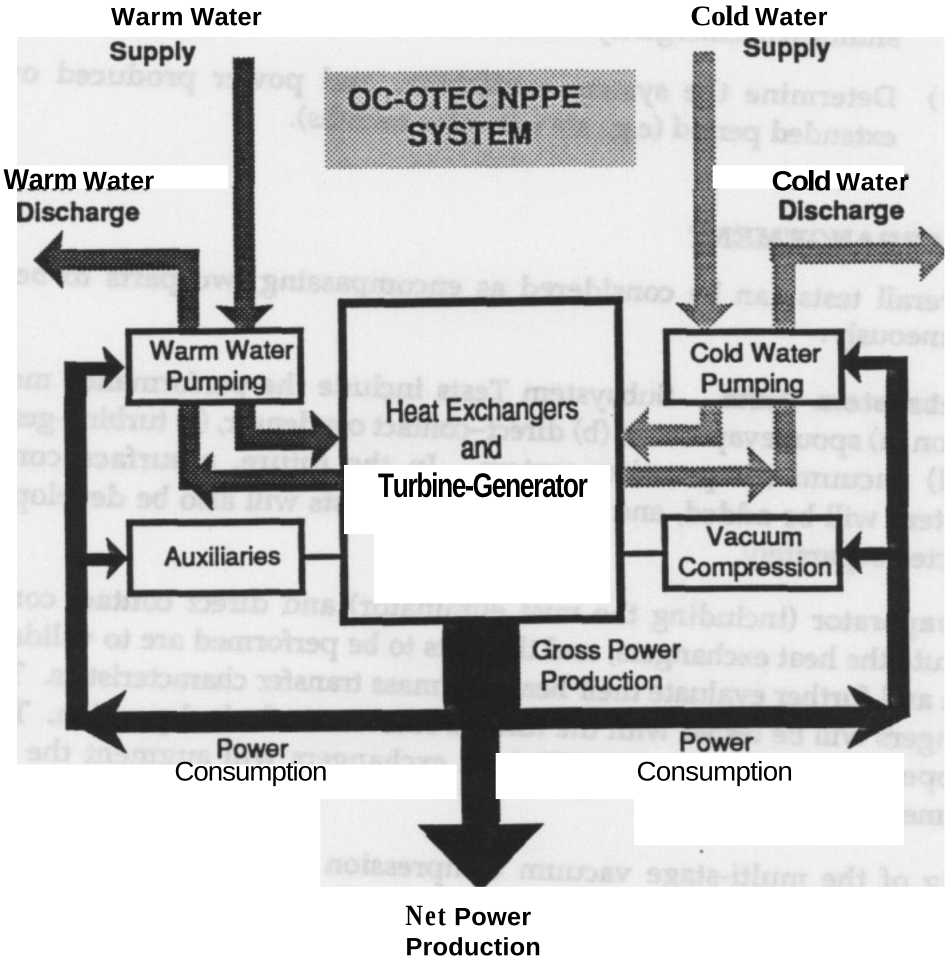
The evaporator (including the mist eliminator) and direct contact condenser constitute the heat exchangers, and the tests to be performed are to validate their design and further evaluate their heat and mass transfer characteristics. The heat exchangers will be tested with the turbine rotor in the locked position. The data developed from the tests of NPPE heat exchangers will augment the existing experimental data base.

Testing of the multi-stage vacuum compression subsystem and the turbine-diffuser-generator (TG) subsystem will, for the first time, provide data on their performance and controllability under OC-OTEC conditions. The TG unit was designed by Mechanical Technology Inc. (MTI) and the vacuum compressor subsystem by Barber-Nichols. The vacuum compressor subsystem will be tested with the turbine rotor in the locked position.

(2) System Tests. The system tests will focus on the power production of the OC-OTEC NPPE system.

A schematic of the system is given below. The net power generation (PW_{net}) is defined as the difference between gross power at the generator terminal (PW_{TG}) and the power required to pump the cold (PW_{cw}) and warm (PW_{ww}) seawater from the intake ports to the discharge trench; as well as the power required to operate the vacuum compression (PW_{nc}) subsystem, and the essential auxiliaries (PW_{aux}):

$$PW_{net} = PW_{TG} - (PW_{nc} + PW_{ww} + PW_{cw} + PW_{aux})$$



210 kW_e (gross) OC-OTEC Experimental Apparatus

In the open-cycle OTEC system, warm seawater will be flash evaporated in the concrete vacuum structure at pressures of about 3%atmospheric. The steam produced will be used to drive a turbine-generator unit located on top of the vacuum structure. Cold seawater will condense the steam after it exits the turbine. The warm and cold seawater will be returned to the ocean via a disposal trench.

The following facilities are identified on the attached *Site Plan*—

1. Vacuum Structure

The warm and cold seawater will be supplied via existing pumps and pipelines. The interface point is here at the flow meter box The design flow rates of warm and cold seawater are 9600 and 6500 gpm, respectively.

The warm seawater (average temperature: 26°C), enters the 24" diameter evaporator manifold and steam will be produced at each of thirteen spouts.

Steam will flow up from the evaporator and enter the turbine radially, flowing through the inlet nozzles. Steam will exit the turbine axially into a conical exhaust diffuser.

A direct contact condenser will use cold seawater (average temperature: 6°C) to condense the steam.

Noncondensible gases released from the seawater in the evaporator, and a small amount of uncondensed steam, will be removed from the vacuum structure by the vacuum compression system.

2. Seawater Discharge Pumps

The warm and cold seawater will be pumped out of the vacuum structure by two vertical pumps. A 48" pipeline will convey the water to the disposal trench.

3. Vacuum Compression System

The five-stage compression system will be located on top of the Vacuum Structure. Direct contact-type precooler and intercoolers will condense any steam and cool the gases between stages. This equipment will be mounted on the top and side of the Vacuum Structure.

4. Auxiliary Equipment

The Auxiliary Equipment consists of auxiliary seawater pumps, fresh water cooling system, plant air compression and the electrical load bank.

5. Control Building

This building contains an Electrical Room, Control Room, and a Conference Room. The Main Switchgear and Motor Control Center will be in the Electrical Room. Feeders *are* installed to supply power from NELH to the **OC-OTEC** experimental apparatus during start–up and to feed **surplus** power to NELH during operations.

The Control Panels for the turbine–generator and the other process equipment and auxiliaries will be in the Control Room. A computer data acquisition & control system will monitor and control the operations and record data for analysis. Instruments will measure pressures, temperatures, speeds, flow rates, and electrical production and consumption. Signals will be carried to the Control Room via cables in overhead cable trays.

6. The Turbine Control Panel (Inside Control Bldg.)

The panel **has** two main **functions:**

- Protection of Equipment
- Turbine Speed / Load Control

The Protection System monitors critical operating conditions **(such** as pressures, temperatures, levels, and speed) A 16–point annunciator panel displays system **alarms** and **trips.**

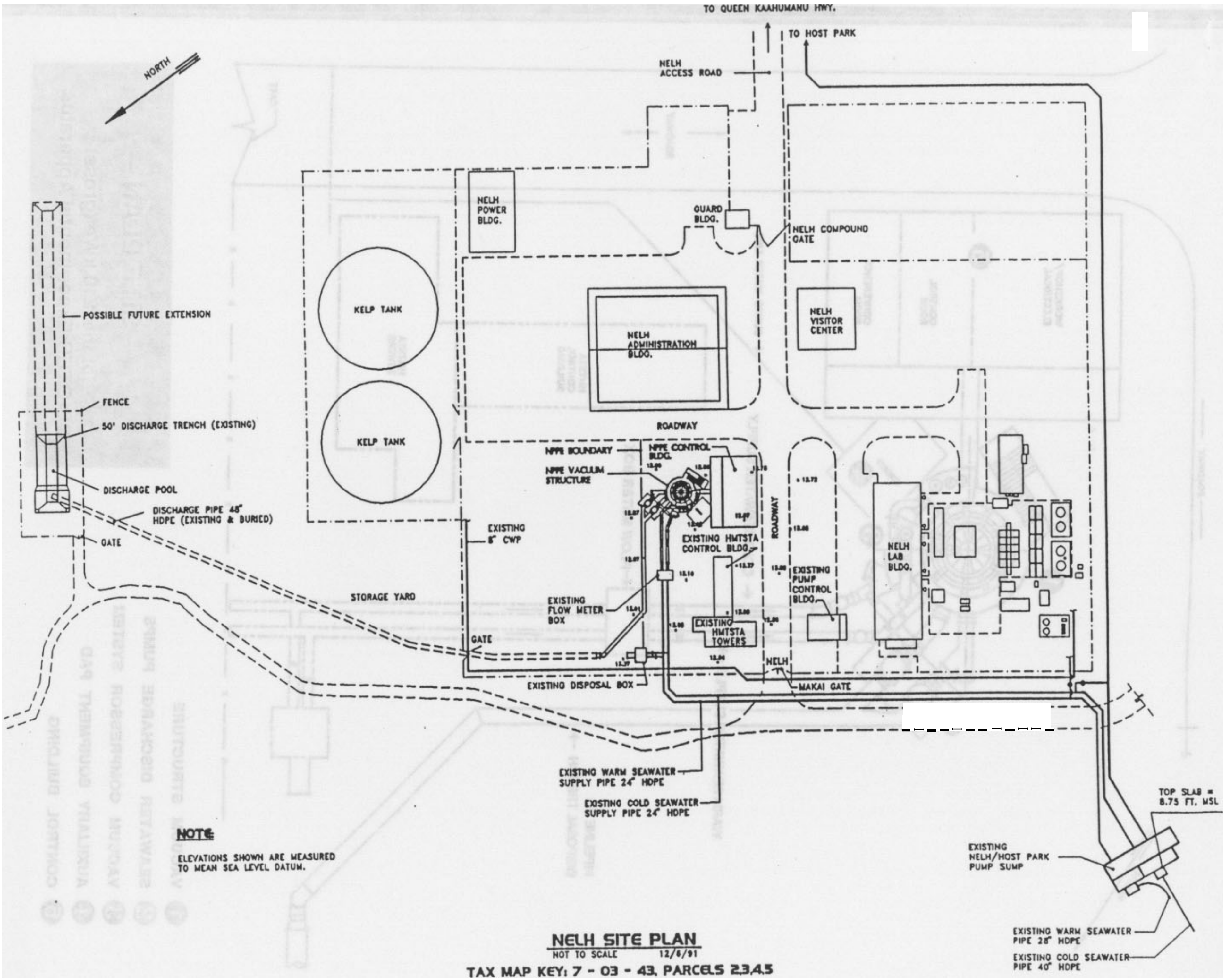
The Turbine Speed / Load Control for startup and shutdown **utilizes** the load bank to control speed by automatically adding or removing discrete resistive elements.

When the turbine generator is rotating at 1800 rpm, it will be synchronized with the NELH bus and the generator breaker **closed.** With the generator locked into frequency with the NELH bus, load bank resistance will be removed and power fed to the OTEC equipment. **Surplus** power will be **fed** to the NELH bus.

Gross power output of 210 kW is expected. Net power should be 40 to 60 kW.

7. Schedule

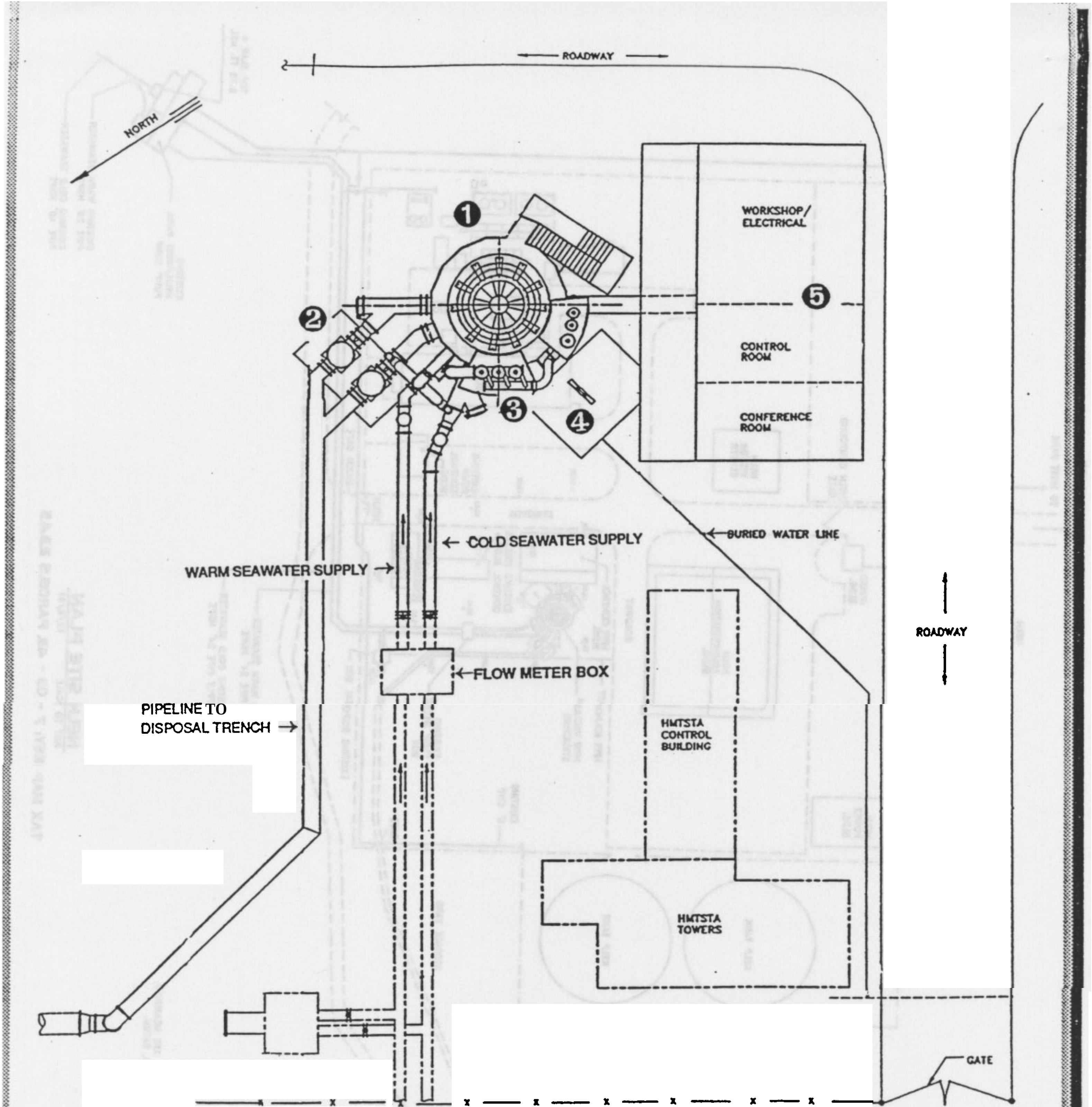
Shakedown tests are scheduled to start in November 1992. Two years of operation are planned (February 1993 to February 1995).



NELH SITE PLAN

NOT TO SCALE 12/6/91

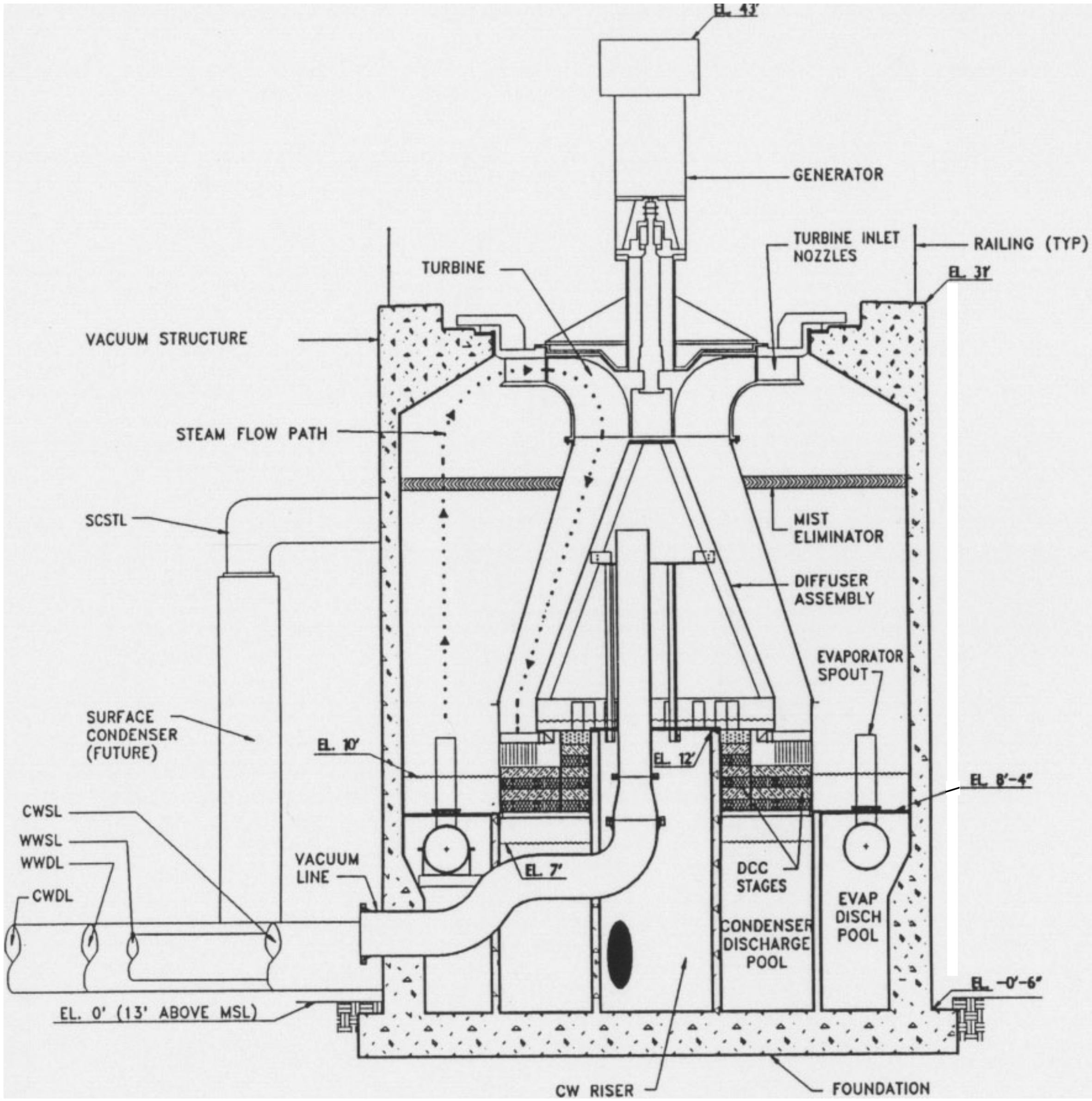
TAX MAP KEY: 7 - 03 - 43, PARCELS 2,3,4,5



1. VACUUM STRUCTURE
2. SEAWATER DISCHARGE PUMPS
3. VACUUM COMPRESSOR SYSTEM
4. AUXILIARY EQUIPMENT PAD
5. CONTROL BUILDING

– SITE PLAN –

for the 210 kWe (gross) OC-OTEC Experimental Apparatus



SPECIFICATIO4

Vacuum Structure

Material:	Reinforced & Post-Tensioned Concrete
Wall Thk:	0.3 m (1 ft)
Outside Dia:	7.6 m (25 ft)
Height:	9.5 m (31 ft)
Overall Ht:	13.1 m (43 ft)
Base Elev:	4 m (13 ft) above MSL

OC-OTEC Process

Warm Seawater:	620 kg/s (9,600 gpm), 26° C (79° F)
Cold Seawater:	420 kg/s (6,500 gpm), 6° C (43° F)
Evaporator:	0.6 m (2 ft) dia manifold w/13 spouts 3.5 kg/s steam (0.5% of WW Flow) 2600 Pa (0.38 psia)
Condenser:	two-stage direct contact w/packing 1300 Pa (0.19 psia)
Surface Cond:	0.35 kg/s (5 gpm) fresh water production

Power Budget

Generator:	210 kW (synchronous, 1800 rpm)
Vacuum Pump:	40 kW (five-stage train)
Discharge Pumps:	80 kW (60 hp WW, 50 hp CW)
Supply Pumps:	40 kW (not installed; 25 hp each)
Net Power:	50 kW (on paper)

PROJECT TITLE:

OC-OTEC NET POWER PRODUCING EXPERIMENT

SHEET TITLE:

VERTICAL SECTION

APPROVALS/INT	DATE	FIGURE __, PAGE __ OF __
L. VEGA	7/10/92	PICHTR Honolulu, Hawaii