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PERFORMANCE AND OPERATIONAL EXPERIENCE OF A PROTOTYPE BINARY GEOTHERMAL POWER PLANT

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Abstract

The development of moderate temperature geothermal resources as a viable energy source for electrical power generation is dependent upon the development of energy conversion systems and components that can more effectively extract the energy from a geothermal resource and minimize the costs associated with the supply and disposal of the geothermal fluid. At the Raft River geothermal site in south central Idaho, the Idaho National Engineering Laboratory is investigating and demonstrating the production of electrical power from a moderate temperature (140° to 145°C) geothermal resource. The initial production of electrical power at the Raft River site was accomplished with the Prototype Power Plant which was built to investigate and demonstrate the operation of binary power cycles where the energy in the geothermal fluid is transferred to a secondary working fluid. This plant serves as a test bed for testing pilot scale components, systems, and/or concepts that have the potential for enhancing the feasibility of power generation from moderate temperature geothermal resources.

During the automatic run test the plant was able to produce a maximum of 59kW(e). Although the plant was not (and has not) operated at design turbine conditions, performance was predictable. During the automatic run test, the plant operation was stable and the facility was operated for 1,357 hours producing electrical power approximately 87% of the time geothermal fluid was available for operation.

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Background

The Prototype Power Plant (PPP) is a pilot scale binary geothermal power plant located at the Idaho National Engineering Laboratory Raft River Geothermal Test Site. The plant is a test facility to be used in investigating various concepts that have the potential to enhance the commercial production of electrical power from moderate temperature geothermal resources. The size of the plant allows the different components to be replaced with an alternate component that performs the same function but uses an advanced or unconventional design concept. In this way, different concepts can be tested in an operational environment that would closely resemble that of a full scale plant without the associated costs.

The overall test program for the prototype plant consists of several phases in which such variables as automatic control, heat exchange components, and working fluids will be tested. The primary emphasis of testing to date has been continuous operation in an automatic control mode with an isobutane working fluid. The plant is currently in a test phase where the operation and performance of a sieve tray direct contact heat exchange column is being investigated.

Facility Description

Although the prototype plant is considerably smaller than a full scale binary plant in size and power output, its major systems are similar and function. The plant was designed and built initially with sufficient flexibility to be operated as a power loop (i.e., producing electrical power or as a thermal loop (i.e., the turbine being bypassed). The description of the PPP may be more easily understood if one refers to the flow schematic and isobutane pressure-enthalpy diagram shown in Figures 1 and 2.

The flow schematic in Figure 1 identifies the major cycle components for the automatic control test phase, but not the auxiliary systems, i.e., fire protection, vent and drain, storage, flare, control, etc. In the plant configuration for the automatic run test, the preheating and boiling of the secondary isobutane working fluid occurred in a single heat exchanger unit. The hot geothermal fluid is circulated through the tube side of the boiler/preheater where it is cooled as heat is transferred to the working fluid circulating past the outer tube surfaces. The isobutane working fluid is first preheated to the saturation temperature and then vaporized. The vapor leaving the boiler is expanded through the turbine which drives the generation producing electrical power or is expanded through a valve which bypasses the turbine. After discharging from the bypass valve or the turbine, the isobutane vapor enters the condenser where the working fluid vapor is cooled and condensed to a liquid. This liquid is then circulated back to the boiler using a boost and feed pump in series. Cooling water circulating through the tube side of the condenser is heated by the processes of desuperheating and condensing of the isobutane on the outer tube surfaces. The cooling water is then circulated through a wet cooling tower where heat added in the condenser is rejected to the atmosphere. The p-h diagram in Figure 2 shows the power cycle at design turbine inlet and exhaust conditions.

The turbine skid, which is a major component for the plant, was designed and built by Barber-Nichols Engineering Company in Arvada, Colorado. This skid, as initially constructed consisted of the turbine, turbine gearbox, induction motor/generator and the boost and feed pumps which were driven off the interconnecting between the turbine gearbox and the motor/generator. The feed pump was later replaced with a unit which had its own driver. The turbine is an axial flow type unit fabricated specifically for the prototype plant by Barber-Nichols. It operates at 22,470 rpm and at design conditions of 2.16 MPa inlet pressure, 0.365 MPa exhaust pressure, and at a saturated isobutane vapor flow of 1.64 Kg/s, it will produce (i.e., generator output) approximately 72kW of three phase, 440-V, 125-A, 60 Hz electrical power.

The boiler/preheater and condenser used in the automatic run test are identical finned U-tube heat exchangers obtained as surplus units from the INEL site. Both units were installed in the vertical position with the vapor leaving the top of the boiler and entering the top of the condenser (as indicated in the flow schematic in Figure 1). The cooling tower is a mechanical draft, cross-flow type manufactured by Marley Cooling Tower Company. It was also obtained as a surplus unit as a cost savings measure.

Automatic Run Test

The major test effort to date with the prototype plant has been the automatic control, continuous operation test which was used to obtain operational experience with the plant and its components and to demonstrate the operation of the plant in the automatic control mode. The plant was initially designed for operation with a minimum of one operator present to monitor the plant, adjust valves, record data, etc. Although it originally was designed with some automatic shutdown logic, except for the high boiler pressure shutdown, all shutdown logic was associated with the turbine skid. After completing the plant checkout testing it was apparent that if the plant were to be operated for extended periods, from both an economic and safety standpoint it would be necessary to automate as much as possible the operation of the plant and to provide the shutdown logic to terminate plant operation in case of some unusual event that posed a potential hazard to personnel or equipment. At this point, the modifications were made to accommodate long term continuous operation of the plant.

The prototype plant condenser does not discharge into a hotwell or condensate storage tank. To provide the NPSH requirements for the working fluid pumps, a liquid level is maintained in the bottom section of the condenser. This liquid level is very sensitive to the plant operation as the condenser cross section is small, and any movement of fluid, density change, or working fluid loss may cause the level to fall below a minimum required for the pumps. aintaining a high liquid level sacrifices condenser thermal performance as the heat exchanger tubes are partially submerged in the liquid. Because of these two factors, the plant was set up to automatically control condenser liquid levels using a bypass line and control valve around the boiler. Although this may have been atypical (as opposed to control of boiler liquid level), it proved to be adequate for controlling the prototype plant operation. Once the plant was started through manual operations, no other controls were necessary other than a reasonably constant supply of hot geothermal fluid which was outside the control of the plant.

The plant was also equipped with alarm and shutdown parameters to identify high or low pressure, flow, or level conditions, alarm the operator or other personnel, and if necessary, shutdown the plant. In a plant shutdown, power was shut off to the working fluid pumps, the turbine isolated, and geothermal flow shut off automatically whenever a specific parameter exceeded a maximum or minimum level.

The automatic run test began in August, 1979 and was completed in January, 1980. Table 1 shows the range of power plant parameters over which the plant operated during these tests. During this period the plant ran whenever geothermal fluid and operators were available. (Operators or other personnel were required for operating in the winter to drain the plant in the event of a shutdown and prevent freezing damage.) The plant operating conditions (see Table 1) were not constant during the course of this test primarily because the supply or flow and temperature of the geothermal fluid varied because of other site activities.

Automatic Run Results

During the period in which the plant was in the automatic run test mode, the operation in automatic control was stable even though the plant was operated considerably off the design boiler pressure of 2.16 MPa. At boiler pressure as low as 1.38 MPa the plant was able to operate and produce power with minimal operator surveillance. (The previous requirements for continuous operator attendance was reduced to approximately eight hours per day, a majority of which was required for data collection.) The alarm and shutdown system worked as intended, alarming personnel and shutting the plant down if required.

The operational time gained with the plant is summarized in Table 2. During this test run the plant operated approximately 87% of the total hours available for operation (defined as the number of hours that geothermal fluid was available and personnel were on site to answer alarms). Although the average power output (21.5kW) was low, this was primarily the result of low geothermal fluid flow rates.

The primary operational problems noted during this period were the introduction of nitrogen into the isobutane system, isobutane system losses, cold weather operation and startup difficulties due to temperature differences in the isobutane system. The isobutane losses in the plant were to be expected given the number of mechanical seals and joints in the isobutane process system. This leakage caused problems only in that the range of operating liquid levels in the plant was small and fluid had to be added to the plant on an almost daily basis. The startup difficulties encountered were primarily the result of uneven solar radiant heating between the insulated condenser vessel and the uninsulated liquid condensate lines to the pumps. The resulting boiling in the condensate lines prevented the isobutane pumps from starting because of an inadequate NPSH. The problems associated with cold weather operation were principally cooling tower icing, potential for freeze damage in the event of a shutdown, and the potential for the plant drawing a vacuum in extreme cold weather with the attendant potential for flammable mixtures of air and isobutane within the system.

The main problem encountered with the plant, however, was the introduction of nitrogen into the isobutane system. Nitrogen was used to purge the plant, to move the isobutane into and out of the plant, i.e., fill and drain, and to assure the plant maintained a positive pressure and did not draw in air. Over the period of extended operation, the isobutane became contaminated with nitrogen and the plant performance adversely affected. This nitrogen would come out of solution in the boiler and would tend to accumulate in the condenser adding its partial pressure to the condenser pressure. Over the period of the test, this partial pressure increased to approximately 0.07 MPa over the isobutane condensing pressure and had a significant impact on the turbine performance (decreased by 25 to 40% depending on operating conditions).

After the problem with noncondensable gas contamination of the working fluid was identified and the contaminated fluid replaced with "clean" isobutane, a series of performance tests were conducted. The results of these tests are summarized in Figure 3 along with the predicted performance at those operating conditions. The predicted performance curves were based on estimated turbine skid power losses, predicted turbine flow rates, and the Barber-Nichols predicted turbine efficiency. The predicted and measured plant output deviate at higher turbine exhaust pressures because of a similar deviation between measured and predicted turbine efficiency at higher velocity ratios (which correspond to lower pressure ratios or higher exhaust pressures) as shown in Figure 4. The data given in Figure 4 shows that at the lower velocity ratios (ratio of tip speed to isentropic nozzle spouting velocity) the measured turbine efficiency, as defined by the power output and estimated skid power requirements, approaches the design value of 74%. This data also shows that efficiency as defined by pressure and temperature measurements has considerable scatter. This scatter is the result of the inability to accurately measure temperature and pressure and the resulting impact a measurement error can have on assessing the relatively small enthalpy change across the turbine.

Aside from the expected deviation at higher turbine exhaust pressures, the predicted and measured power outputs shown in Figure 3 agree quite well with each other and in some cases the measured performance exceeds predicted. This could be due in part to the measured flow rate slightly exceeding the predicted flow rate (see Figure 5). This phenomenon repeats the observations made by Barber-Nichols when the turbine was tested with steam following fabrication. These performance tests confirmed that the prototype plant performance is understandable given the geothermal fluid and cooling water inlet conditions. Performance predictions were generally quite good provided the turbine was operating at or near the design velocity and pressures ratios.

In addition to providing operation experience and confirming that performance could be predicted, the automatic run tests provided data on daily and seasonal power variations due to changes in the ambient air temperatures. This data is summarized in Figure 6 which shows the variation in power output as a function of the air wet bulb temperature (in this figure the dashed line is the author's faring through the test data parallel to predicted performance). This data shows the deviation from predicted (assumed to be the dashed curve) as the wet bulb temperature approaches and falls below freezing, 0°C. The further below freezing, the more significant the deviation. This deviation is thought to be primarily, if not solely, due to icing in the cooling tower which restricts air flow and effectively reduces the area for heat and mass transfer in the tower. Although this is generally recognized and steps are taken to minimize icing in power plant towers, it is important that this deviation in performance is considered in designing and selecting equipment for geothermal binary power plants. These plants have the potential for significant power output increases in the winter if one takes advantage of the cooling potential and designs the cooling system for cold weather operation.

Current Testing

Following the completion of the automatic run tests, the prototype plant was modified and the initial condenser replaced with an enhanced surface unit obtained from Oak idge National Laboratory (ORNL). In addition a direct contact heat exchanger designed and built by Wahl Company of Claremont, California was installed in parallel to the original shell and tube boiler/preheater. The plant schematic following this modification is shown in Figure 7. At this time it is possible to operate the plant in the thermal or power loop mode using either the shell and tube boiler or the direct contact heat exchanger (DCHX).

From September through December, 1980, a series of performance tests were conducted for ORNL using the shell and tube boiler/preheater to generate the condenser heat load. Although ORNL is doing a detailed evaluation of the condenser performance, the unit has a much better thermal performance than the original condenser and it has been possible to approach the design turbine exhaust pressures which was not possible previously.

As mentioned previously, the DCHX was designed and built by the Wahl Company of Claremont, California. t is a sieve tray type column which relies on the buoyancy difference between the isobutane which enters at the bottom of the column and the geothermal fluid which enters near the top of the unit to drive the column. As the geothermal fluid flows down through the column it transfers energy to the lighter isobutane droplets which are rising up the column. The working fluid forms droplets as it flows through the perforated trays in the column. As the droplets rise and are heated, they coalesce under the next tray up and then reform as they leave that tray. A schematic of the column is shown in Figure 8. The column contains 17 preheating trays and two boiling trays. The upper preheating tray is also a drawoff tray that may be used to remove a portion of the liquid flow before it enters the boiling section of the column. This drawoff tray will be used to simulate muliple boiler cycles using direct contact heat exchangers. The column is also instrumented with 17 temperature sensors that are used to obtain a temperature profile of both fluids in the DCHX column and help to define the column thermodynamic capabilities.

The major problems anticipated during the operation of the DCHX are the carry-under of working fluid in the geothermal fluid, the carry-over of geothermal fluid in the isobutane vapor, and the introduction of noncondensables into the isobutane system. The test program for the DCHX will attempt to determine the magnitude of these phenomena for different operating conditions and identify their impact on component and cycle performance.

The checkout of the DCHX was made in January and February, 1981. The DCHX test program is scheduled to start in March, 1981 and be completed in August, 1981. At this time no results are available for publication.

Summary

The operation of the prototype power plant thus far can be summarized as follows:

1. The prototype plant can be operated at considerable "off design" conditions and still maintain stable conditions and produce electrical power. Although this trait may be typical only of this plant because of the design of the turbine skid, it does show that binary systems can have considerable operational flexibility.

2. The plant operated approximately 87% of the time geothermal fluid was available. The binary cycle during this limited period of

operation showed itself to be very reliable. The major problem encountered in keeping the plant on line was a reliable source of geothermal fluid. This will likely be true of other geothermal applications, particularly those attempting to pump the hot water.

3. The required operator surveillance was reduced from 24 hours per day to approximately 8 hours per day. This again indicates the stability and relatively trouble free operation of the plant.

4. Although the plant did not operate at the design conditions, performance could be predicted and there were no "surprises". The maximum power produced during the automatic run test was 59kW(e).

5. Aside from the problems associated with maintaining the supply of geothermal fluid to the plant, the major operational problems encountered was the contamination of the working fluid with nitrogen. Although some contamination of working fluid may be unavoidable, particularly in direct contact power cycles, the exposure of the working fluid to noncondensable should be minimized.

6. The ORNL enhanced surface condenser has been tested using the shell and tube boiler/preheater to provide the heat load. Although detailed evaluations of performance by ORNL has not been completed, the unit does appear to be operating as expected and does provide a substantial improvement in thermal performance over the original unit.

TABLE 1 PROTOTYPE POWER PLANT OPERATING PARAMETERS

Isobutane Working Fluid	
Boiler pressure, MPa	1.31 to 2.137
Boiler inlet temperature, °C	2.11 to 46.1
Boiler outlet temperature, °C	76.7 to 104.4
Turbine inlet pressure, MPa	1.241 to 2.103
Turbine inlet temperature, °C	76.7 to 103.3
Turbine outlet pressure, MPa	0.372 to 0.724
Turbine outlet temperature, °C	43.3 to 65.6
Condenser pressure, MPa	0.372 to 0.724
Condenser inlet temperature, °C	43.3 to 65.6
Condenser outlet temperature, °C	21.1 to 46.1
Working fluid flow rate, kg/s (maximum)	1.6506
Geothermal Fluid	
Flow rate, m^3/s	0.0032 to 0.0073
Inlet temperature, °C	118.3 to 137.8
Outlet temperature, °C	87.8 to 110
Cooling Water	
Flow rate, m^3/s	0.0189 to 0.0221
Inlet temperature, °C	11.7 to 26.7
Outlet temperature, °C	15 to 33.3

TABLE 2   SUMMARY OF AUTOMATIC RUN OPERATION

Total hours - operated	1357
Total hours - available for operation	1557
Plant operating factor	87.2%
Total power produced	29 191 kWh
Average power produced	21.5 kW
Maximum power produced	59kW

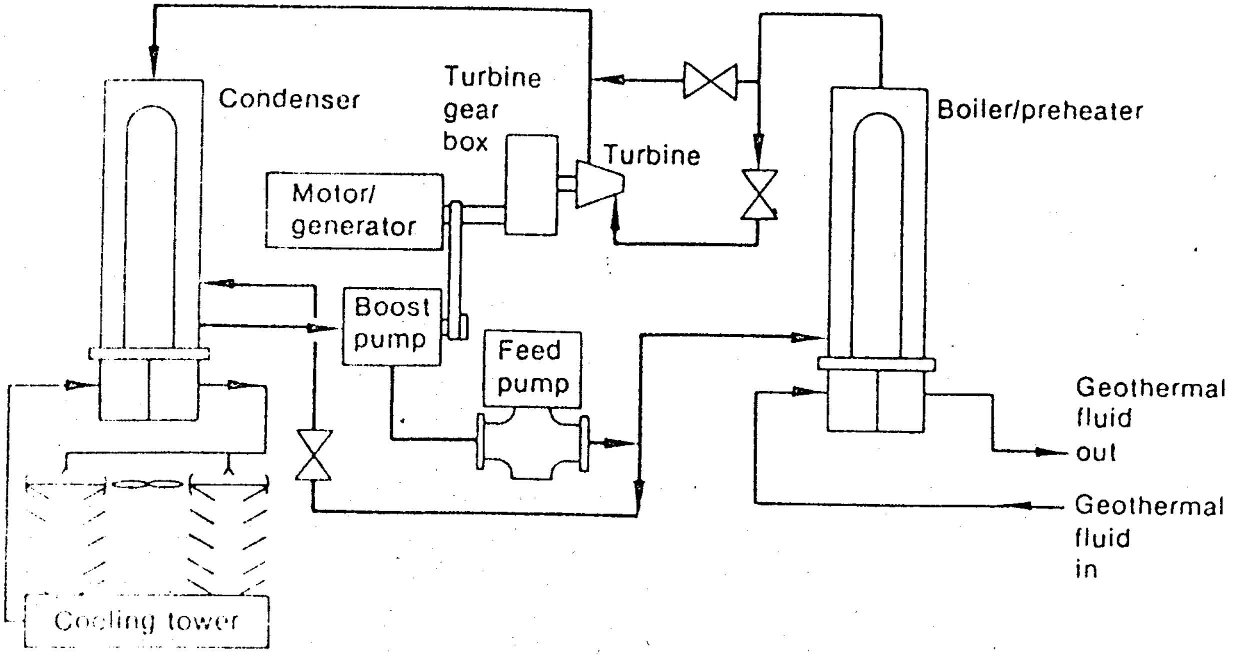

Figure 1. Prototype Power Plant flow schematic.

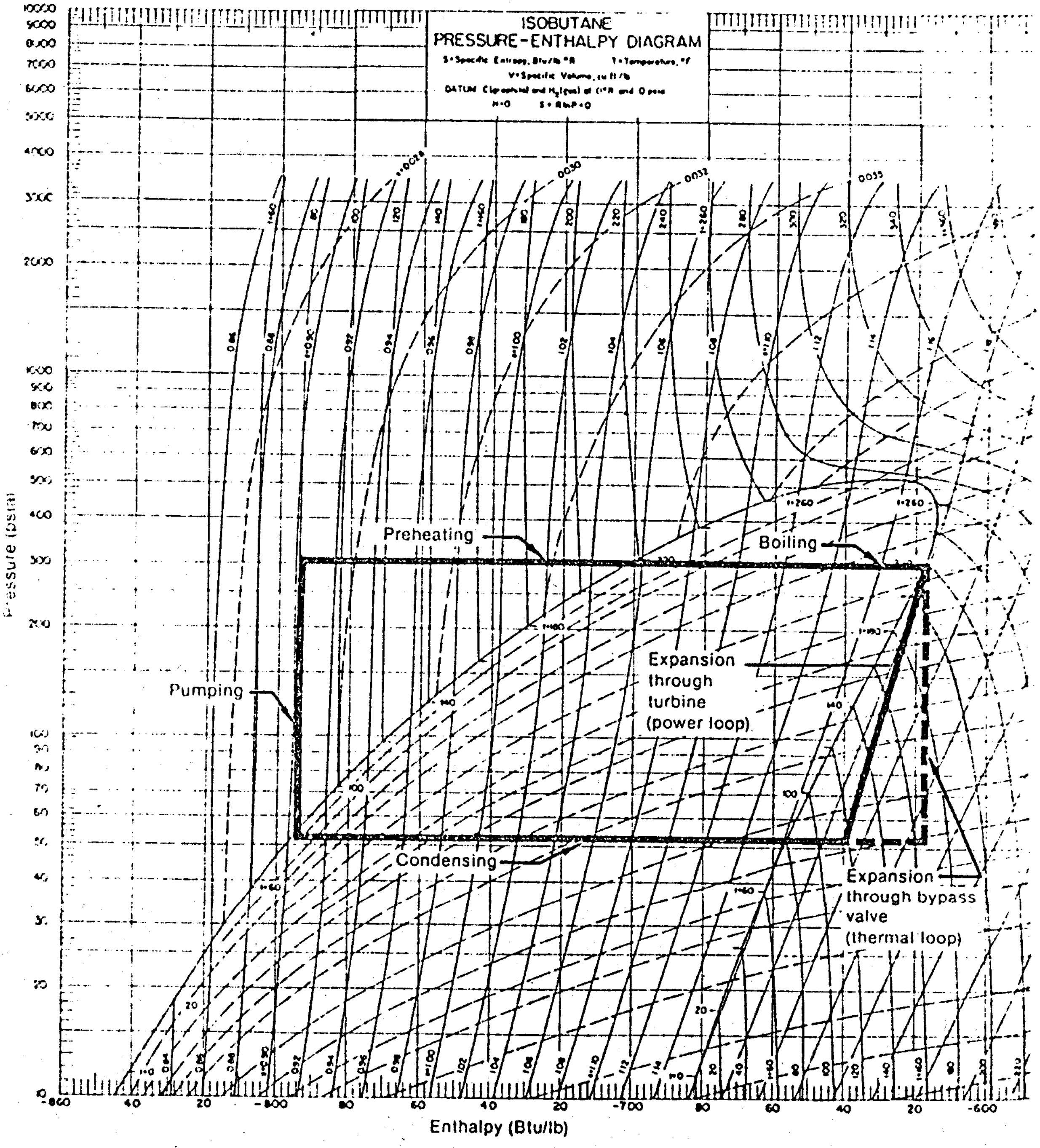

Figure 2. Isobutane pressure-enthalpy diagram.

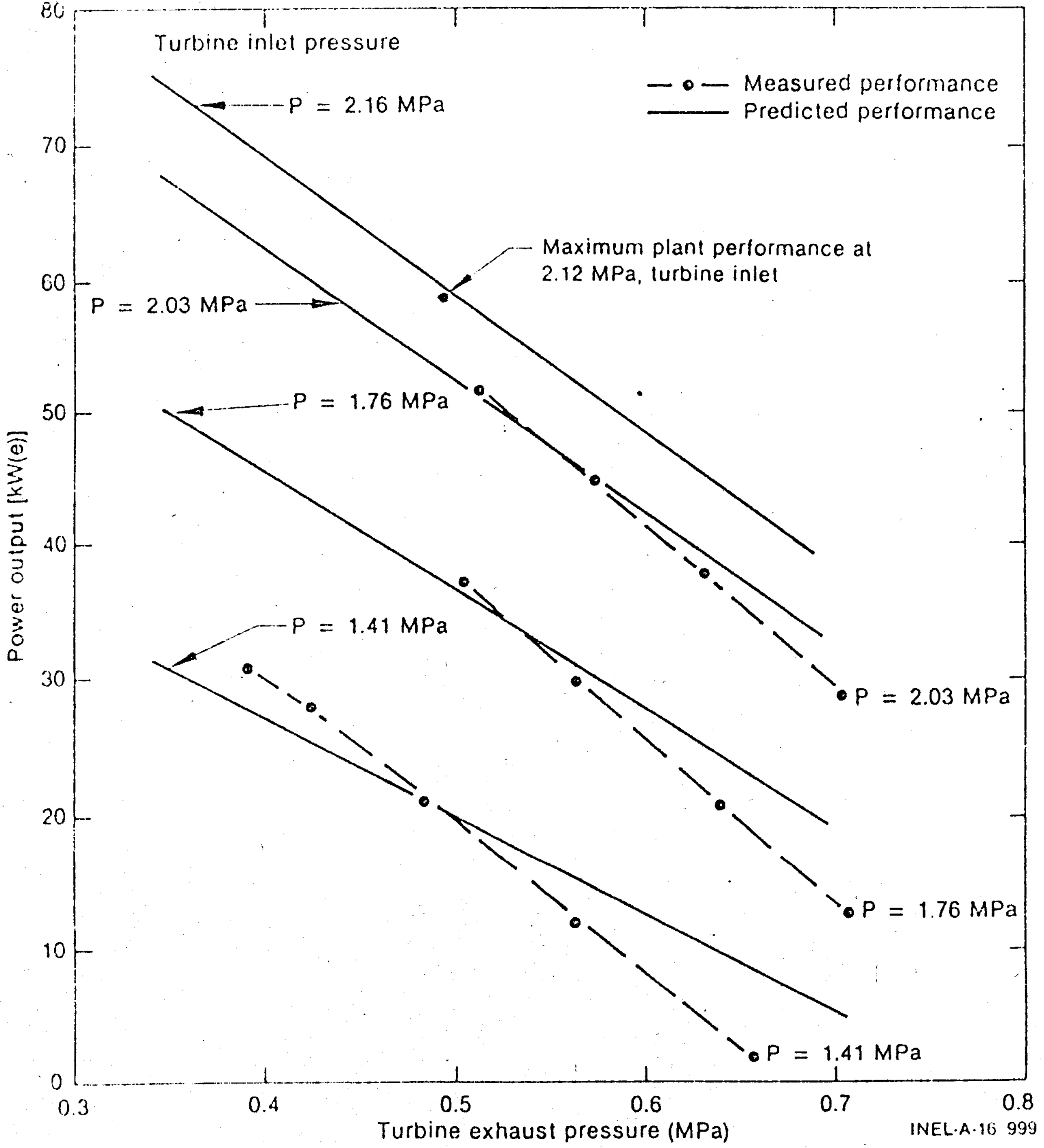

Figure 3. Predicted Prototype System Performance.

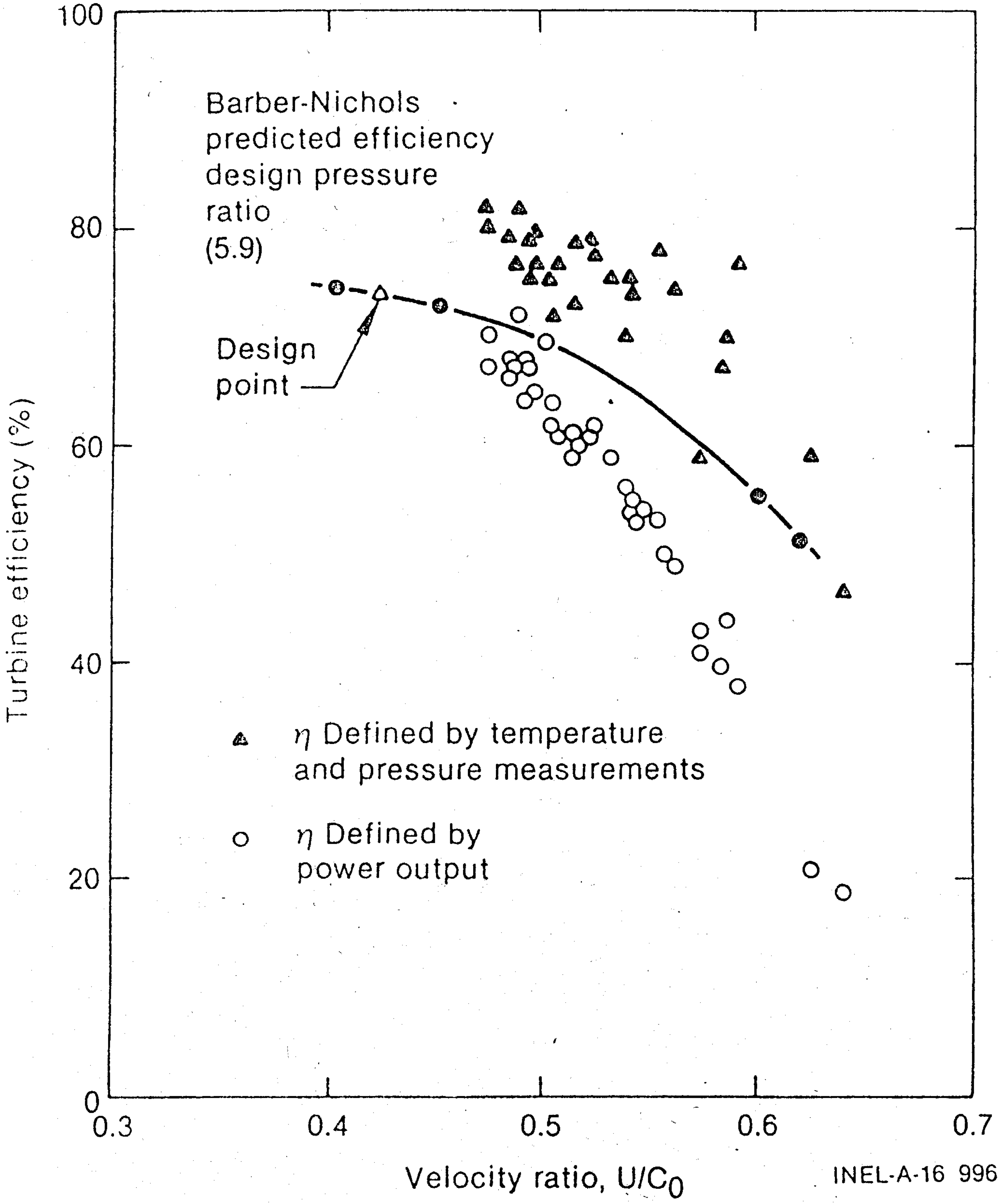

Figure 4. Prototype Turbine Performance Versus Velocity Ratio.

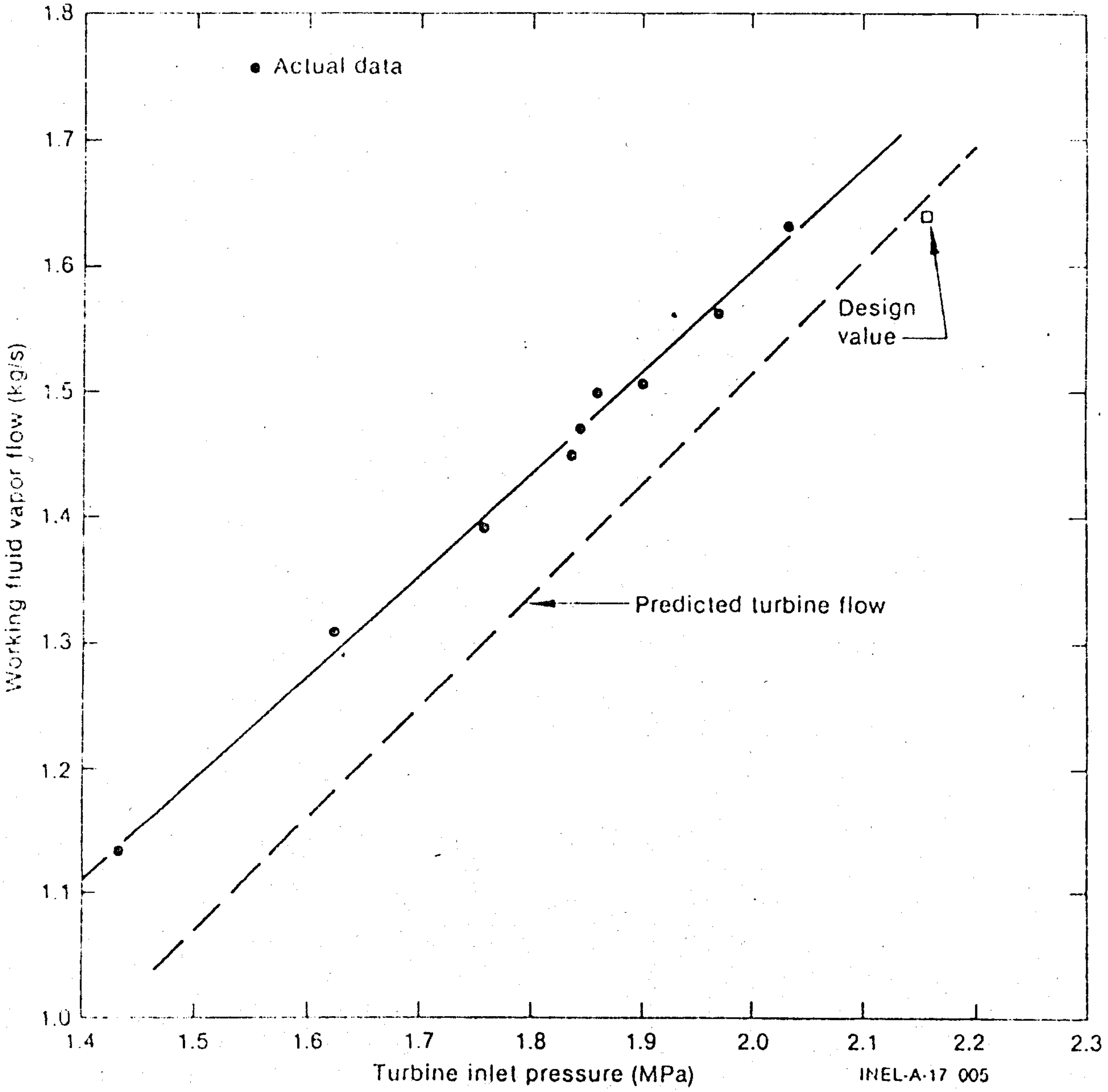

Figure 5. Turbine Vapor Flow Rate, Actual and Predicted.

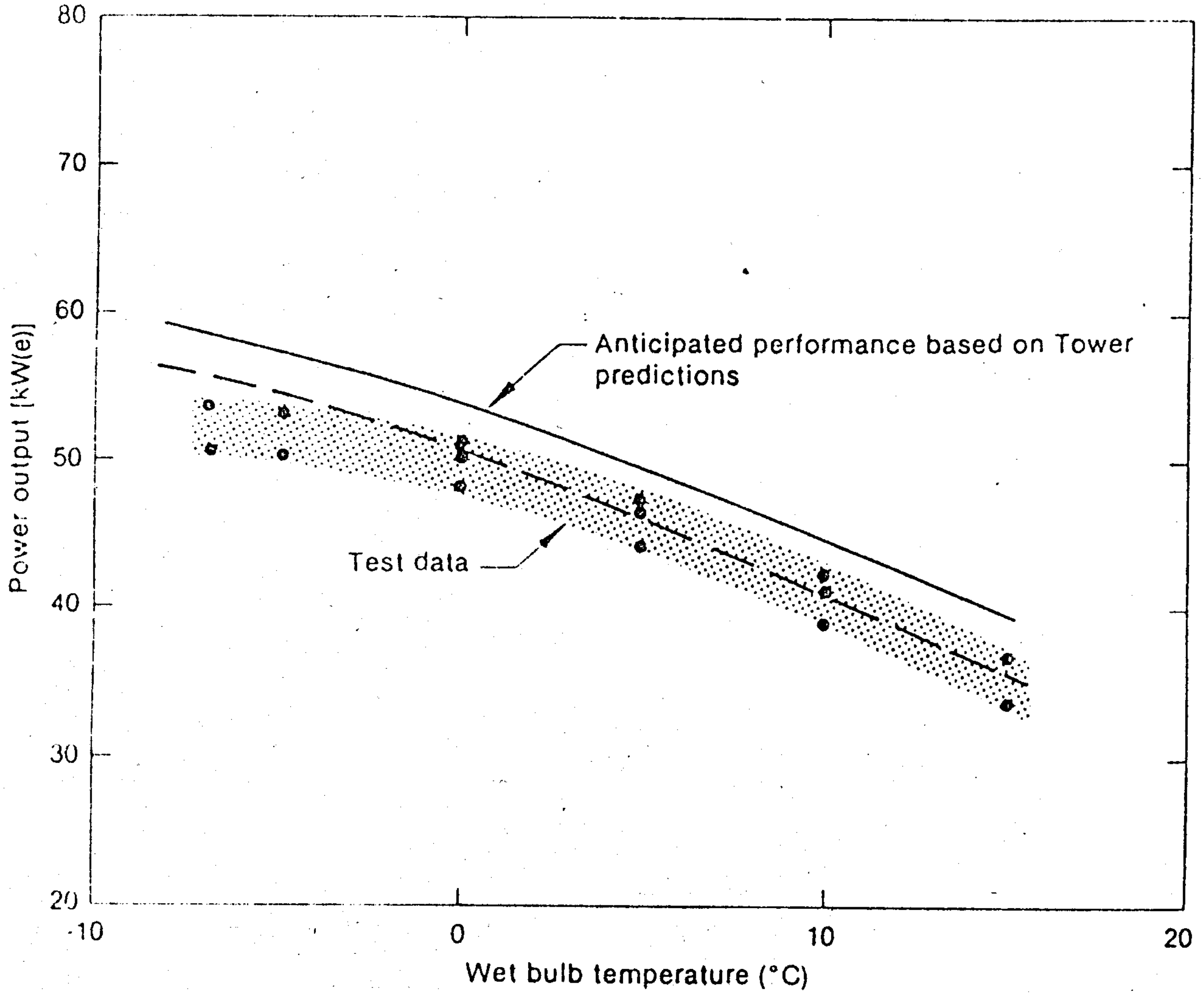

Figure 6. Effect of Cold Temperatures on Tower Performance.

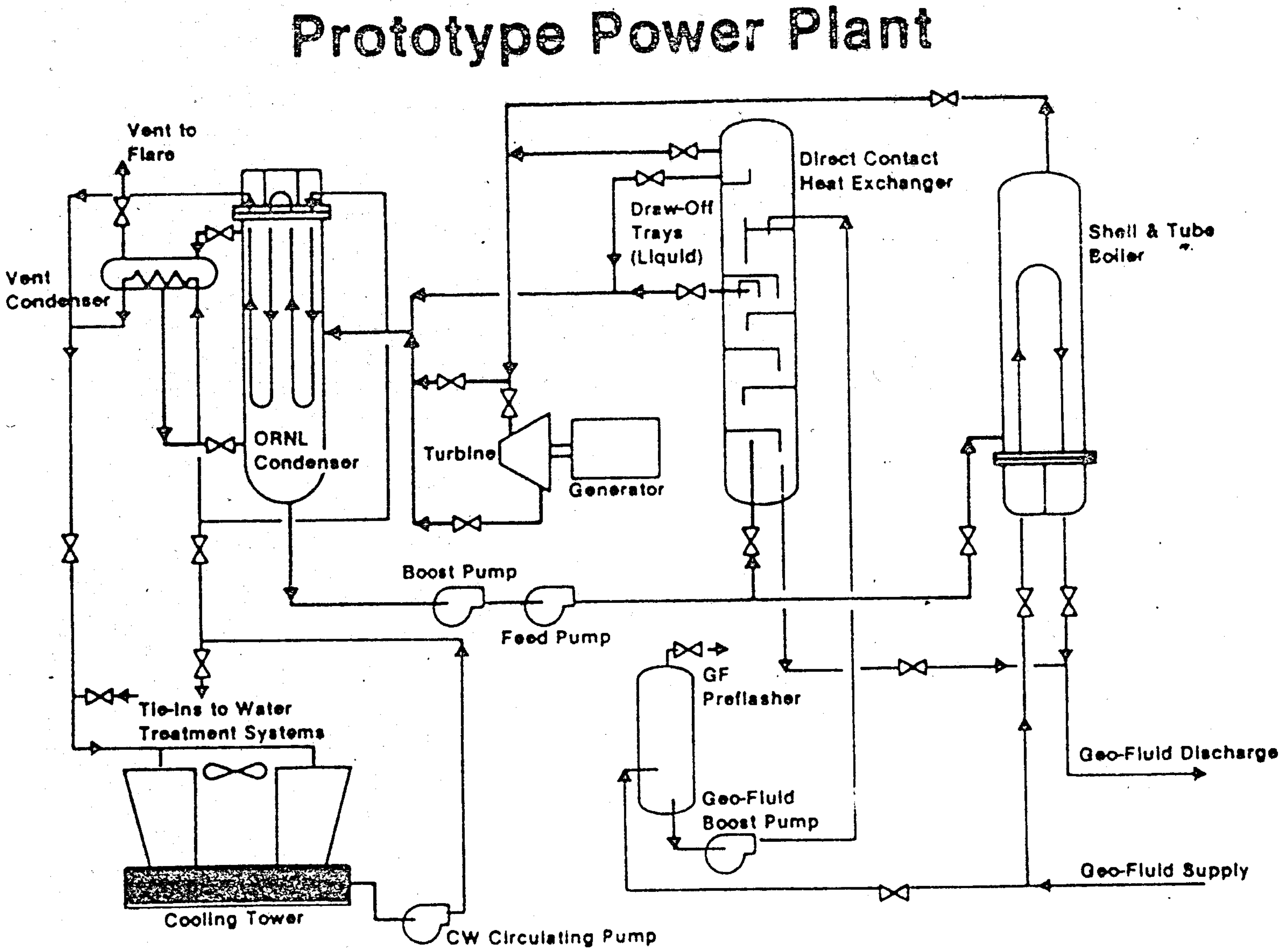

Figure 7. Prototype Power Plant

Prototype Plant
Direct Contact Heat Exchanger

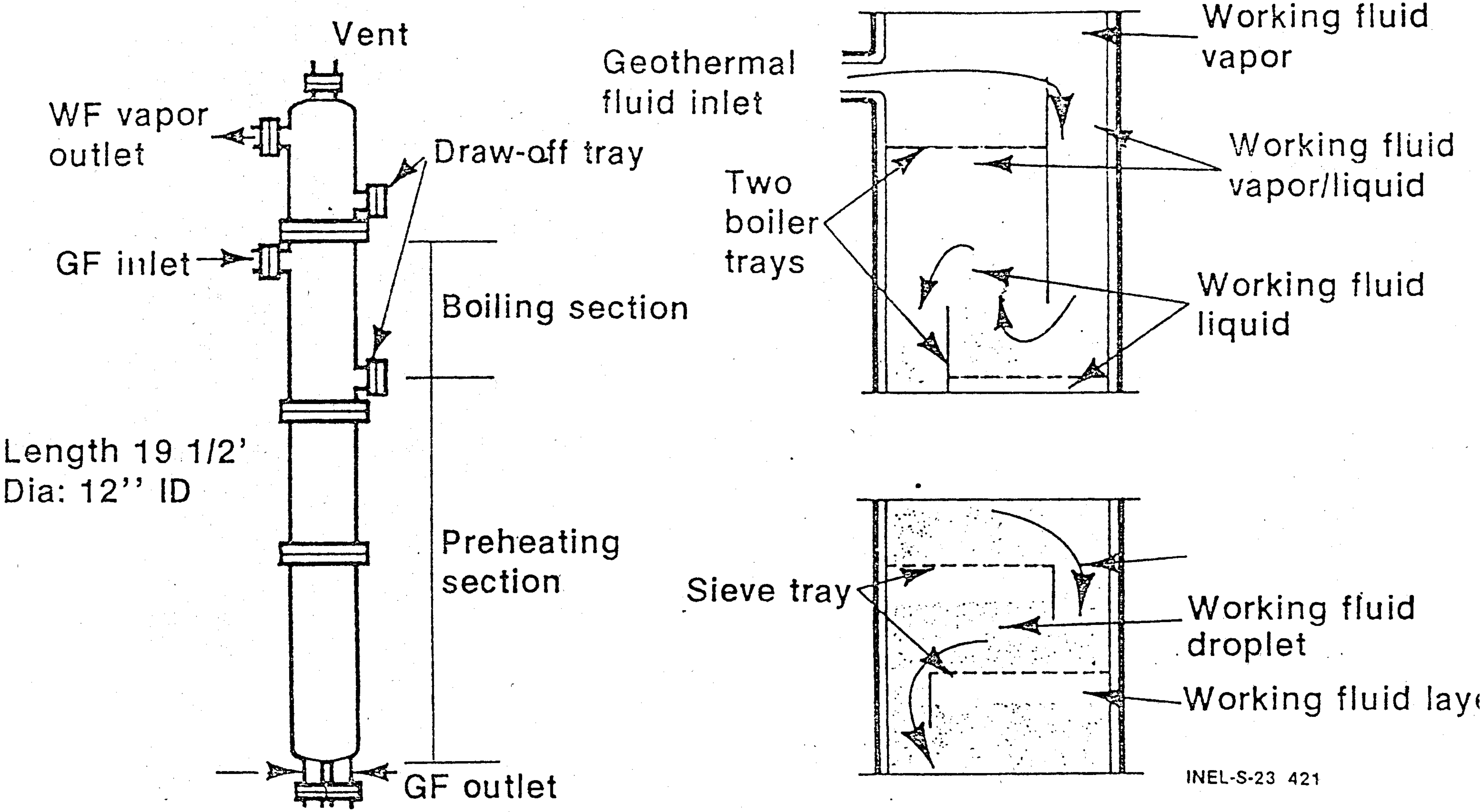

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Figure 8. Prototype Plant Direct Contact Heat Exchanger