THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
Department of Chemical Engineering

Final Report

SPRAY EVAPORATOR FOR STICKWATER FROM RENDERING OF FISH

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DRDA Project 010549

under contract with:

U. S. DEPARTMENT OF COMMERCE
NATIONAL MARINE FISHERIES SERVICE
FISHERY PRODUCTS TECHNOLOGY LABORATORY
CONTRACT NO. N-043-23-71
GLOUCESTER, MASSACHUSETTS

administered through:

DIVISION OF RESEARCH DEVELOPMENT AND ADMINISTRATION   ANN ARBOR

October 1973

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SUMMARY

The objectives of this work were to study the rate of evaporation from a water spray directed cocurrently into a chamber through which hot combustion gases from a natural gas flame were flowing. This involved measurements of fuel economy and heat and mass balances together with evaluation of this performance for various kinds of spray nozzles considered suitable for use with water suspensions of solids and determination of the ability of the procedure to concentrate diluted corn-steep liquor.

For these studies it was necessary to reactivate the cocurrent, spray-type evaporator that had been designed and built for these purposes and which is located on the roof of the George Granger Brown Laboratories of The University of Michigan. Once this was done, the objectives of this study were accomplished. It was found that:

(1) The present apparatus evaporated over 550 lb of water per hour using a fuel consumption of about 1,000,000 Btu/hr with an efficiency close to 60%.

(2) The Bete-Fog nozzles used in the evaporator produced an adequate spray for evaporation purposes and did not clog in the runs where corn-steep liquor was being concentrated.

(3) The presence of corn-steep solids did not materially affect this evaporator operation or the evaporation rate. Nevertheless, such solids would be expected to cause problems if their concentration in the solution being evaporated were allowed to rise much above 30%.

(4) The future design of a concentrator based upon these studies should take into consideration the facts that most of the evaporation occurred in the top 3 to 4 ft of the chamber and that no scorching of corn-steep solids was observed under the operating conditions evaluated.

INTRODUCTION

Stickwater from wet rendering of fish as illustrated in Figure 1 has a very high BOD. It can no longer be discharged untreated into natural waters. Fortunately this stickwater is really a dilute solution of protein that is quite acceptable as a component of chicken feed which many fish rendering plants produce. Before the dissolved protein can be added to the chicken feed, however, it is necessary to concentrate the solution. This originally contains about 5% protein: it should be concentrated to about 35% before being sprayed into the kiln-type dryer. Concentration can be accomplished in double effect evaporators (R-1), but the equipment is costly to buy and difficult to operate. Submerged combustion and Vincent evaporators (R-1), have also been suggested for this duty, but they are reported to present operational problems. None of these appear to have been used effectively in the Great Lakes area.

Our studies of this problem began over five years ago at the suggestion of the then U.S. Bureau of Commercial Fisheries. During the first phase of the work the need for a better stickwater treatment method was documented, the methods of treatment in use were studied and a proposal was made for cocurrent spray evaporation (R-1). The latter evaporation method appeared to offer a number of advantages for small rendering plants. These advantages were discussed in the report for this phase of work (R-1).

Next we received sufficient financial support to build a cocurrent, spray evaporator that used hot combustion gases from a gas-fired burner to evaporate water. This allowed us to begin a study of the possible use of such an apparatus for concentration of stickwater, which constituted the second phase of the study. Design, construction, and preliminary operation characteristics of the concentrator were reported (R-2). On the basis of these studies we received further financial support to continue and the present phase of the work was undertaken.

The proposal for the present work stated three steps to be accomplished. Briefly these included first, putting the equipment in operating condition by replacing the pump and the air duct with better equipment; second, testing the rate of evaporation, fuel economy, various kinds of spray nozzles and the drop sizes that they produced using water as the fluid; and finally, if the above were accomplished with the funds available, testing the equipment by evaporating distiller's solubles or corn-steep liquor. It was pointed out in the proposal that if these tests were encouraging that then the next phase would involve further funds for testing the equipment on actual fish stickwater. Odor problems are to be expected with fish waste and the tests would be best accomplished at a fish rendering site. These objectives then became the basis for the present study.

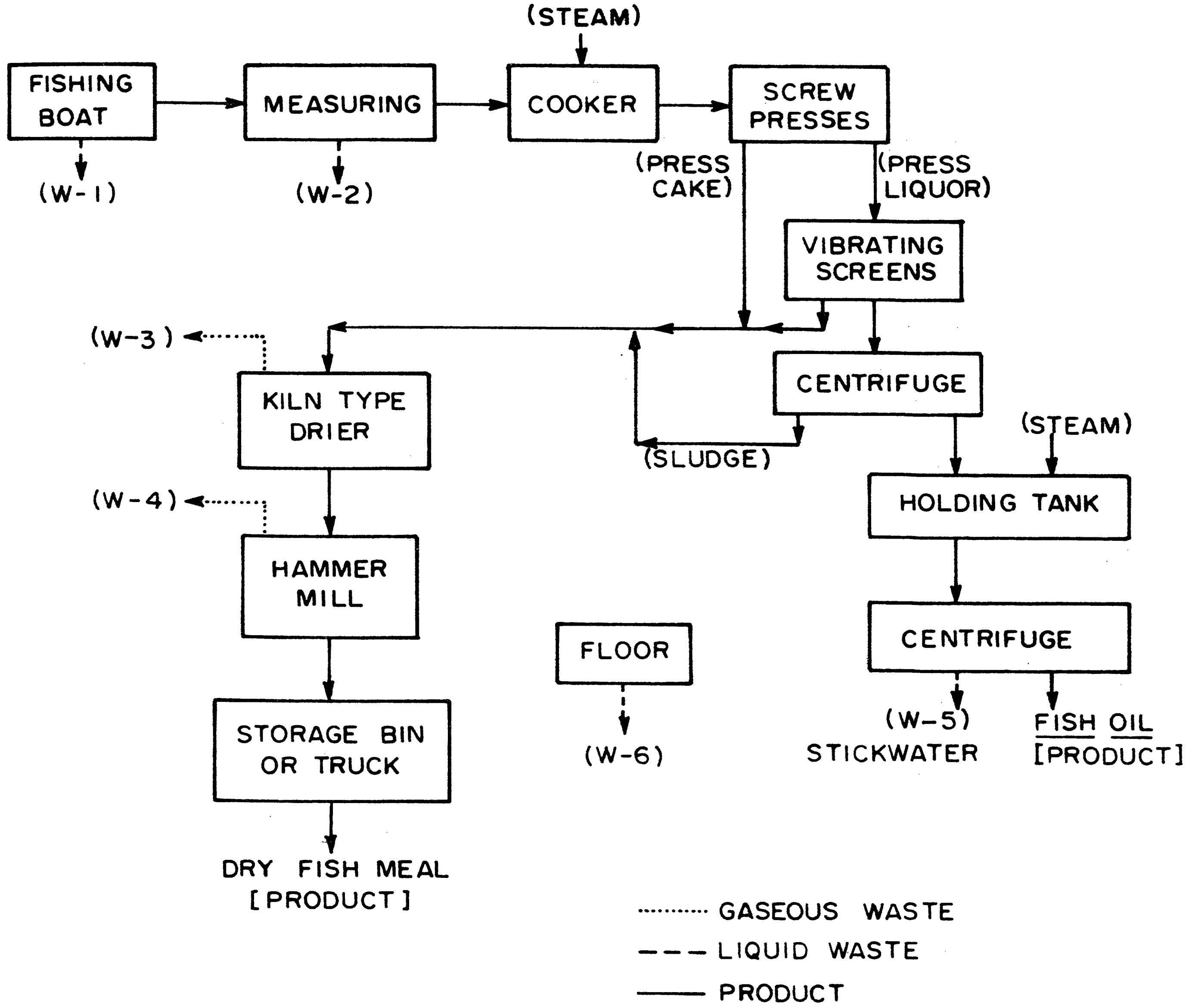

Figure 1. Flow diagram. Alewife rendering plant using the wet rendering process (R-1).

EQUIPMENT AND OPERATING PROCEDURES

With these observations in mind we designed, built, and have tested a device that should effectively concentrate fish stickwater discharged from small rendering plants. It should also eliminate or significantly reduce the deficiencies just discussed for other evaporators that also employ the principle of contacting bulk liquids, jet streams, or drops of water with hot combustion products. A number of preliminary experiments were necessary to provide data upon which to design the apparatus. These include (1) testing of numerous atomizing nozzles to determine their spray patterns for water, (2) assembling and testing the fluid storage and pumping system that is now incorporated in the apparatus, and (3) fabricating a small spray tower from sheet iron to test the assembled equipment, less the burner. This small sheet iron unit was discarded after serving its purpose.

In order to determine the required dimensions of the concentrating chamber and the size of the gas burner for design purposes, the expected evaporation rates of water from drops were calculated using an iterative procedure. This method predicted that 3.45 lb/min of water would be evaporated from 1.05 gal/min of feed using an inlet temperature of the combustion gas at 900°F and a drop size of 800µ. Assuming an efficiency of 50% and a feed rate of 1 gal/min, the approximate heat requirement is 1,000,000 Btu/hr. This was the basis for the purchase of a 1,000,000 Btu/hr, gas-fired burner for this installation.

While evaluating various nozzles to be used for spraying water droplets into the concentrating chamber, we also kept in mind the problems that will likely develop when spraying stickwater. We anticipate that the stickwater will first be passed through a rotary screen. However small particles, together with burn-on, may tend to clog nozzles of the type that are otherwise satisfactory for water.

Tate (R-3) discussed the advantages and disadvantages of alternative drop producing devices in a review article on sprays. The Bete Fog Nozzle, Inc. (R-4) spiral nozzles, the Delavan Manufacturing Company (R-5) centrifugal pressure nozzles and the rotary atomizers all seemed appropriate. Bete and Delavan nozzles were used in the study and are shown in Figures 2 and 3.

SPRAY CONCENTRATOR

The spray concentrator that we have assembled and tested is shown schematically in Figure 4. It has three major components, namely,

(1) Air Heating System,

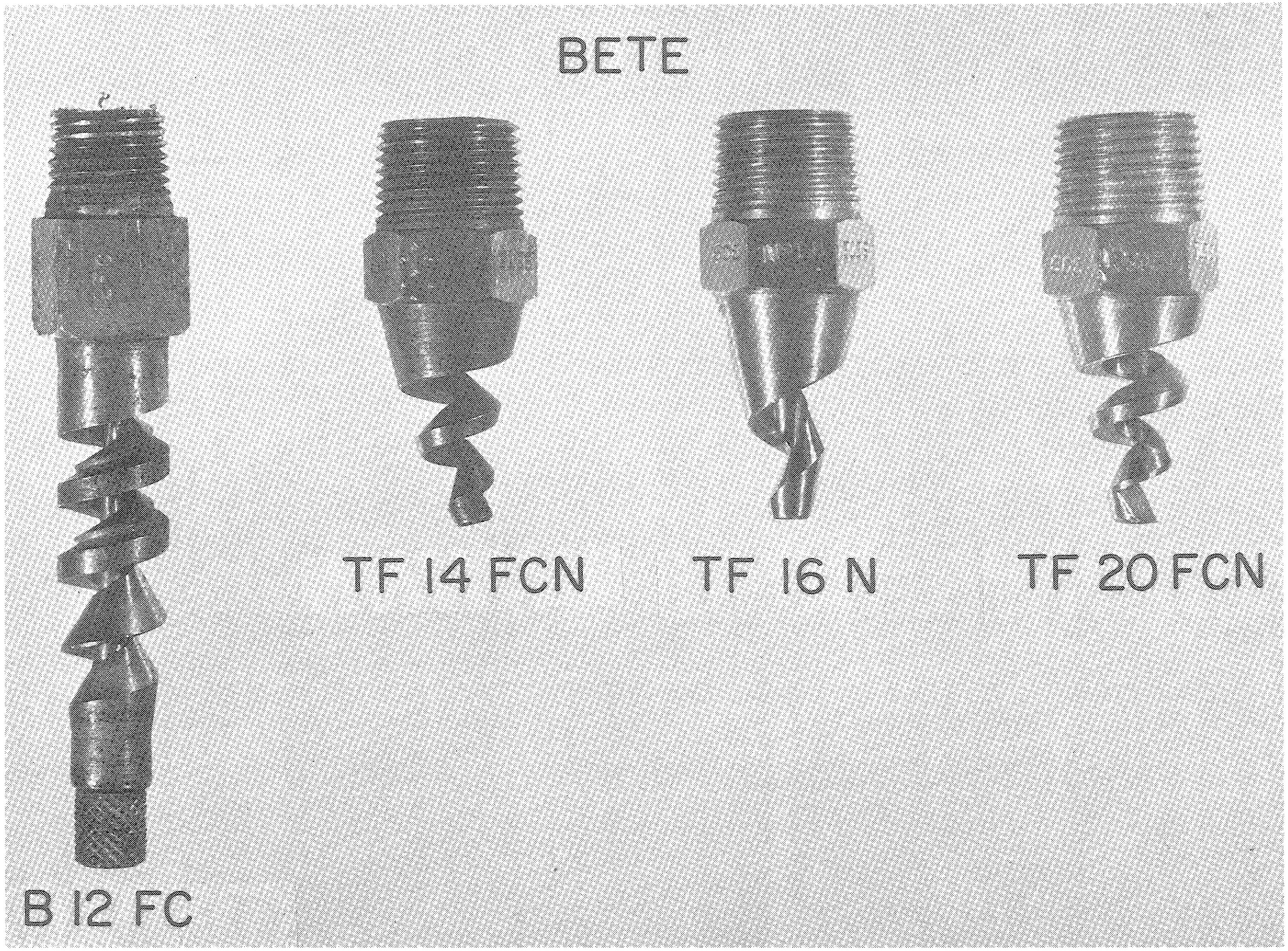

Figure 2. Bete Flow Nozzle, Inc. spiral nozzles tested in the spray concentrator.

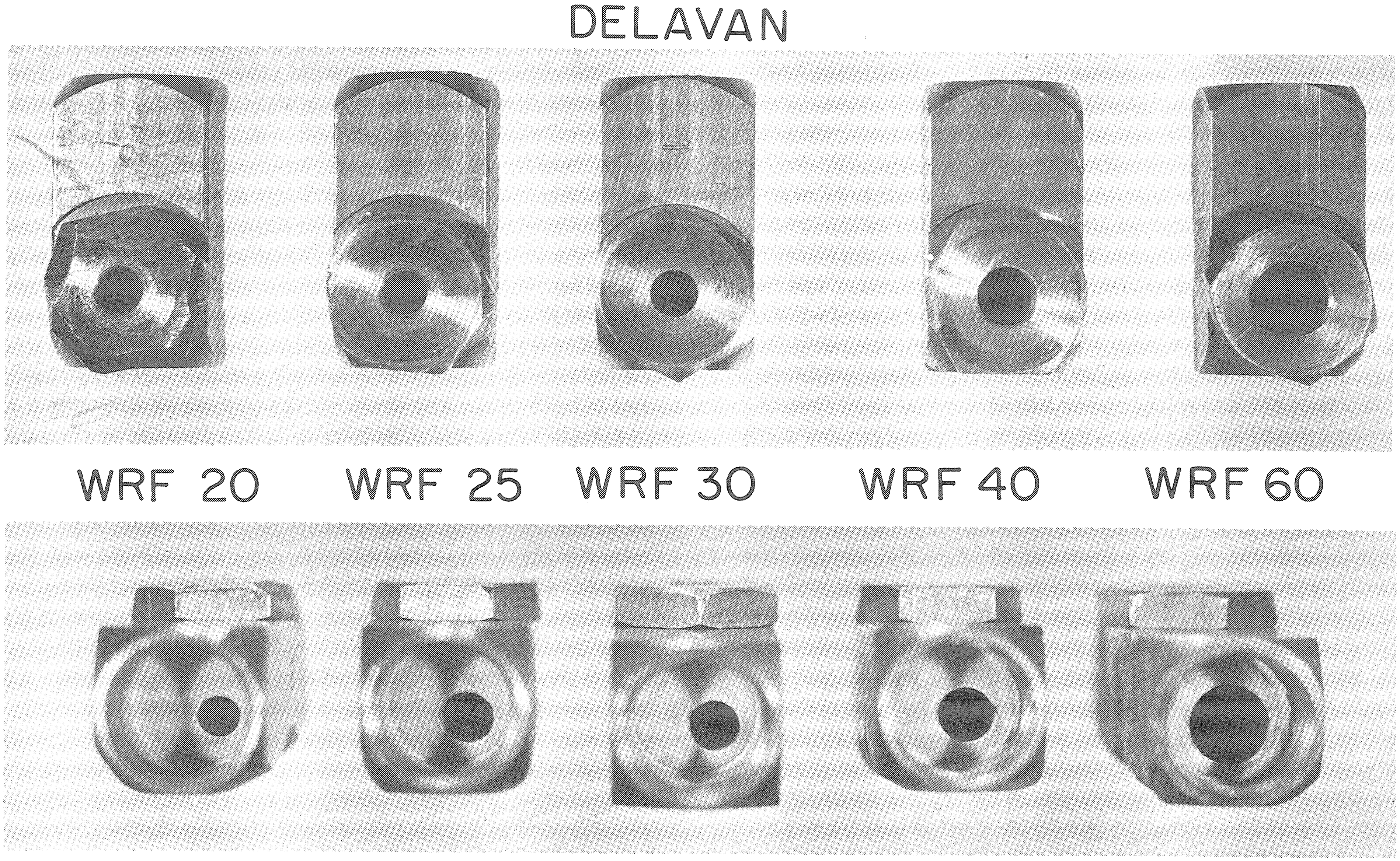

Figure 3. Delavan Manufacturing Company centrifugal pressure nozzles tested in the spray concentrator. Top view shows the outlet orifice and bottom view shows the inlet orifice.

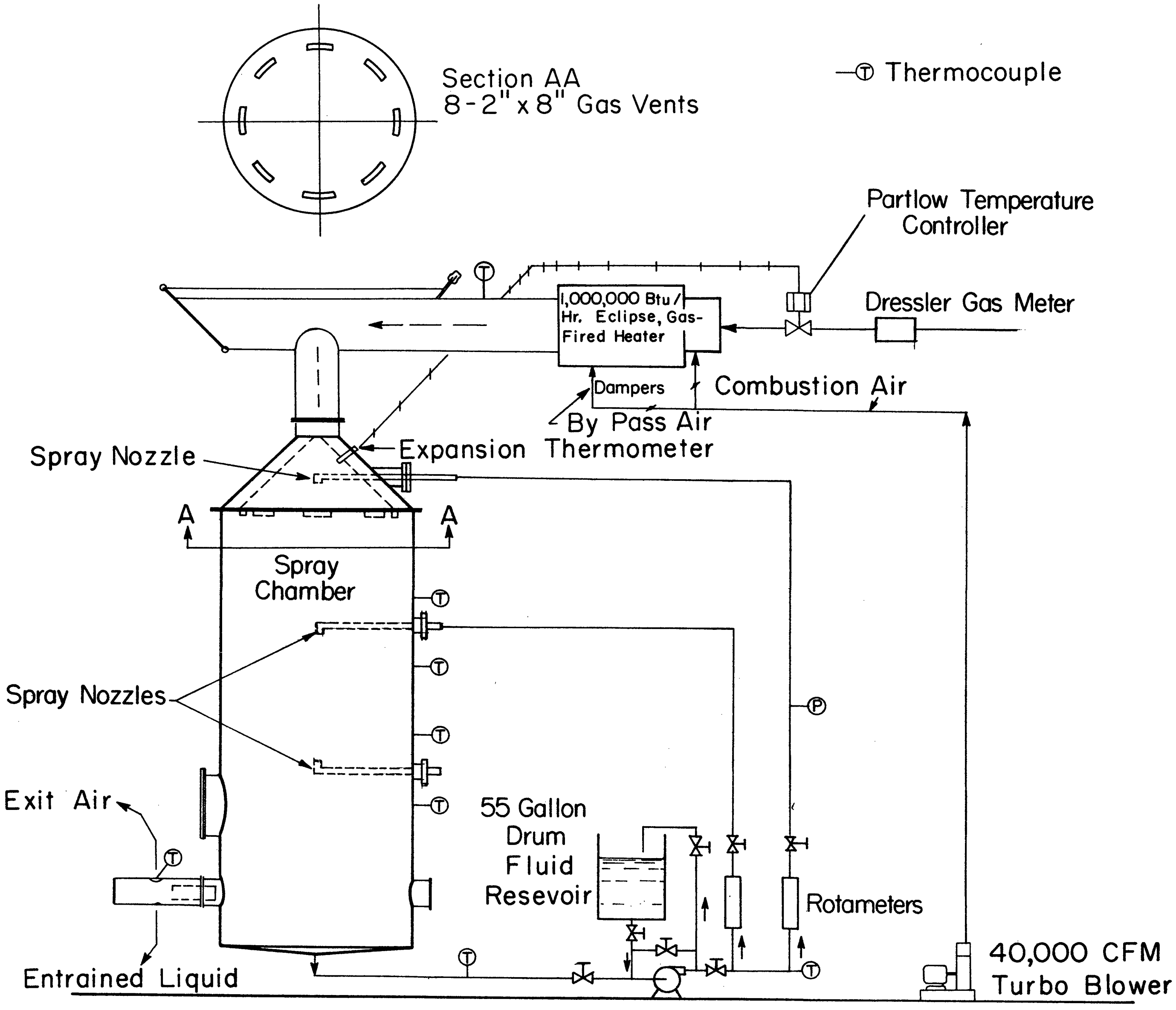

Figure 4. Diagram of spray concentrator for fish stickwater.

(2) Fluid Pumping System,
(3) Concentrating Chamber.

Air Heating System

A 1,000,000-Btu/hr, gas-fired burner with a minimum turn-down ratio of of 40 to 1 is used as the energy source. It was produced by the Industrial Burner Systems, Inc., Detroit, Michigan (R-6). A picture of the burner attached to the spray concentrating chamber through the "T" connection is shown in Figure 5. The flexible hose used for combustion air shown in Figure 5 was replaced by a 6-in. diameter galvinized sheet metal duct after the initial tests.

Included with the burner are a 40,000 standard cubic feet per hour (SCFH) turboblower and a cylindrical chamber in which the hot combustion gases are mixed with excess air. This chamber has a length of 3 ft and a diameter of 16 in. Safety devices, that are required by "Factory Mutual Insurance," have been included in both the gas chain and its accompanying control system. Most important among these safety devices is an electrically operated ECLIPSE, "Safety Shut-Off Valve" (R-6) which is linked with a protection control box that shuts down the system upon failure of the flame or of the blower, or upon loss of electrical power.

The gas chain and safety control systems are shown schematically in Figure 6. It will be noted that a portion of the air is used for initial combustion and enters through the rear of the burner while the remaining fraction enters tangentially into the cylindrical mixing chamber. This chamber is 3 ft long, 16 in. in diameter is covered with a 2-in. layer of insulation. Dampers are present in both lines to regulate air flows. Diluted combustion gases pass from the mixing chamber to a "T" connection between the concentrating chamber and the burner. Here the hot gases can either be vented to the atmosphere or diverted into the chamber by opening or closing the flap-valve at the straight end of the "T." This was installed as a safety device. The "T" is kept open until the burner is operating satisfactorily at start up, then the valve is closed.

A number of component parts are associated with the gas supply for the burner. From upstream to downstream these components are a Nordstrom, manually operated gas cock, a pilot gas cock, an Eclipse Model 204 T-3 electrically operated main-gas safety shutoff valve, and a Partlow indicating temperature controller. The desired temperature at the exit of the cones is monitored by a vapor expansion thermometer. The gas flow is correspondingly adjusted by a controller. There is also an automatic solenoid valve in the pilot gas line.

A "Unified Control Panel," made by Protection Controls, Inc., Skokie,

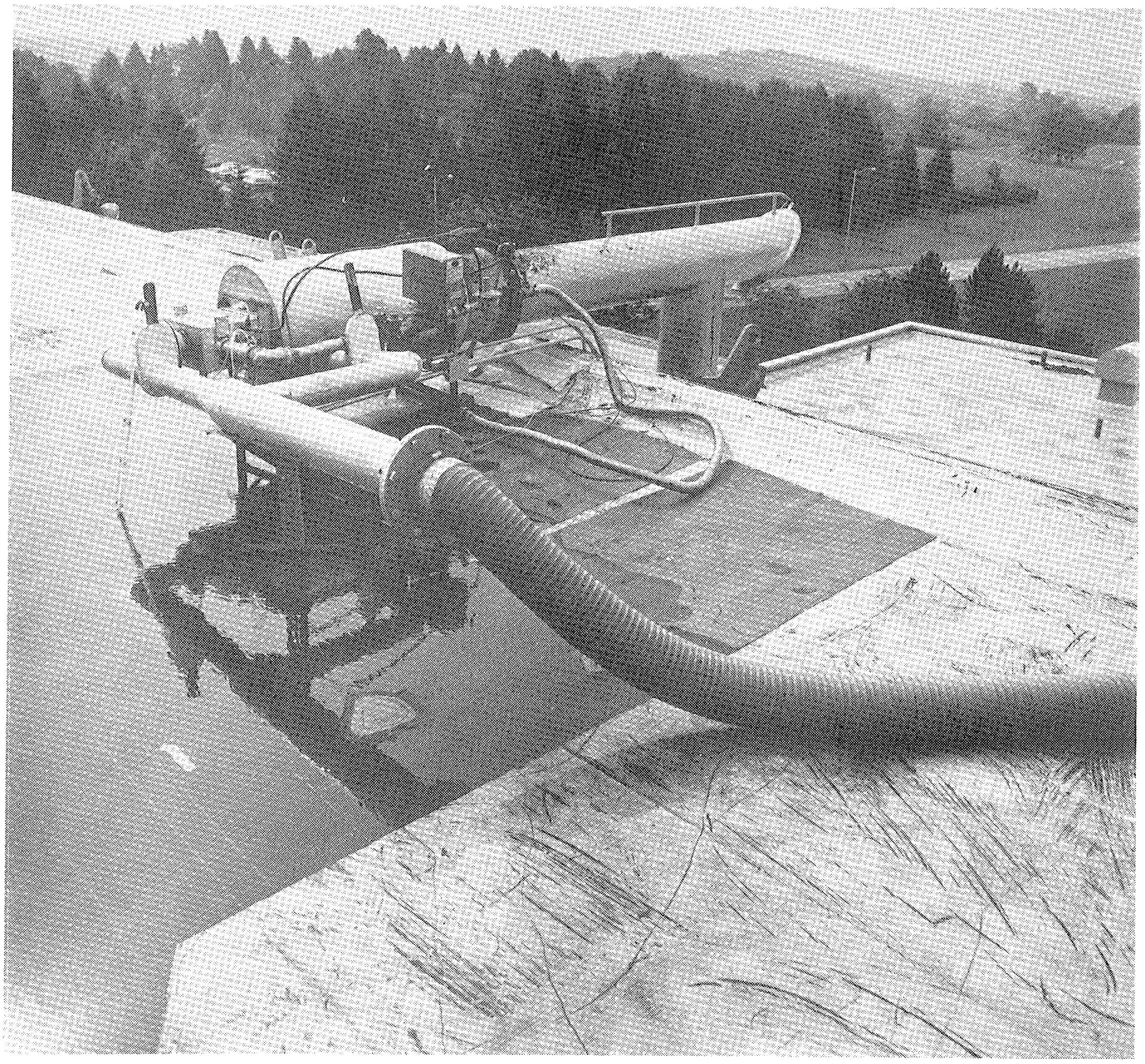

Figure 5. Detail view of gas burner in spray concentrator for fish stickwater.

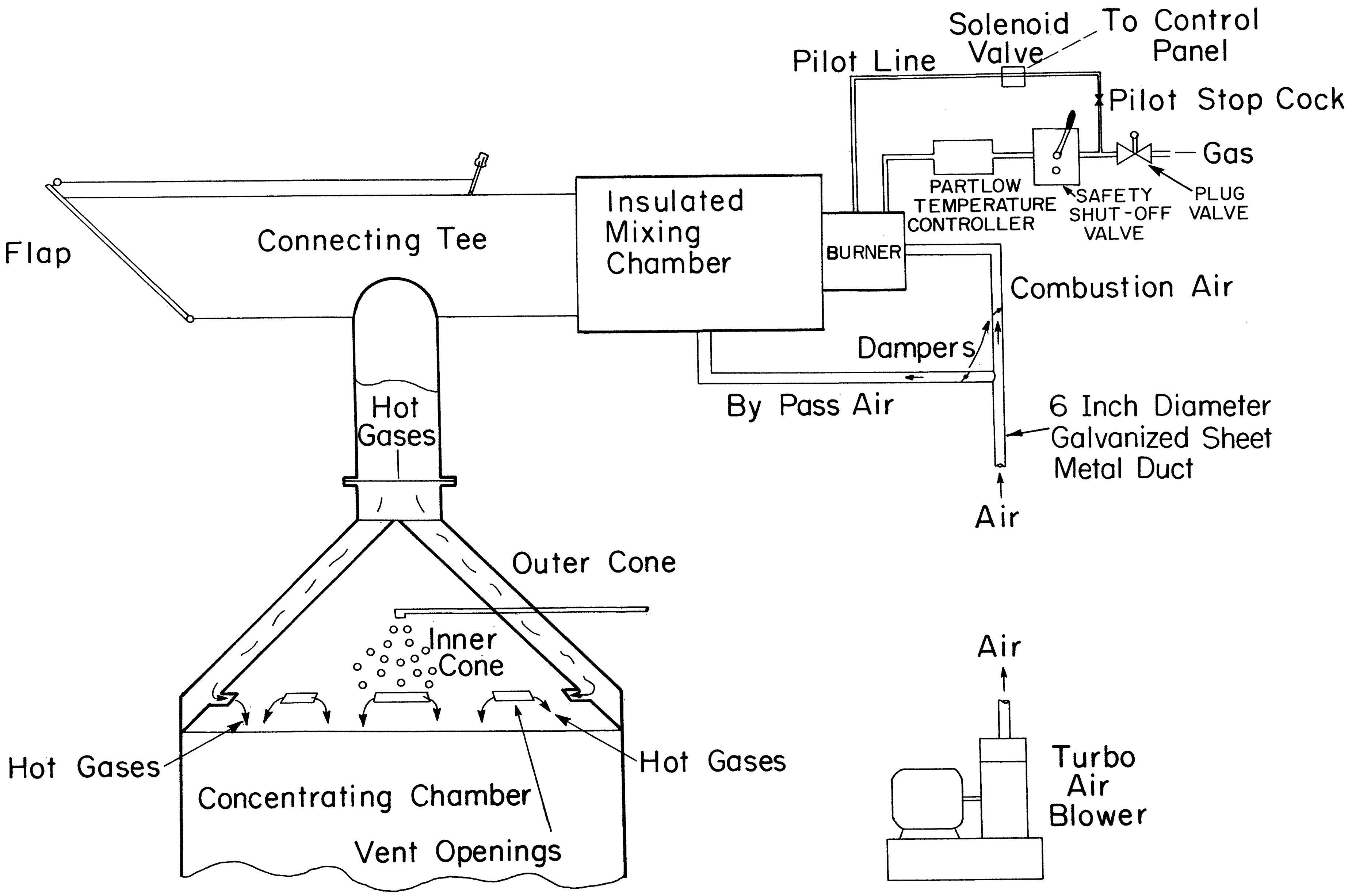

Figure 6. Diagram of air heating equipment in spray concentrator for fish stickwater.

Illinois, controls the ignition and maintenance of the flame. Failure of the blower or of the flame results in automatic closure of the pilot gas valve and of the main-gas safety shutoff valve.

A Dresser Industries, Inc., Model No. 1,5M/TC Rotary Rootsmeter positive displacement gas meter was installed in the gas line to measure the gas flow rate. The manufacturer's calibration indicated a maximum error of 0.68%.

Fluid Pumping System

The fluid to be concentrated is retained in a 55-gal drum shown in Figure 7. A Blackmer rotary pump model SNP 1-1/4 and its accompanying 3-hp electric motor are positioned below the drum. Fluid is drawn from the drum or the concentrating chamber as shown in Figure 8 and is pumped through a 3/4-in. steel pipe and a flexible hose to a 2-ft section of 3/8 in. stainless

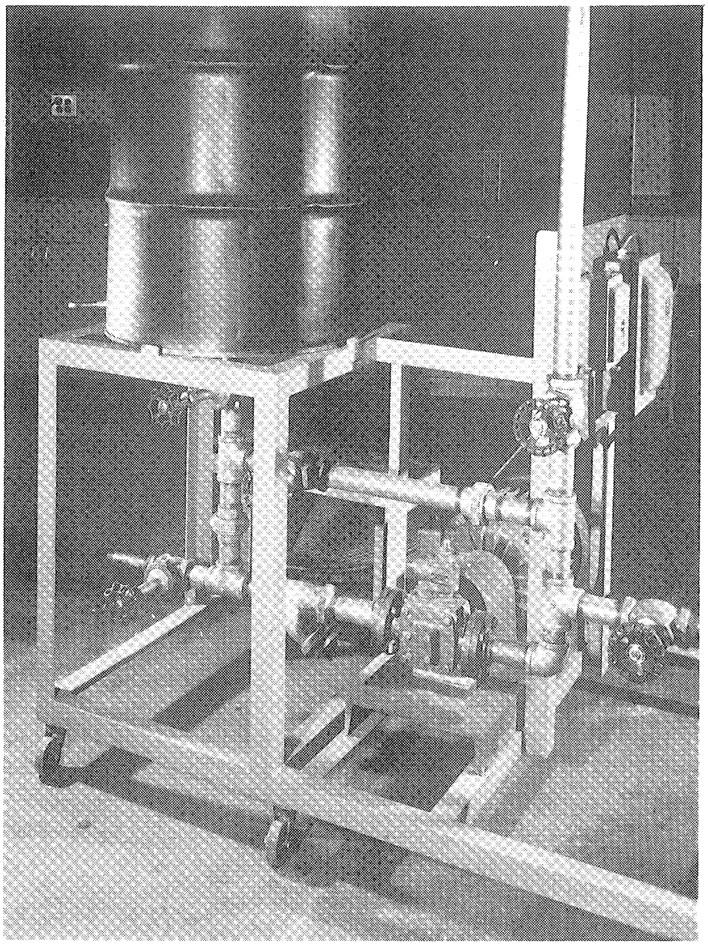

Figure 7. Close-up view of the Blackmer pump and recirculation piping system.

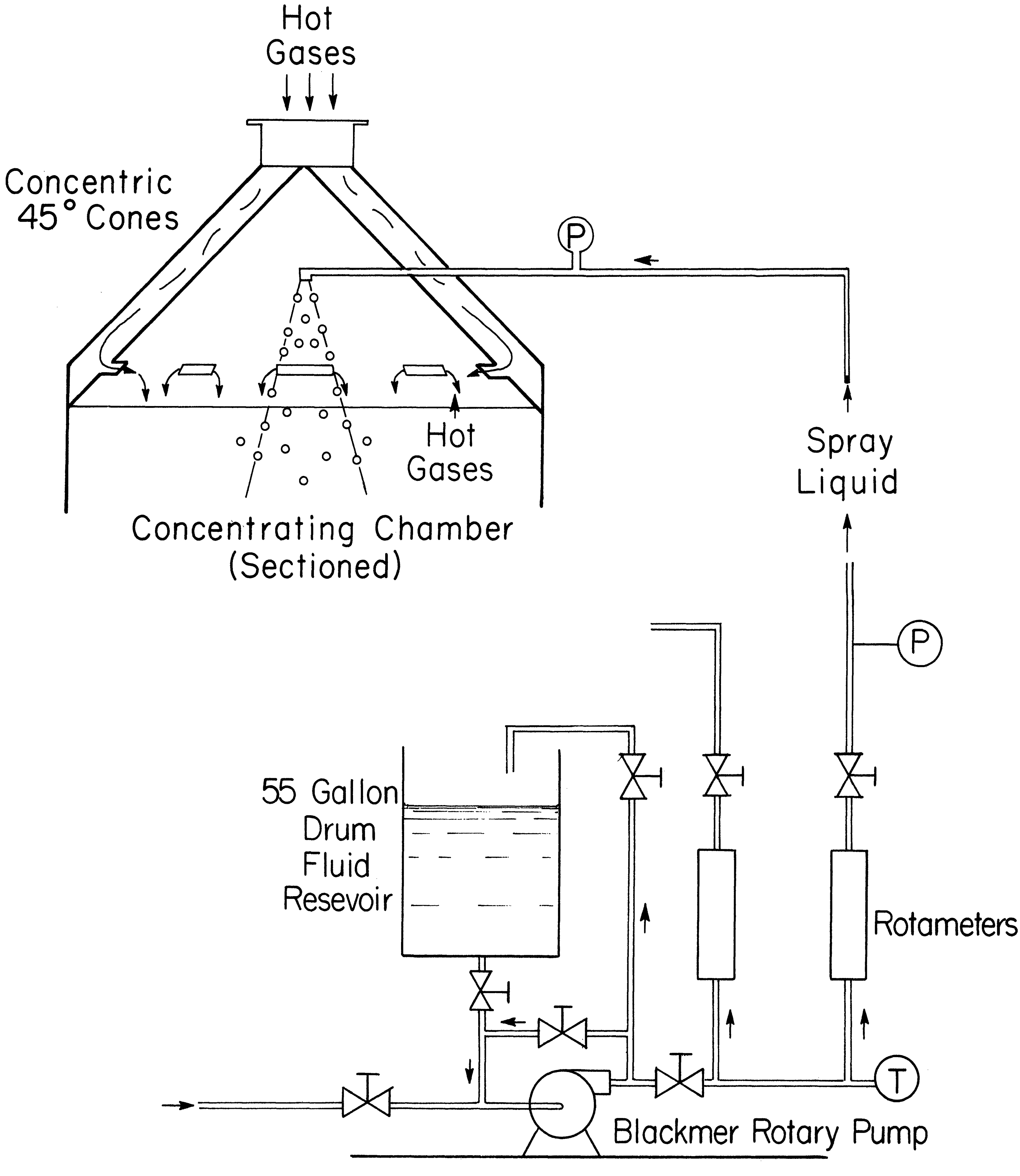

Figure 8. Diagram of fluid pumping system in spray concentrator for fish stickwater.

steel nozzle in the center of the cone, directly above the spray chamber. A flange welded to the pipe is attached to a companion flange connected to the point of attachment of the cones to the top of the chamber.

Two additional spray nozzle locations were added after initial testing. The locations, shown in Figure 9, were selected to give greater spray coverage within the chamber. The spray from the nozzles impinges the chamber walls approximately 4 ft below the nozzle. When the lowest nozzle location was used, the spray from the nozzle was directed upward.

Calibrated rotameters were installed to measure the liquid flow rates through the nozzles. In most of the runs only the uppermost nozzle location was used. In a few instances the uppermost nozzle location was used in conjunction with one of the lower locations. Valves are located at appropriate locations to allow the operator to regulate the liquid flow rate to one or more nozzles and to adjust the amount of recycle compared to fresh liquid feed.

The liquid flow rate through the nozzles influences the drop size. At low flow rates the drops are large; they become smaller as the flow rate increases. Smaller drops are preferred because of the large total surface area available for evaporation.

Evaporation occurs as the sprayed drops fall through the length of the chamber. Approximately 20% of the liquid is evaporated. Concentrated fluid is collected in the bottom of the concentrating chamber and is recycled as desired.

A second feed tank was added for evaporating corn-steep liquor on a once through basis. The tank which was approximately 80 gal in volume was connected in parallel to the existing feed tank. It permitted a constant premixed feed concentration to be fed to the evaporator during the period of a test run. During such a run all the concentrated liquid was collected in the bottom of the concentrating chamber and not recycled.

Concentrating Chamber

The detailed drawing shown in Figure 9 was used for fabricating the spray concentrator. The chamber was constructed from 3/16 in. steel. It stands 18 ft tall, has a diameter of 5 ft 4 in., and weighs approximately 3000 lb. Basically, it consists of a concentrating cylinder covered with two 45° cones. The cylinder itself is 12 ft high. Two, 8-in. exhaust ports are located near the bottom of the cylinder. They are positioned opposite each other with centers 2 ft above the level at which the conical floor of the chamber joins the cylinder and directly above one of the exhaust ports. The chamber stands on four 1-ft legs, each equipped with 8-in. square pads; its conical bottom

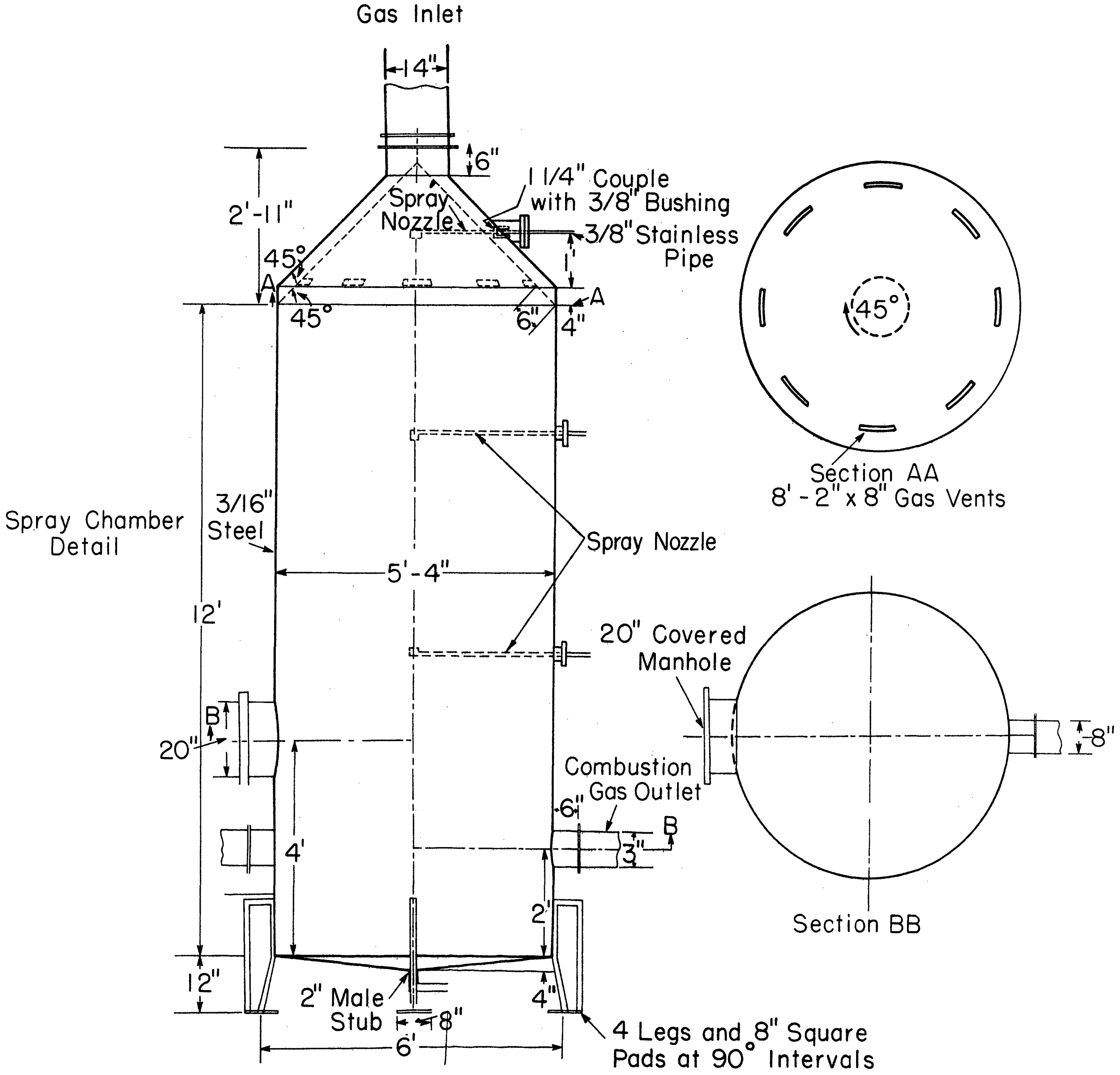

Figure 9. Detailed drawing for the chamber of the fish stickwater concentrator.

drops 4 in. from edge to center to facilitate drainage.

Atop the cylinder are the two concentric, 45° cones (Figure 6). Hot combustion gases are forced into the 2.8-in. annulus between the two cones. Six inches above the base of the interior cone are eight symmetrically spaced slots each of which are 2 in. high and 8 in. wide. These slots direct hot combustion gases out of the annulus perpendicularly into the rain of descending water drops from the nozzle.

This concentrating chamber was fabricated by the Plymouth Tank Company of Plymouth, Michigan. Since the chamber weighs about 3,000 lb a large crane was needed to lift it to the roof of the G. G. Brown Laboratory where it is now located. All of the auxiliary services are located inside the building but the concentrating tank and the burner are outside, exposed to the weather. This was necessary because of the rather large amount of both heat and exhaust vapors involved. The outdoor location however does restrict testing of the equipment to about six months of the year. For other reasons as well, our tests were carried out during the summer months although the tank itself was actually installed in the middle of winter. A picture of the concentrating chamber in position on the roof of the G. G. Brown Laboratory is shown in Figure 10.

Figure 10. General view of the chamber of the fish stickwater concentrator.

TEST EQUIPMENT AND MEASUREMENTS

There are three principal independent variables to be measured and controlled. They are the volume of air flow, the temperature of the gases in the cone of the evaporator and the rate at which fluid sprays from the nozzle (or nozzles). In addition, the fraction of the air which by-passes the burner and is added to the mixing chamber can also be adjusted. This affects the burner temperature for a given cone temperature.

It was also necessary to measure the volume of water evaporated per hour, temperatures and humidities of the inlet and outlet gases, the feed fluid temperature and the product temperature.

The air flow rate was adjusted by setting the air dampers shown in Figure 6 to the positions desired.

Commercially manufactured high-temperature, chromel-alumel thermocouples were screwed into fittings previously welded into the apparatus. Their locations are shown in Figure 4. They were used to measure gas temperatures at any time during a run starting with combustion products from the mixing chamber, then in the annulus, at various points in the chamber and in the exhaust. The liquid feed and product temperatures were also measured with thermocouples. Because of the presence of the spray within the chamber, the wet-bulb temperature rather than the dry-bulb temperature was measured at most locations. It is quite likely that the gas temperature measurement in the cone was influenced by the fine spray which exists behind the nozzle.

Dry-bulb and wet-bulb temperature readings of the inlet and exhaust air were measured by mercury-in-glass thermometers. The humidities of the inlet and exhaust air were determined from the readings.

The amount of water evaporated during the period of a run was determined by noting the amount of fluid added during the run to maintain the same liquid levels in the concentrating chamber and the feed tank. The measurements could be made with a maximum error of 1% or less.

Air flow rates were computed from absolute humidity values and the amount of water evaporated. Inlet and exhaust air flow rate measurements were also made with a vane-type anenometer and a velometer. Since the velocity profile varied across the face of the inlet and exhaust ducts, several readings had to be made to provide an integrated average value. The air flow rates computed from the change in humidity and the water evaporated agreed with the integrated values. Because they were more reproducible and straightforward, the air flow rates tabulated in the report were evaluated from humidity changes.

The spray rates were determined from calibrated rotameter readings.

Rates of gas consumption were measured with a calibrated Dressler Rotary Rootsmeter positive displacement meter. The meter readings were corrected for gas temperature and pressure. Errors in gas flow rates were less than 1%.

The amount of heat absorbed by the evaporator was determined from the feed and product temperatures and the amount of water evaporated.

After the initial run, a demister was fitted to the exhaust port from the chamber; the other port was sealed. The demister consists of a 3-ft long cylinder 12 in. in diameter and closed on one end. Outlet gases enter this demister through an 8-in. pipe that protrudes about 6 in. into the chamber. This was necessary in order to exclude water that runs down the inside wall from mixing with the exit gases. Once inside the demister, the gases exit upwards through a 6-in. hole. Water that is removed by the demister drains from a 2-in. hole in the bottom of the cylinder. The amount of water thus removed was negligible compared to the amount evaporated but its volume was nevertheless included in the calculations.

OPERATION OF EQUIPMENT

In order to successfully fulfill the requirements for a good fish-stick-water concentrator, the equipment must be easy and quick to start and stop as well as easy to use. It should be inexpensive to purchase, install, and operate. With these thoughts in mind, a detailed description of the steps required to start and shut down the spray concentrator are given below.

START UP AND OPERATING PROCEDURES

1. Pour fluid to be concentrated into the 55-gal fluid reservoir (Figure 8) until it is about two-thirds full. Also pour some of the same fluid into the concentrating chamber until the fluid level gage at the bottom of the chamber shows at about the halfway mark (Figure 4). These fluid levels should be approximately maintained during a run; at the end of a run it is particularly important that both levels be exactly reestablished at their original heights in order that precise measurements of the amount of water evaporated can be made.

2. Start the air blower from the control panel

3. Start the fluid pump and adjust the liquid flow rate using the gate valve in the by-pass line around the pump (Figure 8). Usually, only a fraction of the water sprayed evaporates. The excess water collects in the bottom of the evaporator from whence it is pumped back to the spray nozzle.

4. After the blower operates for 5 min, open the by-pass flap-valve on the "T" connection to the chamber.

5. Open the plug valve in the main gas line and also open the pilot stop cock (Figure 6).

6. Open and adjust dampers in the inlet air lines (Figure 6).

7. Set the temperature control at "minimum fire."

8. Start the pilot gas flame from the control panel. A red light indicates ignition has occurred.

9. Ignite the main gas burner by manually opening the Eclipse safety shut-off valve.

10. Adjust the temperature controller and air dampers in order to provide the desired conditions for the run (Figure 6).

11. Close the by-pass flap on the "T" connection in the pipe carrying hot combustion gasses from the burner to the concentrator (Figure 6).

By following this procedure, steady state can be achieved in about 30 min. At steady state, the gas temperatures in the burner exhaust, in the cone, and in the exit gases from the evaporator remain essentially constant.

SHUT DOWN PROCEDURE

The spray concentrator is shut down by effecting the following steps in order:

1. Turn off the fluid pump.

2. Stop the air blower from the control panel. This automatically shuts off the gas burner.

3. Close the main gas stop cock and also the pilot stop cock.

4. Completely drain fluid from the pumping tank, the concentrating chamber and from all pipes.

EXPERIMENTAL RESULTS

The nozzles used in the investigation are shown in Figures 2 and 3. They were all checked in the laboratory to evaluate spray characteristics at different flow rates as illustrated in Figure 11. The nozzle descriptions are given in Table I.

TABLE I

IDENTIFICATION AND DESCRIPTION OF SPRAY NOZZLES

Nozzle Number	Designed Flow Rate,* lb water/hr	Relative Drop Size at Operating Conditions	Spray Cone	Cone Angle, deg
		Delavan Nozzles		
WRF20	1000	Fine	Hollow	65
WRF25	1250	Fine	Hollow	70
WRF30	1500	Fine	Hollow	70
WRF40	2000	Medium	Hollow	70
WRF60	3000	Medium	Hollow	70
		Bete Nozzles		
B12FC	3000	Fine	Full	120
TF14FCN	4050	Fine	Full	90
TF16N	5030	Medium	Hollow	50
TF20FCN	7250	Large	Full	90

*The designed flow rate is the flow rate of water through the nozzle at a pressure drop across the nozzle of 40 psi.

Nozzles are designed to operate over a limited range of flow rates and use the pressure difference across the nozzle to promote drop formation. At low flow rates and small pressure differences the mean drop size is relatively large and the drop size becomes progressively smaller as the flow rate increases. At high flow rates the energy required to overcome the pressure differences across the nozzle exceeds the advantage of smaller drops. The rated flow rates in Table I are for a pressure difference of 40 psi. Under the operating condi-

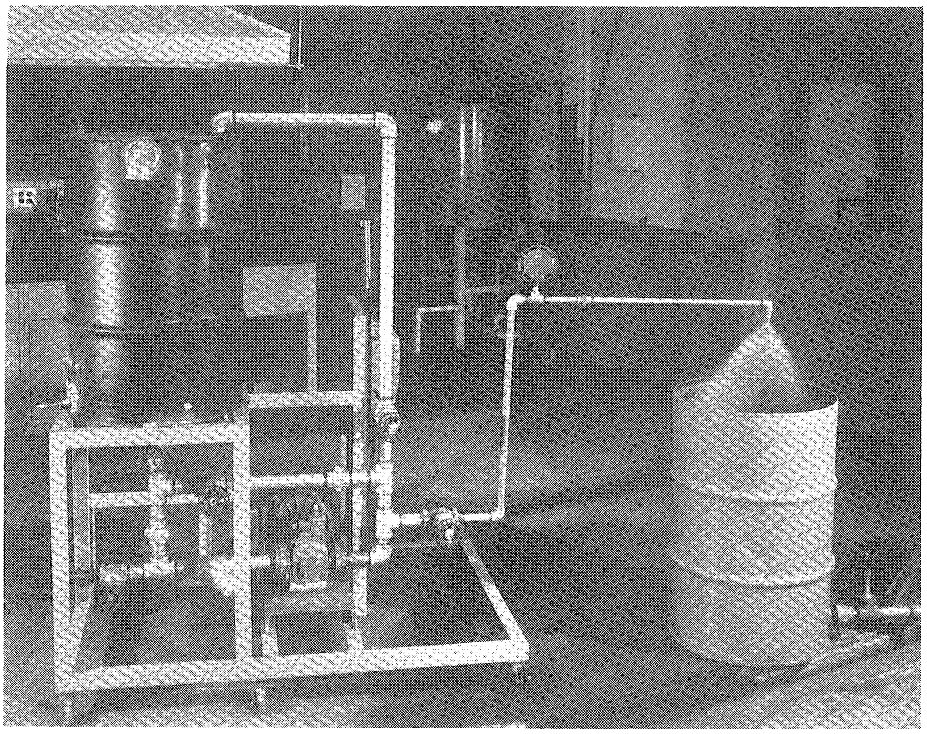

Figure 11A. Laboratory set-up to evaluate spray characteristics of nozzles used in the spray concentrator.

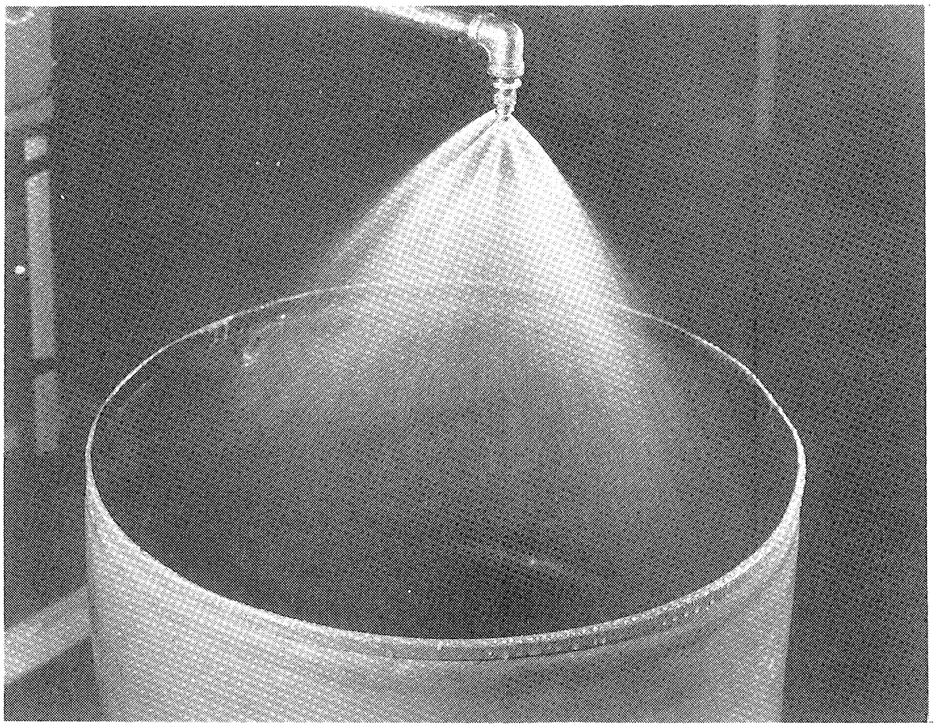

Figure 11B. Close-up view of spray from a Bete spiral nozzle.

tions, the larger nozzles produced medium or large drops as the flow rate was limited by the pump capacity.

The experimental work on the spray concentrator was conducted during the summers of 1971 and 1972. After construction of the equipment and initial checkout, ten runs were made in the summer of 1971 to evaluate the spray concentrator. Water was used as the working fluid. The data are tabulated in Table II.

During the first four runs considerable information was obtained concerning the operation of the evaporator and measurement of operating conditions. At first, the exit wet- and dry-bulb temperatures were measured with a sling psychrometer inserted into the exhaust port at the side and near the bottom of the evaporator through which the exit air passed. The wet- and dry-bulb temperatures were approximately equal. However when the sling psychrometer was placed in the path of the exit gases, but outside of the duct, the dry-bulb temperature was 20° to 40°F higher than the wet-bulb temperature. Inside the duct, entrained water impinging on the dry-bulb thermometer caused the dry-bulb thermometer to behave as a wet-bulb thermometer.

Before Run 5 the expansion thermometer located in the cone was withdrawn a few inches. At the new location, the cone temperature was roughly 300°F higher than at the previous location, under similar operating conditions. Water spray striking the thermometer apparently caused the lower temperature. The cone temperatures listed for Runs 1-4 are therefore low by approximately 300°F.

When the inside of the evaporator was inspected at the end of Run 7, it was found that the spray nozzle insert was missing. Since the operating conditions and results for Runs 2-7 were rather consistent, the insert apparently came out during the first run. A calibration of the nozzle without insert was made to determine water flow rate as a function of pressure. Even though the spray distribution and drop size were not ideal, the results for Runs 2-7 were the best in terms of evaporator efficiency and total evaporation rate indicating that the evaporator could be operated at higher flow rates.

As can be seen from Table II, evaporator efficiencies of over 50% can be achieved at cone temperatures of 800°F and water flow rates of 3200 lb/hr. At these conditions, approximately 17% of the water is evaporated per pass, resulting in an evaporation rate of about 560 lb/hr. The burner temperature is nearly 1400°F. At lower water flow rates the evaporator efficiency is considerably less.

Several equipment modifications were made in the spring of 1973 to improve operations. These included:

1. The replacement of the flexible air duct with a 6-inch diameter galvanized sheet metal duct.

TABLE II

SUMMARY OF SPRAY CONCENTRATOR EVALUATION DATA WITH WATER AS THE TEST LIQUID FOR DELAVAN NOZZLES WRF40 AND WRF45

Run Number	1	2	3	4	5	6	7	8	9	10
Nozzle Number	WRF40[b]	WRF40[b]	WRF40[b]	WRF40[b]	WRF40[b]	WRF40[b]	WRF40[b]	WRF45	WRF40[c]	WRF45
Nozzle Pressure, psig	19	20	20	20	20	20	20	22	22	20
Inlet Air										
Dry-bulb temperature, °F	66	82	91	82	84	84	85	83	84	90
Wet-bulb temperature, °F	62	76	78	75	67	65	67	67	67	69
Humidity, lb water/lb air	0.010	0.017	0.018	0.012	0.010	0.009	0.010	0.011	0.011	0.010
Outlet Air										
Dry-bulb temperature, °F	180	200	202	202	184	187	200	300	256	256
Wet-bulb temperature, °F	154	164	164	162	161	161	163	159	157	155
Humidity, lb water/lb air	0.220	0.310	0.310	0.300	0.290	0.278	0.310	0.230	0.280	0.250
Cone Temperature, °F	470	583	590	573	880	858	805	815	779	810
Burner Temperature, °F	1286	1423	1433	1416	1486[d]	1300	1390	1325	1343	1325
Energy Input, Btu/hr	970,000	1,050,000	1,030,000	1,035,000	1,030,000	1,030,000	1,030,000	1,030,000	1,030,000	1,030,000
Evaporation Rate, lb/hr	402	536	530	547	510	519	557	334	392	331
Air Flow Rate, SCFH	30,200	28,200	27,800	30,900	28,500	29,800	29,000	26,100	29,700	28,000
Heat Absorbed, Btu/hr	449,000	600,000	592,000	611,000	570,000	579,000	623,000	373,000	438,000	372 000
Efficiency, %	46	60	57	59	55	56	60	36	42	36
Nozzle Flow Rate, lb/hr	1,350	3,200	3,200	3,200	3,200	3,200	3,200	1,300	3,420	1,580
Fraction Evaporated/Pass	0.300	0.162	0.166	0.170	0.160	0.161	0.174	0.256	0.114	0.209

[a] Based on water evaporated and humidity change.
[b] Nozzle 40 without insert.
[c] Modified with bored out insert.
[d] Thermocouple burned out during run.

2. The installation of a Dresser gas meter.
3. The installation of rotameters for nozzle flow rates.
4. The installation of a new fluid pumping system.

These changes were accomplished to eliminate deficiencies encountered while operating the previous summer.

During the summer of 1972 forty runs were made with eight different nozzles. Thirty-three runs were made with water as the working fluid and seven were made with diluted corn-steep liquor. The corn-steep liquor concentrate was obtained from CPC International, Argo, Illinois. The data are tabulated in Tables III-VIII and are plotted in Figures 12-19.

From the data taken it has been found that the evaporation rate increases with increased:

1. Feed flow rate through nozzle because of smaller average drop size and greater number of drops.
2. Air flow rate.
3. Air temperature.
4. Sprayed liquid temperature.

The first two conclusions can be seen in Figures 14, 15, and 16 for nozzles TF14FCN and B12FC. For a given air flow rate and temperature, the evaporation rate increases with the flow through the nozzle because of smaller and more drops until the air becomes nearly saturated with water at the exit conditions. Increasing the air flow rate and air temperature increases the water capacity of the exit air for other conditions fixed. The upper limit on inlet air temperature is the temperature which would cause scorching of the solids in the evaporating drops or in the liquid adhering to the internal surface of the spray concentrator. Since the vapor pressure of water increases with temperature, there is an advantage in having the sprayed liquid at as high a temperature as possible. This is accomplished when the flow rate through the nozzle exceeds the evaporation rate and the recycled fluid becomes hotter than the fresh feed.

The nozzles which produced the largest drops at the operating conditions gave the lowest evaporation rates. This can be seen when the results for nozzles WRF60 and TF16N in Figures 12 and 13 are compared with other data. All the nozzles evaluated were capable of evaporating at least 400 lb/hr of water at an air flow rate of 32,000 SCFH and a heat input of 1,000,000 Btu/hr.

In most of the runs, the water put into the bottom of the spray concentrator initially was heated by spraying and recycling until the temperature was nearly constant before experimental data were taken. In a few runs only fresh feed was sprayed and the water evaporated collected in the spray

TABLE III

SUMMARY OF SPRAY CONCENTRATOR EVALUATION DATA WITH WATER AS THE TEST FLUID FOR DELAVAN NOZZLE WRF60 AND BETE NOZZLE TF16N

Run Number	11	12	13	14	15	16
Nozzle Number	WRF60	WRF60	WRF60	WRF60	TF16N	TF16N
Liquid Spray Rate, lb/hr	3000	3000	3500	2500	3000	3500
Inlet Air						
Dry-bulb temperature, °F	69	67	84	79	56	59
Wet-bulb temperature, °F	57	57	71	72	52	51
Humidity, lb water/lb air	0.0072	0.0075	0.0138	0.0159	0.0075	0.0063
Outlet Air						
Dry-bulb temperature, °F	190	187	181	210	224	207
Wet-bulb temperature, °F	158	158	159	159	157	157
Humidity, lb water/lb air	0.2631	0.2655	0.2805	0.2530	0.2442	0.2544
Fresh Water Temperature, °F	68	67	68	74	74	72
Sprayed Water Temperature, °F	153	154	155	153	148	150
Burner Temperature, °F	1321	1318	1332	1332	1312	1309
Cone Temperature, °F	776	772	769	798	781	769
Gas Flow Rate, SCFH	907.1	864.4	912.7	946.9	938.3	943.2
Energy Input, Btu/hr	934,300	890,300	940,000	975,300	966,400	971,500
Evaporation Rate, lb/hr	342.8	348.3	374.9	295.2	300.1	310.8
Air Flow Rate, SCFH	22,970	22,820	23,940	22,670	22,610	22,140
Heat Absorbed, Btu/hr	374,700	381,100	410,000	320,800	326,100	338,400
Efficiency, %	40.2	42.8	43.6	32.9	33.7	34.8
Fraction Evaporated/Pass	.114	.116	.107	.118	.100	.089

TABLE IV

SUMMARY OF SPRAY CONCENTRATOR EVALUATION DATA WITH WATER AS THE TEST FLUID FOR BETE NOZZLE TF14FCN

Run Number	17	18	19	20	21	22	23	39	40
Nozzle Number	TF14FCN	TF14FCN	TF14FCN	TF14FCN	TF14FCN	TF14FCN	TF14FCN	TF14FCN	TF14FCN
Liquid Spray Rate, lb/hr	2500	3000	3335	2500	3000	3000	2500	1500	2000
Inlet Air									
Dry-bulb temperature, °F	73	77	80	74	77	73	88	75	71
Wet-bulb temperature, °F	64	65	65	56	59	58	73	63	64
Humidity, lb water/lb air	0.0107	0.0109	0.0102	0.0059	0.0070	0.0068	0.0147	0.0096	0.0183
Outlet Air									
Dry-bulb temperature, °F	181	173	170	181	177	176	203	344	224
Wet-bulb temperature, °F	160	159	159	160	152	156	156	152	154
Humidity, lb water/lb air	0.2943	0.2872	0.2836	0.2885	0.2223	0.2528	0.2467	0.1750	0.2187
Fresh Water Temperature, °F	72	75	77	77	77	74	78	73	73
Sprayed Water Temperature, °F	155	154	153	155	147	150	152	142	146
Burner Temperature, °F	1322	1319	1317	1319	1072	1144	1103	1069	1094
Cone Temperature, °F	757	733	714	762	642	642	676	705	610
Gas Flow Rate, SCFH	874.0	925.5	925.2	910.7	865.5	901.6	863.0	838.5	853.2
Energy Input, Btu/hr	900,200	953,300	952,900	938,100	891,500	926,600	888,900	963,700	878,800
Evaporation Rate, lb/hr	353.7	363.3	358.1	363.5	423.4	397.2	409.6	263.4	330.7
Air Flow Rate, SCFH	1,240	22,540	22,480	21,790	31,850	26,630	29,180	28,370	27,160
Heat Absorbed, Btu/hr	385,500	394,700	388,400	394,300	457,900	431,500	443,300	285,900	372,800
Efficiency, %	42.8	41.4	40.8	42.1	51.4	46.5	49.9	33.1	42.4
Fraction Evaporated/Pass	.142	.121	.107	.145	.141	.132	.164	.182	.160

TABLE V

SUMMARY OF SPRAY CONCENTRATOR EVALUATION DATA WITH WATER AS THE TEST FLUID FOR BETE NOZZLE B12FC

Run Number	24	25	26	27	28	41
Nozzle Number	B12FC	B12FC	B12FC	B12FC	B12FC	B12FC
Liquid Spray Rate, lb/hr	3000	2500	2000	3000	1000	2000
Inlet Air						
Dry-bulb temperature, °F	84	86	86	76	78	75
Wet-bulb temperature, °F	73	73	73	72	72	69
Humidity, lb water/lb air	0.0154	0.0151	0.0150	0.0163	0.0157	0.0143
Outlet Air						
Dry-bulb temperature, °F	159	166	201	158	268	196
Wet-bulb temperature, °F	153	154	154	156	159	154
Humidity, lb water/lb air	0.2356	0.2352	0.2268	0.2552	0.2137	0.2259
Inlet Water Temperature, °F	80	80	82	80	80	74
Outlet Water Temperature, °F	149	148	148	149	149	136
Burner Temperature, °F	1093	1096	1103	1133	1090	1112
Cone Temperature, °F	661	665	680	657	699	660
Gas Flow Rate, SCFH	880.8	887.7	869.0	903.5	874.3	863.0
Energy Input, Btu/hr	907,300	914,300	895,000	930,600	900,500	888,800
Evaporation Rate, lb/hr	449.1	432.7	400.6	421.0	348.8	355.2
Air Flow Rate, SCFH	33,260	32,310	31,380	29,300	30,090	28,460
Heat Absorbed, Btu/hr	484,600	467,100	431,600	454,600	376,600	385,500
Efficiency, %	54.5	51.0	48.3	48.8	50.6	43.4
Fraction Evaporated/Pass	.150	.173	.200	.140	.349	.178

TABLE VI

EFFECT OF TWO NOZZLE LOCATION AND FLOW RATE ON EVAPORATION RATE FOR A TOTAL WATER FLOW RATE OF 3000 lb/hr THROUGH NOZZLES

Run Number	29	30	31	24
Upper Nozzle Number	B12FC	B12FC	B12FC	B12FC
Lower Nozzle Number	TF14FCN	TF14FCN	TF14FCN	
Lower Nozzle Direction	Upward	Downward	Downward	
Upper Nozzle Flow Rate, lb/hr	2500	2500	2000	3000
Lower Nozzle Flow Rate, lb/hr	500	500	1000	
Inlet Air				
Dry-bulb temperature, °F	85	84	87	84
Wet-bulb temperature, °F	74	70	70	73
Humidity, lb water/lb air	0.0163	0.0216	0.0124	0.0154
Outlet Air				
Dry-bulb temperature, °F	165	164	176	159
Wet-bulb temperature, °F	154	152	152	153
Humidity, lb water/lb air	0.2357	0.2270	0.2217	0.2356
Fresh Water Temperature, °F	81	82	82	80
Sprayed Water Temperature, °F	149	148	148	149
Burner Temperature, °F	1096	1092	1093	1093
Cone Temperature	666	653	658	661
Gas Flow Rate, SCFH	862.0	857.3	851.4	880.8
Energy Input, Btu/hr	887,900	883,000	876,900	907,300
Evaporation Rate, lb/hr	431.3	436.7	414.6	449.1
Air Flow Rate, SCFH	32,220	33,050	32,390	33,260
Heat Absorbed, Btu/hr	465,100	470,200	446,400	484,600
Efficiency, %	52.3	53.2	50.9	54.5
Fraction Evaporated/Pass	.144	.146	.138	.150

TABLE VII

SUMMARY OF SPRAY CONCENTRATOR EVALUATION DATA WITH WATER AS THE TEST FLUID FOR BETE NOZZLE TF20FCN AND DELAVAN NOZZLES WRF20, WRF25, AND WRF30

Run Number	32	33	34	35	36	37	38
Nozzle Number	TF20FCN	TF20FCN	WRF30	WRF20	WRF25	WRF25	WRF25
Liquid Spray Rate, lb/hr	3900	3000	1500	1000	1400	500	1000
Inlet Air							
Dry-bulb temperature, °F	62	68	70	73	74	72	72
Wet-bulb temperature, °F	59	60	61	58	59	59	57
Humidity, lb water/lb air	0.0099	0.0092	0.0093	0.0071	0.0074	0.0076	0.0066
Outlet Air							
Dry-bulb temperature, °F	189	247	210	256	200	447	298
Wet-bulb temperature, °F	151	152	152	154	153	154	152
Humidity, lb water/lb air	0.2066	0.2002	0.2114	0.2083	0.2170	0.1560	0.1839
Fresh Water Temperature, °F	80	78	76	76	76	74	74
Sprayed Water Temperature, °F	147	149	136	135	144	126	129
Burner Temperature, °F	1072	1080	1084	1091	1087	1084	1083
Cone Temperature	699	706	721	718	681	729	700
Gas Flow Rate, SCFH	883.8	843.8	876.3	856.0	859.3	825.9	833.9
Energy Input, Btu/hr	910,300	869,100	902,500	881,700	885,100	850,600	858,900
Evaporation Rate, lb/hr	414.9	380.4	380.0	352.6	393.3	182.7	288.9
Air Flow Rate, SCFH	34,550	32,810	31,250	29,320	30,770	24,140	28,240
Heat Absorbed, Btu/hr	447,300	411,100	411,400	382,000	425,900	198,300	313,300
Efficiency, %	49.1	47.3	45.6	42.8	48.2	23.2	36.4
Fraction Evaporated/Pass	.106	.127	.254	.353	.281	.362	.178

TABLE VIII

SUMMARY OF SPRAY CONCENTRATOR EVALUATION DATA WITH WATER AND CORN-STEEP LIQUOR AS THE WORKING FLUID FOR BETE NOZZLE B12FC

Run Number	42	43	44	45	46	47	48	49	50
Liquid	5%CSL	4.5%CSL	6.1%CSL	10%CSL	10.4%CSL	20%CSL	24.3%CSL	Water	Water
Nozzle Number	B12FC	B12FC	B12FC	B12FC	B12FC	B12FC	B12FC	B12FC	B12FC
Liquid Spray Rate, lb/hr	1000	2000	2000	2000	2000	2000	2000	1000	2000
Type Run	Once-thru	Once-thru	Once-thru	Once-thru	Recycle	Once-thru	Recycle	Once-thru	Once-thru
Inlet Air									
Dry-bulb temperature, °F	86	85	85	81	82	84	84	63	61
Wet-bulb temperature, °F	76	71	74	68	68	72	71	62	59
Humidity, lb water/lb air	0.0173	0.0136	0.0163	0.0123	0.0118	0.0147	0.0139	0.0121	0.0102
Outlet Air									
Dry-bulb temperature, °F	407	174	180	175	173	176	177	370	163
Wet-bulb temperature, °F	154	147	150	146	152	146	148	147	139
Humidity, lb water/lb air	0.1672	0.1821	0.2064	0.1769	0.2217	0.1752	0.1928	0.1541	0.1354
Inlet Fluid Temperature, °F	85	91	120	83	136	93	129	63	65
Outlet Water Temperature, °F	145	131	148	136	145	144	146	122	121
Burner Temperature, °F	1070	1036	1049	1041	1061	1052	1045	1045	1016
Cone Temperature	706	563	588	502	558	595	573	630	590
Gas Flow Rate, SCFH	823.9	808.0	837.5	832.9	834.3	845.4	821.1	821.4	830.4
Energy Input, Btu/hr	853,800	832,200	862,700	857,900	859,400	870,700	845,700	846,100	855,300
Evaporation Rate, lb/hr	247.7	309.4	364.6	267.3	459.3	304.4	366.9	155.4	255.6
Air Flow Rate, SCFH	30,170	31,460	32,192	28,930	34,980	32,970	34,070	22,810	36,460
Heat Absorbed, Btu/hr	266,100	329,700	378,400	286,800	469,900	323,600	377,200	169,900	279,200
Efficiency, %	31.2	39.6	43.9	33.2	54.7	37.2	44.6	20.1	32.1
Fraction Evaporated/Pass	.248	.154	.183	.133	.229	.152	.184	.155	.128

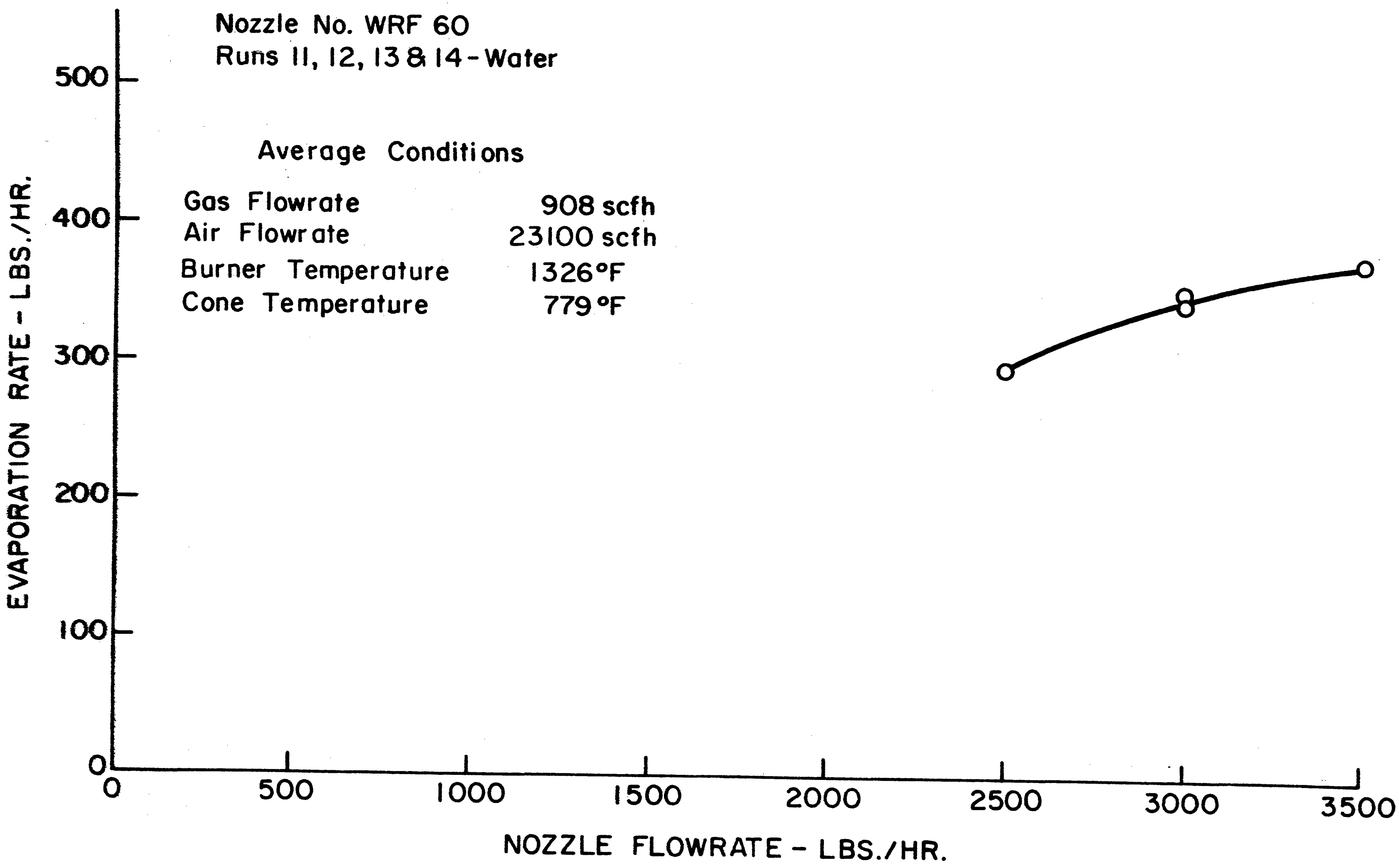

Figure 12. Effect of nozzle flow rate for Delavan nozzle WRF60 on the evaporation rate of water in the spray concentrator.

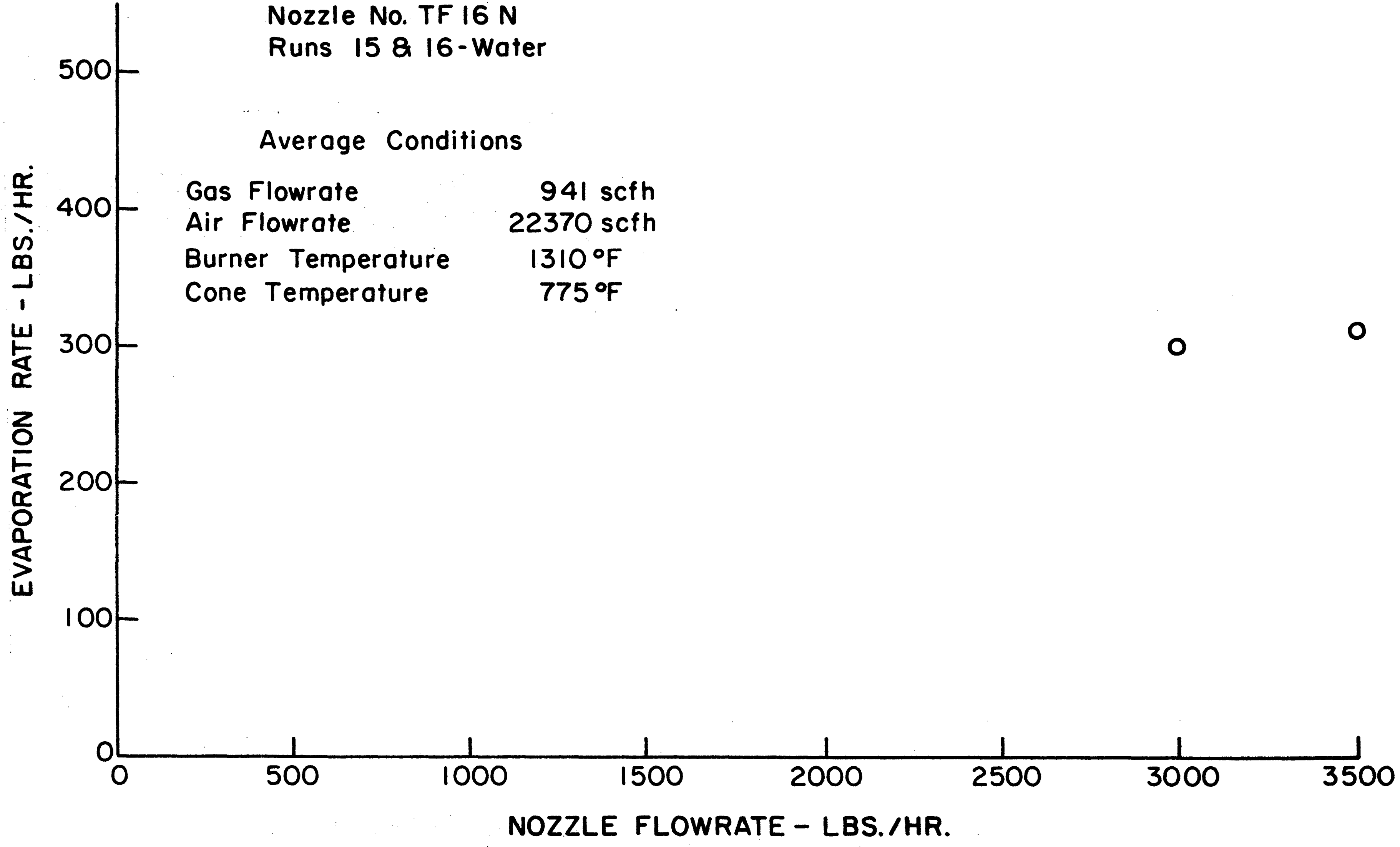

Figure 13. Effect of nozzle flow rate for Bete nozzle TF16N on the evaporation rate of water in the spray concentrator.

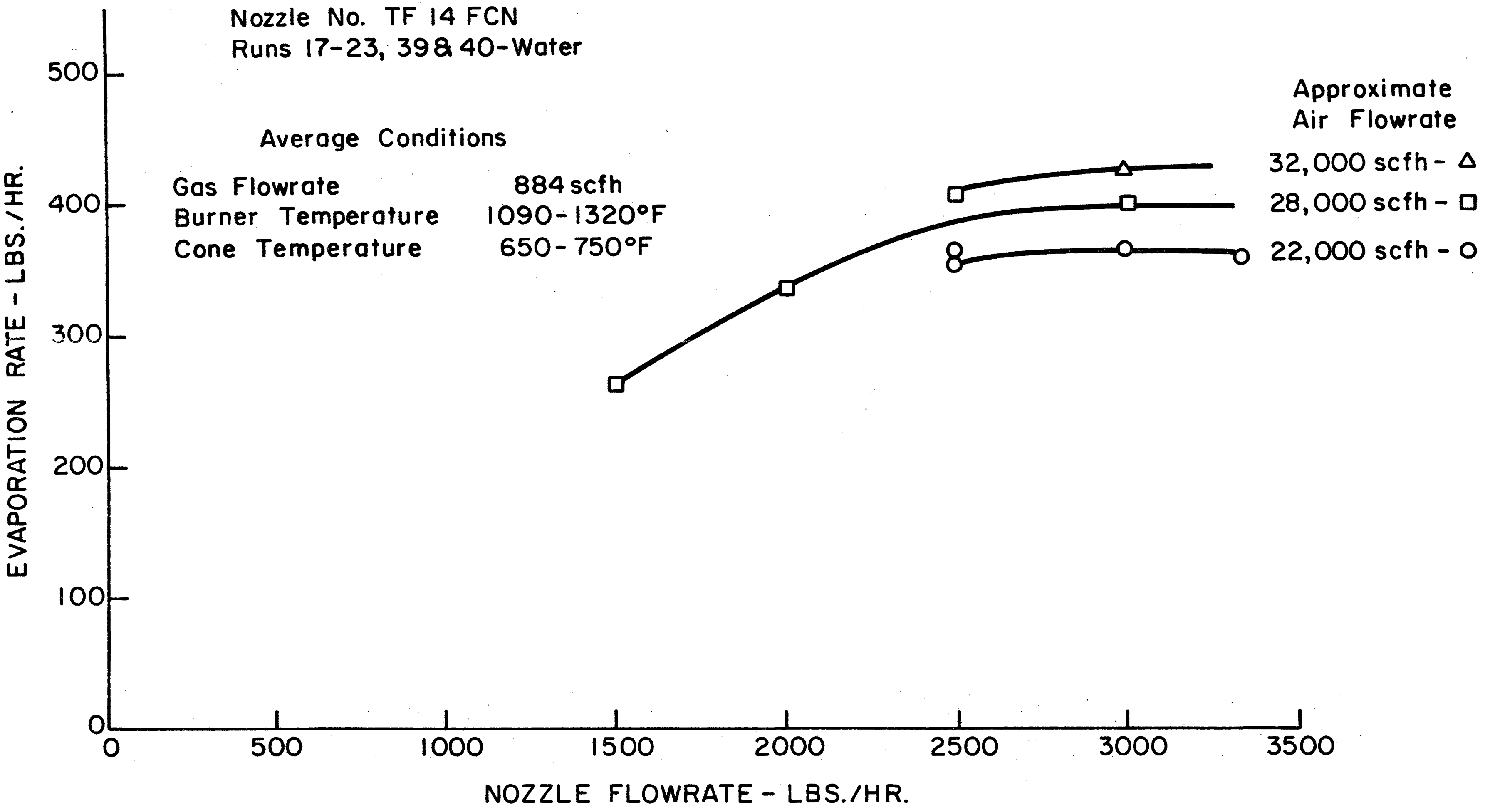

Figure 14. Effect of air flow rate and nozzle flow rate for Bete nozzle TF14FCN on the evaporation rate of water in the spray concentrator.

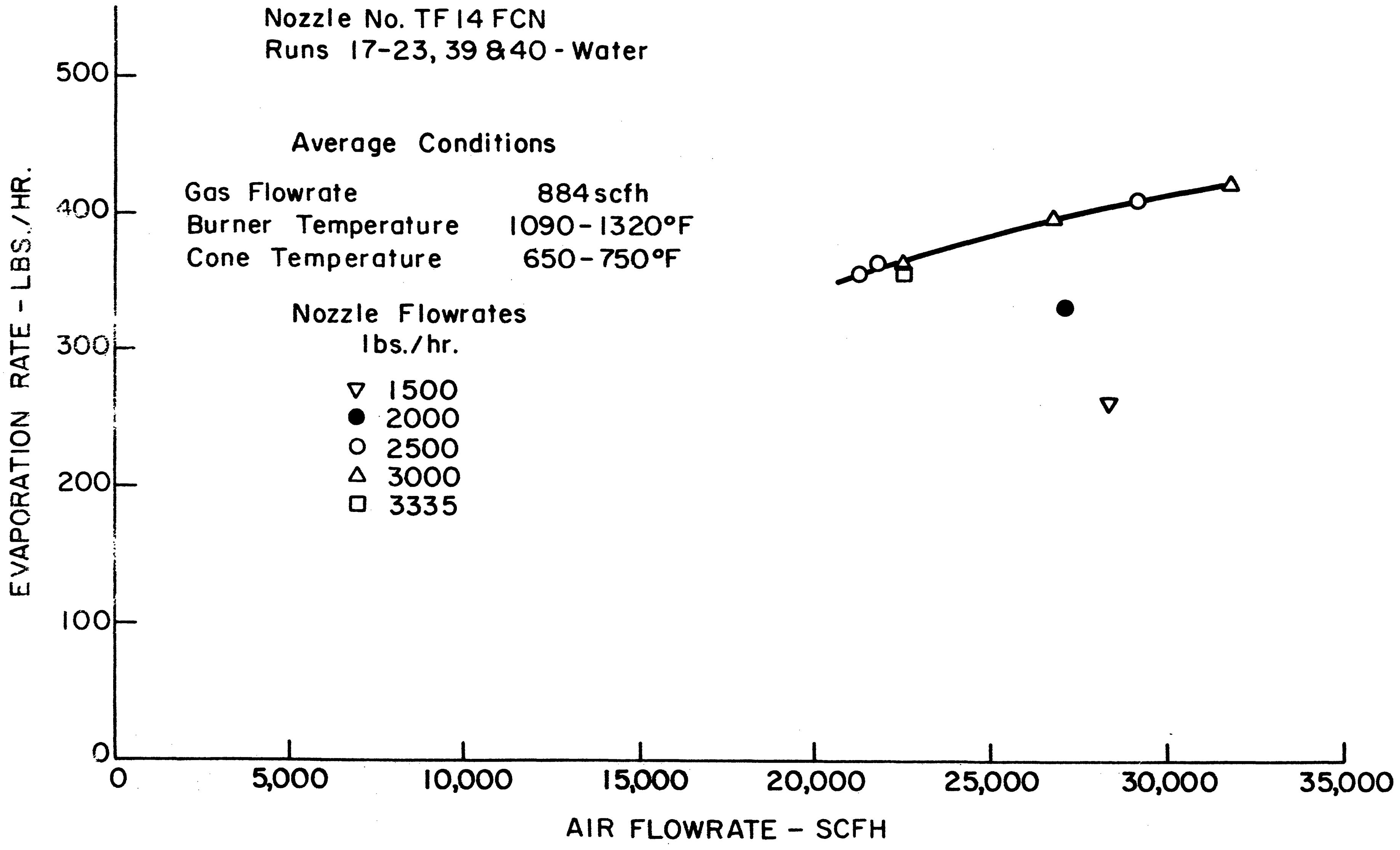

Figure 15. Effect of air flow rate and nozzle flow rate for Bete nozzle TF14FCN on the evaporation rate of water in the spray concentrator.

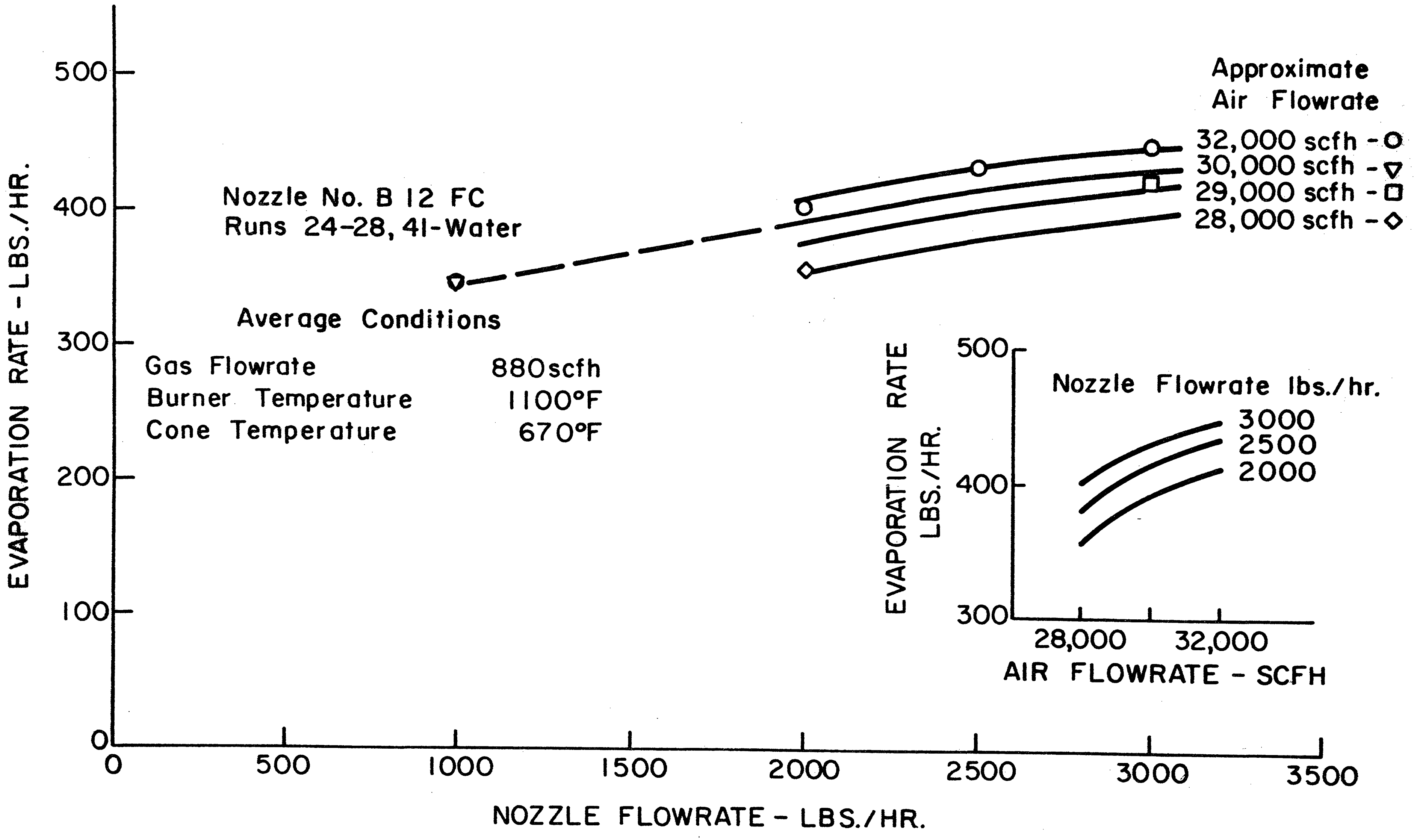

Figure 16. Effect of air flow rate and nozzle flow rate for Bete nozzle B12FC on the evaporation rate of water in the spray concentrator.

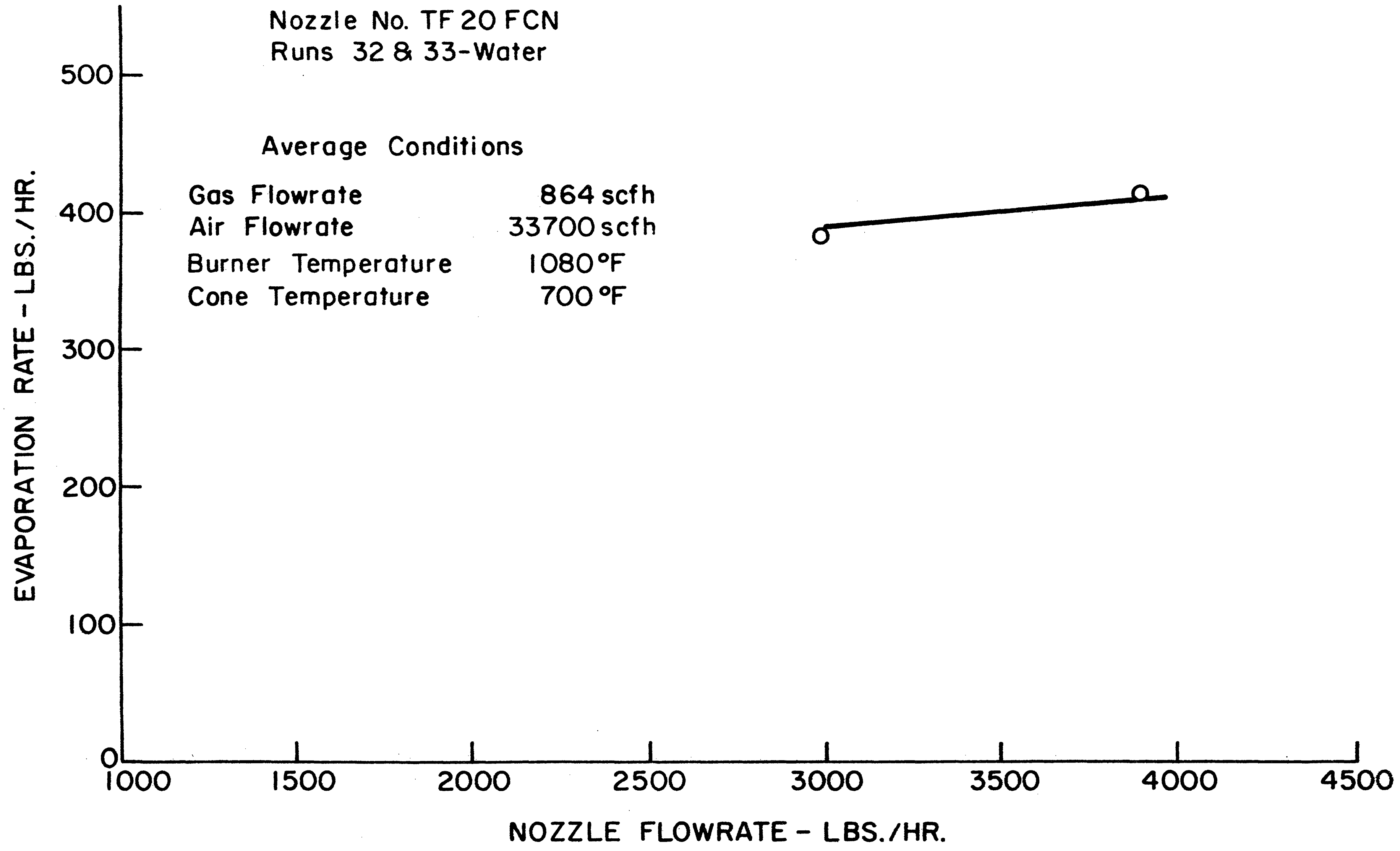

Figure 17. Effect of nozzle flow rate for Bete nozzle TF20FCN on the evaporation rate of water in the spray concentrator.

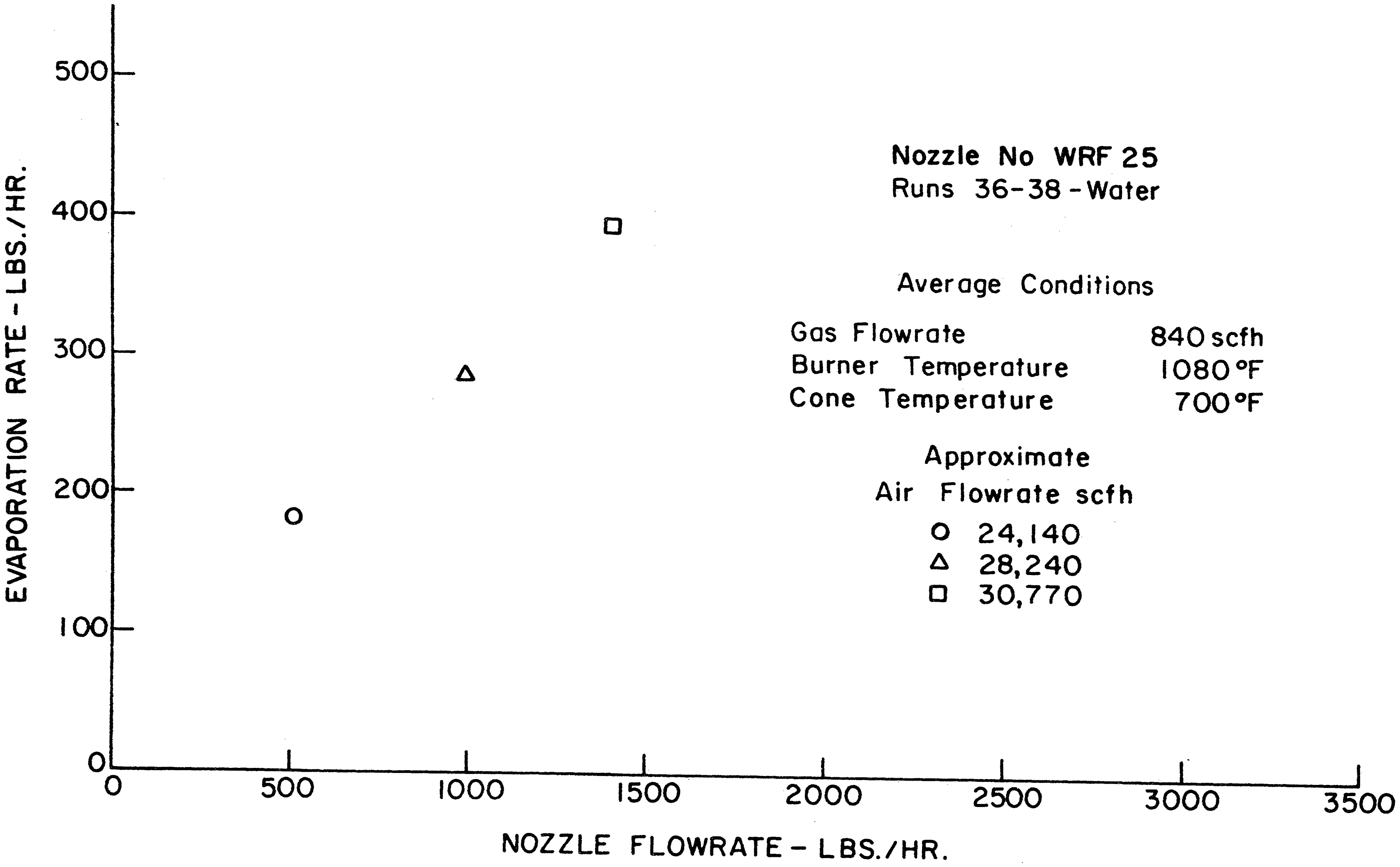

Figure 18. Effect of air flow rate and nozzle flow rate on the evaporation rate of water in the spray concentrator.

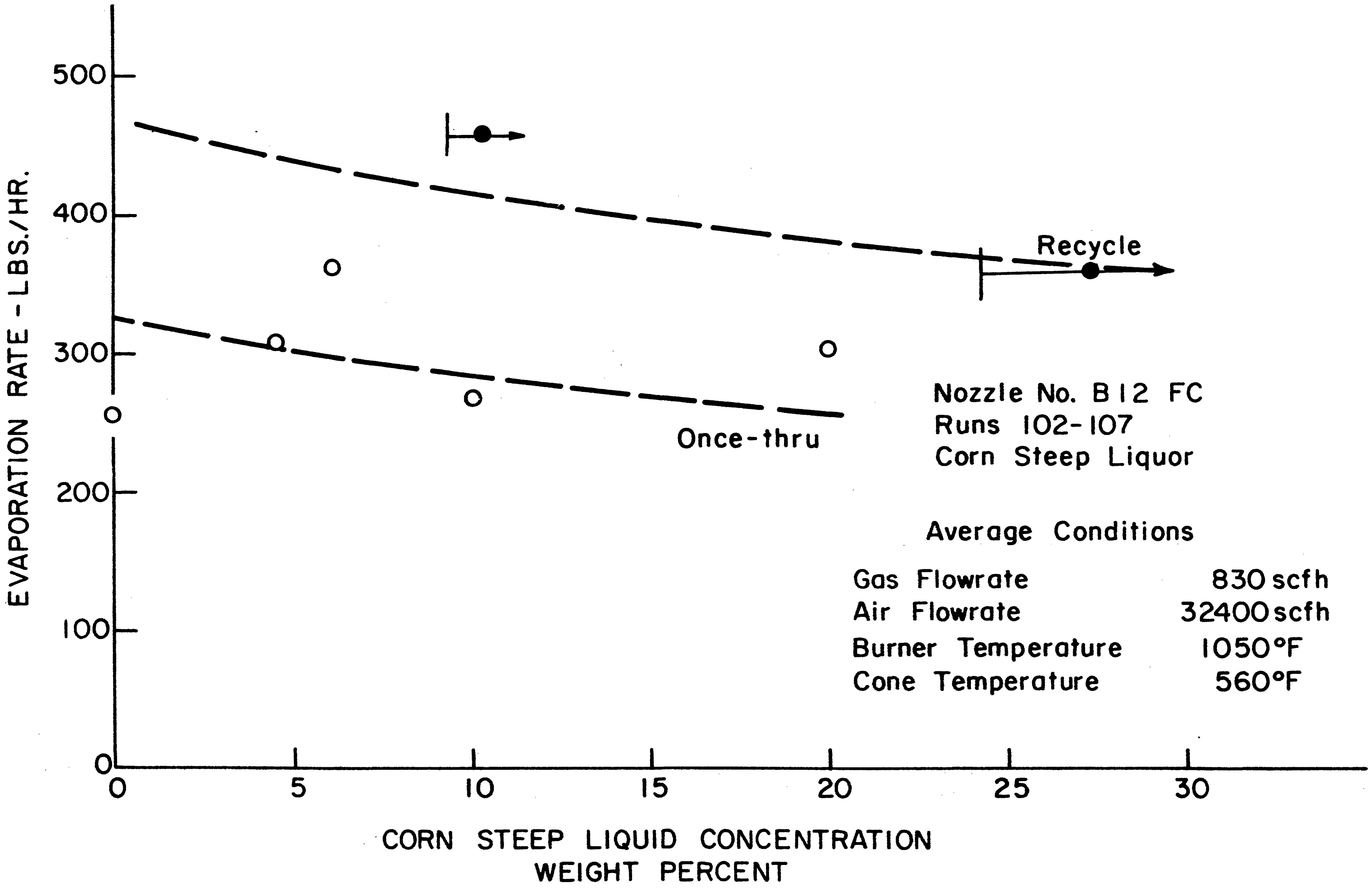

Figure 19. Effect of corn-steep liquor concentration on the evaporation rate of water in the spray concentrator.

concentrator but not recycled. When Runs 26 (recycle) and 50 (once-thru) are compared, there is significant difference between the evaporation rates of 400.6 lb/hr and 255.6 lb/hr, respectively. The sprayed water temperatures were 148° and 65°F, respectively. Differences in air temperatures, gas flow rates, and air flow rates make a precise comparison impossible, but the evaporation rate appears to be most significantly affected by the sprayed water temperature. Mass transfer is limiting the evaporation under the operating conditions.

Seven runs were made with corn-steep liquor to evaluate the performance of the spray concentrator with a material comparable to stickwater. The corn-steep liquor concentrate contained approximately 50% by weight solids and had to be diluted with water to approximate a stickwater solids concentration. Table IX contains the corn-steep liquor physical characteristics.

TABLE IX

PHYSICAL CHARACTERISTICS OF CORN-STEEP LIQUOR

Solids	54.25% as-received
Soluble solids	50.03% as-received
Suspended solids	4.22% as-received
pH	3.5
Viscosity at 10.8% solids ambient temperature	1.19 Cp

Five runs were made with once-thru fluid spray to determine the evaporation rate as a function of concentration. Runs 43-46 were conducted with the operating conditions nearly identical except for the corn-steep liquor concentration. Although there is some scatter in the data, there appears to be a slight decrease in evaporation rate with concentration as shown in Figure 19.

No evidence of corn-steep liquor scorching was observed during the operations with the liquor.

Some makeshift fiberglass insulation was wrapped around the connecting "T" during Runs 1-10 which were taken during the summer of 1971. Because it was difficult to maintain, it was removed during subsequent runs. The insulation did improve the thermal efficiency somewhat as can be seen from the data. In a permanent installation, the hot surfaces should be insulated for improved thermal efficiency as well as for safety.

Three runs, Runs 29-31, were made with two nozzles being used as indicated in Table VI. The total flow rate was maintained at 3000 lb/hr. The purpose was to determine if greater spray coverage would improve the total evaporation capacity of the spray concentration. There was little, if any, difference between using a single nozzle or two nozzles. At the air flow rate through the chamber, the exit air is nearly saturated and the driving forces for evaporation becomes small.

The experimental data in this report were processed with a digital computer program prepared for this investigation. A listing of the computer program is given in Appendix A. A sample calculation, giving the procedure used in the computer analysis, can be found after the computer listing.

CONCLUSIONS

The conclusions of this investigation are summarized as follows:

1. The Blackmer Rotary, Pump, Model SNP 1/4 operated continuously, without trouble during testing. It provided adequate pressure. It should be adaptable to use on fish stickwater.

2. The present apparatus is capable of evaporating over 550 lb of water per hour with a fuel consumption of about 1,000,000 Btu/hr and an efficiency close to 60%. It should be evident that the apparatus was not insulated so its efficiency could be improved.

3. The Bete-Fog nozzles produced fine drops and an essentially full cone of spray. These nozzles were chosen because they are designed to resist clogging. They should be applicable to spraying fish stickwater that is first screened to remove coarse particles.

4. Tests with corn-steep liquor (Table VIII), indicated that the presence of corn-steep liquor in the liquid being evaporated does not substantially affect the evaporation rate, fuel economy or other important operating variables even up to a concentration of 24.3% corn-steep liquor. While this data cannot be extrapolated directly to apply to fish stickwater, they are an indication that the equipment should concentrate such wastes reasonably well. Obviously, the final phase of this study should include evaporation of fish stickwater. Funds, however, were not made available for such a study.

5. The operating experience on the spray concentrator indicated that nearly all the evaporation took place in the top 3 to 4 ft of the chamber. A design for a 10,000 gal/day fish stickwater spray concentrator is included in Appendix B. The design concept incorporates experience obtained in this investigation.

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(R-5) Industrial Spray Nozzles, Catalog No. 1118A-1169 (1969). Delavan Manufacturing Co., 811 Fourth St., West Des Moines, Iowa 50265.

(R-6) Eclipse Fuel Engineering Co., Combustion Division, Rockford, Ill., and Industrial Burner Co., 16911 Eight Mile R., Detroit, Michigan 48235.

APPENDIX A

LISTING OF COMPUTER PROGRAM FOR PROCESSING DATA AND SAMPLE CALCULATION

```
C        THIS PROGRAM TAKES DATA FROM THE EVAPORATOR RUNS AND COMPUTES
C        THE AMOUNT OF AIR NEEDED TO COMPLETE THE MATERIAL BALANCE
C
C        BELOW IS A LIST OF SYMBOLS USED IN THIS PROGRAM
C
C        ATM = ONE ATMOSPHERE IN INCHES MERCURY
C        BTJ = BTJ'S PRODUCED BY COMBUSTION PER HOUR
C        CFA = CUBIC FEET OF AIR USED PER HOUR
C        DBO = DRY BULB TEMPERATURE OF OUTLET GASES
C        DI  = DRY BULB TEMPERATURE OF INLET AIR
C        GF = FINAL GAS READING IN CUBIC FEET
C        GI = INITIAL GAS READING IN CUBIC FEET
C        HI  = HUMIDITY OF INLET AIR IN LB. WATER/LB. DRY AIR
C        HIT = HUMIDITY OF AIR AT INLET IN LB. WATER/LB. WET AIR
C        HO = HUMIDITY OF OUTLET GASES IN POUNDS WATER/POUND DRY GAS
C        HOF = HUMIDITY OF OUTLET GASES IN VOLUME FRACTION
C        HOP = HUMIDITY OF OUTLET GASES IN VOLUME PERCENT
C        HOT = HUMIDITY OF OUTLET GASES IN LBS. WATER/LB. WET GAS
C        ITER = ITERATIONS USED TO APROACH MOLECULAR WEIGHT OF DRY
C        OUTLET GASES
C        MDGP = MOLES OF DRY GASES PRODUCED FROM COMBUSTION OF GAS
C        MEA = MOLES OF DRY AIR NOT USED IN COMBUSTION
C        MNG = MOLES NATURAL GAS USED PER HOUR
C        MPWI = MOLE FRACTION OF WATER IN INLET AIR
C        MWA = AVERAGE MOLECULAR WEIGHT OF DRY AIR
C        MWAI = MOLECULAR WEIGHT OF WET AIR AT INLET
C        MWDGO = MOLECULAR WEIGHT OF DRY GASES AT OUTLET
C        MWNG = AVERAGE MOLECULAR WEIGHT OF NATURAL GAS
C        MWW = MOLECULAR WEIGHT OF WATER
C        NI = NUMBER OF TEMPERATURE MEASUREMENTS OF INLET AIR
C        NO = NUMBER OF TEMPERATURE MEASUREMENTS OF OUTLET GASES
C        NRUN = RUN NUMBER
C        PA = AMBIENT PRESSURE IN ATMOSPHERES
C        PDA = POUNDS OF DRY AIR USED PER HOUR
C        PG = PRESSURE OF GAS IN INCHES WATER ABOVE AMBIENT
C        PGA = ABSOLUTE PRESSURE OF NATURAL GAS IN ATMOSPHERES
C        PM = AMBIENT PRESSURE IN INCHES MERCURY
C        PWA = POUNDS WET AIR USED PER HOUR
C        R = GAS CONSTANT IN ATM*CUBIC FEET/LB.MOLE*DEGREE R
C        SCFA = STANDARD CUBIC FEET OF AIR USED PER HOUR
C        SCFG = STANDARD CUBIC FEET OF GAS BURNED PER HOUR
C        TAD = AVERAGE DRY BULB TEMPERATURE OF INLET AIR
C        TAW = AVERAGE WET BULB TEMPERATURE OF INLET AIR
C        TG = TEMPERATURE OF GAS IN DEGREES F
C        TGD = AVERAGE DRY BULB TEMPERATURE OF OUTLET GASES
C        TGW = AVERAGE WET BULB TEMPERATURE OF OUTLET GASES
C        TIM = TIME OF RUN IN MINUTES
C        TS = STANDARD TEMPERATURE IN DEGREES R
C        WE  = WATER EVAPORATED IN LBS./HOUR
C        WET = TOTAL WATER EVAPORATED IN POUNDS
C        WI = WET BULB TEMPERATURE  OF INLET AIR
C        WNG = WEIGHT OF NATURAL GAS USED PER HOUR
C        WO = WET BULB TEMPERATURE OF OUTLET GASES
C        WPG = WATER PRODUCED FROM COMBUSTION OF GAS IN LBS. / HOUR
C        Z = COMPRESSIBILITY FACTOR FOR WATER VAPOR UNDER OUTLET
C        CONDITIONS
C
      REAL MWNG, MWW, MWA, MPWI, MWDGO, MWAI, MNG, MDGP, MEA
      DIMENSION WI(6), DI(6), WO(10), DBO(10)
      NAMELIST /DATA/ WI, DI, WO, DBO, NI, NO, GF, GI, TIM, WET,
     1 ITER, PG, PM, TG, NRUN
    1 READ (5, DATA, END=999)
      WRITE (6,200) NRUN, NI, NO, GF, GI, TIM, WET, ITER, PG, PM, TG
      WRITE (6,201) (WI(I), I=1, NI)
      WRITE (6,201) (DI(I), I=1, NI)
      WRITE (6,201) (WO(I), I=1, NO)
      WRITE (6,201) (DBO(I),I=1, NO)
      R = 0.7302
      Z = 0.99
      MWW = 18.016
      MWA = 29.03
```

```
C       INITIAL GUESS OF MOLECULAR WEIGHT OF DRY GASES IN EXIT STREAM
C
      MWDGO = 29.4124
      ATM = 29.92
      TS = 520.
      MWNG = 16.51
      HI = 0.0
      HOP = 0.0
      DO 2 I=1, NI
C
C       THE FOLLOWING EQUATION IS A CURVE FIT OF HUMIDITY CHART AT WET
C       BULB TEMPERATURES BETWEEN 50 & 75 DEGREES F
C
    2 HI = HI+0.0001*(-(0.00296667*WI(I)+2.1247)*DI(I)+0.08443*
     1 (WI(I))**2-3.44985*WI(I)+153.7003)
      HI = HI/NI
      DO 3 I=1, NO
C
C       THE FOLLOWING EQUATION IS A CURVE FIT OF HUMIDITY CHART AT
C       WET BULB TEMPERATURES BETWEEN 140 & 160 DEGREES F
C
    3 HOP = HOP-0.0001*(-1.041667*(WO(I))**2+331.25*WO(I)-26033.33)*
     1 DBO(I)-0.011875*(WO(I))**2+4.55625*WO(I)-387.7
      HOF = HOP/(100.*NO)
      MPWI = (HI/MWW)/(HI/MWW+(1./MWA))
      MWAI = MWA*(1.-MPWI) + MWW*MPWI
      HIT = HI/(HI + 1.)
      PA = PM/ATM
      PGA = PA +PG/(ATM*13.546)
      SCFG = TS*60.0*PGA*(GF-GI)/((TG+460.)*TIM)
      WPG = 0.0956*SCFG
      MNG = SCFG/(R*TS)
      WNG = MNG*MWNG
      WE = WET*60.0/TIM
      TAD = 0.0
      TAW = 0.0
      DO 4 I=1, NI
      TAW = TAW+WI(I)
    4 TAD = TAD + DI(I)
      TAD = TAD/NI
      TAW = TAW/NI
      TGD = 0.0
      TGW = 0.0
      DO 6 I=1,NO
      TGD = TGD+DBO(I)
    6 TGW = TGW+WO(I)
      TGD = TGD/NO
      TGW = TGW/NO
      MDGP = MNG*8.675
C
C       ITERATION USING SUCCESSIVE SUBSTITION TO FIND ACTUAL MOLECULAR
C       WEIGHT OF DRY GASES IN EXIT STREAM AND THUS AMOUNT OF AIR USED
C
      DO 5 I=1, ITER
      HO = (HOF/((1.-HOF)*Z))*MWW/MWDGO
      HOT = HO/(HO+1.)
      PWA = (WPG+WE-HOT*(WE+WNG))/(HOT-HIT)
      PDA = (1.-HIT)*PWA
      MEA = PDA/MWA-MNG*9.678
    5 MWDGO = (MEA*MWA+MDGP*30.0323)/(MEA+MDGP)
      CFA = R*(TAD+460)*PWA/(MWAI*PA)
      SCFA = CFA*PA*TS/(460+TAD)
      BTU = SCFG*1030.
      WRITE (6,202) HI, HO, SCFG, WE, CFA, SCFA, BTU,TAD,TAW,TGD,TGW
      GO TO 1
  999 CALL EXIT
  200 FORMAT ('1NRUN   = ', I6/'NI     = ', I6/'NO     = ', I6/
     1 'GF     = ', F9.2/'GI     = ', F9.2/'TIM    = ', F9.2/
     2 'WET    = ', F9.2/'ITER   = ', I6/'PG     = ', F9.2/
     3 'PM     = ', F9.2/'TG     = ', F9.2)
  201 FORMAT ('0'/10F8.1)
  202 FORMAT ('0'/'      HI          HO          SCFG        WE
     1CFA         SCFA        BTU        TAD        TAW       TGD       TGW
     2'/' '/2F12.5,4F12.2,F11.1,4F10.2)
      END
```

Sample Calculation

Run 20
Nozzle TF14FCN

Experimental Data

Duration of run: 127 min

Inlet dry-bulb temperatures (°F): 73.5, 75.0, 74.0, 72.5, 73.0

Inlet wet-bulb temperatures (°F): 57.0, 57.0, 56.6, 55.5, 56.0

Outlet dry-bulb temperatures (°F): 181.5, 179.0, 179.0, 180.0, 180.0, 184.5, 181.5, 177.0, 183.0

Outlet wet-bulb temperatures (°F): 161.0, 159.0, 159.0, 160.0, 159.0, 162.0, 160.0, 159.0, 160.0

Flow through nozzle from rotameter: 2500 lb H_2O/hr

Initial gas reading: 30,102 ft^3

Final gas reading: 32,085 ft^3

Temperature of gas: 81.0°F

Pressure of gas: 14.1 in H_2O gauge

Ambient pressure: 29.22 in. Hg

Water added at 77°F: 769 lb

Mass Balance to Obtain Air Flow

A mass balance on the water gives:

Water out/hr = Water in/hr + water produced/hr

Water out/hr = X_oG_o

where: X_o = lb water/lb wet outlet gas

G_o = lb wet gas out/hr

but since G_o is the only outlet

G_o = total mass in./hr

$G_o = W_e + N.G. + Aw_i$

where: W_e = mass water evaporated/hr

N.G. = mass of natural gas used/hr

Aw_i = mass of wet air in./hr

Water out/hr $= X_o(W_e + N.G. + Aw_i)$

Water in/hr + water produced/hr $= W_e + X_i\,Aw_i + W_g$

where: X_i = lb water/lb set inlet air

W_g = lb water produced from combustion/hr

Thus: $X_o(W_e + N.G. + Aw_i) = W_e + X_i\,Aw_i + W_g$

$$Aw_i = \frac{W_g + W_e - X_o(W_e + N.G.}{X_o - X_i}$$

Thus: X_i, X_o, W_e, N.G., and W_g must be derived from data.

Calculated Results

$$\text{Average inlet humidity*} = \frac{0.0063 + 0.0059 + 0.0054 + 0.0056 + 0.0058}{5}$$

Average inlet humidity = 0.0059 lb water/lb dry air

$$\text{Pounds water/lb wet air (at inlet)} = \frac{0.0059 \text{ lb water/lb dry air}}{0.0059 \text{ lb water/lb dry air} + 1 \text{ lb dry air/lb dry air}}$$

Pounds water/lb wet air (X_i) = 0.0059 lb water/lb set air
(at inlet)

---

*Taken from Air Pollution Engineering Manual U. S. Department of Health, Education, and Welfare 999-AP-40. Charts were curve fit to equations which were corrected for average pressure.

Average outlet humidity* (in volume fraction) =

$$= \frac{.3266 + 0.3114 + 0.3114 + 0.3190 + 0.3111 + 0.3384 + 0.3186 + 0.3120 + 0.3181}{9}$$

$$= \frac{.3180 \text{ ft}^3 \text{ water}}{\text{ft}^3 \text{ wet gas}}$$

Humidity of oulet gases (using 29.412 lb/mole as average molecular weight of dry gases out and .99 as compressibility of steam) =

$$= \left[\frac{.3180 \text{ ft}^3 \text{ water/ft}^3 \text{ wet gas}}{\{(1.0 - .3180) \text{ ft}^3 \text{ dry gas/ft}^3 \text{ wet gas}\} \cdot 99 \dfrac{\text{mole dry gas} \cdot \text{ft}^3 \text{ water}}{\text{mole water} \cdot \text{ft}^3 \text{ dry gas}}}\right] \cdot$$

$$\cdot \frac{18.016 \text{ lb water/lb mole}}{29.4124 \text{ lb dry gas/lb mole}}$$

Humidity of outlet gases = .2885 lb water/lb dry gas

Pound water/lb wet outlet gas =

$$= \frac{.2885 \text{ lb water/lb dry gas}}{1.0 \text{ lb dry gas/lb dry gas} + .2885 \text{ lb water/lb dry gas}}$$

Pound water/lb wet outlet gas (X_o) = .2239 lb water/lb wet gas

$$\text{Water evaporated/hr } (W_e) = \frac{(769.5 \text{ lb water})(60 \text{ min/hr})}{127 \text{ min}} = 363.5 \frac{\text{lb water}}{\text{hr}}$$

$$\text{Absolute pressure of gas} = \frac{29.22 \text{ in. Hg}}{29.92 \text{ in. Hg}} +$$

$$+ \frac{14.10 \text{ in. } H_2O}{(29.92 \text{ in. Hg/atm})(13.546 \text{ in. } H_2O\text{/in. Hg})}$$

---

*Taken from Air Pollution Engineering Manual U. S. Department of Health, Education, and Welfare 999-AP-40. Charts were curve fit to equations which were corrected for average pressure.

Absolute pressure of gas = 1.0114 atm

$$\text{Gas flow rate} = \frac{(520°\text{R})(0.0114\ \text{atm})(32085\ \text{ft}^3 - 30102\ \text{ft}^3)(60\ \text{min/hr})}{(81 + 460)°\text{R}\ (127\ \text{min})(1\ \text{atm})}$$

Gas flow rate = 910.7 standard ft^3 gas/hr

$$\text{Moles gas used} = \frac{(910.74\ \text{ft}^3/\text{hr})(1\ \text{atm})}{(0.7302\ \text{atm ft}^3/\text{lb mole °R})(520°\text{R})} = 2.399\ \text{moles/hr}$$

Pounds gas used (N.G.) = (16.507 lb/lb mole)(2.399 moles/hr) = 39.600 lb/hr

Water produced by combustion of natural gas (W_g) = (910.7 ft^3 gas/hr)(0.0956 lb H_2O/ft^3 gas) = 87.06

Wet air in (Aw_i) =

$$= \frac{87.06\ \text{lb water/hr} + 363.5\ \text{lb water/hr} - .2239\ \text{lb water/lb wet gas}\ (363.5\ \text{lb water/hr} + 39.6\ \text{lb N.G./hr})}{.2239\ \text{lb water/ lb wet gas} - .0059\ \text{lb water/lb wet air}}$$

= 1652.8 lb wet air/hr

Since molecular weight of dry gases out was just a guess and was used in calculations, an iterative process is needed to obtain correct value. A new molecular weight for the dry gases out must be obtained by using the results of the previous iteration.

Dry air in = [(1.0 - 0.0059) lb dry air/lb wet air][1652.8 lb wet air/hr] = 1643.05 lb dry air/hr

$$\text{Moles air not used in combustion} = \frac{1643.05 \text{ lb dry air/hr}}{29.03 \text{ lb dry air/lb mole dry air}} - \left(2.399\ \frac{\text{moles gas}}{\text{hr}}\right)\left(9.678\ \frac{\text{moles dry air}}{\text{mole gas}}\right) =$$

$$= 33.381\ \frac{\text{moles dry air}}{\text{hr}}$$

Moles of dry gas that would result from a complete combustion of the natural gas with stoichiometric air =

$$= (2.399 \text{ moles gas/hr})\left(8.675\ \frac{\text{moles dry gas}}{\text{mole natural gas}}\right) = 20.811\ \frac{\text{moles dry gas}}{\text{hr}}$$

New molecular weight of dry gas out =

$$= \frac{(33.381 \text{ moles dry air/hr})(29.03 \text{ lb/lb mole dry air}) + (20.811 \text{ moles dry gas/hr})(30.0323 \text{ lb/lb mole dry gas})}{(33.38 \text{ moles dry air/hr} + 20.811 \text{ moles dry gas/hr})}$$

New molecular weight of dry gas out = 29.4154

New humidity of outlet gases =

$$= \left[\frac{0.3180 \text{ ft}^3 \text{ water/ft}^3 \text{ wet gas}}{[(1.0 - .3180) \text{ ft}^3 \text{ dry gas/ft}^3 \text{ wet gas}].99\ \dfrac{\text{mole dry gas} \cdot \text{ft}^3 \text{ water}}{\text{mole water} \cdot \text{ft}^3 \text{ dry gas}}}\right] \frac{18.016 \text{ lb water/lb mole}}{29.4154 \text{ lb dry gas/lb mole}}$$

New humidity of outlet gases = .2885 lb water/lb dry gas

This is the same as original humidity so no iterations are needed. In some cases two or more iterations are required.

Mole fraction of water in inlet air =

$$= \frac{\dfrac{0.0059 \text{ lb water/lb dry air}}{18.016 \text{ lb water/lb mole}}}{\dfrac{0.0059 \text{ lb water/lb dry air}}{18.016 \text{ lb water/lb mole}} + \dfrac{1.00 \text{ lb dry air/lb dry air}}{29.03 \text{ lb dry air/lb mole}}} = \frac{0.0094 \text{ lb moles water}}{\text{lb mole wet air}}$$

Molecular weight of wet air in =

$$= \frac{29.03 \text{ lb}}{\text{lb mole dry air}} (1.0 - 0.0094) \frac{\text{lb mole dry air}}{\text{lb mole wet air}} + \frac{18.016 \text{ lb}}{\text{lb mole water}} (0.0094) \frac{\text{lb mole water}}{\text{lb mole wet air}}$$

Molecular weight of wet air in = 28.9262 lb/lb mole wet air

$$\text{Average temperature of air in} = \frac{73.5 + 75.0 + 74.0 + 72.5 + 73.0}{5} = 73.6°\text{F}$$

$$\text{Volume air used} = \frac{(0.7309 \text{ atm ft}^3\text{/lb mole °R})(73.6 + 460)\text{°R})1652.8 \text{ lb wet air/lb})}{(28.9262 \text{ lb/lb mole wet air})\left(\dfrac{29.22}{29.92}\right) \text{atm}}$$

$$= 22{,}797 \text{ ft}^3\text{/hr}$$

Volume air used corrected to standard conditions $= \dfrac{\left(22{,}797\ \dfrac{\text{ft}^3}{\text{hr}}\right)\left(\dfrac{29.22\ \text{in. Hg}}{29.92\ \text{in. Hg}}\right)(520°\text{R})}{460 + 73.6)\ °\text{R}} = 21{,}696\ \dfrac{\text{ft}^3}{\text{hr}}$

Heating value of gas = 1030 Btu/ft^3

Energy released = (910.7 SCFH)(1030 Btu/SCF) = 938,000 Btu/hr

Energy absorbed = (363.45 lb water/hr)(1084.9 Btu/lb water) = 394,300 Btu/hr

Efficiency $= \dfrac{394{,}300\ \text{Btu/hr}}{938{,}000\ \text{Btu/hr}} \times 100 = 42.0\%$

Fraction water evaporated pass $= \dfrac{363.45\ \text{lb/hr}}{2500\ \text{lb/hr}} = 0.145$

APPENDIX B

SUGGESTED DESIGN OF A MODIFIED 10,000-GALLON PER DAY SPRAY CONCENTRATOR

DESIGN BASES

Process 10,000 gallons/day of fish stick liquor in 24 hr with a density of 1.015 g/ml at 5% solids by weight to produce a product containing 30% solids.

Feed temperature: 60°F
Inlet air: 60°F
Outlet air: 200°F
Air flow rate: 110 standard cu ft/lb water evap
Nozzle flow rate/evaporation rate: 10
Energy efficiency: 50%

WATER EVAPORATION REQUIRED

$$\text{Feed weight} = 10{,}000\ \text{gal/day}\ \ 8.33\ \frac{\text{lb water}}{\text{gal}}\ \ \frac{1.015\ \text{g/ml}}{1.000\ \text{g water/ml}}$$

$$= 84{,}600\ \text{lb/day}$$

$$\text{Weight solids} = (0.05)(84{,}600) = 4{,}270$$

$$\text{Weight product} = \frac{4{,}270}{0.30} = 14{,}230$$

$$\text{Water evaporated} = 84{,}600 - 14{,}230 = 70{,}370\ \text{lb/day}$$

$$= 2{,}930\ \text{lb/hr}$$

NOZZLE FLOW RATE

$$\text{Nozzle flow rate} = 10(2{,}920) = 29{,}300 \text{ lb/hr}$$

$$= \frac{29{,}300 \text{ lb/hr } (1.00 \text{ g water/ml})}{(8.33 \text{ lb water/gal})(1.015 \text{ g/ml})(60 \text{ mm/hr})}$$

$$= 57.7 \text{ gpm}$$

AIR FLOW RATE

$$\text{Air flow rate} = 110 \text{ SCFH/lb water evap } (2{,}930 \text{ lb/hr})$$

$$= 322{,}000 \text{ SCFH}$$

ENERGY ABSORBED

Air:

$$Q = m\,Cp\,\Delta t$$

$$m = 322{,}000 \text{ SCFH } (0.0763 \text{ lb/SCFH})$$

$$m = 24{,}600 \text{ lb air/hr}$$

$$Q = (24{,}600 \text{ lb/hr})(0.24 \text{ Btu/lb})(200^\circ - 60^\circ\text{F})$$

$$Q = 825{,}000 \text{ Btu/hr}$$

Water:

$$Q = m(H_{vapor} - H_{feed})$$

$$Q = 2{,}930 \text{ lb/hr } (1145.9 \text{ Btu/lb} - 28.1 \text{ Btu/lb})$$

$$Q = 3{,}275{,}000 \text{ Btu/hr}$$

$$Q_{total} = 825{,}000 + 3{,}275{,}000 = 4{,}100{,}000 \text{ Btu/hr}$$

ENERGY REQUIRED

$$\text{Energy} = \frac{4{,}100{,}000}{0.50} = 8{,}200{,}000 \text{ Btu/hr}$$

RECOMMENDED DESIGN

Use three nozzles with a flow rate of 20 gpm for each nozzle at a pressure drop across each nozzle of 40 psi. The spray angle should be 75°. The nozzle layout should be as shown in Figure B-1. A schematic of the spray concentrator is also given in Figure B-1.

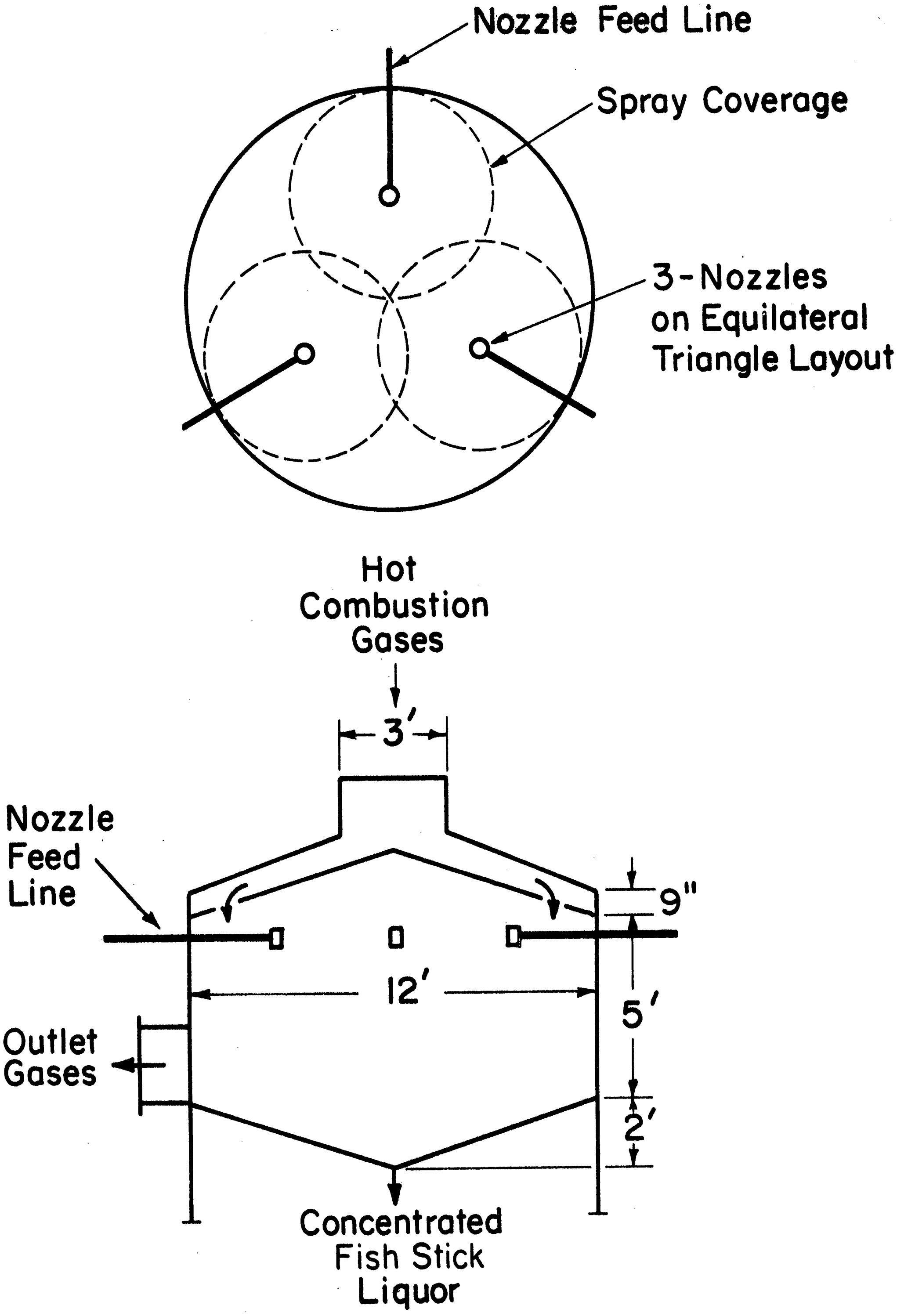

Figure B-1. Schematic drawing of recommended spray concentrator showing nozzle layout.