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PRELIMINARY REPORT ON THE BASELINE THERMAL AND HYDRAULIC PERFORMANCE TESTS OF A SIEVE TRAY DIRECT CONTACT HEAT EXCHANGER

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DISCLAIMER

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1. SUMMARY

As part of the conversion technology effort at the Idaho National Engineering Laboratory (INEL), a sieve tray direct contact heat exchanger was designed, built and then tested in a binary power cycle at the INEL Raft River geothermal test site. In this heat exchanger the energy from a hot geothermal fluid was transferred to a secondary working fluid which was vaporized during the heat exchange process. This working fluid vapor could then be expanded through a turbine generating electrical power. In the direct contact heat exchanger (DCHX), the two fluids are in physical contact with each other, i.e., there are no physical boundaries between the fluids as heat is exchanged. These devices have been widely used in mass transfer applications, however little experience exists in heat transfer applications.

A series of baseline thermal and hydraulic tests were conducted with an isobutane working fluid. The evaluation of these tests are the subject of this preliminary report. The testing of the DCHX confirmed that the repeated forming and coalescence of the working fluid drops in the sieve tray column produce excellent heat transfer performance. Tray thermal efficiencies were at or above the design value of 70% and the pinch points were well under the design goal of 1°F (too small to be measured with installed instrumentation). From a hydraulic standpoint, the column operated at the working fluid velocities from the plate holes corresponding to the predicted condition of maximum total drop surface area (or minimum drop size) when the unit was operating near the "flooding" limits, or throughputs. This is the recommended working fluid hole velocity for use in designing sieve tray columns. The geothermal flow limits encountered (at flooding) corresponded roughly to the terminal rise velocity of a 1/32-inch drop. This is a drop size commonly used for specifying the terminal velocity (or continuous fluid velocity) in the design of columns for mass transfer applications.

Few operational or major equipment problems were encountered. Aside from trying to run the unit in cold weather (and the associated freezing problems), the major problem encountered was caused by the excellent thermal performance

of the unit. A significant volume of working fluid (liquid) was very near the boiling temperature corresponding to the boiler pressure. Valve changes (a pressure drop) could cause this fluid to begin to boil prematurely in the preheating section causing the column to flood.

From these tests sufficient information has been generated to design the next phase of testing which will examine the relationships between heat transfer, mass transfer, and column hydraulics. At this point, the DCHX could be designed to increase its throughput capacity, but it is not known what, if any, sacrifices might have to be made in terms of thermal performance or the penalty that would have to be paid in working fluid losses (or recovery), to provide this additional hydraulic capacity. The data taken does indicate that the tray thermal efficiency is dependent upon hydraulics. These tests will provide the baseline for the testing that will attempt to resolve some of these questions. This next series of tests are planned after the completion of the supercritical testing with shell and tube heat exchangers.

2. INTRODUCTION

As part of the Department of Energy, Division of Geothermal Energy effort in conversion technology, EG&G Idaho, Inc., has been investigating different methods of utilizing the energy contained in a moderate temperature (140°C) geothermal resource at the INEL Raft River geothermal test site. The major emphasis of the conversion technology effort has been the testing of binary power cycles with a prototype plant test facility which has been in operation since 1978. This report will present the results of that portion of the latest sequence of tests conducted from April 1981 to July 1982 utilizing a direct contact heat exchanger (DCHX) as the preheater/evaporator and an isobutane working fluid.

The interest in direct contact heat exchangers in geothermal applications has developed because these devices have the potential to provide efficient heat transfer service without the scaling or corrosion problems that could arise with conventional heat exchangers. Because the working and geothermal fluids physically contact each other during the heat exchange process, there is no physical heat transfer surface, i.e., tube wall, to foul or corrode due to exposure to a hot brine containing varying levels of dissolved solids. This lack of a physical boundary between the two fluids also presents problems to a system using these heaters in that some contamination of the secondary working fluid occurs (in the form of noncondensable gases and water vapor) due to the exposure to the geothermal fluid; despite the fact that the two fluids are relatively insoluable, some working fluid is dissolved and/or mechanically entrained in the brine leaving the unit. Both the working fluid losses and the contamination of the working fluid system represent a cost and power penalty to a facility using these exchangers.

The testing of direct contact heat exchange with the prototype plant investigated the performance of a sieve tray, or perforated plate-type direct contact column. In addition to testing the performance of the unit with a single component working fluid, isobutane, the fluid chemistry of the streams leaving the column were examined to determine working fluid losses and the levels of contamination in the working fluid vapor flow.

During the last six weeks of operation, the facility was operated using different combinations of working fluid mixtures. This preliminary report will deal primarily with the performance results with the single component working fluid, isobutane. A more detailed description of the facility and the methods used will be included in the final report along with an analysis of performance with working fluid mixtures and the results of the fluid chemistry testing.

3. FACILITY AND COMPONENT DESCRIPTION

The prototype plant is a small scale geothermal binary power plant which is similar to a full scale plant in most aspects except size. As the primary purpose of the plant is to be used as a test facility, it has been built with the flexibility to allow for operation in different configurations utilizing various components; the basic plant cycle, though, remains essentially the same. Heat from a hot geothermal fluid is tranferred to a secondary working fluid in one of the heater units. This working fluid (isobutane) is first heated to saturation conditions and then vaporized. This high pressure working fluid vapor (refer to flow schematic in Figure 1) is then expanded through a turbine which drives an electrical generator or is expanded through a turbine bypass valve to the condenser. This low pressure vapor (low relative to the heater pressure) is desuperheated and condensed in the condenser. The liquid condensate is then pumped back up to boiler pressure and recirculated back to the heaters, and the cycle is repeated. The cooled geothermal fluid leaving the heater is discharged to a holding pond. The condensing heat load is transferred to cooling water circulating through the condenser which in turn rejects this energy to the atmosphere in a conventional wet cooling tower.

The subject of this report is the operation and performance of the plant when the direct contact heat exchanger (DCHX) was used. The heat exchanger is a sieve tray or perforated plate column designed and built for this application by Wahl Company of Claremont, California. The column is a vertical unit containing 20 trays and downcomers which provide for the ordered passage of flow through the column. The geothermal fluid and isobutane working fluid have countercurrent flow paths through the column which are maintained by the force of gravity acting on the density difference between the two immiscible fluids. In this application the lighter working fluid is dispersed as drops from the holes or perforations in each plate. These drops rise through the heavier geothermal fluid because of the buoyancy force on the drop, and collect and coalesce under the next tray and vessel wall. This process of drop forming and coalescing is repeated at each tray as the working fluid moves up the column, heating as it rises through the geothermal fluid. The heavier geothermal fluid flows as the continuous medium horizontally across each plate transferring heat to the wroking fluid, and then passes down to the next plate through a disengagement space formed by the downcomer on each plate.

The prototype DCHX is shown schematically in Figure 2. The lower 17 of the 20 trays comprise the preheating section where the working fluid is heated up to the boiling temperature corresponding to the boiler pressure. The next two trays, i.e., 18 and 19, make up the boiling section where the working fluid is vaporized. The upper tray, number 20, was included for draw-off testing with a hydrocarbon mixture working fluid. Geothermal fluid enters the column just above the upper boiling tray and is cooled as it flows down the column and out the very bottom of the unit. As indicated in Figure 2, the geothermal fluid temperature is measured in the downcomer regions at various locations as the fluid flows through the heat exchanger. The liquid working fluid enters the bottom of the column and is dispersed just under the bottom plate. The working fluid temperature is measured under different trays as it rises up through the column. The working fluid vapor leaves the unit near the top.

The DCHX is 30.48 cm (1 ft) in diameter and approximately 5.94 m (19.5 ft) long. The performations in the trays have a diameter of 0.3175 cm (1/8-inch) and the trays (in the preheating section) are spaced at 15.24 cm (6-inch) intervals with 7.62 cm (3-inch) long downcomers).

4. DIRECT CONTACT HEAT EXCHANGER THERMAL AND HYDRAULIC PERFORMANCE TESTS

4.1 Test Description

The first sequence of performance tests with the prototype DCHX was to provide thermal and hydraulic performance data for the unit with an isobutane working fluid. These tests, which are outlined in Table 1, provide temperature data to be used in determining tray efficiencies and heat exchanger pinch points and the column "flooding" data which established the mass throughput limits for the column. "Flooding" in these direct contact tests was defined as the point where the dispersed fluid was entrained in the continuous fluid at levels where the column operation became unstable. In conducting these performance tests, the DCHX was brought to the desired boiling conditions at flow rates well below the predicted flooding limits. Flow rates were then increased in regular increments (still maintaining the boiling conditions) until flooding occurred. This was repeated for each of the conditions listed in Table 1.

4.2 Discussion of DCHX Thermal and Hydraulic Performance

In the direct contact heat exchanger both the geothermal fluid and the working fluid are in contact with each other during the heat exchange process, i.e., no tube wall or other physical boundary separates the fluids. The driving mechanism for moving both fluids through the column is the force of gravity and the density difference between the fluids. This process of the lighter working fluid rising up through the heavier geothermal fluid which is flowing down and out of the bottom of the column produced the countercurrent flow patterns desirable in the heat transfer process. The countercurrent flow path and lack of a tube wall or other boundary between fluids allows these units to be built and operated as a single heater/vaporizer unit without special considerations other than providing sufficient flow area and volume for preheating and boiling to occur. Since boiling is a constant temperature process (with a single component working fluid), the countercurrent flow path for the fluids is not necessarily desired during boiling, provided a large enough "pot" is available to vaporize all the working fluid. In evaluating the performance of the prototype DCHX the main emphasis was placed on the the preheating section.

The direct contact heat exchanger primarily used or tested in geothermal applications is the spray or Elgin tower. This type of column is characterized by its simplicity, i.e., it contains no special internals other than distributor plates or nozzles used to introduce the two fluids into the column. The prototype DCHX, whose test results are reported here, is a sieve tray column which uses internal trays and downcomers to provide for an ordered repeated mixing and separation of the fluids as they move through the column. These internals eliminate the recirculation of fluids characteristic of Elgin towers which tends to reduce thermal performance. The repeated formation and coalescence, i.e., heating and mixing, of the drops can also provide a potential improvement in thermal performance in that more of the fluid is exposed to the source of heat than in the case of a single drop rising in a spray column where the fluid at the center of the drop must be heated by conduction through the drop from its surface.

One indicator of the thermal performance of the sieve tray DCHX is the tray efficiency which is a measure of how efficiently heat is transferred during the contacting of the two fluids between plates, or trays. The tray efficiency is defined as the ratio of the actual temperature change of a fluid through a tray section to the maximum temperature change the fluid could have undergone. The maximum temperature change is the difference between the inlet fluid temperature and the temperature both fluids would come to if allowed to mix in the tray and temperatures equilibrate. The tray efficiency is always greater than zero and less than one (100%). It should be noted that this definition of tray efficiency when applied to the working fluid temperature, is useful for the preheating portion of the column but not the boiling trays. (In the boiling trays, efficiency derived from working fluid temperatures must be based on enthalpy differences as the working fluid boils at a constant temperature.) The thermal and hydraulic tests with the DCHX were to provide the data for evaluating the tray efficiencies at different column conditions and compare these efficiencies with the estimated design value of 70%. An example of an anticipated temperature profile in the preheating section of the DCHX is shown in Figure 3 at the design efficiency of 70% (the geothermal fluid outlet temperature was based on a 0°F pinch point).

If the tray efficiencies are high and the column has a sufficient number of boiling and preheating trays, then the DCHX should be able to achieve small pinch points, as shown in Figure 3. (The pinch point is the minimum temperature difference between the two fluids, generally occurring at or near the point where the working fluid begins to boil.) In conventional shell and tube heat exchangers, a typical pinch point might be 10°F or higher. In order to achieve smaller pinch points, these units would require more area corresponding to higher costs. With the large number of preheating trays in the DCHX, it was anticipated that the unit would be able to operate with a pinch point of about 1°F or less. The predicted temperature profile in Figure 3 indicates that at a tray efficiency of 70%, the DCHX would produce a pinch point of well under 1°F at the conditions for which the prediction was made. Lower preheating tray efficiencies would change the temperature profile producing higher pinch points. The uncertainty in the tray efficiency when designing the unit dictated that additional trays be added with the provision that plates 9 through 16 (with plate 1 being the lower plate) could be removed.

If the assumption is made that the resistance to heat transfer between a working fluid drop and the geothermal fluid does not vary signficantly with the drop diamter, then producing smaller drops and exposing more of the working fluid to the brine, i.e., more surface area, should increase the total amount of heat transferred in the regions between plates. The reduction in drop size to increase the amount of heat transferred, however, must be tempered by the increased mass transfer rate between fluids and the consideration of the driving mechanism for the DCHX hydraulics. As mentioned earlier, the dispersed working fluid drops rise in the column due to the density difference between the fluids or the drop's buoyancy. The velocity at which the drop rise, or its terminal velocity, is approximately proportional to the square root of the drop diameter, thus smaller drops rise more slowly in the column. If the velocity of the continuous fluid exceeds the drop terminal velocity, then the drop will be swept along in the continuous fluid stream, or mechanically entrained. Thus the terminal velocity of the working fluid drop establishes the maximum velocity of the geothermal fluid in the column. The reduction in drop size to provide more heat transfer area must be traded off with reduced mass throughputs of both fluids and/or a larger vessel at higher costs.

The intent of the DCHX hydraulic and thermal performance tests was not to investigate the different mechanisms involved in the drop formation process, however, some consideration must be made of these mechanisms in interpreting the operating limits encountered. Investigations have found that at low orifice or hole velocities the drops will form at a uniform size and break off at regular intervals. (Some of the different correlations were used to predict the drop size at these low velocities and produced estimated diameters ranging from 0.6 cm to over 1 cm.) As the velocity through the orifice is increased, a point is reached where the mechanism for the drop formation changes. A short jet of dispersed fluid extends from the nozzle and drops form by a "necking-in" at the top of the jet. The drops formed from the jet, while not as uniform in size as the drops formed prior to jetting, have some consistency in size at the lower jet velocities and their average diameter can be predicted.[1]

As the orifice velocity increases, the jet increases in length. Skell and Johnson[1] investigated the formation of drops from the breakup of jets and defined correlations which predict the conditions producing the maximum interfacial area. This condition defines the point where the interfacial or surface area between the contacting fluids is at a maximum. It was initially defined as an important parameter in the design of liquid-liquid columns in mass transfer applications. It would assume the same importance in the design of columns for liquid-liquid heat transfer applications in that it defines the conditions for maximum drop surface area (total) which corresponds to the minimum average drop size. The orifice velocity corresponding to this condition is recommended by Jacobs and Boehm(2) as the maximum hole velocity to use in the design of a sieve tray direct contact heat exchanger.

The jet length increases with the orifice velocity to a point where the length reaches a maximum after which the jet decreases in length as velocity increases.(3) The maximum jet length condition defines the point where jet begins to breakup in a random manner and the drops have no uniformity in size. The jet length will continue to decrease with increasing velocity until the point is reached where the jet disappears and the working fluid stream leaving the orifice is atomized producing a cloud of small droplets.

The velocities of working fluid through the plate perforations which are predicted to produce jetting, the maximum interfacial area, and the maximum jet length are shown in Figure 4. These predictions are made along the length of the preheating sections for conditions for some of the test runs (2, 3, 4, 6, and 7) and for the hole sizes and fluids used in the DCHX. The predicted velocity at which jetting initiates from the plate perforations varied little over the range of conditions considered, indicating fluid properties had little effect on the predicted value. The predicted velocities for the maximum interfacial area and jet length did vary both along the length of the preheating section and from run to run. If the prototype DCHX was designed around the recommended maximum interfacial area conditions, then the plates should have working fluid velocities through the perforations of about 22 to 26 cm/s. These velocities should produce optimum thermal performance.

The geothermal, or continuous fluid, flow through the column is based on the terminal velocity of a drop as discussed previously. This analysis requires that the drop diameter be known in order for the velocity to be predicted, and assumes that the drop behaves as a solid sphere as it rises. Investigators of the formation of drops in liquid-liquid systems have noted that this assumption is valid to a certain drop diameter after which the terminal velocity no longer increases and in some instances may decrease slightly with increasing drop in diameter. This transition is felt to be the result of internal circulation within the drop and oscillations and distortion of the drop surface which increase the drag forces on the drop. A correlation developed by Treybal and Klee[4] was used to predict this limiting terminal velocity. The resulting velocity predictions are shown in Figure 4. This velocity represents the maximum continuous fluid velocity in the column. Higher geothermal fluid velocities would entrain any drop formed regardless of size. The design of a direct contact column would not be based on this maximum or limiting terminal velocity. It would instead be based on the terminal velocity of the maximum sized droplet that would be allowed to be carried under. Usually this drop diameter is arbitrarily selected. Values commonly used in the design of sieve tray columns are 0.0794 cm (1/32-inch) and 0.1588 cm (1/16-inch).[5] Both of these values are below the diameter at which the drop is predicted to no longer behave as a solid sphere (0.18 to 0.24 cm). The predicted terminal velocities for a 0.0794 cm (1/32-inch) drop for the range of operating conditions in the prototype DCHX is shown in Figure 4.

4.3 Test Results

The sequence of thermal and hydraulic tests (listed in Table 1) were conducted with the prototype DCHX and the hydraulic throughput limits established for each of the conditions listed with two exceptions. It was not possible to reach the column flooding limit in test run 1, i.e., the highest boiler pressure, primarily because the inlet geothermal fluid temperature (approximately 130°C or 266°F) was lower than the design value (143°C or 290°F) requiring higher geothermal fluid flow rates to vaporize a given amount of working fluid. The upper flow limit of the geothermal fluid boost pump was exceeded before the column flooded. The second exception was test run 5 where the initial efforts resulted in premature flooding as the result of instabilities in the control system. Later efforts to establish the flooding limit for this run were successful, however, some inconsistencies were found in the data. If these inconsistencies can be sorted out, this data will be included in the final DCHX report.

Even though two of the seven test runs were not totally successful, a fairly wide range of operating conditions were obtained with the unit up to its flooding limits. The "near flooding" conditions for the column are listed in Table 2 except for test run 5 (maximum flow conditions for test run 1 are given). The trends in flow rates for both fluids shown in Table 2 are consistent with the operating characteristics of other direct contact columns; that is, as the dispersed or working fluid flow increased, the continuous or geothermal fluid flow decreased. This trend did not follow terminal velocity predictions (see Figure 4) which estimated an almost constant terminal velocity over the range of conditions considered. It should be noted that the terminal velocity prediction considers only a single drop system, i.e., no interference from adjacent orifices and does not consider the drop formation processes, i.e., the smaller drops formed at the higher orifice velocities.

Thermal Performance

The data provided in Table 2 indicates that with the exception of test run 1, the heat balances in the DCHX unit were good and all were within the range of error one might expect with the instrumentation used (within 5% was considered acceptable). The data collected for each of the "near flooding" conditions listed in Table 2 was input into a program developed for the analysis of the thermal performance of the DCHX preheating section. The results of the DCHX thermal analysis for each of these conditions at the measured flows and temperatures and the design tray efficiency of 70% are shown in Figures 5, 6, 7, 8, 9, and 10. These figures show the predicted column temperature profile for the measured parameters and the selected tray efficiency along with the measured column temperature profile. With some exceptions, the data in these figures fits the predicted performance curves fairly well. The exceptions are most apparent in the results for test runs 4 and 6 (Figures 8 and 9) where the predicted performance deviates from the actual data in the upper preheating section. It was found that the deviation at the upper end of the preheating section, i.e., plates 8 through 17, was the result of a poor preheating section heat balance which could be corrected through an adjustment of the flow rate and/or the temperatures. A deviation in the lower end of the preheating section, i.e., plates 1 through 8, resulted from an incorrect efficiency assumption.

The data for each of the test runs was adjusted to balance the preheating section heat loads which produced good agreement between the measured and predicted temperature profiles in the upper preheating section, i.e., near the boiling trays. This was accomplished using two methods; adjustment of the mass flow ratio or adjustment of the geothermal fluid outlet temperature. The tray efficiency was then adjusted until the predicted geothermal fluid temperature profile matched the measured profile along the entire length of the column. The results of the heat balance and tray efficiency adjustment for the near flooding conditions are shown in Figures 11 through 16. For the analysis shown in these figures, the heat balances were adjusted by varying the mass flow ratio. When the outlet temperatures were adjusted, similar results were obtained. Except for test run 1 (Figure 11), the tray efficiencies which best fit the measured profile were at the design value of 70% or slightly higher (up to 74%) indicating that from the thermal standpoint, the column was performing as designed.

The effect of tray efficiency on the column temperature profile is demonstrated in Figure 17 for the conditions in test run 3. In this figure, predicted column temperature profiles are shown at three different efficiencies, i.e., 50%, 70%, and 90%. In all three cases, by the time the fluids reach the last preheating tray, plate 17, they have reached essentially the same temperatures. However, in the lower portion of the preheating section, the assumed efficiency does have a considerable impact on the predicted profile. If the trays had an efficiency of 50%, most, if not all, of the trays would be required to bring the working fluid up to the boiling temperature. At a 90% tray efficiency there is an excess of preheating trays in the column. It is apparent from these predicted profiles that for the conditions in this test run, a tray efficiency of 70% produces a temperature profile that comes quite close to matching the test data.

In the temperature profiles shown in Figures 5 through 17, it is apparent that some heat transfer occurred in the column before the working fluid entered the first tray or heat transfer zone between plates 1 and 2. This heat transfer was occurring in the tube (pipe) which brought the working fluid into the downcomer region under plate 1 and in the region between the discharge of this nozzle and the coalescing working fluid layer under plate 1 (see Figure 2). Initially it was suspected that the temperature probe had not been placed properly. In examining the profiles, however, it was noted that the geothermal fluid temperature was decreasing from the downcomer leaving tray 1 to the column outlet. Since the column was not near the flooding conditions, this temperature change could not be attributed to working fluid carryunder and must have been the result of a heat exchange with the working fluid. This temperature change was most significant at the lower working fluid flow rates (see data for test run 1, Figures 5 and 11) and decreased as the working fluid flow rate increased (see data for test run 7, Figures 10 and 16). Although the temperature change in the geothermal fluid decreased with an increase in the working fluid flow rate, the working fluid temperature measurement under plate 1 continued to provide inconsistencies, i.e., see data for test run 7, which were not resolved. In the analysis of the data, this region under plate 1 was defined as a tray or heat transfer zone and an efficiency calculated for this area. This was done to account for the heat transfer occurring there and provide a more accurate determination of the efficiency of the trays designed to accomplish the heat transfer.

The DCHX thermal performance for these test runs is summarized in Table 3. The tray efficiencies are given for both methods of data adjustment for the preheating section, along with the pinch point, heat loads, and volumetric heat transfer coefficients. Trends in the efficiencies are not apparent except in the region under plate 1, which was termed the distributor tray. This efficiency generally decreased with an increasing working fluid flow rate which would be expected as the layer of working fluid should become thicker as the flow rate increases, decreasing the size of this heat transfer zone. Although it is difficult to identify any trends in the preheating tray efficiency, it is significant that the efficiencies obtained (except in test run 1 which was not brought to flooding) were equal to the design value of 70%. Boiling tray efficiencies were calculated using a combination of temperature measurements and predicted enthalpy changes. The 0% tray efficiencies obtained in test runs 4 and 6 for plate 18 are suspect given that this efficiency depends on a geothermal fluid temperature measurement in a region where neither fluid is the continuous fluid and in a sense a "boiling pot" exists. It would appear from the data that as the boiling heat load increases and working fluid flow rate increases (geothermal fluid flow rate decreases) the boiling shifts from occurring in both trays to occurring mainly in the top tray. This might be explained by the lower boiling tray assuming some preheating duty; however, from the analysis of the preheating tray performance, it would appear that there is an excess of preheating trays in the column. Given the uncertainty in obtaining an accurate intermediate geothermal fluid temperature between boiling trays, any significance of apparent trends in boiling tray efficiencies is questionable. The only significant conclusion that one can define is that boiling trays had sufficient capacity for the conditions tested.

The pinch points for tests conducted were small, much smaller than could be accurately measured with the instrumentation available. In matching the preheating section temperature profile pinch points ranging from 0.02°F to 0.30°F were obtained. These pinch points increased as the heat load for the column increased. It would appear from the results obtained that the pinch point is more sensitive to the heat load in the boiling section than that in the preheating section (the largest pinch point obtained occurred at the lowest preheating heat load).

The volumetric heat transfer coefficients (Uv) were also calculated for the different runs and are presented in Table 3. These values were defined using the heat transfer that occurred in these sections, the total volume in this section where heat transfer could have occurred, and the log mean temperature difference. The log mean temperature differences in the preheating and boiling sections were defined using the pinch point obtained in matching the preheating section temperature profiles. The distributor tray volume was defined as the volume between the working fluid inlet nozzle and plate 1, enclosed by the downcomer leaving tray 1. The preheating section volume was defined as the volume of the column from the top of plate 1 to the bottom of plate 18, less the volume of the downcomers. The boiling section volume was defined as the volume in the column from the top of plate 18 to the bottom of the demister. It should be noted that these volumes are not the volumes in which the heat transfer takes place, although the preheating section volume best approximates the actual volume. In the distributor tray and in the preheating section the layer of working fluid under each plate reduces the actual volume, and the heat transfer done in the inlet pipe is not considered. This layer may have been thick enough in test runs 6 and 7, that there was no space for heat transfer to occur thus producing a zero heat transfer coefficient. The volume used in defining the boiling section heat transfer coefficient is also larger than that actually used. In the boiling section it is difficult to estimate the "thickness" of the region in which boiling occurs. The bottom of the demister was selected, as this represents the upper limit as far as the thickness of the boiling region is concerned. (If the boiling occurred at a level above the demister, excessive carryover of water could occur and the column would be unstable.) Perhaps the most significant observation one might make from these heat transfer coefficients is that the Uv values for the preheating section are relatively constant. This may be due to the fact that the preheating occurs over a fairly well defined region, and there is not the same degree of uncertainty in the volume to use. The decreasing boiling tray Uv with increasing heat load is rather disturbing as it is expected that the volume actually required for boiling increases with heat load. Thus the Uv values at the lower boiler heat loads would be even higher if actual volume were used. Trying to compare the Uv values between test runs or for different heat exchangers is difficult unless volumes and pinch points are well defined. In the case of this heat exchanger unit, questions relative to the actual pinch points and volumes in which heat transfer occurs produce sufficient uncertainty to not merit more detailed comparisons of Uv values with other heat exchangers.

Hydraulic Performance

The fluid flow rates listed in Table 2 are those obtained in the DCHX unit just before the flow change that produced flooding and approximate the upper mass throughput limits for this column. Flooding in the DCHX, as defined in this report, was that point where the operation of the column became unstable and was characterized by very large carryunder. Carryunder in this instance is a qualitative indication measured by the size of the flame present over the tank into which the geothermal fluid discharged. (A continuous pilot flame was maintained over the tank to burn off any working fluid in the geothermal fluid.) Carryunder was noted at lower flow rates (again as a flame on the tank water level), however the column operated stabily at these flow rates (approximately 16 to 20 gpm WF).

The velocities for the "near flooding" conditions in test runs 2, 3, and 4 are shown in Figure 18 as the working fluid hole velocity and the geothermal fluid downcomer velocity for each plate in the preheating section. Also shown are the predicted velocities from Figure 4 and the geothermal fluid downcomer and working fluid hole velocities at plates 1 and 17 for test runs 6 and 7.

The geothermal fluid velocities (shown as open circles) in the downcomer region are below the predicted limiting terminal velocity for all the test runs. For runs 2, 3, 4, and 6, the geothermal fluid velocity in the downcomers for plates 2 through 17 is equal to (run 6) or exceeds (2, 3, and 4) the predicted terminal velocity for a 0.0794 cm (1/32-inch) drop. Geothermal fluid velocities were lower in the downcomer leaving tray 1 as this downcomer was designed with approximately 40% more cross sectional area to decrease the velocity and reduce the potential for mechanical entrainment of the working fluid in the outlet geofluid. The data implies that a downcomer sized for a 0.0794 cm (1/32-inch) diameter drop terminal velocity would allow for continuous fluid velocities near the operating limits encountered with the DCHX.

The working fluid hole velocities at the near flooding conditions for the test runs are, with the exception of run 2, above the velocity predicted for jet formation. The hole velocity for run 2 is above the predicted jet velocity from all the plates, except plates 2 and 6 where the hole area (total) increases. For the most part, the working fluid hole velocity data for all of the test runs approximates the predicted velocity where the maximum interfacial area (minimum average drop size) occurs. The plate hole area changes (increase in the number of performations in the plate) designed into the column by the designer (Wahl), produced a working fluid velocity pattern similar to that predicted for maximum interfacial area velocity. The data implies that the working fluid throughput limits encountered by the column generally correspond to the predicted velocity which produces the minimum average drop size (maximum interfacial area) as the working fluid leaves the plate perforations. The correlation that predicted this average drop size produced an estimated average drop diameter in the range of 0.5 cm (approximately 1/5-inch). A drop of this size would require a geothermal fluid velocity at the limiting terminal velocity to be mechanically entrained and carried under. Unfortunately, these correlations do not provide a drop size distribution so that one could estimate the number of these drops that might have been carried under at the geothermal fluid velocities encountered.

The DCHX was designed with the upper preheating tray (plate 17) to allow a portion of the working fluid to be removed from the column at or near the saturation temperature. To ensure that the fluid under plate 17 being removed was working fluid and not geothermal fluid, the total hole area in plate 17 was reduced in order to "back-up" or thicken the layer of working fluid under the plate. This reduction in hole area (approximately 60%) resulted in very high working fluid hole velocities at the operating limits (see Figure 18). Except for the conditions in test run 2, the velocities from the performations in plate 17 exceeded those predicted for maximum jet length and the resulting irregularity in the size of drops formed from the breakup of the jet. (The velocities for test runs 6 and 7, not shown in Figure 18, were 61.2 cm/s and 60.7 cm/s, respectively.) It appears that this condition was occurring in plate 17 near the operating flow limits encountered, however, its effect on the column hydraulics is difficult to define. If a number of small drops were formed and entrained in the geothermal fluid leaving tray 17, they could begin rising when the geothermal fluid velocity slows over plate 16 or they could be carried on farther down and/or out the bottom of the column.

At this point, without removing or modifying plate 17, it is not possible to associate the column operating hydraulic limits with either the maximum jet length velocity at plate 17, or the maximum interfacial area velocity in the remainder of the column. It is also possible that neither these represent an operating limit, though at this time they are the most logical candidates.

The predicted velocity at the maximum interfacial area condition is recommended by Jacobs and Boehm[2] as the maximum hole velocity to use in designing a sieve tray direct contact heat exchanger. If this velocity does produce the maximum surface area it should provide the most efficient heat transfer operating condition. The tray efficiency of two of the test runs (runs 3 and 4) were examined as a function of flow rate as the column was brought to the flooded condition. In both cases the tray efficiency increased as the flow rate increased, although at the highest flow for test run 4, the efficiency decreased slightly. The tray efficiencies for these two runs as well as the efficiencies at the maximum flow conditions for the other test runs are shown in Figure 19. Also shown are the flow rates at which jetting and the maximum interfacial area condition are predicted to occur in the column. The data indicates that the tray efficiency does increase with flow, and suggest that it may peak at an inlet flow rate around 20 gpm and decrease slightly as flow continues to increase. The data also indicates that the tray efficiency reaches its peak (if it does in fact peak) or plateau before the predicted maximum interfacial area and before jetting is predicted. At this point no explanation is offered other than the predicted velocity values may have used a interfacial surface tension higher than the actual value. The interfacial surface tension was estimated as the difference between the individual surface tensions. Perry[6] indicates that this method can be used when data on the mixture is not available, although it does provide a predicted value higher than the actual interfacial tension. If a lower interfacial surface tension were used, the predicted velocities would be lower and a little better agreement between predicted and data would have been obtained.

It is interesting to note that during the operation of the DCHX, carryunder as indicated by a flame on the surface of the geothermal fluid discharge tank, was first noted at the working fluid flow rates of 15 to 20 gpm. This corresponds roughly to the flows where the tray efficiencies approaches or reached their maximum. Except for run 1, where carryunder was noted earlier and geothermal flow rates were higher, this carryunder of working fluid occurred at roughly the same flow each time suggest perhaps a change in the drop formation mechanism producing smaller drops (perhaps jetting).

In comparing spray tower and sieve tray direct contact columns as heat exchange devices, the sieve tray column is reputed to have a thermal advantage, but is said to have a lower mass throughput capacity than a spray tower of similar dimensions[2]. The tests conducted with the prototype DCHX confirm that the sieve tray column provides excellent heat exchange performance. To determine mass throughput capacity of the sieve tray unit relative to spray towers, the superficial velocities of the sieve tray DCHX were compared to those of the DSS spray tower[7] and the 500kW spray tower.[8] This comparison is shown in Figure 20. The superficial velocities, which were defined as the volume flow rate of a fluid at the bottom of the column divided by the total column cross sectional area, enables vessels of different diameters to be compared on an equivalent basis. The prototype DCHX data in Figure 20 generally follows the trends indicated by Treybal[9] in his discussion of the flooding limits of different types of direct contact columns (in mass transfer applications). It is difficult to draw detailed conclusions about the throughput capacity of the sieve tray unit relative to the spray towers. The throughput performance of the sieve tray column compares favorably with the design point for the 500kW spray tower. This design point, however, does not represent the throughput limits as this column was operated at or near this condition without flooding. The operating data from the DSS spray tower indicates that during the low temperature cycle testing (i.e., low brine inlet and working fluid outlet temperatures), the DSS unit operated at higher relative throughputs than the sieve tray column. During the high temperature cycle tests, the maximum flow rates at which the DSS spray tower operated stabily produced superficial velocities lower than those obtained during operation of the sieve tray DCHX. It is not apparent whether this limit encountered during the high temperature cycle testing is due to flooding or some other factor. Given the throughputs obtained during the low temperature cycle tests, the DSS unit should be able to operate at higher superficial velocities when operated at higher temperatures without flooding, i.e., data should follow a trend similar to the sieve tray DCHX data. If it is assumed then that the higher DSS throughput values represent the flooding limit of that spray tower, the sieve tray DCHX does have a lower relative throughput capacity.

Effects of Control System on Column Hydraulics

The discussion of the flooding limits of the prototype plant DCHX to this point has primarily involved the process of drop formation and the size of drops that result, and the terminal velocities required to mechanically entrain the working fluid drops. One point not discussed is the effect of the control system on the hydraulic performance of the unit. The DCHX was installed and operated with two automatic (or manual if so desired) control valves. The pressure of the column was maintained by a control valve in the working fluid vapor stream leaving the unit, and the geothermal fluid liquid level was controlled by a valve in the effluent geothermal fluid stream. In examining the column temperature profiles (Figures 11 through 16), it is apparent that much of the working fluid in the column is at or very near the saturation temperature corresponding to the column operating pressure. This poses an operational and control problem as the column is slow to react to flow changes (particularly the level). On several occasions the column flooded because the level valve kept opening in response to an apparent high liquid level in the column. A point was reached where the pressure control valve did not react fast enough to compensate for the drop in column pressure caused by the opening level control valve. At this point the column pressure had decreased to the value where the working fluid previously near saturation temperature was at the saturation temperature corresponding to the lower column pressure and began to vaporize. As this liquid began to boil in the preheating section, the geothermal fluid was in a sense "lifted" and the level control system saw a rising liquid level and opened the control valve to compensate. This compounded the problem dropping pressure and forcing the boiling further down into the preheating section. The net result was the column rapidly reached a flooded condition where large amounts of working fluid was being carried under and the control system was unable to compensate or correct the problem.

The contribution of the control system to the definition of the column flooding limits is not at this time felt to be significant as considerable care was taken in bringing the unit to flooding to minimize the effects just described. It is important, however, to note that the excellent thermal performance of the unit and the resultant excess of preheating trays produced significant problems when trying to operate the column in an automatic control mode whether for an extended period or during the start-up. The end result was an operation where the pressure was controlled automatically and the level controlled manually, with adjustment of the level being based on the operator experience and "feel" for running the column.

5. CONCLUSIONS

The testing of the INEL prototype plant DCHX confirmed that in thermal applications, the sieve tray column is an excellent heat exchange device. Very small pinch points were obtained, well under the design goal of 1°F. The column operated at or above the design tray thermal efficiency of 70% when flow rates were above certain levels. The tray efficiency generally increased with the working fluid flow to a given flow range (16 to 20 gpm) after which it was constant or decreased slightly with increasing flow. At the tray efficiencies obtained, the temperatures of both fluids were within 1° to 2°F of each other in the upper preheating section (trays 9 through 17) indicating that for the boiling temperatures operated at, the unit had an excess of preheating trays. At this performance level, the number of trays in the preheating section and the column length could be reduced without a corresponding sacrifice in thermal performance. The existing column could also be operated at an elevated brine inlet and working fluid vapor outlet temperatures and still maintain an acceptable performance level.

Although the column did not operate at a geothermal flow rate corresponding to the design terminal velocity of a 1/16-inch diameter drop, it did operate at the working fluid velocities from the plate performations recommended[2] for the design of a sieve tray column. The data suggests that premature flooding may have occurred due to the reduced total hole area in the upper preheating (drawoff) tray. The reduced hole area produced working fluid velocities from the holes in excess of the velocity limit beyond which the drops forming from the jet have no uniformity in size. This may have produced local flooding, i.e., carry-under of the smaller drops, or it may have produced a sufficient number of small drops which could have been swept down the length of the preheating section flooding the tower. The hole area for the plates in the rest of the preheating section provided working fluid hole velocities corresponding to the predicted values for producing the maximum interfacial area condition, or the minimum average drop size. This is the hole velocity recommended by Jacobs and Boehm.[2]

Comparisons of the mass throughput capacities of a sieve tray unit with a direct contact spray tower are somewhat inconclusive. The performance of the sieve tray DCHX compares favorably with the relative capacity of the 500kW spray tower, however, this spray tower was never brought to a "flooded" condition so that an increment in capacity performance could be estimated. A comparison with the high temperature cycle test performance of the DSS spray tower indicates the sieve tray DCHX had a throughput advantage. When compared to the low temperature cycle test performance of the DSS unit, the spray tower had an advantage. Given the general trends for flooding of spray towers, the DSS unit performance during the low temperature cycle tests probably represent the maximum limit for that spray tower due to flooding. In this case the spray tower does have a throughput advantage over the sieve tray column as reputed.[2]

The excellent thermal performance of the unit also presented an operational problem in that a significant quantity of working fluid in the column was near the saturation temperature. A drop in column pressure due to the opening of a control valve or change in flows could start boiling of this volumne of fluid in the preheating section. Once started, the control system tended to perpetuate the phenomenon until flooding was produced. Generally, manual control of liquid levels corrected or reduced the problem.

At this point a considerable amount has been learned about the design and operation of a sieve tray direct contact heat exchanger. The column tested was an excellent device for heat transfer. While the hydraulics of the unit are not totally understood, enough has been learned to design a sieve tray unit which would probably produce higher throughput capacities than were produced during these initial tests. The major question yet to be resolved is the impact of the hydraulic design on the thermal performance and mass transfer. If, for instance, drop sizes are increased by increasing hole sizes, what happens to the tray efficiency, and does the amount of working fluid dissolved in the geothermal fluid increase or decrease? The data taken during this baseline sequence of tests suggests tray efficiency is dependent upon the size of drops formed or perhaps on the formation of a jet from the holes. With what has been learned during these baseline tests, the next sequence of testing can be designed to answer these questions and provide the data to allow for the design of a sieve tray unit that would operate close to the optimum thermal and hydraulic conditions.

6. REFERENCES

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2. Jacobs, H. R., and Boehm, R. F., "Direct Contact Binary Cycles", Sourcebook on the Production of Electricity from Geothermal Energy, Brown University, DOE/RA/4051-1, pp. 413-471, 1980.

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8. "500kW DCHX Pilot Plant", Handout in Second Geothermal Direct Contact Heat Exchange Workshop, East Mesa, California, prepared by Barber-Nichols, Engineering, January 1981.

9. Treybal, R. E., Liquid Extraction, 1st Edition, McGraw Hill, 1951.

TABLE 1. DCHX THERMAL AND HYDRAULIC PERFORMANCE TESTS

	Parameter	Run No. 1	Run No. 2	Run No. 3	Run No. 4	Run No. 5	Run No. 6	Run No. 7
1.	Preflasher	Operating, $\Delta T \sim 1°F$						
2.	Vent Condenser	Operating, $P_{N2} < 1$ psia						
3.	Boiler Temperature	250°F	230°F	220°F	210°F	200°F	190°F	150°F
4.	Boiler Pressure	~ 450 psia	~ 366 psia	~ 330 psia	~ 296 psia	~ 265 psia	~ 237 psia	~ 146 psia
5.	Mass Flow Ratio $\dot{m}_{IC4}/\dot{m}_{GF}$	0.26 - 0.53	0.48 - 0.67	0.53 - 0.74	0.59 - 0.80	0.66 - 0.86	0.72 - 0.92	0.97 - 1.13
6.	Geo-Fluid Flow Rate @ Flooding	14100 to 15100 lb/hr	13600 to 14500 lb/hr	13400 to 14200 lb/hr	13200 to 14000 lb/hr	12900 to 13700 lb/hr	12700 to 13500 lb/hr	12600 to 12000 lb/hr
7.	Working Fluid Flow Rate @ Flooding	3600 to 7000 lb/hr	6100 to 8800 lb/hr	7200 to 9500 lb/hr	8000 to 10300 lb/hr	8900 to 10900 lb/hr	9600 to 11500 lb/hr	12100 to 13500 lb/hr
8.	Cooling Water Flow Rate - thru Condenser	300 gpm or maximum flow rate that can be attained (not to exeed 300 gpm)						
9.	Boiler Level	To be established during check out tests						
10.	Condenser Level	Maximum and minimum values to be established during checkout						

TABLE 2: NEAR FLOODING CONDITIONS IN THE PROTOTYPE DCHX

PARAMETER	TEST RUN 1*	2	3	4	6	7
Boiler Pressure, Psia	446.7	365.0	329.4	294.2	236.3	146.2
Outlet WF Vapor Temperature, °F	249.6°	230.7°	221.0°	210.8°	190.4°	150.6°
Inlet WF Liquid Temperature, °F	91.6°	99.1°	99.9°	94.2°	98.5°	97.1°
Inlet WF Flow Rate, lb iC_4/HR	3636	6282	6984	7569	8325	8887
Inlet GF Temperature, °F	265.9°	267.7°	268.3°	268.4°	266.1°	267.6°
Outlet GF Temperature, °F	223.9°	191.1°	177.9°	165.7°	146.3°	119°
Inlet GF Flow Rate, lb GF/hr	17605	15537	14354	13334	12136	9656
Flow Ratio Preheating Section $(\dot{M}_{WF})_{IN}/(\dot{M}_{GF})_{OUT}$	0.2075	0.4072	0.4906	0.5727	0.6920	0.9274
Average Total Heat Load, Btu/hr x 10^6	0.743	1.204	1.311	1.404	1.470	1.437
% Difference in Heat Loads $(Q_{GF} - Q_{WF})/Q_{GF}$	4.6%	2.5%	2.4%	0.1%	1.26%	2.5%

*Flooding Conditions Not Reached

TABLE 3: THERMAL PERFORMANCE OF DCHX

PARAMETER	TEST RUN 1*	2	3	4	6	7
Measured Flow Ratio	0.2074	0.4073	0.4906	0.5727	0.6920	0.9273
Adjusted Flow Ratio	0.2159	0.4135	0.5006	0.5614	0.7202	0.9367
Distributor Tray Efficiency	58.3%	23.9%	31.6%	7.1%	7.1%	0%
Preheater Tray Efficiency	60%	70%	74%	71%	73%	71%
Boiling Tray Efficiency, Plate 18	99.6%	99.5%	99.6%	0%	0%	90%
Plate 19	92.8%	97.9%	96.7%	100%	99.4%	98.9%
Measured Geothermal Outlet Temp, °F	223.9°	191.1°	177.9°	165.7°	146.3°	119°
Adjusted Geothermal Outlet Temp, °F	225.2°	191.6°	178.4°	164.7°	148.1°	119.5°
Distributor Tray Efficiency	52.9%	21.6%	29.6%	12.4%	0%	0%
Preheater Tray Efficiency	55%	70%	75%	71%	70%	69%
Boiling Tray Efficiency, Plate 18	99.5%	99.6%	99.8%	0%	0%	86%
Plate 19	93%	98%	96.8%	100%	99.4%	99%
Pinch Point, Predicted, °F	0.02°	0.02°	0.02°	0.05°	0.10°	0.30°
Total Heat Load, x 10^6 Btu/hr	0.743	1.204	1.311	1.404	1.470	1.437
Preheating Heat Load, x 10^6 Btu/hr	0.434	0.601	0.608	0.611	0.520	0.304
Boiling Heat Load, x 10^6 Btu/hr	0.309	0.603	0.703	0.793	0.950	1.133
Volumetric Heat Transfer Coefficient						
Distributor Tray Btu/hr-ft^3-°F	12199	6523	9641	4225	0	0
Preheater Trays Btu/hr-ft^3-°F	4952	9109	10705	10354	10666	9670
Boiling Trays Btu/hr-ft^3-°F	29987	28992	27300	22957	19689	13690

*Flooding not reached

Prototype Power Plant

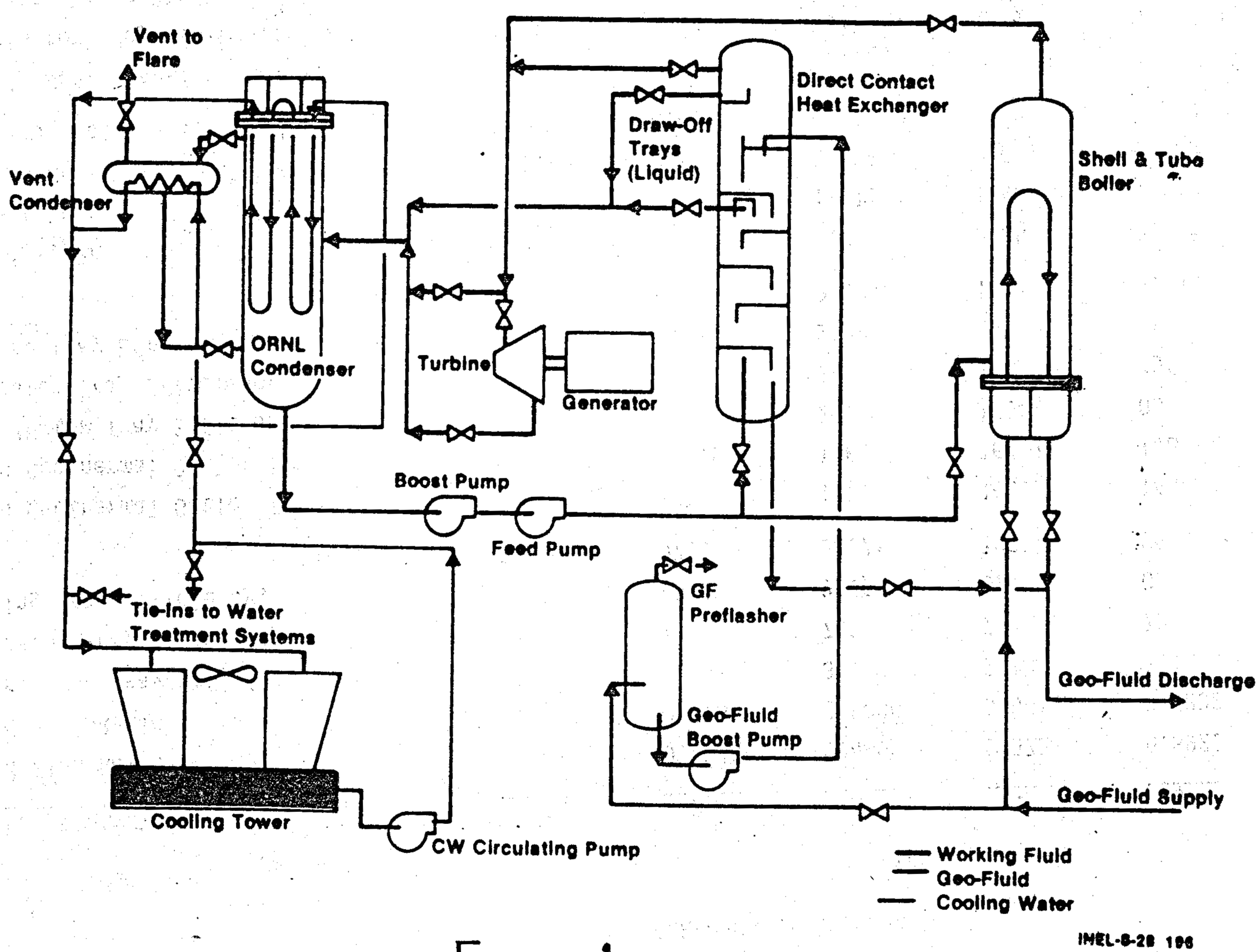


Figure 1

PROTOTYPE PLANT
DIRECT CONTACT HEAT EXCHANGER SCHEMATIC

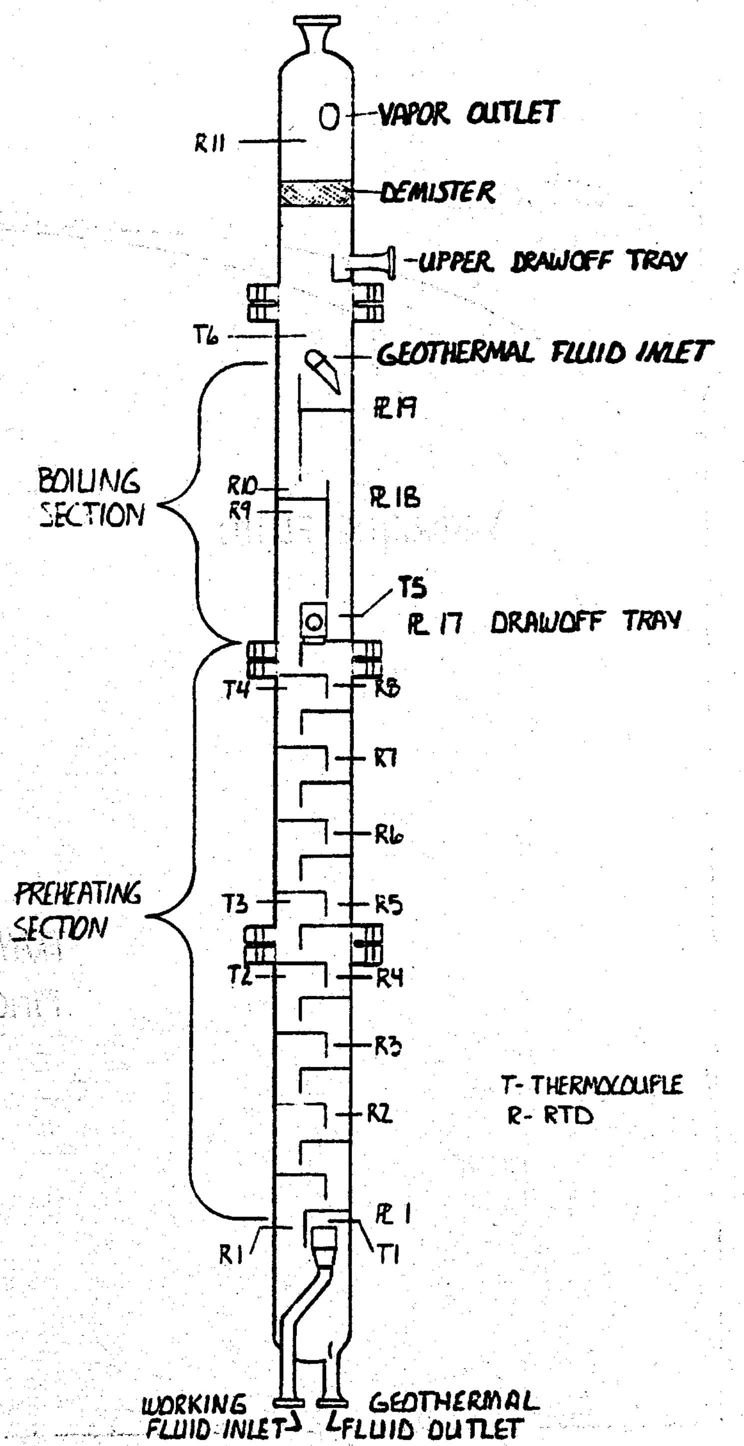


Figure 2

PREDICTED TEMPERATURE PROFILE FOR PREHEATING SECTION

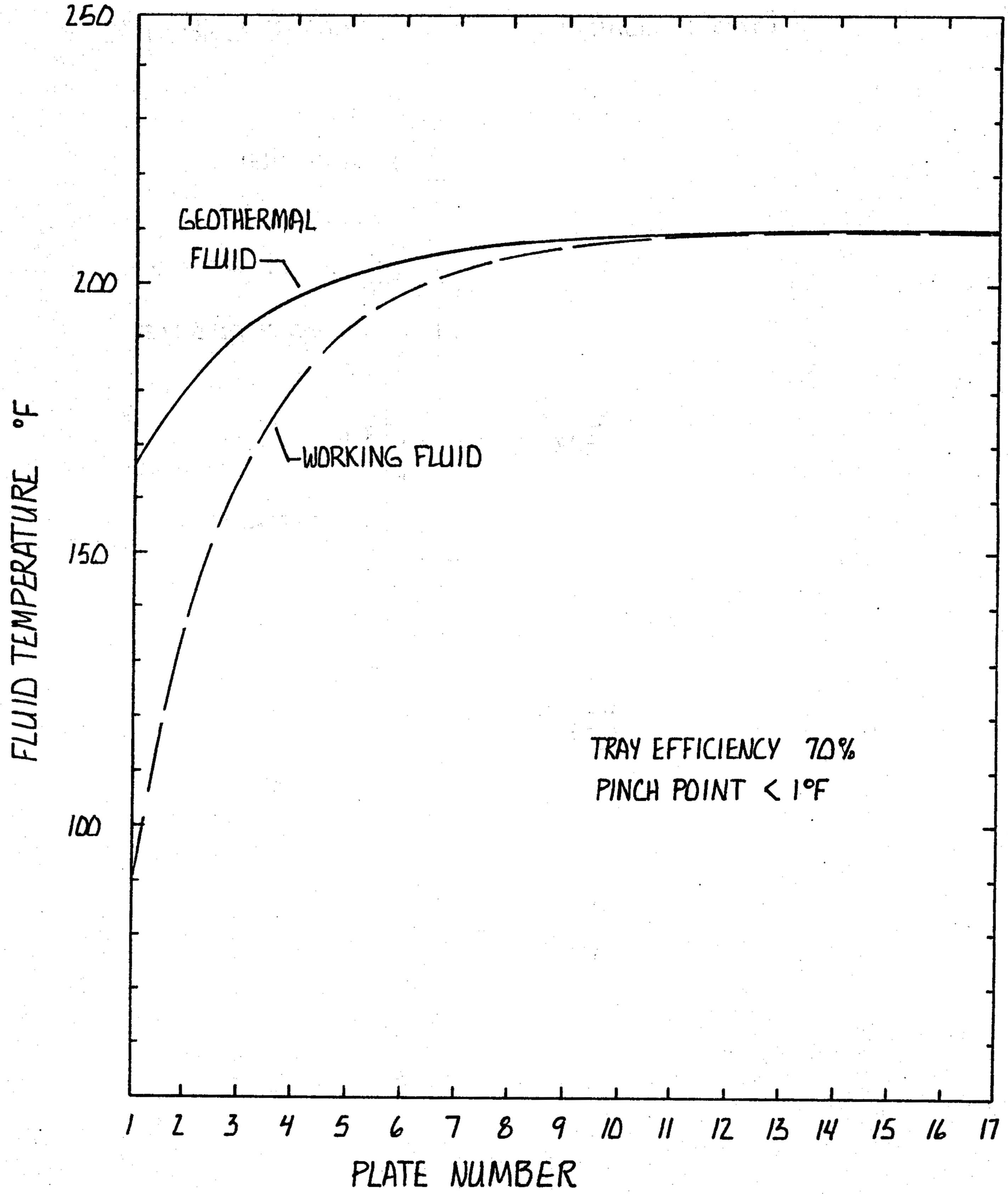


Figure 3

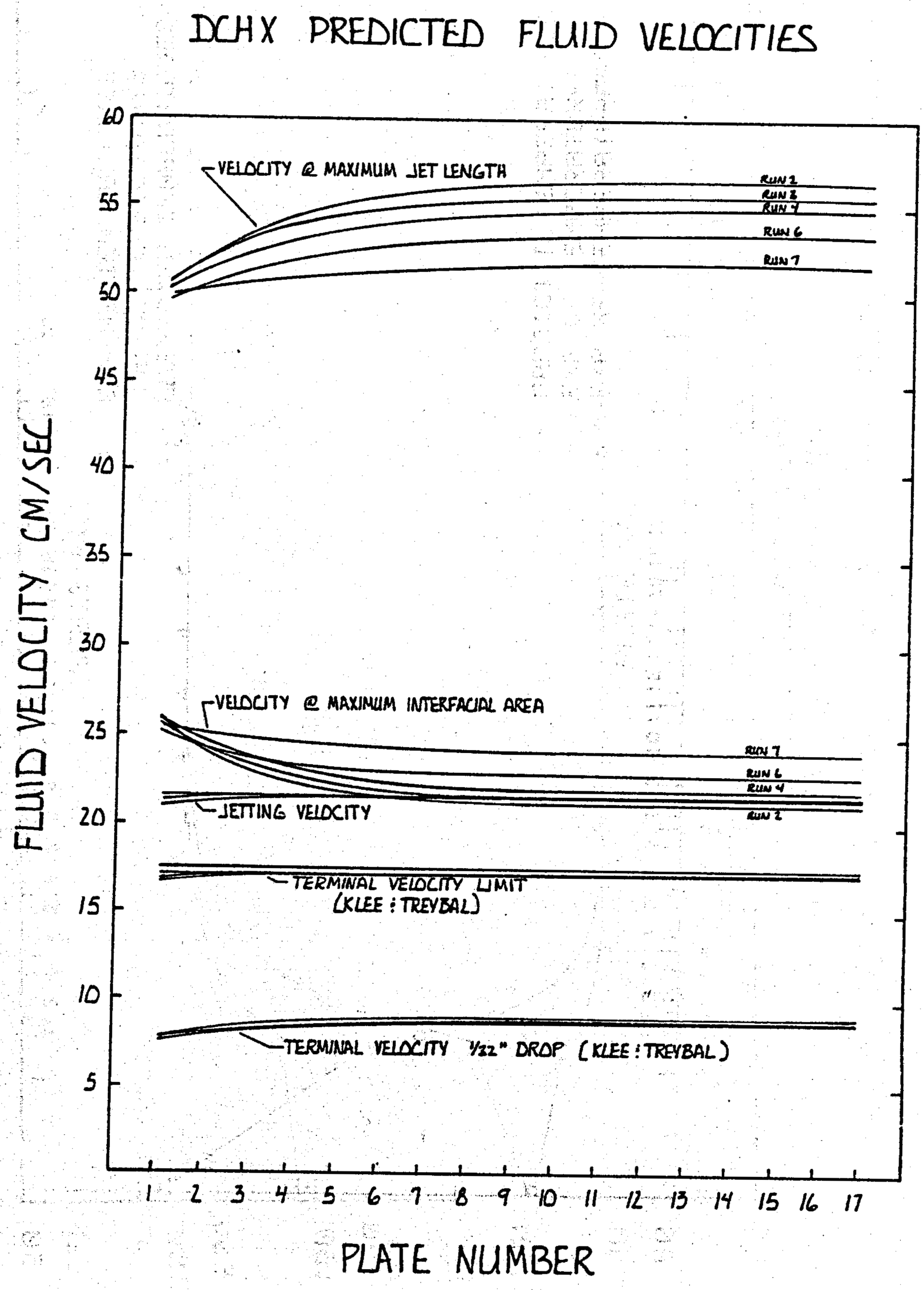

DCHX PREDICTED FLUID VELOCITIES
VELOCITY @ MAXIMUM JET LENGTH
RUN 2
RUN 3
RUN 4
RUN 6
RUN 7
VELOCITY @ MAXIMUM INTERFACIAL AREA
RUN 7
RUN 6
RUN 4
RUN 2
JETTING VELOCITY
TERMINAL VELOCITY LIMIT
(KLEE : TREYBAL)
TERMINAL VELOCITY 1/32" DROP (KLEE : TREYBAL)
FLUID VELOCITY CM/SEC
60
55
50
45
40
35
30
25
20
15
10
5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
PLATE NUMBER

Figure 4

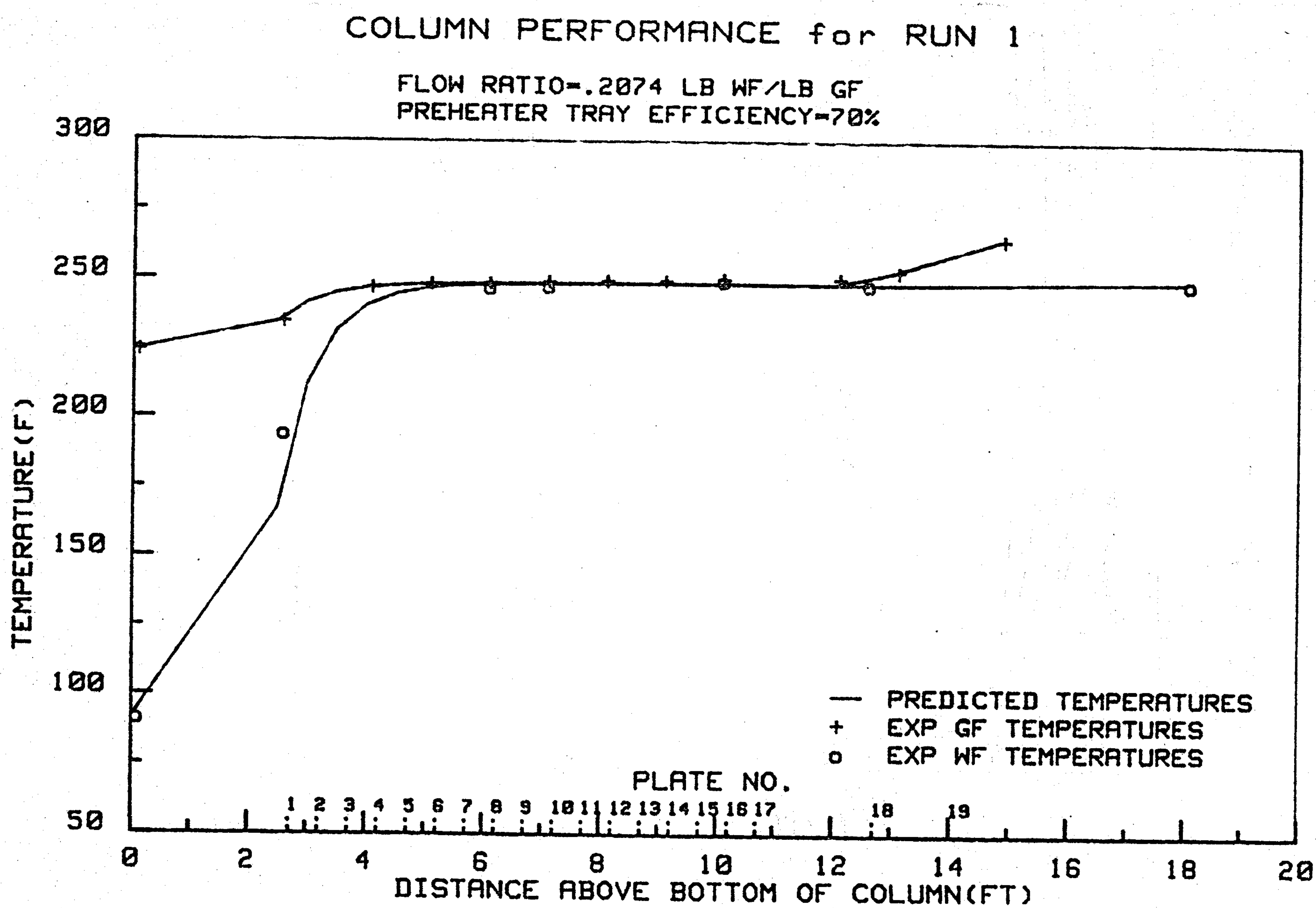

COLUMN PERFORMANCE for RUN 1
FLOW RATIO=.2074 LB WF/LB GF
PREHEATER TRAY EFFICIENCY=70%
TEMPERATURE(F)
300
250
200
150
100
50
— PREDICTED TEMPERATURES
+ EXP GF TEMPERATURES
o EXP WF TEMPERATURES
PLATE NO.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
0 2 4 6 8 10 12 14 16 18 20
DISTANCE ABOVE BOTTOM OF COLUMN(FT)

Figure 5

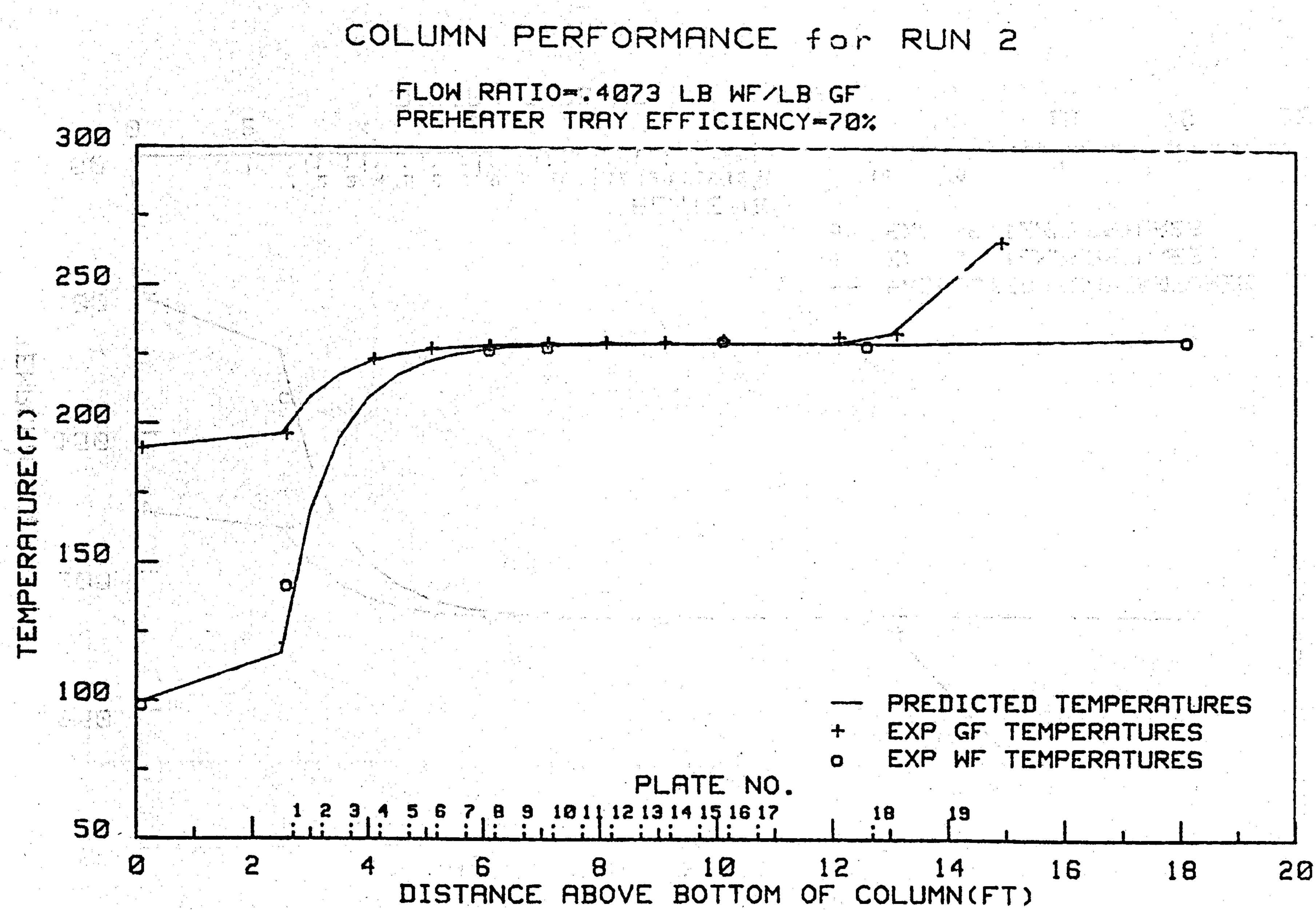

COLUMN PERFORMANCE for RUN 2
FLOW RATIO=.4073 LB WF/LB GF
PREHEATER TRAY EFFICIENCY=70%
TEMPERATURE(F)
300
250
200
150
100
50
— PREDICTED TEMPERATURES
+ EXP GF TEMPERATURES
o EXP WF TEMPERATURES
PLATE NO.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
0 2 4 6 8 10 12 14 16 18 20
DISTANCE ABOVE BOTTOM OF COLUMN(FT)

Figure 6

COLUMN PERFORMANCE for RUN 3

FLOW RATIO=.4906 LB WF/LB GF
PREHEATER TRAY EFFICIENCY=70%

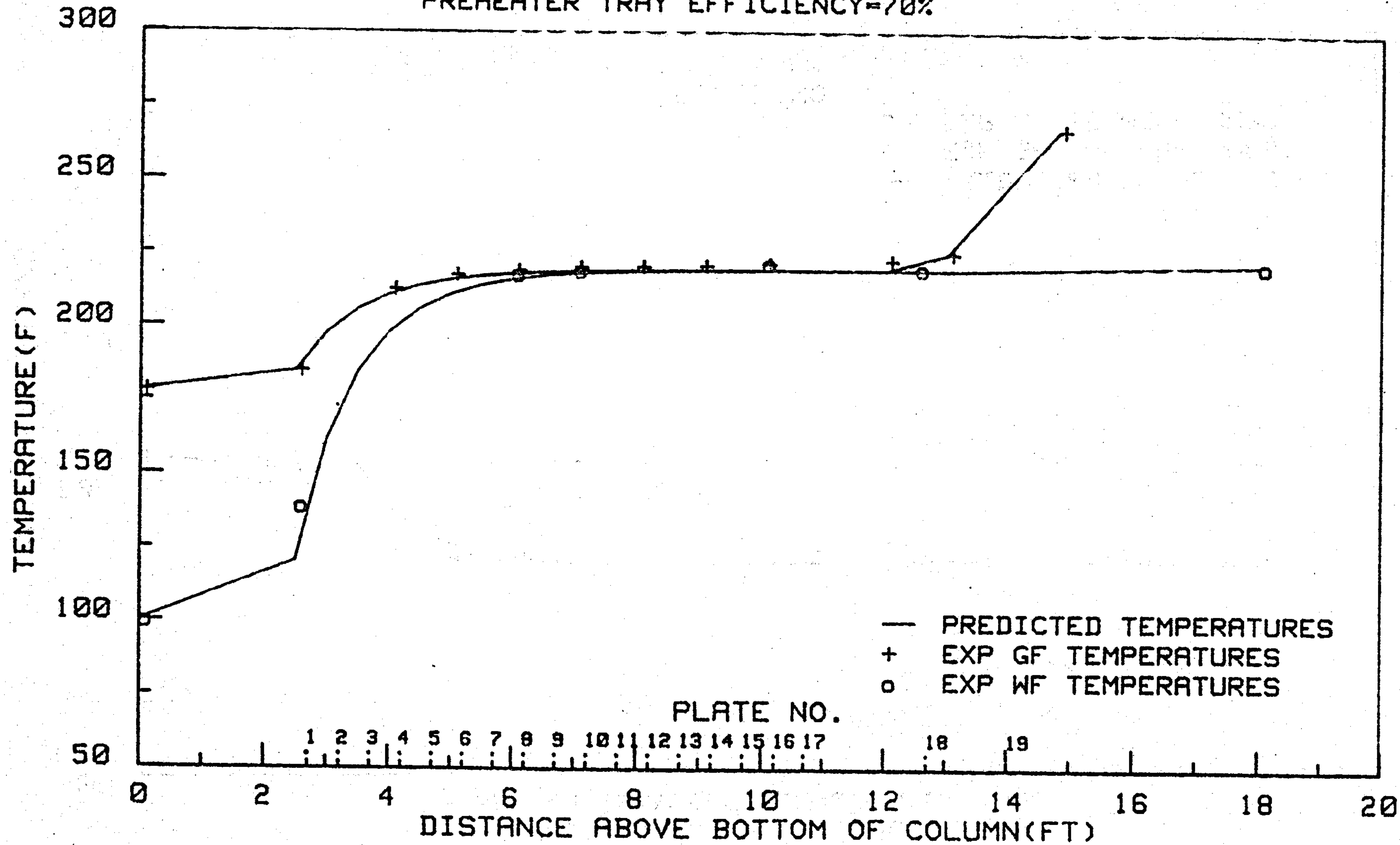


Figure 7

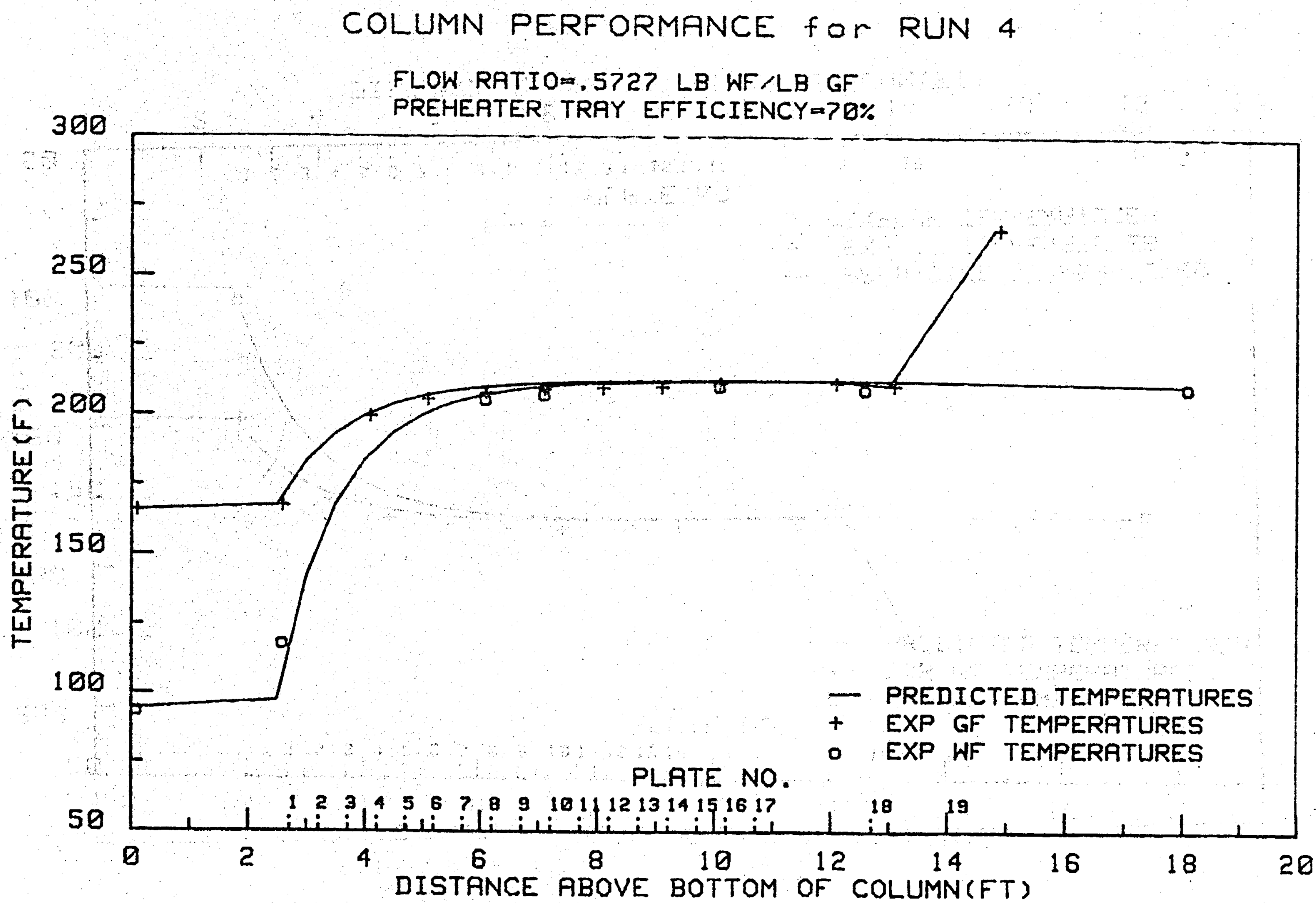

COLUMN PERFORMANCE for RUN 4
FLOW RATIO=.5727 LB WF/LB GF
PREHEATER TRAY EFFICIENCY=70%
TEMPERATURE(F)
300
250
200
150
100
50
DISTANCE ABOVE BOTTOM OF COLUMN(FT)
0
2
4
6
8
10
12
14
16
18
20
PLATE NO.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
PREDICTED TEMPERATURES
+ EXP GF TEMPERATURES
o EXP WF TEMPERATURES

Figure 8

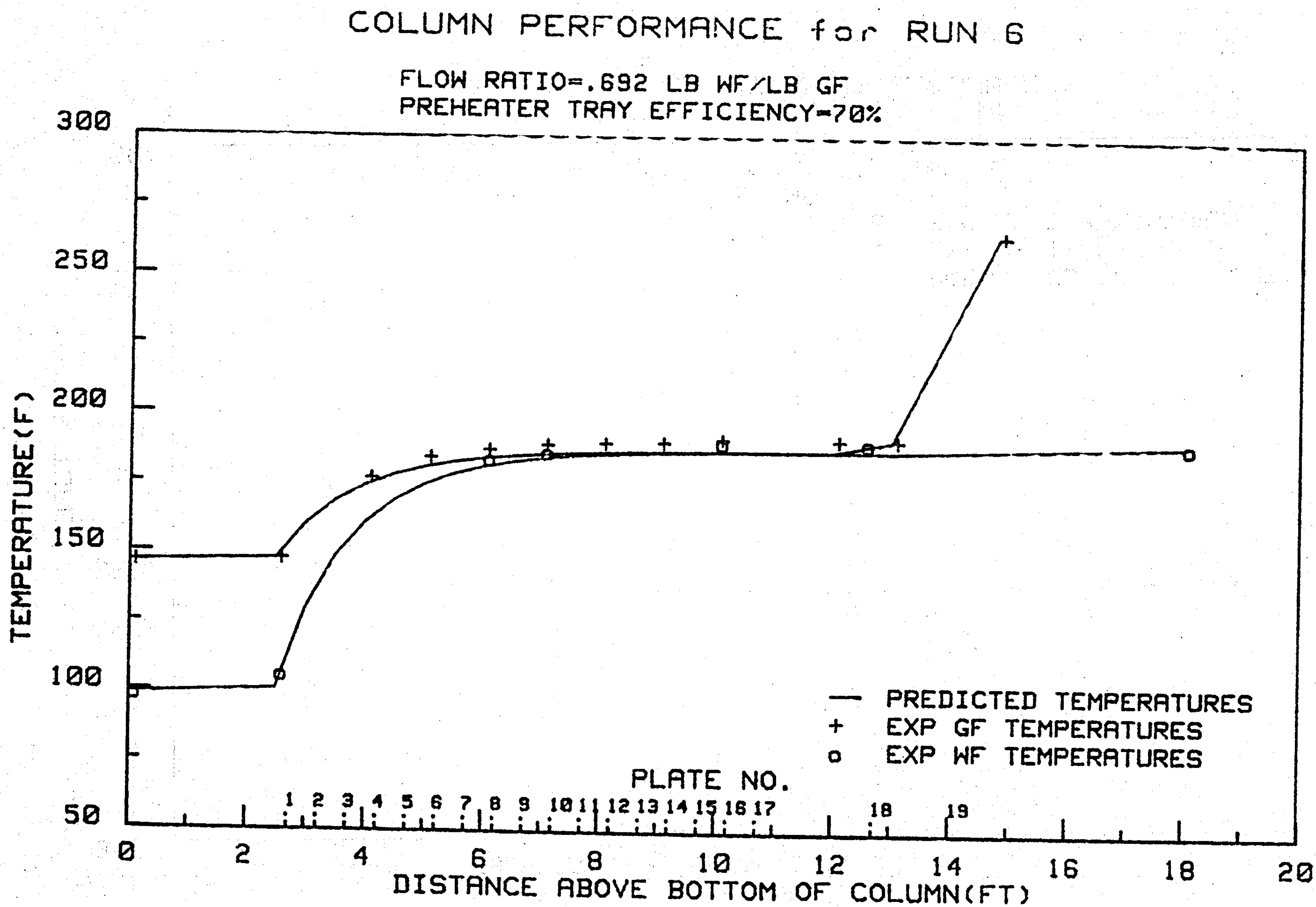

COLUMN PERFORMANCE for RUN 6
FLOW RATIO=.692 LB WF/LB GF
PREHEATER TRAY EFFICIENCY=70%
TEMPERATURE(F)
300
250
200
150
100
50
PREDICTED TEMPERATURES
EXP GF TEMPERATURES
EXP WF TEMPERATURES
PLATE NO.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
0 2 4 6 8 10 12 14 16 18 20
DISTANCE ABOVE BOTTOM OF COLUMN(FT)

Figure 9

COLUMN PERFORMANCE for RUN 7

FLOW RATIO=.9273 LB WF/LB GF
PREHEATER TRAY EFFICIENCY=70%

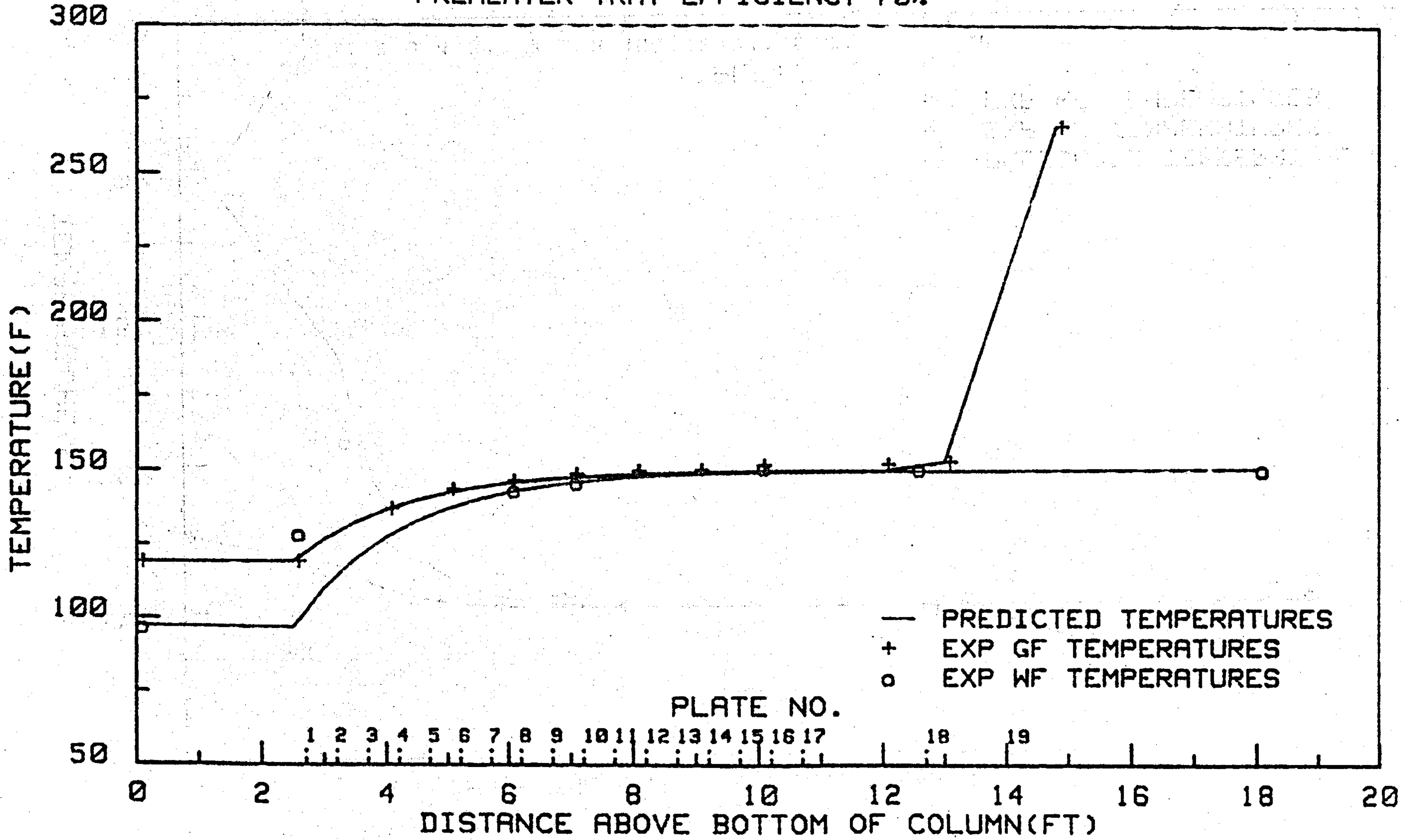


Figure 10

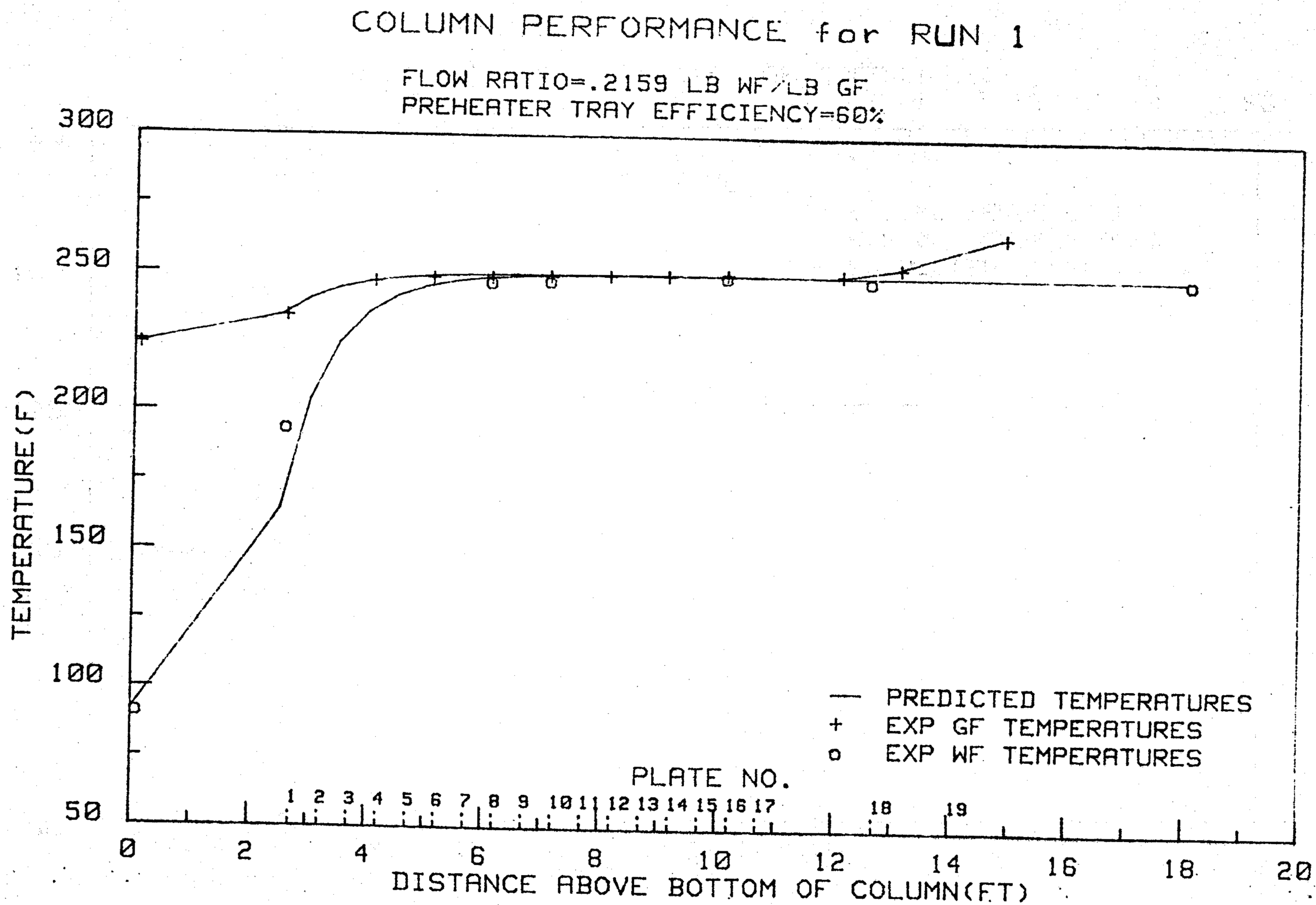

COLUMN PERFORMANCE for RUN 1
FLOW RATIO=.2159 LB WF/LB GF
PREHEATER TRAY EFFICIENCY=60%
TEMPERATURE(F)
300
250
200
150
100
50
PREDICTED TEMPERATURES
EXP GF TEMPERATURES
EXP WF TEMPERATURES
PLATE NO.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
0 2 4 6 8 10 12 14 16 18 20
DISTANCE ABOVE BOTTOM OF COLUMN(FT)

Figure 11

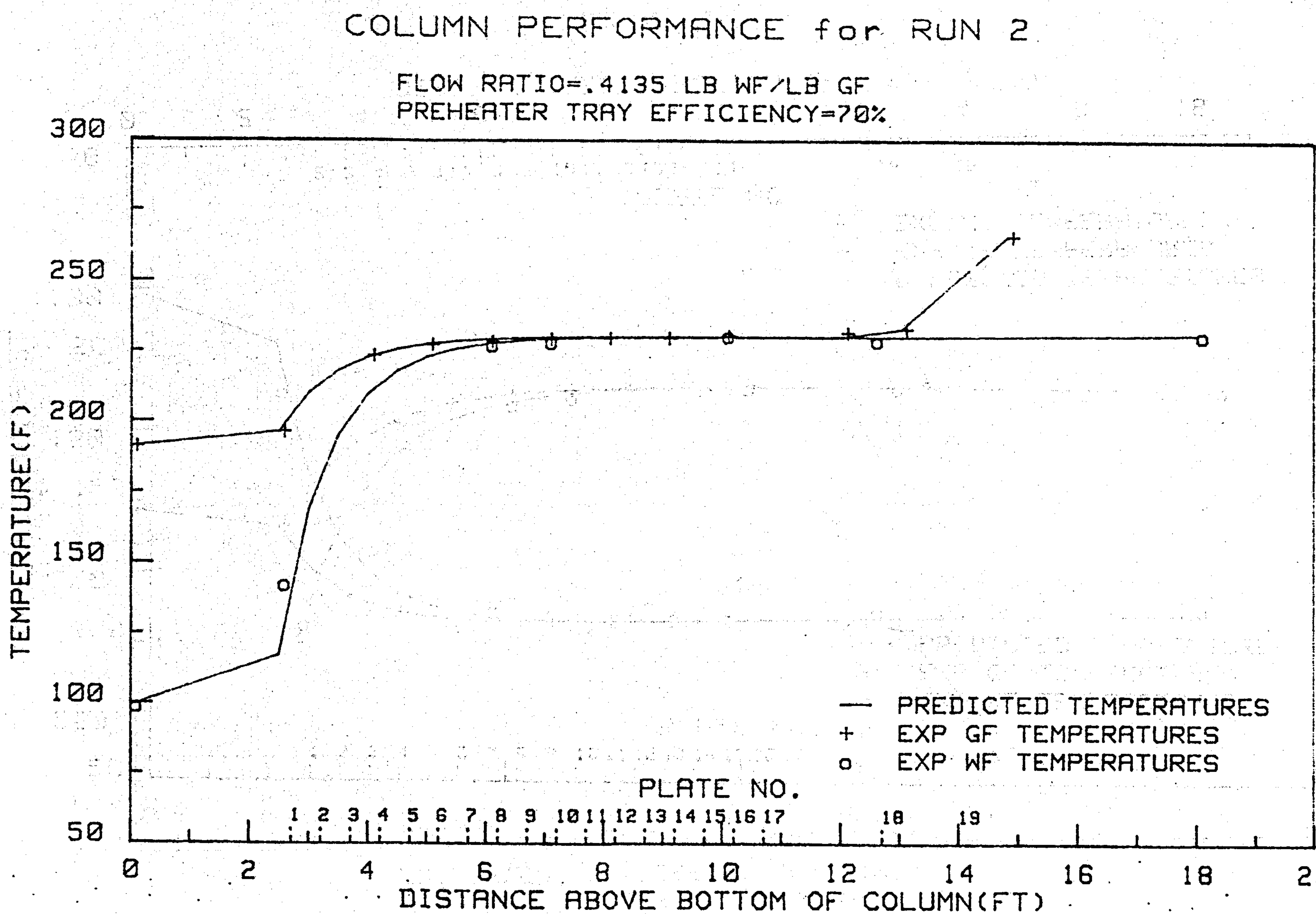

COLUMN PERFORMANCE for RUN 2
FLOW RATIO=.4135 LB WF/LB GF
PREHEATER TRAY EFFICIENCY=70%
TEMPERATURE(F)
300
250
200
150
100
50
PREDICTED TEMPERATURES
+ EXP GF TEMPERATURES
o EXP WF TEMPERATURES
PLATE NO.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
0 2 4 6 8 10 12 14 16 18 20
DISTANCE ABOVE BOTTOM OF COLUMN(FT)

Figure 12

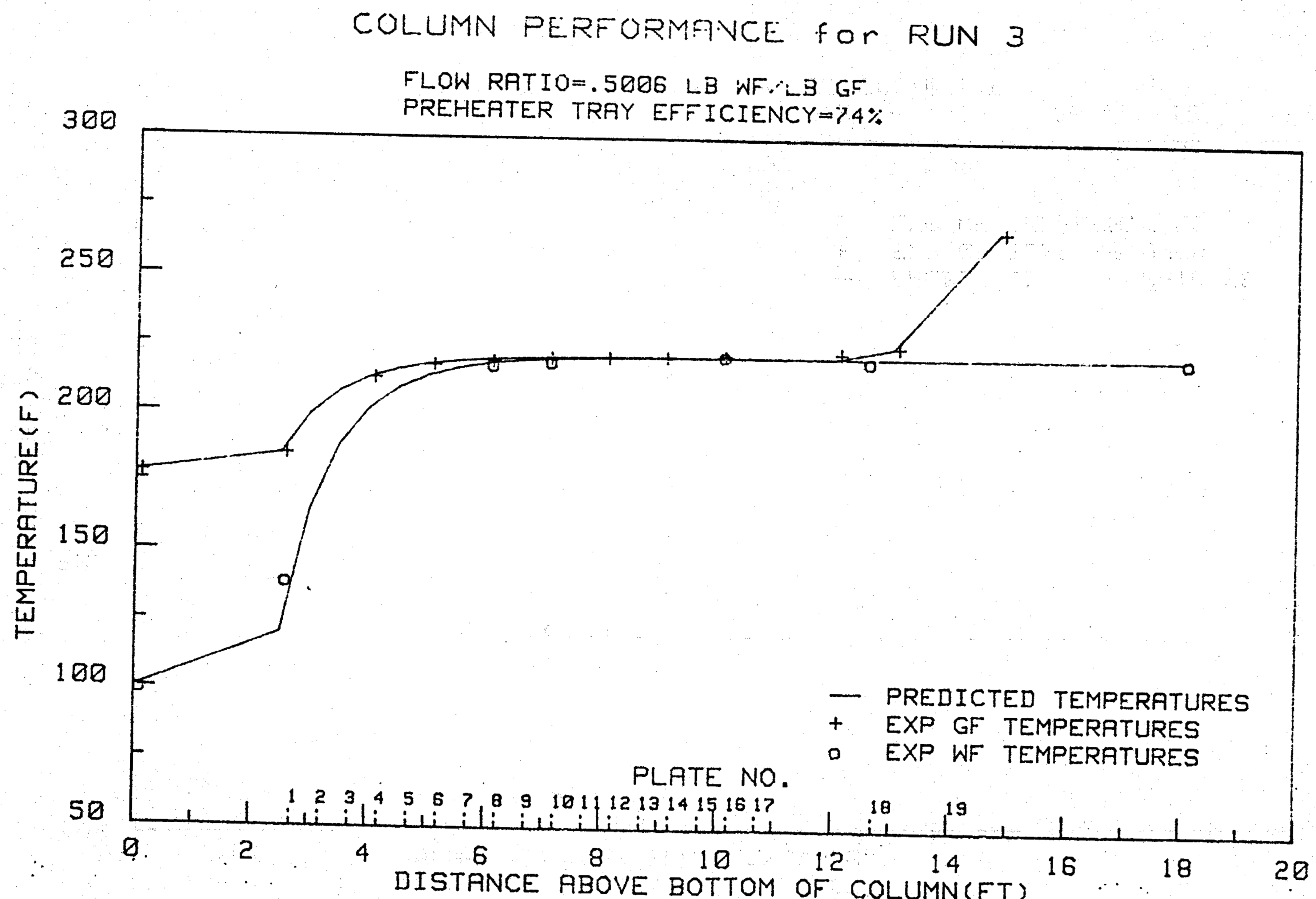

COLUMN PERFORMANCE for RUN 3
FLOW RATIO=.5006 LB WF/LB GF
PREHEATER TRAY EFFICIENCY=74%
TEMPERATURE(F)
300
250
200
150
100
50
PREDICTED TEMPERATURES
+ EXP GF TEMPERATURES
o EXP WF TEMPERATURES
PLATE NO.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
18
19
0. 2 4 6 8 10 12 14 16 18 20
DISTANCE ABOVE BOTTOM OF COLUMN(FT)

Figure 13

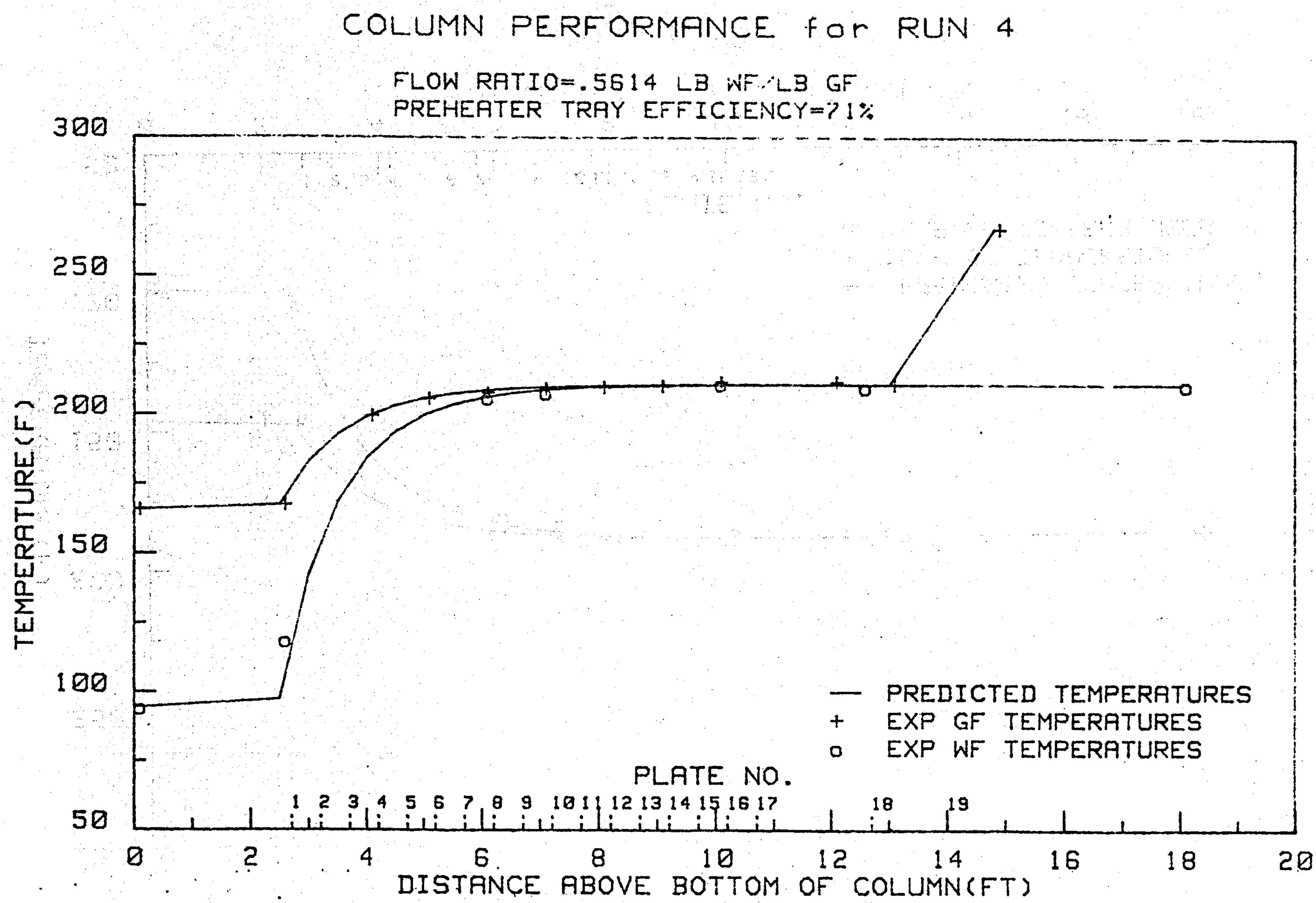

COLUMN PERFORMANCE for RUN 4
FLOW RATIO=.5614 LB WF/LB GF
PREHEATER TRAY EFFICIENCY=71%
TEMPERATURE(F)
300
250
200
150
100
50
PREDICTED TEMPERATURES
EXP GF TEMPERATURES
EXP WF TEMPERATURES
PLATE NO.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
0 2 4 6 8 10 12 14 16 18 20
DISTANCE ABOVE BOTTOM OF COLUMN(FT)

Figure 14

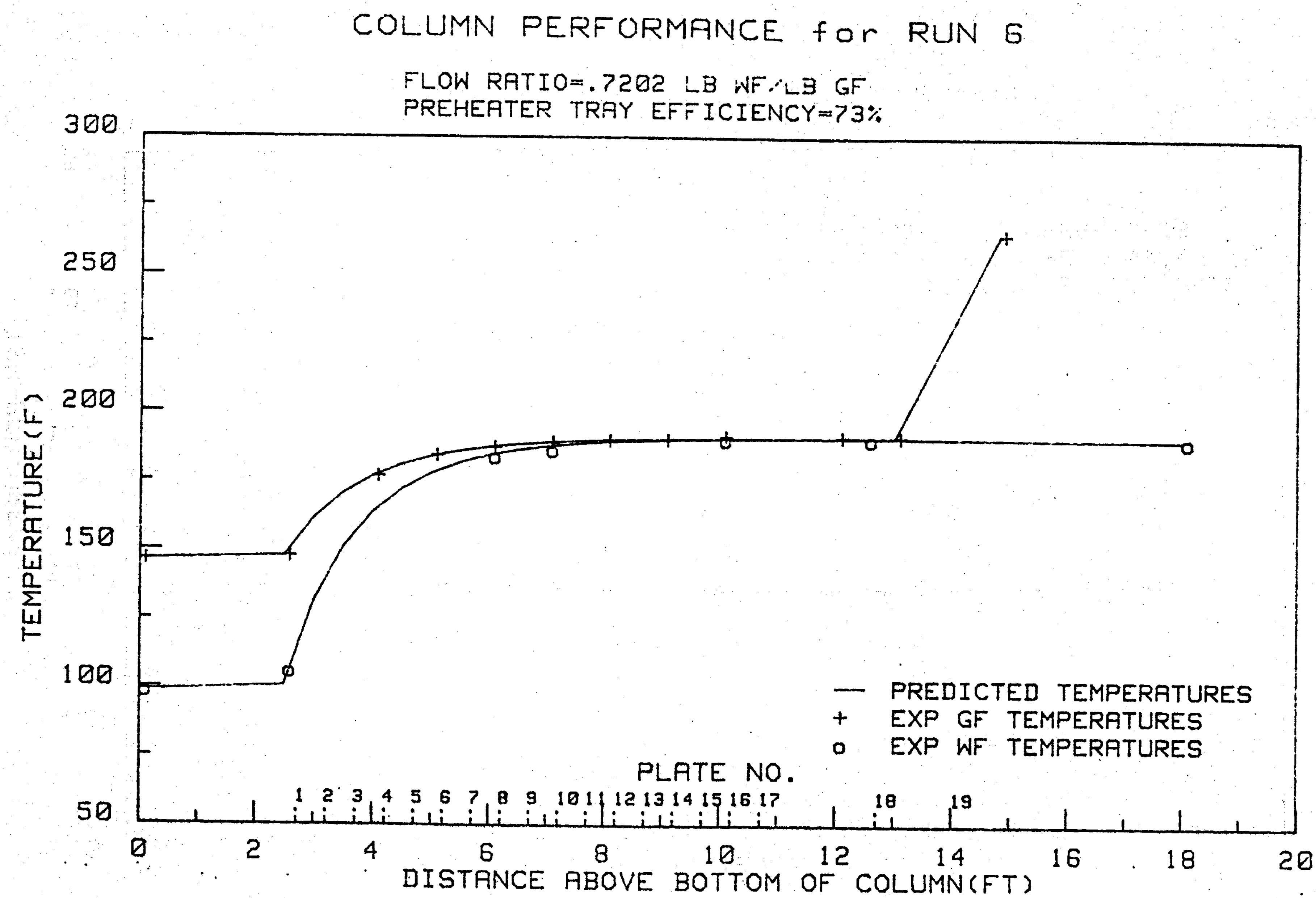

COLUMN PERFORMANCE for RUN 6
FLOW RATIO=.7202 LB WF/LB GF
PREHEATER TRAY EFFICIENCY=73%
TEMPERATURE(F)
DISTANCE ABOVE BOTTOM OF COLUMN(FT)
PLATE NO.
PREDICTED TEMPERATURES
EXP GF TEMPERATURES
EXP WF TEMPERATURES

Figure 15

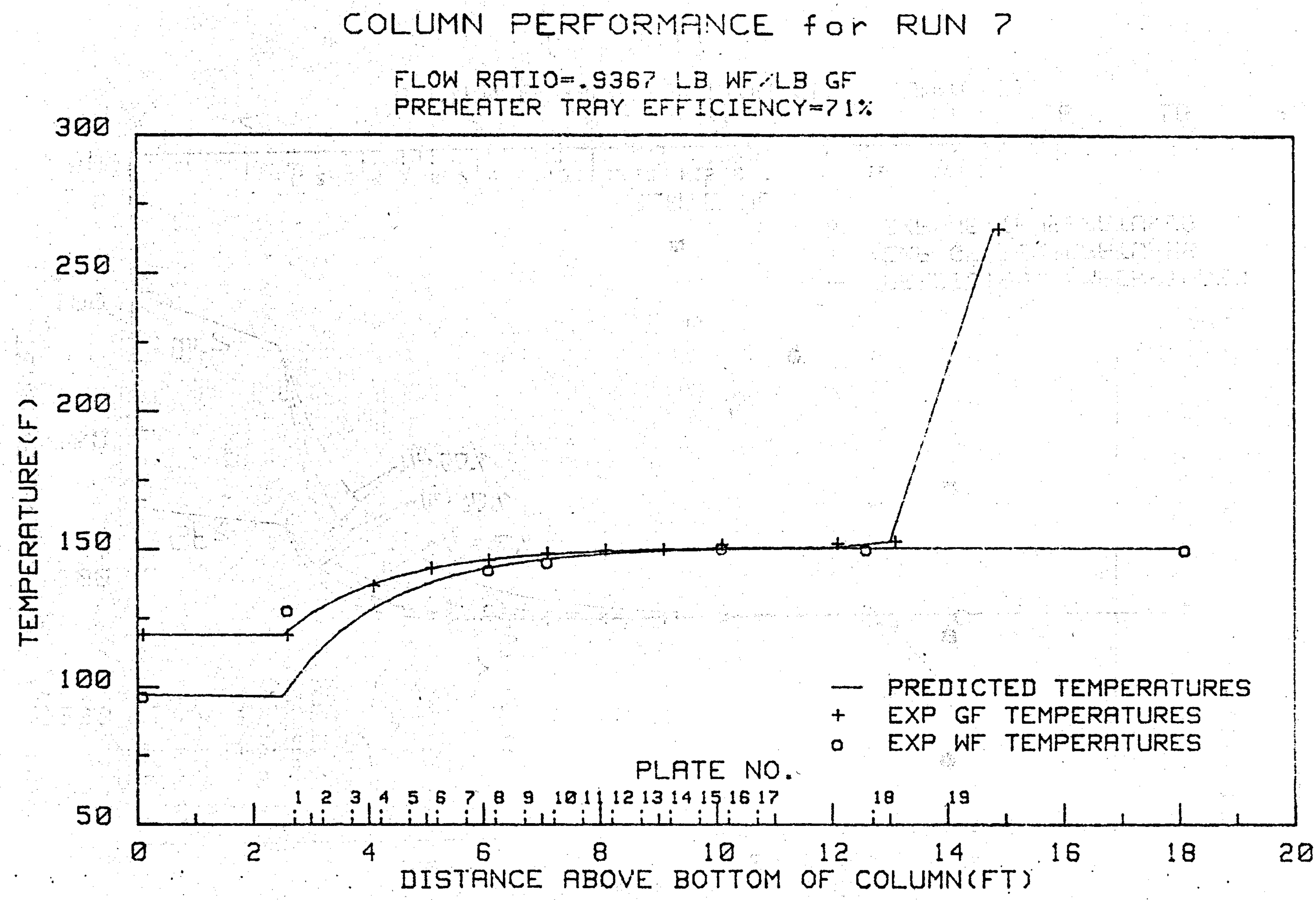
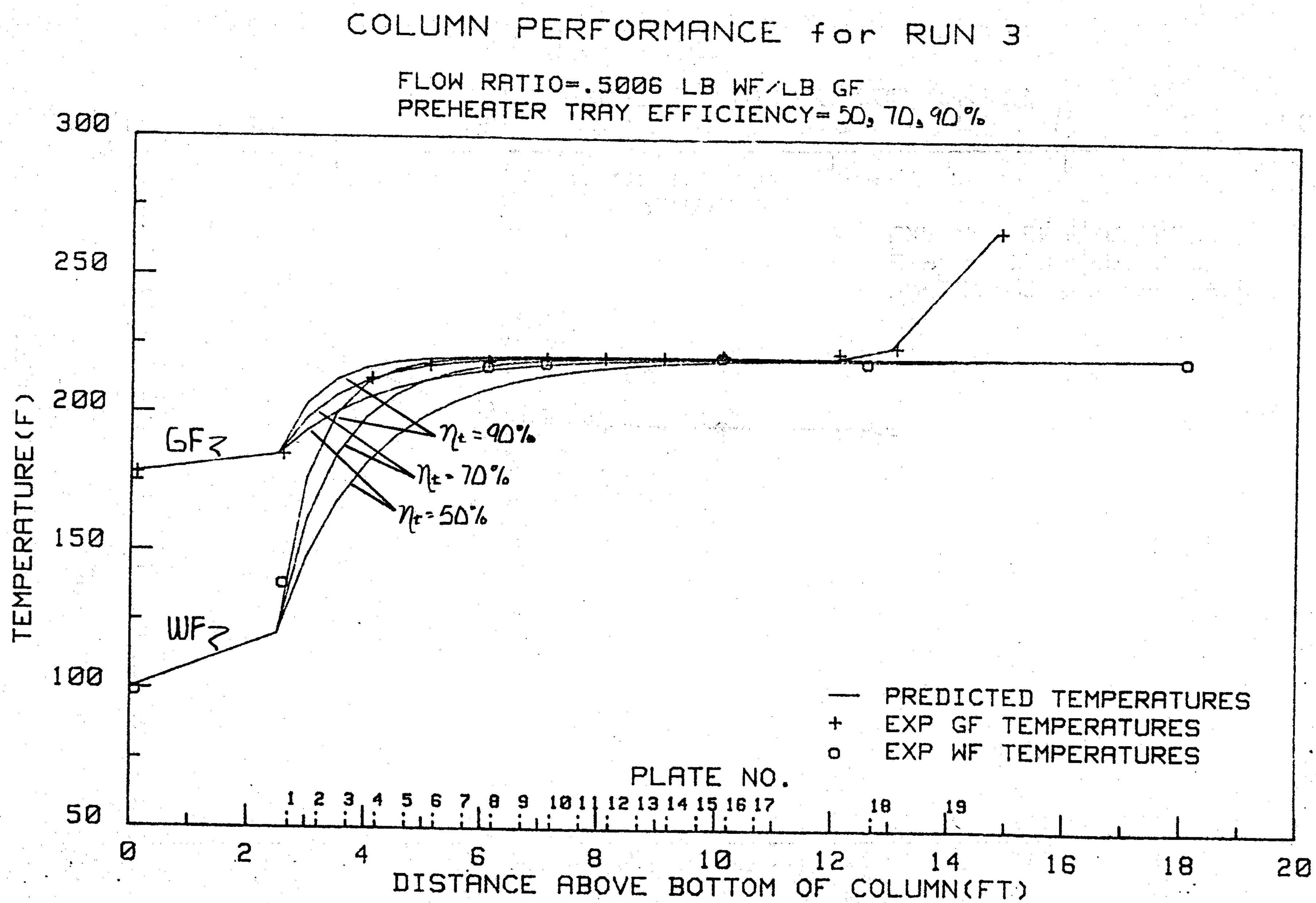

COLUMN PERFORMANCE for RUN 7
FLOW RATIO=.9367 LB WF/LB GF
PREHEATER TRAY EFFICIENCY=71%
TEMPERATURE(F)
300
250
200
150
100
50
PREDICTED TEMPERATURES
+ EXP GF TEMPERATURES
o EXP WF TEMPERATURES
PLATE NO.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
0 2 4 6 8 10 12 14 16 18 20
DISTANCE ABOVE BOTTOM OF COLUMN(FT)

Figure 16



COLUMN PERFORMANCE for RUN 3
FLOW RATIO=.5006 LB WF/LB GF
PREHEATER TRAY EFFICIENCY= 50, 70, 90 %
TEMPERATURE(F)
300
250
200
150
100
50
GF
WF
η_t = 90%
η_t = 70%
η_t = 50%
— PREDICTED TEMPERATURES
+ EXP GF TEMPERATURES
o EXP WF TEMPERATURES
PLATE NO.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
18
19
0 2 4 6 8 10 12 14 16 18 20
DISTANCE ABOVE BOTTOM OF COLUMN(FT)

Figure 17

COMPARISON OF PREDICTED AND NEAR FLOODING FLUID VELOCITIES

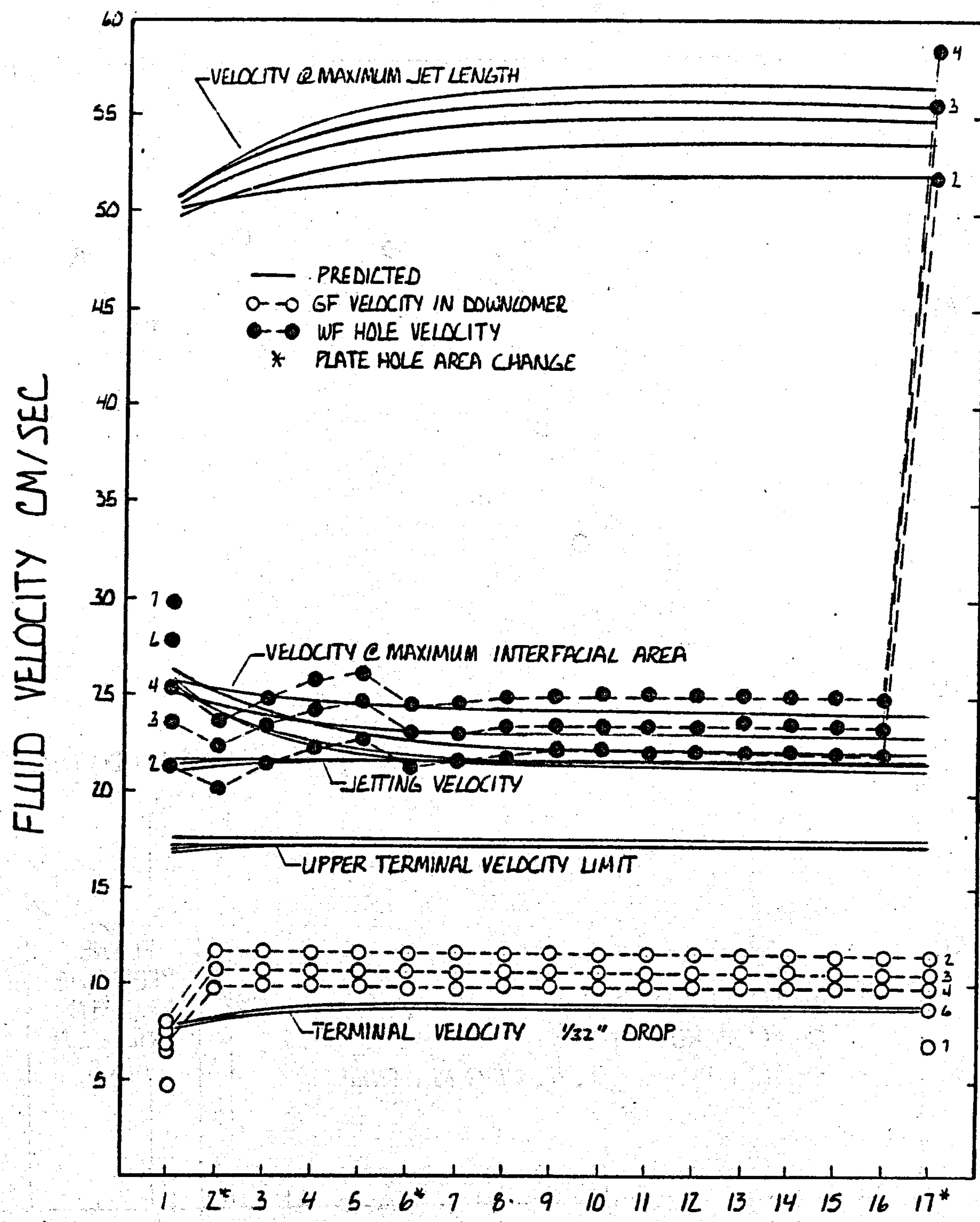


Figure 18

VARIATION IN DCHX PREHEATER TRAY EFFICIENCY WITH WORKING FLUID FLOW

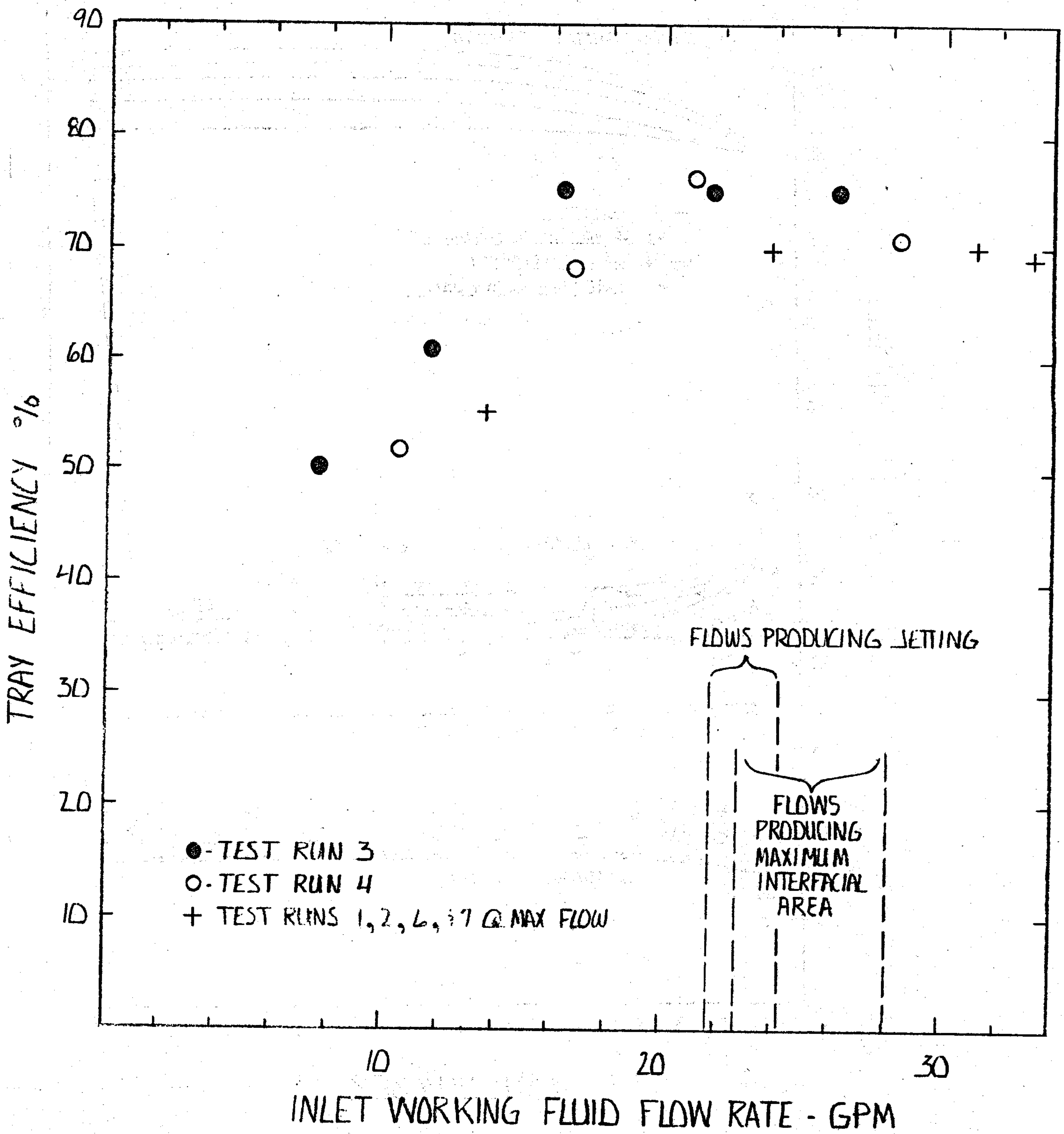


Figure 19

DCHX THROUGHPUT COMPARISON

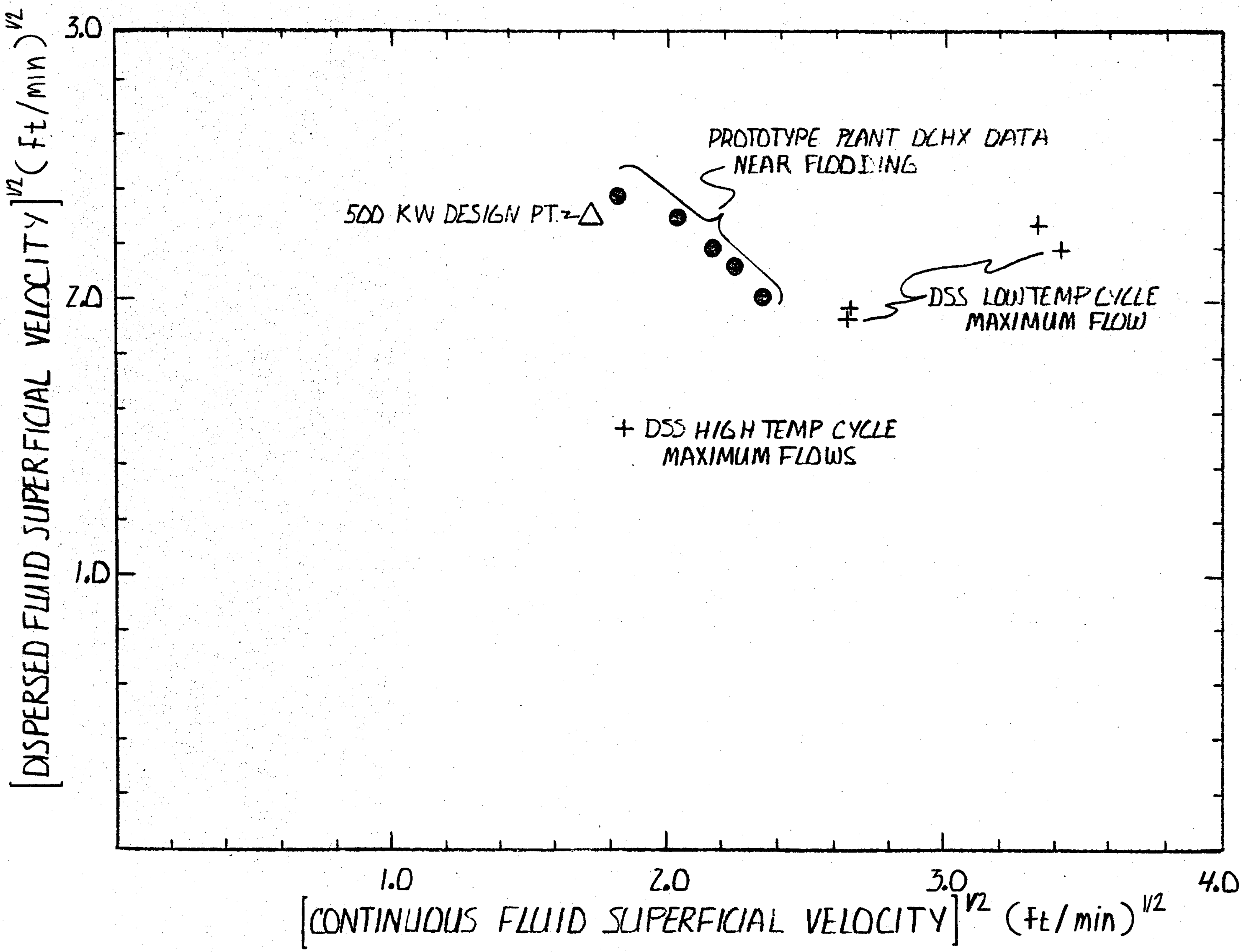


Figure 20