Atmospheric Bubbling Fluidized Bed Combustion and The PEPSE® Code

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INTRODUCTION TO FLUIDIZATION

"Fluidization is the operation by which fine solids are transformed into a fluidlike state through contact with a gas or liquid"[1]. If one starts with a bed of sand particles of similar size and introduces air at the bottom, the air will percolate upward through the fixed bed of material. This is known as a "Fixed Bed"(see Figure 1). As the velocity of the air is increased, the bed will reach a gas velocity known as the "Minimum Fluidization Velocity". At this point, the particles are just suspended in the gas flow, and very little particle movement is observed. As the gas velocity is increased beyond the minimum fluidization velocity, bubbles or pockets of air begin to form. This is known as a "Bubbling Bed". As the gas velocity is further increased, the bubbling becomes more violent, and the particles will be carried out of the dense phase of the bed by pneumatic transport. This velocity is approaching the terminal velocity of the particles, and the condition is referred to as a "Circulating Fluidized Bed".

Pressure drop across the bed is linear as flow is increased through the fixed bed(see Figure 2). The bubbling regime displays an essentially constant pressure drop until the terminal velocity is reached. At this point, the fluidized bed ceases to be.

COMBUSTION IN FLUIDIZED BEDS

In a fluidized bed, conditions are ideal for combustion. The three T'^{s} of combustion (time, temperature, and turbulence) are satisfied, once the temperature of the bed is raised sufficiently. As the fuel is burned, the temperature of the bed increases, and would continue to increase if some heat were not removed. So, bundles of heat exchange surface are added within the dense phase of the bed. This allows the temperature of the bed to be maintained, and prevent the ash from becoming molten. The bed material quality and condition must be maintained by draining and adding new bed material.

Only a portion of the combustion occurs within the bed itself. The rest of the combustion occurs in the zone above the bed called the "Freeboard".

ADVANTAGES OF FLUIDIZED BED COMBUSTION

Fluidized bed combustion offers several advantages over other methods of combustion. First, the bed material may consist of limestone or other calcium containing material. The calcium is usually present in the form of calcium carbonate ($CaCO_3$). At these temperatures, the calcium carbonate calcines forming calcium oxide and carbon dioxide:

$$CaCO_3 \quad \overset{\substack{\text{Heat}\\ \nearrow}}{-\!-\!>} \quad CaO \quad + \quad CO_2$$

which is an endothermic reaction. The calcium oxide is then free to react with any sulfur dioxide and oxygen present to form calcium sulfate:

$$CaO \quad + \quad SO_2 \quad + \quad \tfrac{1}{2}\, O_2 \quad \overset{\substack{\text{Heat}\\ \swarrow}}{-\!-\!>} \quad CaSO_4 \; .$$

This reaction is exothermic. Sulfur capture on the order of 90% can be achieved. The net result, with respect to energy, must be evaluated on a "case by case" basis.

Second, combustion normally occurs at approximately 1500 - 1600 °F. In this temperature range the formation of oxides of nitrogen are greatly reduced.

Also, heat transfer is greatly enhanced. The outside film coefficient of heat transfer can be 4 to 5 times the normal heat transfer coefficient for a convection pass tube bundle. However, this coefficient is very difficult to determine accurately, so empirical correlations are best to use.

DISADVANTAGES OF FLUIDIZED BED COMBUSTION

Fluidized Bed Combustion does have some minor disadvantages. First, the pressure drop across the bed can be quite high(80 to 100 inches of H_2O). This requires more fan horsepower and increases station power.

Second, fouling within the bed heat exchange surface can be very difficult and time consuming to remove. With operator experience, this condition can be minimized.

MONTANA-DAKOTA UTILITIES HESKETT STATION, UNIT 2

Montana-Dakota Utilities Heskett Station, Unit 1, used a Riley Spreader Stoker boiler for steam generation. It was rated at 25 mW, but was capable of producing up to 27 mW if necessary. Since its construction in 1953, it proved to be a very dependable and reliable unit with very few problems. Because of its exceptional performance, it was decided to build Unit 2 based on the same basic design configuration, only larger. Its capacity was 75 mW.

Unit 2 was one of the largest spreader stoker boilers ever built. It had 10 spreader stokers. Since its construction, it had been plagued with boiler fouling and slagging problems. This had caused many deratings and unscheduled shutdowns to clean the boiler surfaces. This was very costly because most of the lost electric generation had to be purchased from other utilities.

FBC RETROFIT

In 1986, Babcock and Wilcox began the retrofit project to convert Unit 2 to an AFBC boiler. This type of combustion offered many advantages over other conventional methods. It would keep the flue gas temperatures down to approximately 1500°F, thereby reducing the slagging problem; unit capacity would be increased to

700,000 lbs/hr (80 mW); future environmental regulations would be more easily met; and boiler efficiency would be increased.

As much of the existing boiler was used as possible. The following items were added or replaced:

1) A modular bed with water cooled walls and floor. The in-bed surface was approximately 2/3 steam generation, and 1/3 superheat surface.

2) A new, larger forced draft fan to meet the increased capacity and pressure requirements that the fluidized bed required.

3) A new tubular air heater to replace the old Lungstrom air heater, as the old air heater would have too much leakage due to the increased pressure on the air side.

4) Three boiler circulating pumps to force the circulation through the in bed boiling surface.

5) A sand system to dry and feed the bed material to the bed (by design, the bed used river sand, not limestone as the bed material).

6) An ash system to remove and cool the bed material that must be removed from the bed.

7) A Bailey Net 90 computer system for boiler control and data acquisition.

OPERATIONAL HISTORY

The retrofit boiler was first fired with coal on April 16, 1987. The first generation occurred on May 12. The unit was on line for only 9 minutes because some of the in-bed thermocouples were erroneously reading high. The unit was again put on line on May 15 and ran for 5 days at loads up to 65 mW. Figure 3 shows unit availability history.

DEVELOPMENT OF NEW PEPSE SUBROUTINES

While attending one of the PEPSE training courses, I spoke with Energy Incorporated about how one would model a boiler such as this. It soon became obvious that it would be very difficult with the existing available components. Shortly after this, an agreement was made between Energy Incorporated and Montana-Dakota Utilities to develop 2 subroutines for new PEPSE components: a bubbling bed combustor, and a heat exchanger to go in it.

THE FLUIDIZED BED COMBUSTOR COMPONENT (TYPE 71)

The type 71 combustor component operates very much like the type 70. One of the major differences is in the combustion calculations, as described previously. Since the sorbent is not inert, some major decisions needed to be made concerning how it is to be treated within PEPSE. It was determined that the sorbent would be input as ash. Sufficient information would be input with the combustor for PEPSE to convert some of the ash to CO_2 and remove some of the SO_2 from the flue gas. This then is added to the bed drain ash to maintain a mass balance.

Another major difference is in the energy balance. Since the sorbent reactions also consume and release energy, this must also be accounted for. The loss due to calcination of the sorbent is[2]:

$$L_{CAL} = \{(Ca - \frac{40.08}{44.01} * \Sigma \frac{W_{d'p'ei} * CO_{xRi}}{W_L}) * 1913 + Mg * 2262\} * W_L / W_{fe}$$

Now this tampering with energy is very hazardous to second law calculations. Therefore, the second law output is meaningless.

The next energy difference is the credit supplied by sulfation. The credit supplied by sulfation is:

$$B_S = 6733 * \frac{ks}{100} * S$$

So one can see how the energy is very dependant on the amount of calcination and sulfation that actually occurs.

THE FLUIDIZED BED HEAT EXCHANGER COMPONENT (TYPE 24)

The type 24 heat exchanger is very similar to the type 29. This heat exchanger is responsible for removing energy from the combustor. At the present time, performance mode operation is the only mode of operation available. However, I will briefly cover the theory behind its design mode. The most difficult portion of the calculations involves the calculation of the outside coefficient of heat transfer.

This coefficient is a function of many variables. These are:

1) Bed depth
2) Temperature of the bed
3) Density of the bed material
4) Particle size of the bed material
5) Gas velocity within the tube bundles

and much more. The method used is one developed by Divillio[3]. This method was developed from operating data from the EPRI 6X6 test facility in Alliance, Ohio, the TVA-EPRI 20 mW pilot plant in Paducah, Kentucky, and cold modeling work performed by MIT. It has also been tested on the Heskett Station, Unit 2 satisfactorily[4].

PEPSE COMPONENT INPUTS

Some of the performance mode inputs for these routines are very similar to their counterparts (Type 70 and 29). In fact, the performance mode inputs for the type 24 heat exchanger are identical to the type 29:

1-I	CTYPE	= 24
2-I	NMODHX	Calculational Mode Flag. = 1, Design mode. = 2, Performance mode. At the present time, performance mode is the only mode available.
3-I	RESIDE	User identification number of the fluid bed combustor component within which this heat exchanger component resides.
4-R	TTTORH	Measured tube side outlet temperature, °F (°C). Alternate meaning: quality,-, when the input value is less than 10.0

MIN. DATA

5-R	PDHXTU	The constant A in Equation (7-1) for the tube side pressure drop description.
6-R	PDHXT2	The constant B in Equation (7-1) for the tube side pressure drop description.
7-R	PDHXT3	The constant C in Equation (7-1) for the tube side pressure drop description.
8-R	ZTIN	Elevation of tube side inlet port, feet (m).
9-R	ZTOUT	Elevation of tube side outlet port, feet (m).
10-R	PPTORH	Measured tube side outlet pressure, psia (kPa).

The inputs for the type 71 FBD combustor are not identical:

1-I	CTYPE	= 71
2-I	IDXAIR	= Identification number of the demand supplier. This may be a demand splitter or infinite source which supplies the combustion air to the fluid bed combustor. If zero, the fluid bed combustor uses whatever flow is supplied at the air inlet (IA) port.
3-R	ROSUBS	Density of bed material, lbm/ft^3 (kg/m^3).
4-R	DSUBP	Mean particle size of bed material, in. (mm).
5-R	EXAIR	Fraction of excess air for combustion,-. EXAIR must be greater than or equal to zero. A typical value is 0.2. EXAIR will be ignored if there is no combustion air flow updating (IDXAIR = 0).
6-R	TBDGSS	Initial guess of bed temperature, °F (°C).
7-R	ASUBS	Plan area of bed, ft^2 (m^2).
8-R	XHSUBS	Static depth of bed material, Ft (m).
9-R	XHSUBT	Distance from air distributor plate to top of tube bundle, ft (m).
10-R	XHSUBB	Distance from air distributor plate to bottom of tube bundle, ft (m).
11-R	XCACIS	Mass fraction of $CaCO_3$ in sorbent, -.
12-R	XMGCIS	Mass fraction of $MgCO_3$ in sorbent, -.
13-R	XASHIS	Mass fraction of ash in sorbent, -.
14-R	XH2OIS	Mass fraction of H_2O in sorbent, -.

15-R FRCAL	Fraction of $CaCO_3$ that calcines (and captures sulfur), -.
16-R TEXF	Measured component exit temperature, °F (°C). If zero, PEPSE will calculate a value. TEXF is ignored if any one of the following is true: (1) No heat exchangers are present. (2) Any of the residing heat exchangers are performance mode components (NMODHX = 2 on fluid bed heat exchanger input card). (3) Any of the residing heat exchangers have user specified heat transfer coefficients ($0.0 < HTTIRH$ on radiant stage input card).
17-R UFRL	Fractional fluid bed combustor radiation losses to the environment based upon the high heating value of the fuel (Btu lost/Btu fuel input), -. $0.0 \le UFRL \le 1.0$.
18-R UFL	Fractional unburned fuel loss based on the high heating value of the fuel (Btu lost with refuse/Btu fuel input), -. $0.0 \le UFL \le 1.0$.
19-R UFUNL	Fractional unaccounted heat loss based on higher heating value of the fuel (Btu lost/Btu fuel input) -. $0.0 < UFUNL < 1.0$.
20-R XCRFUZ	Mass fraction of unburned carbon in the refuse (lbm C/lbm refuse), -. The unburned fuel loss calculated with XCRFUZ will override the value of UFL (Word 18-R).
21-R XREFFL	Fractional refuse carryover in the flue gas (lbm refuse in the flue gas/lbm refuse produced), -. $0.0 \le XREFFL \le 1.0$.
22-R TTRFUZ	Measured temperature of refuse exiting combustor B port, °F (°C). Default value is the same as the calculated flue gas temperature leaving the fluidized bed combustor.
23-R PDFR	Pressure drop through the fluid bed combustor, psi (kpa).

24-R PEXF Measured fluid bed combustor exit pressure, psia (kpa).

The performance mode components have been tested, and do function properly. These are the inputs as they currently stand. As the design mode components become available, there will be more inputs, and they will be more complicated.

VARIABLE DEFINITIONS

L_{CAL} = Loss due to calcination, Btu/pound "as fired" fuel
Ca = Pounds of calcium per pound of sorbent, -
$W_{d'p'ei}$ = Dry refuse flow rate at point i, pounds/hr
CO_{xRi} = Pounds of carbon dioxide retained/pound of dry refuse, -
W_L = Sorbent flow rate, pounds/hr
Mg = Pounds of magnesium per pound of "as fired" sorbent, -
W_{fe} = Fuel flow rate, pounds/hr
B_s = Heat supplied by sulfation, Btu/pound "as fired" fuel
ks = Sulfur retention, %
S = Pounds of sulfur per pound of "as fired" fuel, -

REFERENCES

[1]. Kunii, Daizo; Fluidization Engineering; Robert E. Krieger Publishing Company, Inc., 1984.

[2]. Sotelo, E.; Performance Test Code For Atmospheric Fluidized-Bed Combustion Steam Generators; EPRI report number RP 2303.

[3]. Divillio, R. J., Carson, W. R., and Tavoulareas, S.; Correlations to Predict Bed Expansion and Heat Transfer in Atmospheric Fluidized-Bed Boilers; 7th Miami International Conference on Alternative Energy Sources, Session 6D; Dec. 9-11, 1985.

[4]. Hall, B. A.; An Evaluation of FBCBAL for the Prediction of Gross Boiler Efficiency for an Atmospheric Bubbling Fluidized Bed Boiler; Masters of Engineering, Final Project Report; May 1990.

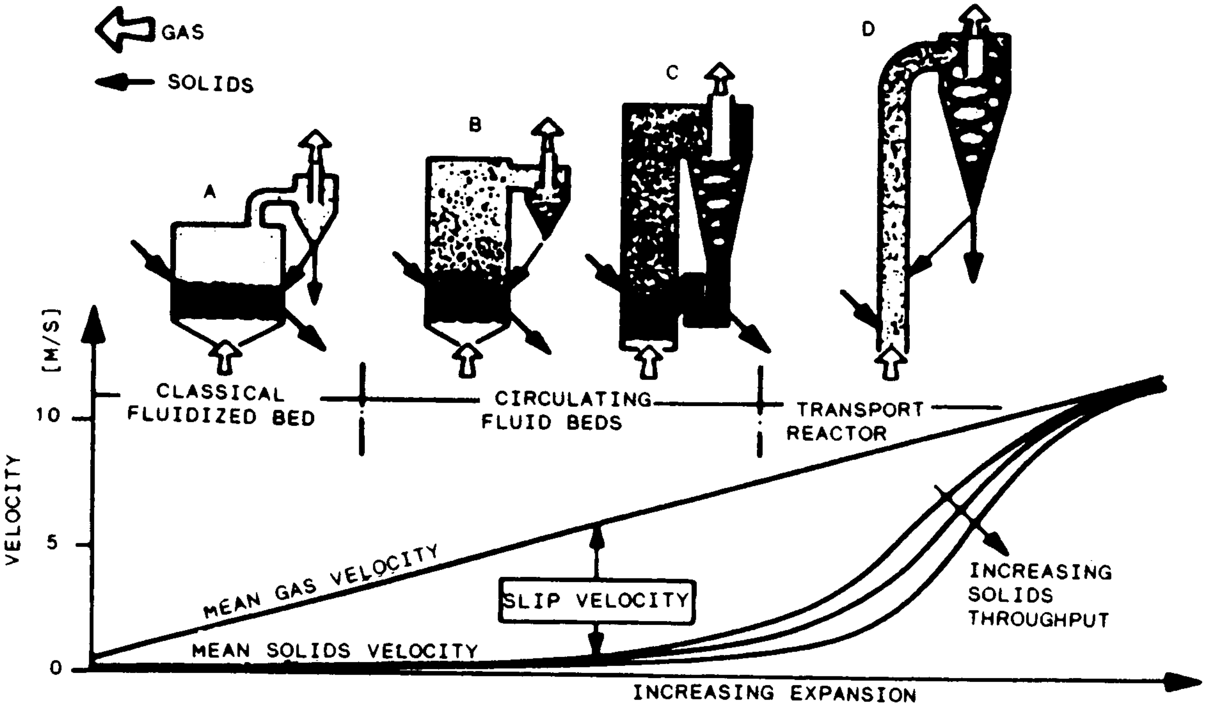
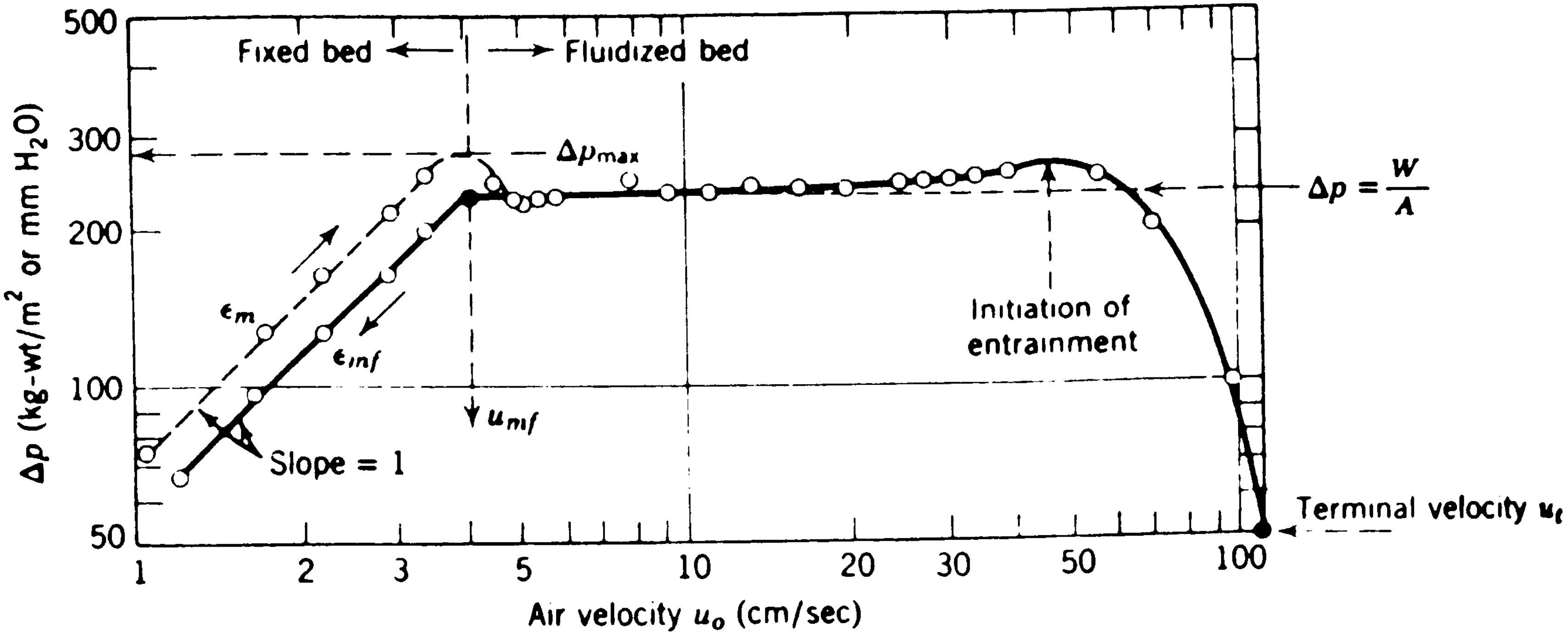


Figure 1

Modes of fluidization of fine particles



500
300
200
100
50
Δp (kg-wt/m^2 or mm H$_2$O)
1
2
3
5
10
20
30
50
100
Air velocity u_o (cm/sec)
Fixed bed
Fluidized bed
Δp_{max}
ϵ_m
ϵ_{mf}
u_{mf}
Slope = 1
Initiation of entrainment
$\Delta p = \frac{W}{A}$
Terminal velocity u_t

Figure 2

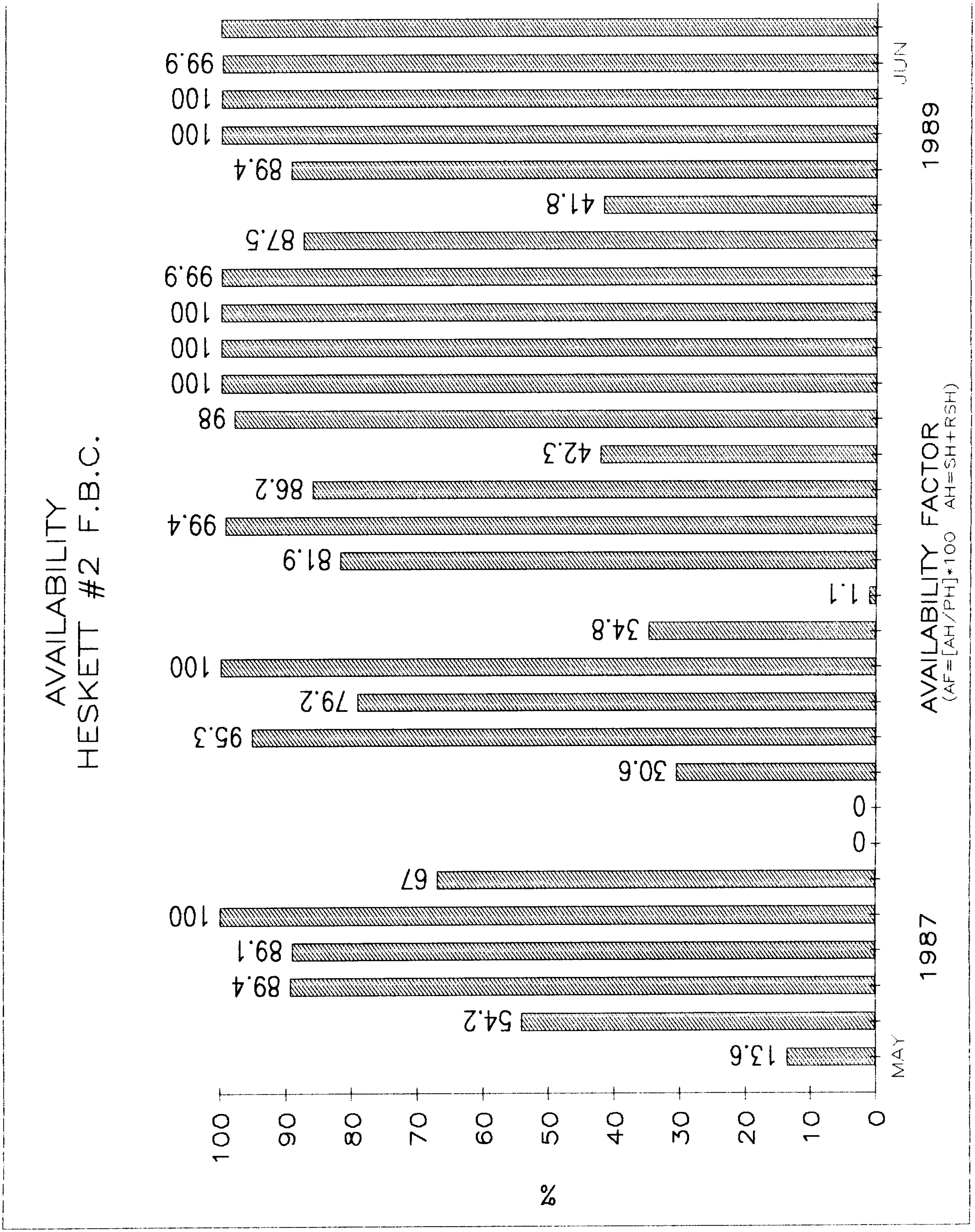

AVAILABILITY
HESKETT #2 F.B.C.
%
100
90
80
70
60
50
40
30
20
10
0
MAY
1987
1989
JUN
13.6
54.2
89.4
89.1
100
67
0
0
30.6
95.3
79.2
100
34.8
1.1
81.9
99.4
86.2
42.3
98
100
100
100
99.9
87.5
41.8
89.4
100
100
99.9
AVAILABILITY FACTOR
(AF=[AH/PH]*100 AH=SH+RSH)

Figure 3