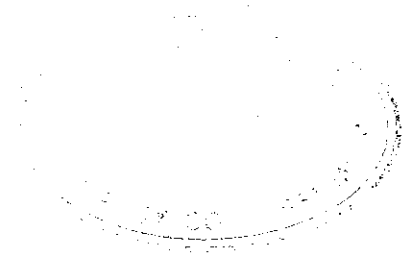


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**AUSTRALIAN ATOMIC ENERGY COMMISSION  
RESEARCH ESTABLISHMENT  
LUCAS HEIGHTS**

**A COMPARISON BETWEEN EXPERIMENTALLY DETERMINED  
FLOW INSTABILITY THRESHOLDS AND CALCULATIONS  
USING THE COMPUTER CODE TOSCLE**

by

**D. J. WILSON**

**December 1973**

**ISBN 0 642 99613 X**



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ABSTRACT

Experimental results from the Canadian forced convection loop FLARE (D'Arcy 1968) have been used to assess the value of the TOSCLE computer code (Spinks 1971) for calculating flow stability characteristics of pressure tube reactor systems.

Good agreement has been found between TOSCLE calculations and the FLARE results for high values of subcooling. TOSCLE indicated a crucial boiling length as supposed by Shotkin (1967). However, this does not appear to be consistent with the FLARE experimental data and large discrepancies occur at low subcoolings.

The experimental results showed an increased scatter in the low subcooling region. A possible cause for this and for the discrepancy with calculated

results at low subcooling are suggested.

The sensitivity of TOSCLE results to various input parameters was examined. Most parameter variations were found to have only a minor effect on the results.

Further experimental work in conjunction with detailed theoretical analysis is essential, particularly in the area of low subcooling which is of great importance in power reactor design.

National Library of Australia card number and ISBN 0 642 99613 X

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COMPARATIVE EVALUATIONS; COOLANT LOOPS, INSTABILITY; PRESSURE TUBE REACTORS; SENSITIVITY; SUBCOOLING; T CODES; TWO-PHASE FLOW; UNSTEADY FLOW

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## 1. INTRODUCTION

Flow stability is one of the important items to be investigated during the design and assessment of any nuclear reactor system employing a boiling water coolant. The TOSCLE code (Spinks 1971) was written to assess the stability characteristics of parallel channel, forced convection systems such as CANDU-BLW and SGHWR.

TOSCLE uses equations derived from linearised Laplace transformations of the mass, energy and momentum conservation equations; the resultant one-space-dimension equations are solved analytically along a straight, uniform cross-section pipe having uniform heat addition or removal per unit length. Separate solutions are obtained for single-phase and two-phase regions of the pipe. Single-phase regions can be either subcooled liquid or superheated vapour. Complicated circuits can be analysed by subdividing the components until they conform to the 'straight, uniform cross-section, uniform heat input' description.

The code calculates steady-state pressure drop for given inlet velocity and then perturbed pressure drop for given inlet velocity perturbation. The latter calculation is repeated at a number of frequencies to obtain a Nyquist locus of the inlet velocity to pressure-drop/frequency-response function.

To determine the reliability of the code, it is necessary to compare its predictions with available experimental data. At present, there is a general shortage of reliable experimental data from high pressure multi-channel loops. As an interim measure the TOSCLE code was compared (Spinks 1972) to a finite difference code OWEN. Reasonable agreement was found when the codes were applied to a problem involving a natural circulation loop.

This report describes a comparison of the TOSCLE code with data from the Canadian forced convection rig FLARE (D'Arcy 1968).

## 2. TOSCLE CALCULATIONS FOR FLARE RIG

The Canadian rig FLARE contained a test section comprising three parallel channels (shown schematically in Figure 1). It was designed to form the basis of an experimental programme intended to provide an understanding of parallel channel flow stability at pressures up to 1,000 psig and flows similar to typical reactor conditions.

To apply the TOSCLE code to a stability assessment of the FLARE rig, it was assumed that the pressure drop between inlet and outlet plena was constant, therefore a single channel could be treated independently.

The basic system dimensions were obtained from the experimental report by D'Arcy (1968). The current best estimates of pressure loss factors,

two-phase multiplier and slip correlations were obtained as detailed in Appendix A. Initially, the stability threshold for an inlet subcooling of  $110 \text{ Btu lb}^{-1}$  at a given input power was determined by varying the mass flowrate. Keeping the input power constant, the subcooling was varied by a small amount and new stability points determined using the iterative procedure available in the code. Curves of flow stability threshold at constant power versus mass flowrate and inlet subcooling were thus produced for comparison with the experimental lines shown in D'Arcy (1968, Figure 17).

### 3. RESULTS FOR THE FLARE RIG

#### 3.1 TOSCLE Results Using 'Standard' Data

A 'Standard 90 kW' case was defined using the parameters given in Table 1. The results obtained with this set of data, and for similar cases with 70 kW and 80 kW power inputs, are shown in Figure 2.

TOSCLE produced results agreeing within 3 to 6% over a large range of inlet subcoolings ( $110\text{-}150 \text{ Btu lb}^{-1}$ ). However, at low subcoolings there was a marked disagreement; the experimentally derived line remains straight whereas TOSCLE predicts a definite curve with a maximum in the inlet velocity indicative of a crucial boiling length (Table 2) as suggested by Shotkin (1967).

#### 3.2 Sensitivity Analysis

Various input data required by TOSCLE could not be defined accurately due to lack of available information. The effect of these variables within a credible tolerance band was studied. Variable parameters include the following:

- . K factors for pressure loss.
- . Slip coefficient C, and drift velocity V.
- . Two-phase multiplier coefficients AA, BB and AR, BR.

Values for the above parameters were varied independently between 10% and 100% within the test section and in the inlet and outlet feeders (Table 3). It was noted that the changes shifted the position of the curve either to the left or to the right of the 'Standard' curve thus affecting the inlet velocity threshold values (Figure 3). No credible changes to any of the above variables resulted in a change either to the general shape of the curve or to the position of its maximum with respect to inlet subcooling.

### 4. SCATTER IN THE EXPERIMENTAL RESULTS

D'Arcy (1968, Figure 11) shows straight lines dividing stable from unstable points on the subcooling versus mass flowrate map. However, if all the points on the map are considered to be of equal accuracy the dividing

lines may be re-drawn as indicated in Figure 4. Thus it may be concluded that the dividing lines should not, in fact, be straight at low subcooling; indeed, the almost random nature exhibited by them suggests the possible influence of additional unknown parameters. It is in this region of low subcoolings that other experimental work (Gouse and Andrysiak 1963, Ozisik and Cebeci 1965, Crowley, Deane and Gouse 1967) shows a large change in gradient in the stability threshold curve and the occurrence of a 'crucial' boiling boundary position. In the FLARE experiments it is possible that results in the critical region were swamped by some additional effect.

#### 5. PREDICTIONS FOR THE FLARE RIG USING THE POISE CODE

Carver (1967) has reported the results of calculations using the computer code POISE and has given detailed results from a further series of experiments on the FLARE loop. TOSCLE was applied to these cases using the data shown in Table 1 with some modifications as detailed in Table 4. The results of these calculations are presented in Table 5 and Figure 5 together with experimental values and POISE predictions. Although no results were given by Carver for low subcoolings, possibly because of the extensive computer times involved with finite difference stability codes (Spinks 1972), POISE appears to indicate a similar trend to TOSCLE at intermediate subcoolings. However, the results are inconclusive without further points at low subcoolings.

#### 6. INFLUENCE OF HEATER END ARRANGEMENT

For the range of subcoolings at which the discrepancy with experimental results was most marked, the boiling boundary position was calculated to coincide with the lower end of the heaters. It is possible that the flow in this region would be influenced by the effects of the 45° bend and change from pipe to annular flow occurring slightly downstream (W.J. Green, private communication). In addition, depending on the construction methods employed for the heaters, the power profile at the end of the heated length might be expected to influence the boiling boundary position, particularly at low subcoolings where only a small total power input is required to produce boiling.

TOSCLE requires that the power shape in each section be flat; hence, to simulate any non-uniform power shape, it is necessary to use a series of step power variations. An attempt was made to simulate a number of power profiles along the first 7.5% of the length of the FLARE rig heater, the remainder of the power profile staying flat.

It was found that a large range of threshold power curves (Figures 6 and 7) could be produced with relatively minor variations to the power profile

(Figures 8 and 9) with total power input remaining constant. No simple power shape could be found to match exactly the experimental stability lines.

#### 7. DIFFICULTIES WITH TOSCLE

TOSCLE was found to predict singularities when the boiling boundary position coincided with a mesh point at which a change in power rating occurred, this being due to a deficiency in the TOSCLE model. The singularities became less pronounced when a finer mesh was used, permitting smaller changes in power rating for each step. This phenomenon, together with the difficulties reported earlier (Spinks 1972) with regard to mesh problems near the boiling boundary in finite difference stability codes, suggest that special boiling boundary treatment should be considered for all stability codes.

#### 8. CONSTANT PRESSURE DROP ASSUMPTION

It has been suggested (Professor J.J. Thompson, private communication) that the dynamics of an asymmetric three-channel arrangement such as FLARE could be far more complex than TOSCLE could be expected to analyse. It was suggested that the channel oscillations would be coupled by the action of the headers and that TOSCLE could not be applied independently to a single channel. T.M. Romberg (private communication) has suggested that the instrumentation of the FLARE rig may have been insufficiently sensitive to make any apparent short period pressure fluctuations between the headers.

#### 9. TRENDS SHOWN IN OTHER WORK

For two-phase flow in a heated channel, Shotkin (1967) postulated the existence of a crucial boiling length for which the channel is least stable. A number of experiments have indicated a curve with a maximum as predicted by TOSCLE for the FLARE rig. Gouse and Andrysiak (1963, Figure 4) report a curve in two parts similar to the upper and lower portions of the TOSCLE lines shown in Figure 1. In the stability map on a subcooling versus mass flowrate plane Gouse and Andrysiak (1963, Figure 5) show a complete curve of the TOSCLE type. A similarly shaped curve is also indicated in results presented by Ozisik and Cebeci (1965, Figure 2). Again, in work reported by Crowley, Deane and Gouse (1967, Figures 4, 8 and 16) experimental points at low subcoolings show a definite bend in the curve, concurrent with the shape predicted by TOSCLE. This evidence tends to support the idea that there should be a crucial boiling boundary position as shown in the FLARE results. From Figures 6 to 9 it appears that minor variations from the intended flat power input profile could have given rise to quite different stability threshold curves than those theoretically predicted using the intended flat power profile. This could account both for the discrepancy in the results and the apparent increased

scatter in the FLARE results at low subcoolings (see Figure 4). Yadigaroglu and Bergles (1971) have shown that quite different instability threshold curves can be produced using different power profiles in otherwise identical systems.

#### 10. CONCLUSIONS

- . Good agreement has been found between TOSCLE and the FLARE results at high subcoolings. This suggests that the basic formulation of the code is acceptable.
- . A large discrepancy has been found between TOSCLE and the FLARE results for low subcoolings of interest in typical reactor designs. A large scatter is shown in the experimental results in this region, and insufficient data are available to determine a cause.
- . It is suggested that, in the FLARE rig, the occurrence of the boiling boundary in a region influenced by entrance effects (at the inlet end of the heater) may have caused some increased scatter in the experimental results. This scatter occurs in the region in which a crucial boiling boundary position might have been expected.
- . Further experiments and theoretical work is required, particularly at low subcoolings, to clarify flow stability phenomena in areas of interest in reactor design. Particular attention is needed to determine the influence of power profile on stability characteristics.

#### 11. NOTATION

A	Flow area (ft <sup>2</sup> )
AA,AR	Two-phase multiplier coefficients used in
BB,BR	$\Psi = 1 + A.X + B.X^2$
C	Slip correlation coefficient
DE	Hydraulic diameter (ft)
G	Mass flowrate
G <sub>MAX</sub>	Mass flowrate at peak of TOSCLE curve
GRAV	Gravity (ft s <sup>-2</sup> )
<j>	Average volumetric flux density
N	Section number
Q	Input power
Q <sub>CRIT</sub>	Input power at stability threshold
QkW	Input power (kW)
RK	K factor for pressure loss
RR	Relative roughness
V	Drift velocity

$V_{\text{INLET}}$	Inlet velocity to first section
$V_{\text{MAX}}$	Inlet velocity to first section at crucial boiling length
$\bar{V}_g$	Vapour phase velocity
$X$	Quality ( $\text{ft s}^{-1}$ )
$\Psi$	Two-phase multiplier

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TABLE 1

INPUT DATA FOR STANDARD 90 KW CASE

Section	Length (ft)	Hydraulic Diameter (ft)	Flow Area (ft <sup>2</sup> )	Power Input Q <sub>CH</sub> (N)	Gravity (ft s <sup>-2</sup> )	Slip Correlation Coefficient C(N)	Drift Velocity (ft s <sup>-1</sup> )	Relative Roughness RR(N)	K Factor for pressure Loss KK(N)	Coefficients for Two-Phase Multiplier		Two-Phase Multiplier Coefficients for RK		Description of Section
										AA(N)	BB(N)	AR(N)	BR(N)	
N														
1	3.5	0.06183	3.003x10 <sup>-3</sup>	-10 <sup>-3</sup>	32.2	1.0	0.0	2.695x10 <sup>-3</sup>	0.7043	0.0	0.0	0.0	0.0	Inlet header to flow contraction
2	1.645	0.04550	1.626x10 <sup>-3</sup>	-10 <sup>-3</sup>	32.2	1.0	0.0	3.663x10 <sup>-3</sup>	0.5334	0.0	0.0	0.0	0.0	Flow contraction to valve
3	2.0	0.04550	1.626x10 <sup>-3</sup>	-10 <sup>-3</sup>	32.2	1.0	0.0	3.663x10 <sup>-3</sup>	5.0	0.0	0.0	0.0	0.0	Valve to bend in inlet feeder
4	0.938	0.04550	1.626x10 <sup>-3</sup>	-10 <sup>-3</sup>	20.0	1.0	0.0	3.663x10 <sup>-3</sup>	0.160	0.0	0.0	0.0	0.0	Bend to annular section inlet
5	0.625	0.01833	1.701x10 <sup>-3</sup>	-10 <sup>-3</sup>	32.2	1.0	0.0	2.26x10 <sup>-4</sup>	0.500	0.0	0.0	0.0	0.0	Unheated annular section
6 to 18	0.750	0.01833	1.701x10 <sup>-3</sup>	6.75	32.2	1.08	2.461	2.26x10 <sup>-4</sup>	0.015	30.0	2.0	30.0	2.0	13 equal sections of heater each starting at spacer
19	0.250	0.01833	1.701x10 <sup>-3</sup>	2.25	32.2	1.08	2.461	2.26x10 <sup>-4</sup>	0.015	30.0	2.0	30.0	2.0	Top end of heater after final spacer
20	0.625	0.01833	1.701x10 <sup>-3</sup>	-10 <sup>-3</sup>	32.2	1.08	2.461	2.26x10 <sup>-4</sup>	0.015	30.0	2.0	30.0	2.0	Unheated outlet annular section
21	0.938	0.04550	1.626x10 <sup>-3</sup>	-10 <sup>-3</sup>	20.0	1.20	0.50	3.663x10 <sup>-3</sup>	0.30	30.0	0.0	30.0	0.0	Inclined section to bend in out- let feeder
22	3.145	0.04550	1.626x10 <sup>-3</sup>	-10 <sup>-3</sup>	32.2	1.20	0.50	3.663x10 <sup>-3</sup>	0.16	30.0	0.0	30.0	0.0	Outlet feeder from bend to header

TABLE 2

EXIT QUALITY AND POSITION OF BOILING BOUNDARY FOR  
THE PREDICTED CONDITIONS OF MAXIMUM INSTABILITY

Input Power	kw	90.0	80.0	70.0	70.0
Inlet Subcooling (at peak of $V_{INLET}$ )	Btu lb <sup>-1</sup>	45.6	45.6	45.6	45.7
Heated Length to Boiling Boundary	ft	1.56	1.53	1.50	1.50
Steam Quality at Exit	%	39.9	40.8	41.9	41.8

TABLE 3

VARIATIONS OF 90 kW CASE

(Power Constant at 90 kW, Subcooling Constant at 110 Btu lb<sup>-1</sup>.  
Parameter Varied and Change of Mass Flowrate, G', at Stability  
Threshold Noted)

Parameter Varied	From (Standard Value)		To	$\frac{X_2 - X_1}{X_1}$	Effect of Change on Value of G at Stability Threshold (Constant Power & Subcooling)	
	$X_1$	$X_2$			SG/G	$\frac{SG}{G} * \left( \frac{X_1}{X_2 - X_1} \right)$
RK (VALVE)	5.0	2.0		-0.60	0.13376	-0.2229
RK (SPACERS)	0.015	0.030		1.00	0.00315	+0.00315
RK (SECTION 21)	0.300	0.200		-0.33	-0.01361	+0.04083
C <sub>ANNULUS</sub>	1.080	1.200		0.111	-0.09603	-1.15707
C <sub>OUTLET FEEDERS</sub>	1.200	1.100		-0.083	+0.01174	-0.14089
V <sub>ANNULUS</sub>	2.461	4.000		0.6254	-0.05298	-0.03313
V <sub>OUTLET FEEDERS</sub>	0.500	1.000		1.00	+0.00356	+0.00356
AA+AR (ANNULUS)	30.0	35.0		0.1667	+0.017465	+0.10479
BB+BR (ANNULUS)	2.0	4.0		1.00	-0.001752	-0.001752
AA+AR (OUTLET FEEDERS)	30.0	40.0		0.333	+0.05169	+0.15507

TABLE 4  
INPUT DATA FOR TOSCLE

The input data describing the FLARE loop is basically as given in Table 1. The modifications required to allow for the smaller shroud are given below :

Sections	Item	Changed	
		From	To
5 to 20	Hydraulic Diameter, DE (ft)	0.01833	0.01337
5 to 20	Flow Area, A (ft <sup>2</sup> )	0.001701	0.001190
5 to 20	Relative Roughness, RR	2.260E-4	3.108E-4
3	Valve Loss Coefficient, RK	5.000	7.000

TABLE 5  
COMPARISON OF SELECTED FLARE RESULTS WITH PREDICTIONS ON THE  
POISE AND TOSCLE CODES

Test	-	37.1	37.5	37.8	-	-
Inlet Subcooling	Btu lb <sup>-1</sup>	108	73	40	25	15
Mass Flow	lb ft <sup>-2</sup> s <sup>-1</sup>	131.1	128	124	128	128

EXPERIMENT

Pressure	psi	1026	1016	1020	-	-
Q <sub>CRIT</sub>	kW	59.9	46.8	40.8	-	-
Δp IN	psi	3.03	3.06	3.28	-	-
Δp OUT	psi	1.53	1.56	1.22	-	-
Δp CH	psi	7.20	6.92	5.96	-	-

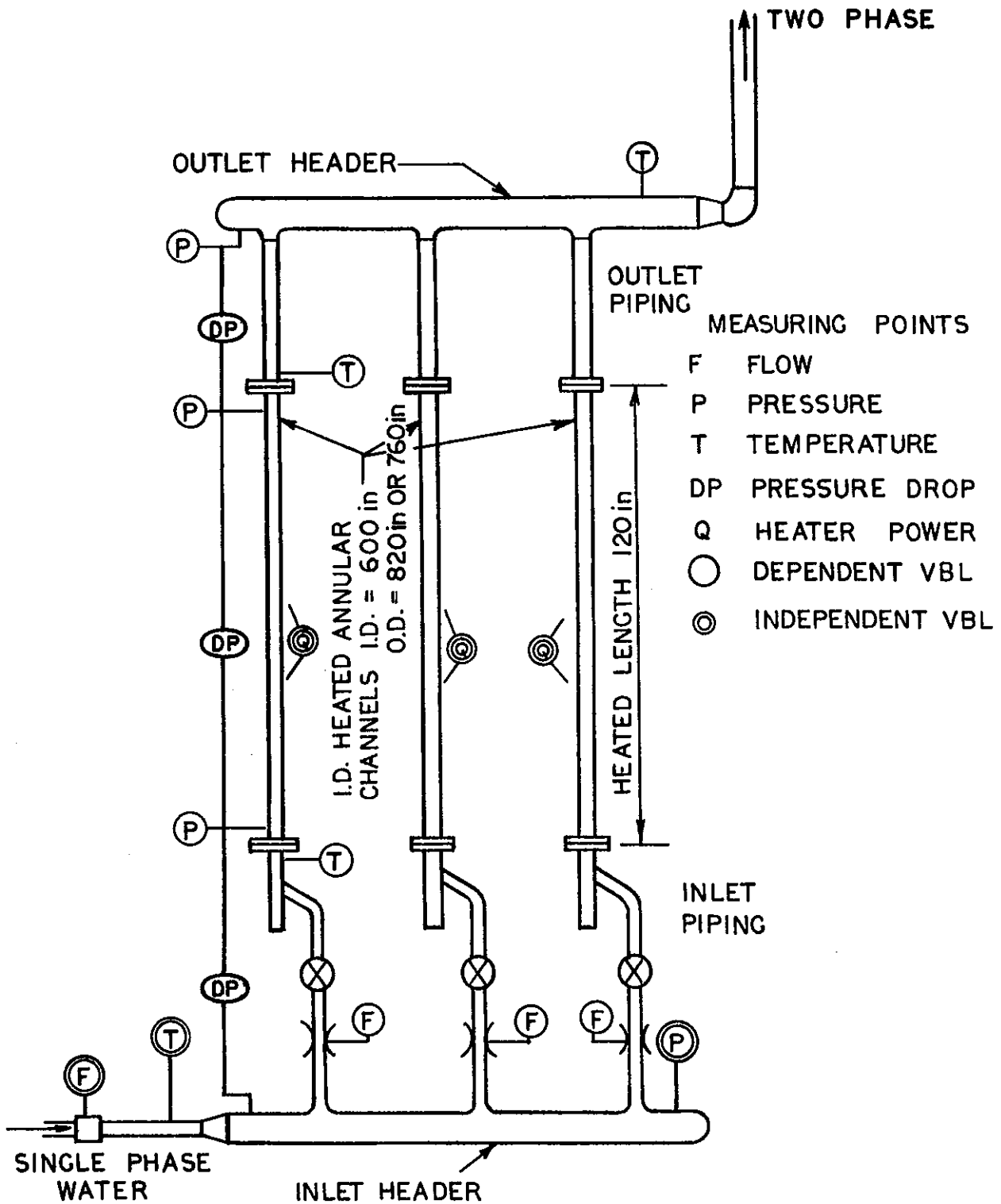
POISE

Q <sub>CRIT</sub>	kW	54.4	44.7	46.3	-	-
Δp IN	psi	3.21	3.13	-	-	-
Δp OUT	psi	1.54	1.27	-	-	-
Δp CH	psi	7.72	6.86	-	-	-

TOSCLE

Pressure	psi	1000	1000	1000	1000	1000
Q <sub>CRIT</sub>	kW	58.06	50.80	46.99	52.30	62.09
At	Δp IN Δp OUT Δp CH	psi	2.90	2.88	2.85	-
Q <sub>CRIT</sub>		psi	1.35	1.19	1.15	-
EXPT.)		psi	7.45	6.75	6.76	-





**FIGURE 1. SCHEMATIC DIAGRAM OF THE FLARE THREE-CHANNEL TEST SECTION**

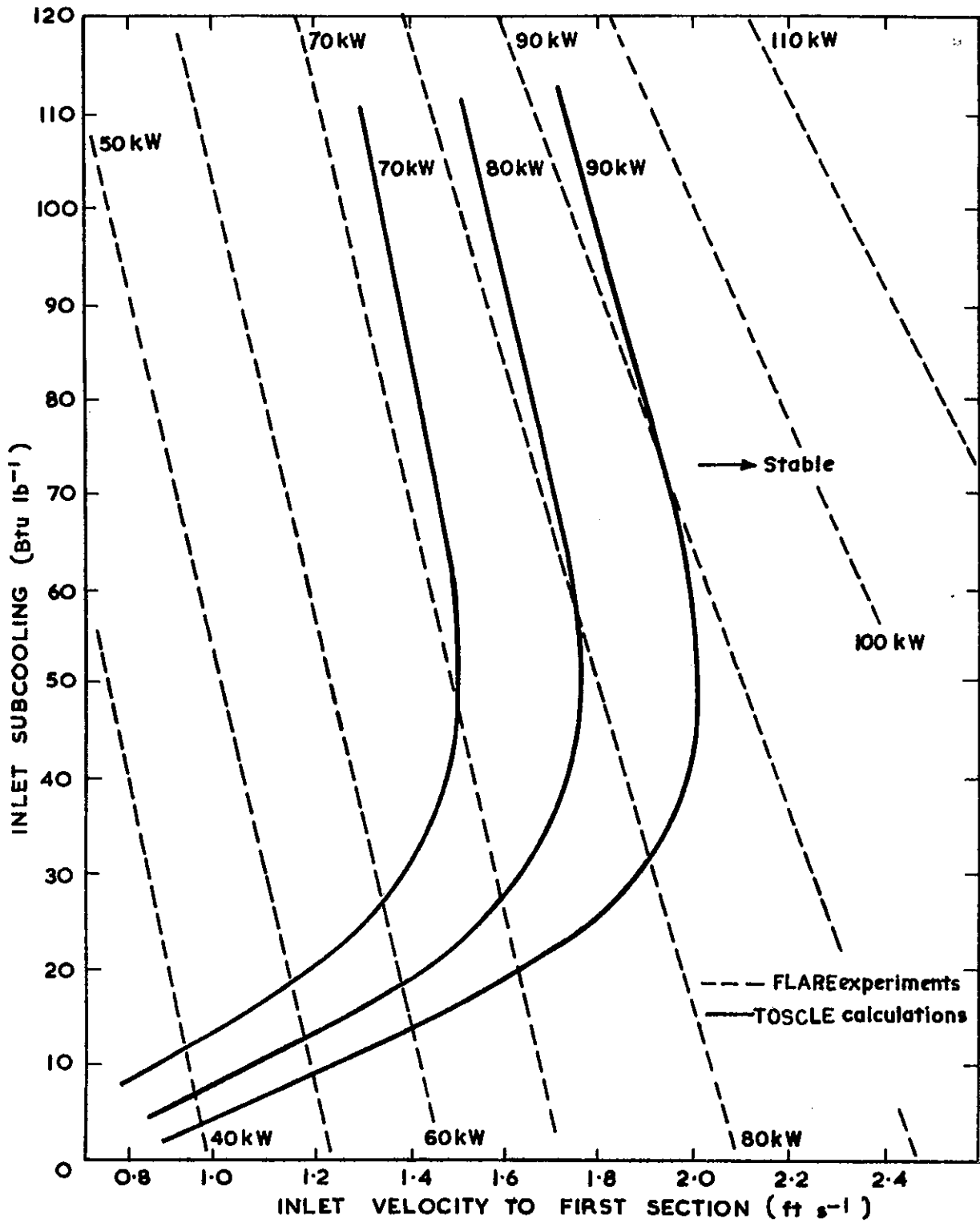
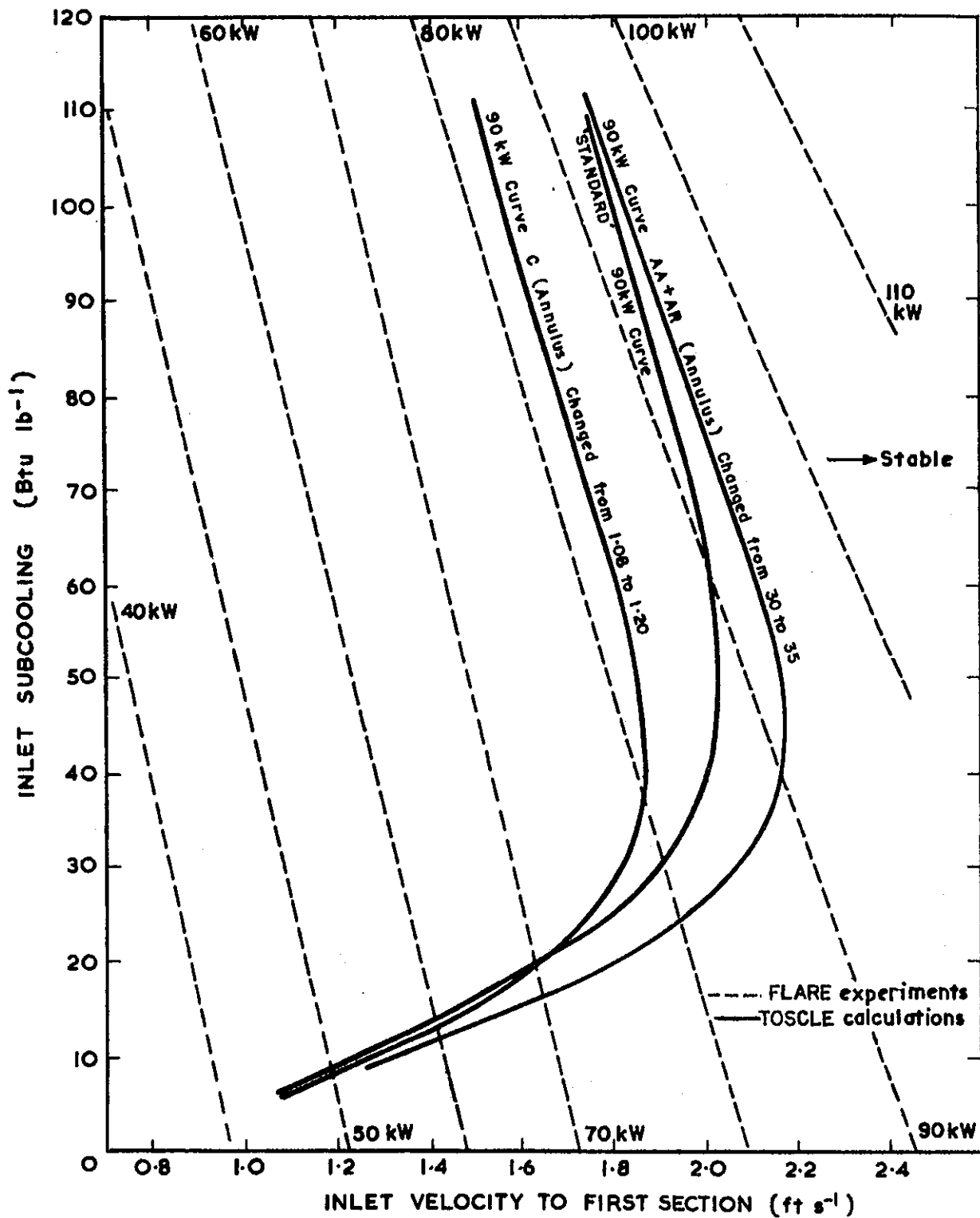


FIGURE 2. FLOW STABILITY THRESHOLDS



**FIGURE 3. FLOW STABILITY THRESHOLDS. VARIATIONS PRODUCED IN TOSCLE 90 kW CURVE DURING SENSITIVITY ANALYSIS**

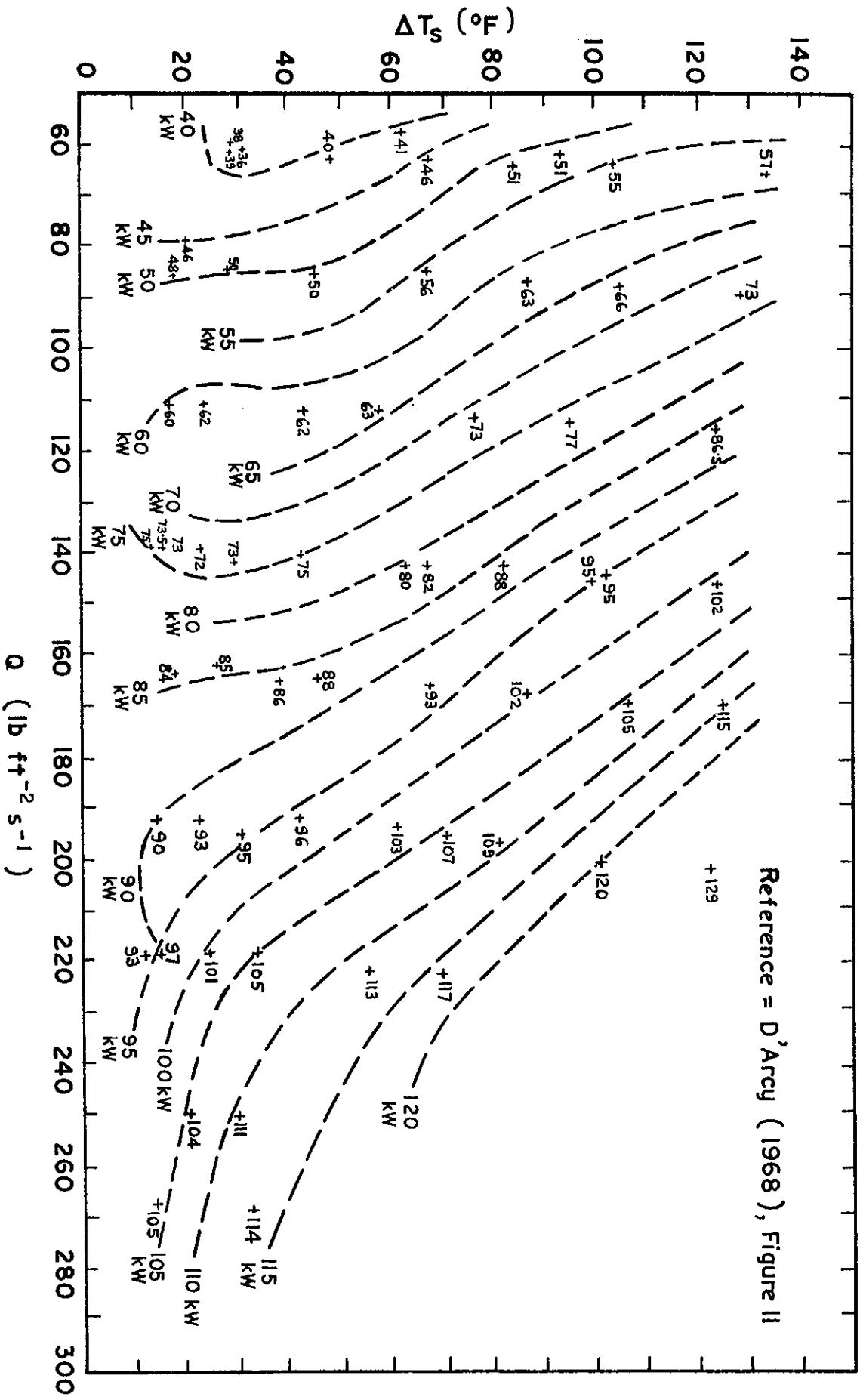


FIGURE 4. EXPERIMENTAL VALUES OF THRESHOLD POWER FOR FLARE RIG (CURVES REDRAWN)

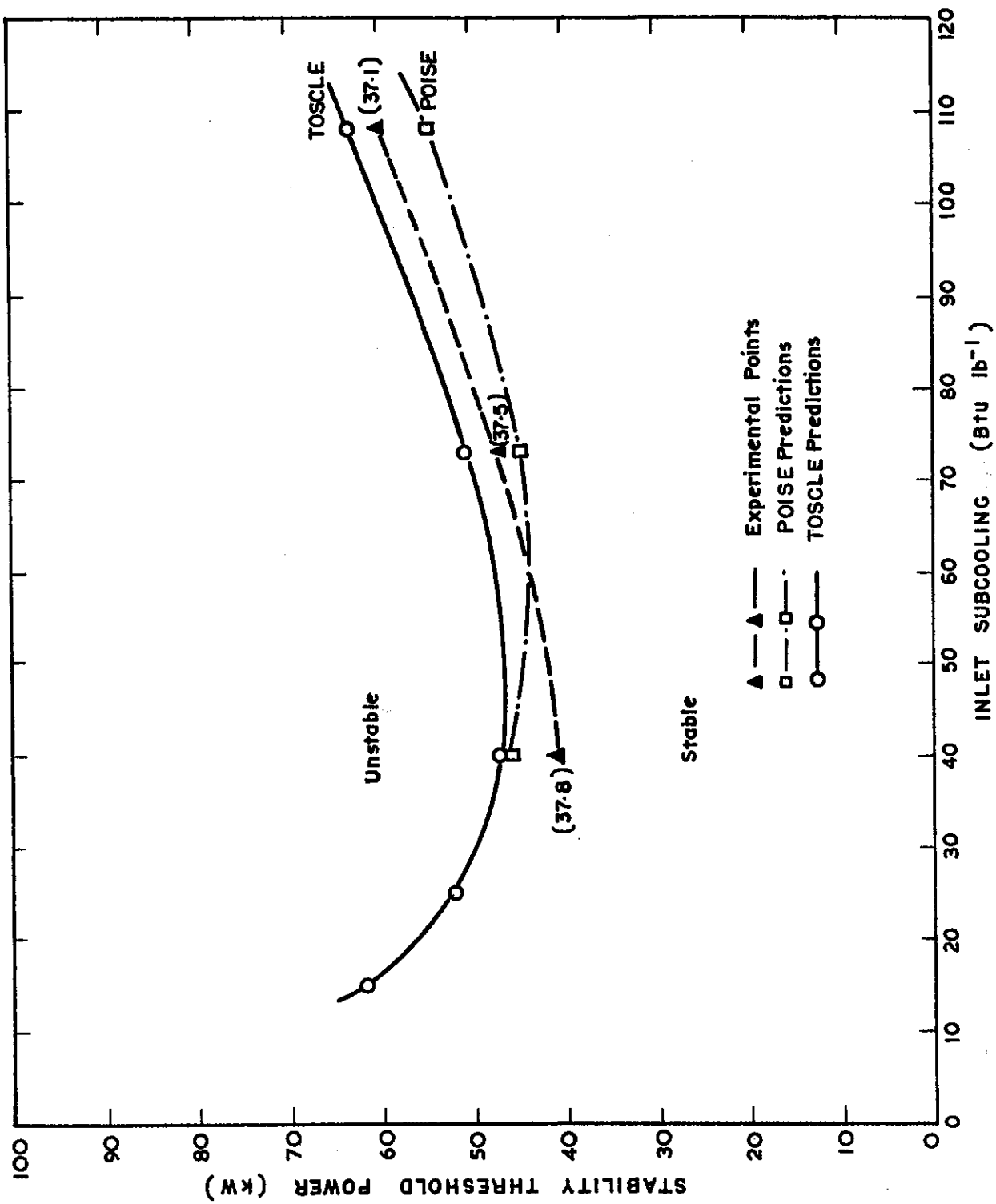
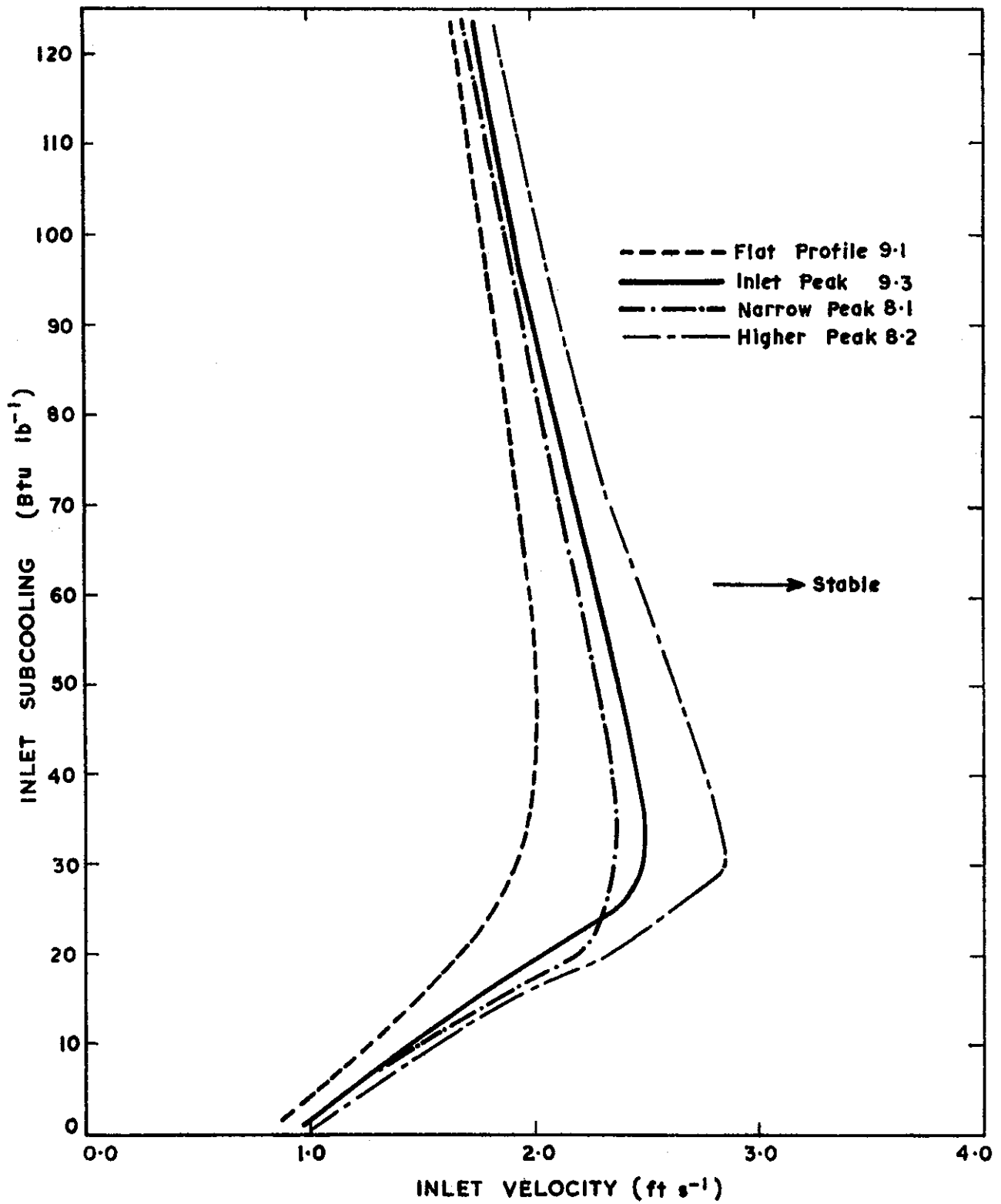


FIGURE 5. INSTABILITY POWERS - FLARE SERIES 37



**FIGURE 6. FLOW INSTABILITY THRESHOLDS FOR FLARE RIG 90 kW; VARIOUS POWER PEAKS AS CALCULATED BY TOSCLE**

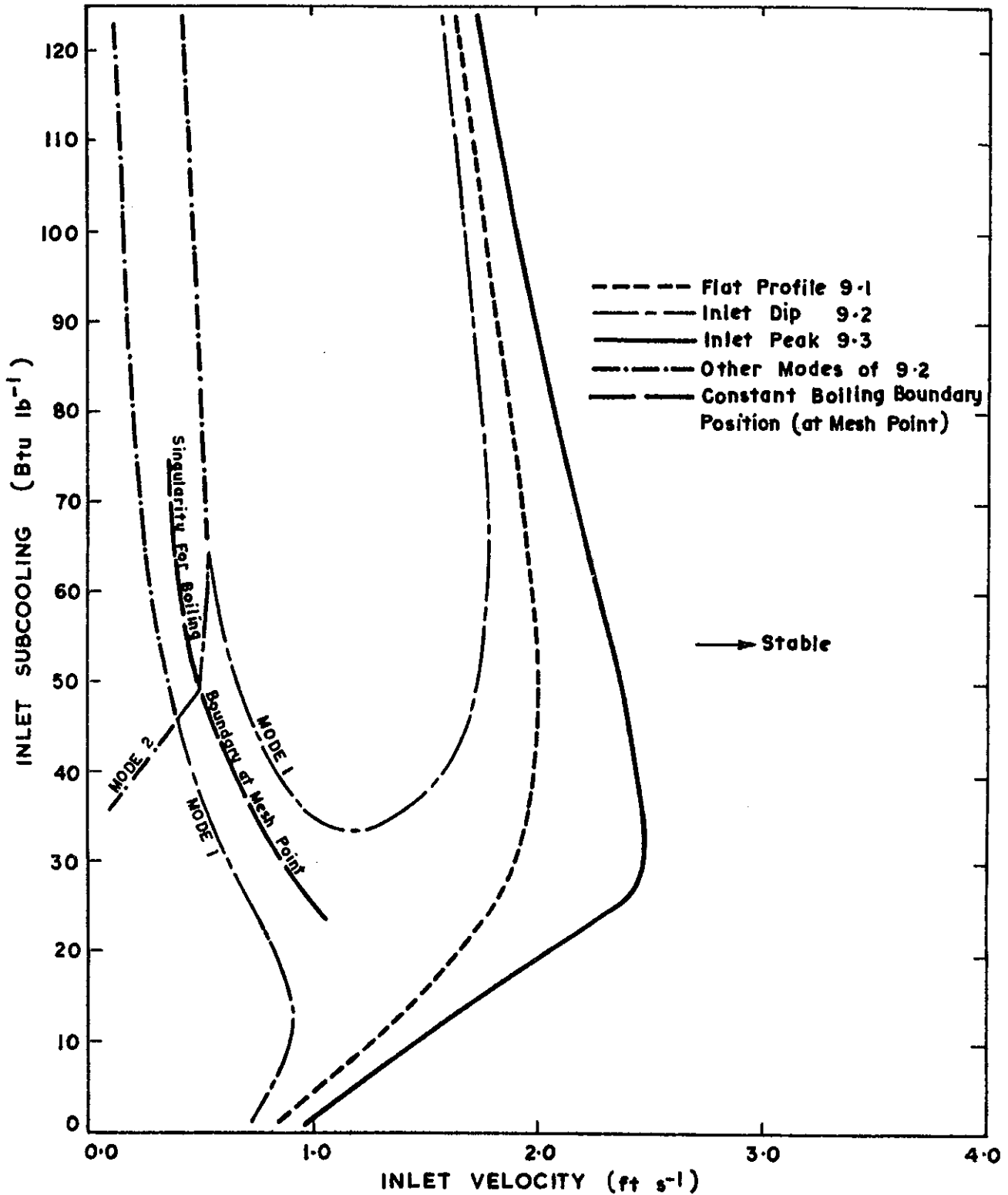
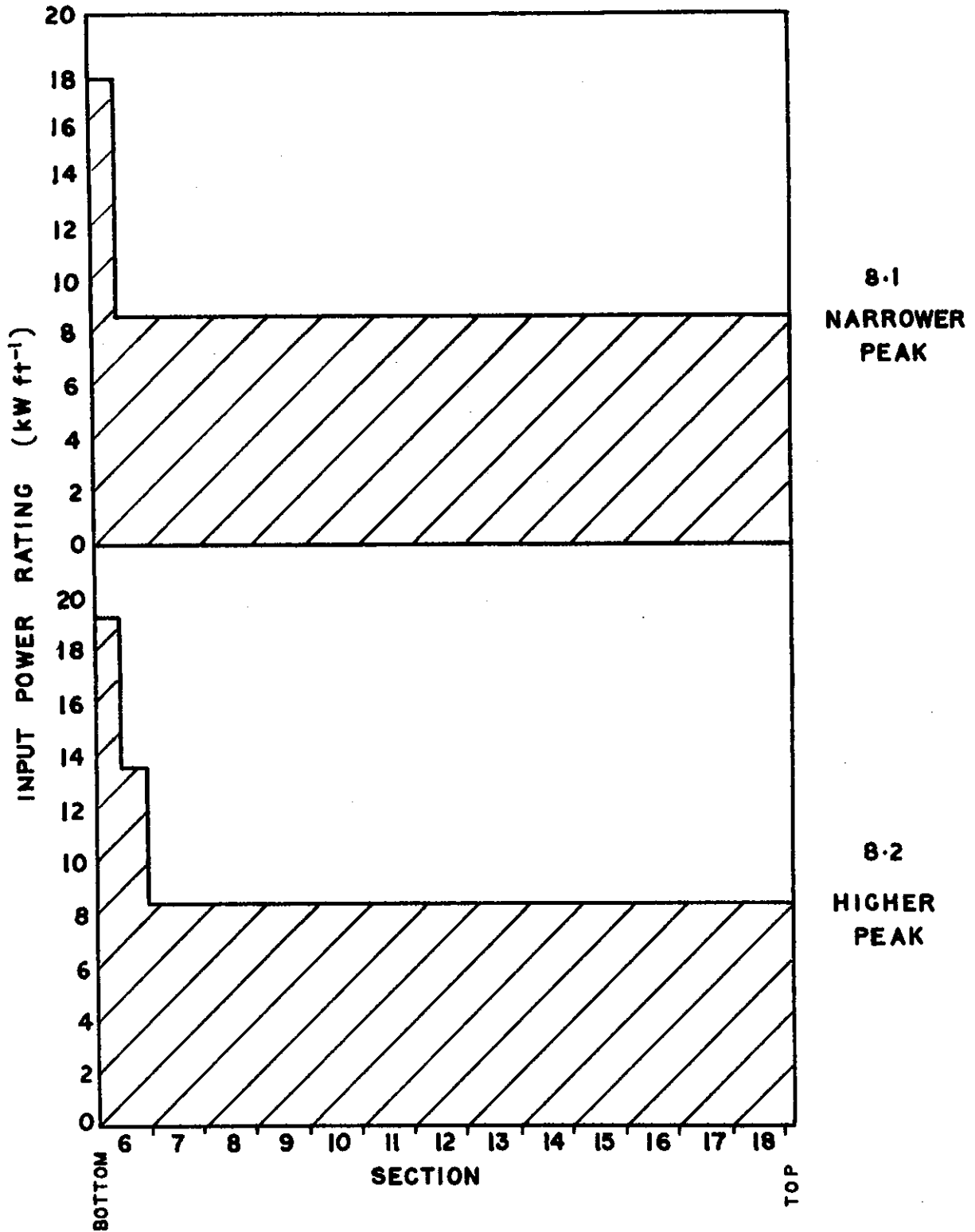
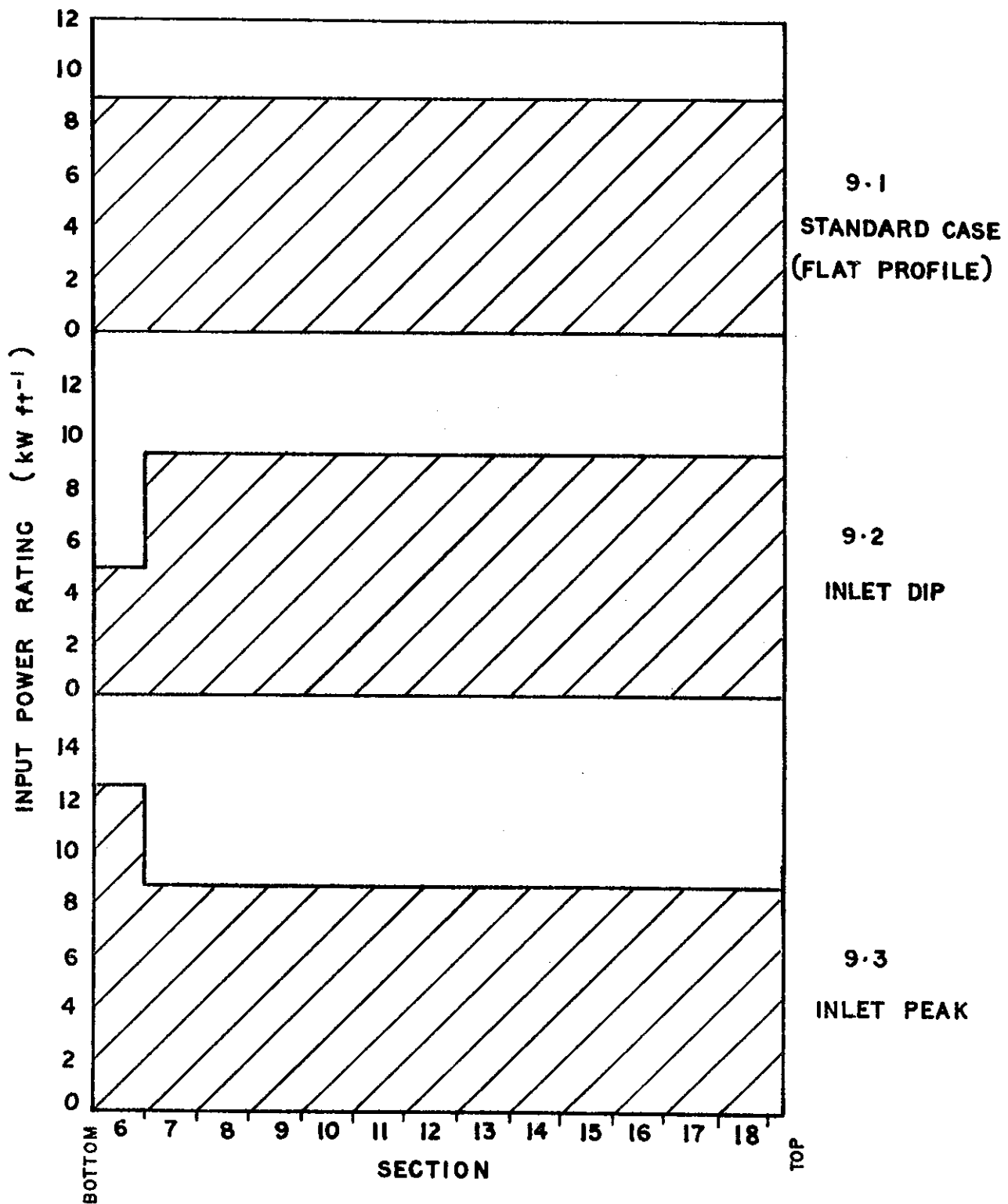


FIGURE 7. FLOW INSTABILITY THRESHOLDS FOR FLARE RIG 90 kW;  
 VARIOUS POWER SHAPES AS CALCULATED BY TOSCLE



**FIGURE 8. INPUT POWER PROFILES - NARROWER PEAK AND HIGHER PEAK**



**FIGURE 9. INPUT POWER PROFILES - STANDARD CASE, INLET DIP AND INLET PEAK**



## APPENDIX A

### DERIVATION OF INPUT DATA FOR TOSCLE

#### A1. K FACTORS FOR PRESSURE LOSSES

The loss factors associated with bends, area changes and restrictions were calculated using the recommendations of Bonnington (1957). At changes in area, the reversible pressure change factors required by TOSCLE were added. These were determined using the rules of Spinks (1972)

#### A2. SLIP CORRELATION COEFFICIENT AND DRIFT VELOCITY

TOSCLE uses a slip correlation of the form:

$$\bar{V}_g = C.<j> + V \quad \dots(1)$$

where the vapour phase velocity  $\bar{V}_g$  is related to the average volumetric flux density  $<j>$  by the slip coefficient  $C$ ,  $V$  is the drift velocity.

For the annular sections, data was obtained from the correlation given by V.M.M. Brown (unpublished work on two phase void data in complex geometries):

$$\bar{V}_g = <j> + 75 \text{ cm s}^{-1} \quad \dots(2)$$

For the outlet feeders, values recommended by Zuber, Staub, Bijwaard and Kroeger (1967) were used. (Table 1.)

#### A3. COEFFICIENTS FOR TWO-PHASE MULTIPLIER

The TOSCLE code requires the two-phase multiplier to be expressed as a quadratic in quality:

$$\Psi = 1 + AA.X + BB.X^2 \quad \dots(3)$$

For the annular sections in the heater, the coefficients  $AA$  and  $BB$  were calculated to give agreement with the more complex function of quality given by D.H. Beattie (private communication):

$$\Psi = 1 + 32.X^{13/12} \quad \dots(4)$$

For the outlet feeders the multiplier was taken to be linear in quality as recommended by Beattie.

