TID/SNA--1440

LIQUID ROCKET PLANT

OPERATIONAL DESCRIPTION

OF

THE DUCT ANALYSIS PROGRAM

JOB 12007

Report 8209-64-7 February 1964

AEROJET
GENERAL TIRE
GENERAL

T/D/SNA--1440

MASTER

OPERATIONAL DESCRIPTION

OF

THE DUCT ANALYSIS PROGRAM

JOB 12007

Report No. 8209-64-7

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TABLE OF CONTENTS

I. OBJECTIVE

The purpose of the Duct Analysis Program, IBM Job Number 12007, is to compute flow rate, pressures, and the shock location, if there is one, in a system containing a converging diverging nozzle and a long duct.

II. SUMMARY

The Duct Analysis Program, using an iterative logic scheme, calculates flow rate, pressures and temperatures, and determines if the flow is subsonic or supersonic for any duct fed by a converging,diverging nozzle.

The analysis assumes an isentropic nozzle, a constant area duct, and an adiabatic system.

III. TECHNICAL DISCUSSION

A. Mathematic Model

The mathematical development used as the analytical model for the duct analysis is attached as Appendix A.

B. Logic

The program assumes supersonic flow, and calculates the pressure at the duct exit. The calculated back pressure is compared with the input pressure; if the input back pressure is smaller, the problem is solved. If not, the program assumes a shock at the duct exit and compares pressures again. If the exit pressure is higher than the back pressure, the program is terminated; if not, the program assumes a shock at the exit of the nozzle which coincides with the duct entrance. The revised duct exit pressure is again calculated, and the program investigates three possibilities: (1) the back pressure equals the exit pressure and the system is balanced; (2) the back pressure is lower than the duct exit pressure, and the shock is standing in the exit duct. The program iterates and finds the shock position that results in a system balance; and (3) the back pressure is larger than the duct exit pressure, therefore, the shock is in the nozzle or the system is subsonic. The program iterates on the shock location to balance the system. If the shock occurs at a mach number of one or less, the system is treated as being subsonic and is solved.

IV. PROGRAM OPERATION

Attached as Appendix B is a sample input and its resulting output.

A. Input

The following is a list of the input parameters:

Location	Symbol	Remarks
L_o	K	Ratio of specific heats (dimensionless)
L_1	R	Universal gas constant $(\frac{\text{in-lbm}}{\text{lbf-°R}})$
L_2	A_i	Inlet nozzle area (in.^{2})
L_3	A*	Throat area (in.^{2})
L_4	A_2	Duct area (in.^{2})
L_5	L	Duct equivalent length (in.) (as used in 4 FL/D)
L_6	F	Friction factor of the pipe (as used in 4 FL/D)
L_7	D	Duct diameter (in.)
L_8	P_i	Initial stagnation pressure (psia) (not inputed if $\dot{w}$ is input)
L_9	T_i	Initial stagnation temperature (°R)
L_{10}	P_e	Static back pressure (psia)
L_{11}	W_i	Initial $\dot{w}$ (lb/sec). If $\dot{w}$ is inputted, P_i is calculated; if not P_i input is used. (if flow is subsonic, $\dot{w}_i$ may not be inputted)
L_{12}	Dump Flag	= 1 for dump of all calculated parameters = 0 no dump

Each case must be followed by a card with "T" in column one. Columns 2-72 of this card may be used for identification. This identification will be printed for each case.

"Stacked" cases may be run; the parameters that are to be changed are inputed directly behind the previous "T" card and an additional "T" card is added.

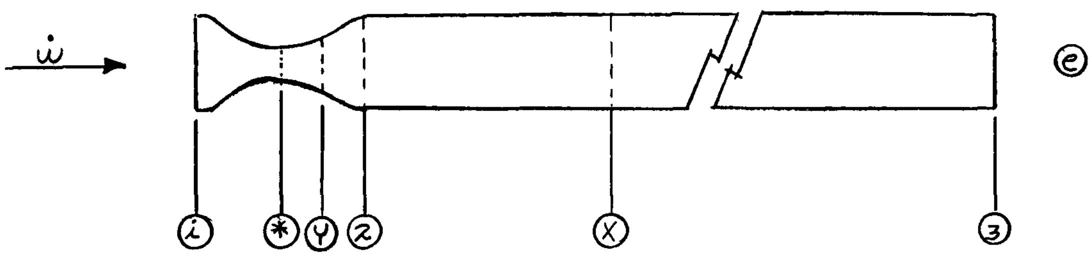
B. Output

The program output consists of the input parameters, a message, and either the flow rate or the inlet pressure which ever is applicable.

The following are messages that may be incurred as output:

Message	Remarks
Supersonic - no shock	The entire duct is supersonic and the exit pressure is greater than or equal to the back pressure.
Shock at exit of duct	The system is balanced with a shock standing at the exit of the duct.
Shock at Station 2	The system is balanced with a shock standing at the duct entrance.
Shock at A_y and M_y	The system is balanced with a shock standing in the nozzle exit cone at a Mach No. and area of M_y and A_y
Shock at L_x and M_y	The system is balanced with a shock standing L_x equivalent inches down the duct from the nozzle exit; the Mach No. at the shock is M_x.
Flow is subsonic	The system balances subsonicly. The flow rate is $\dot{w}$.
Impossible Physical Condition	There is an input error and the program converged on an impossible balance.

DUCT SHOCK ANALYSIS



SYSTEM SCHEMATIC

SYMBOL

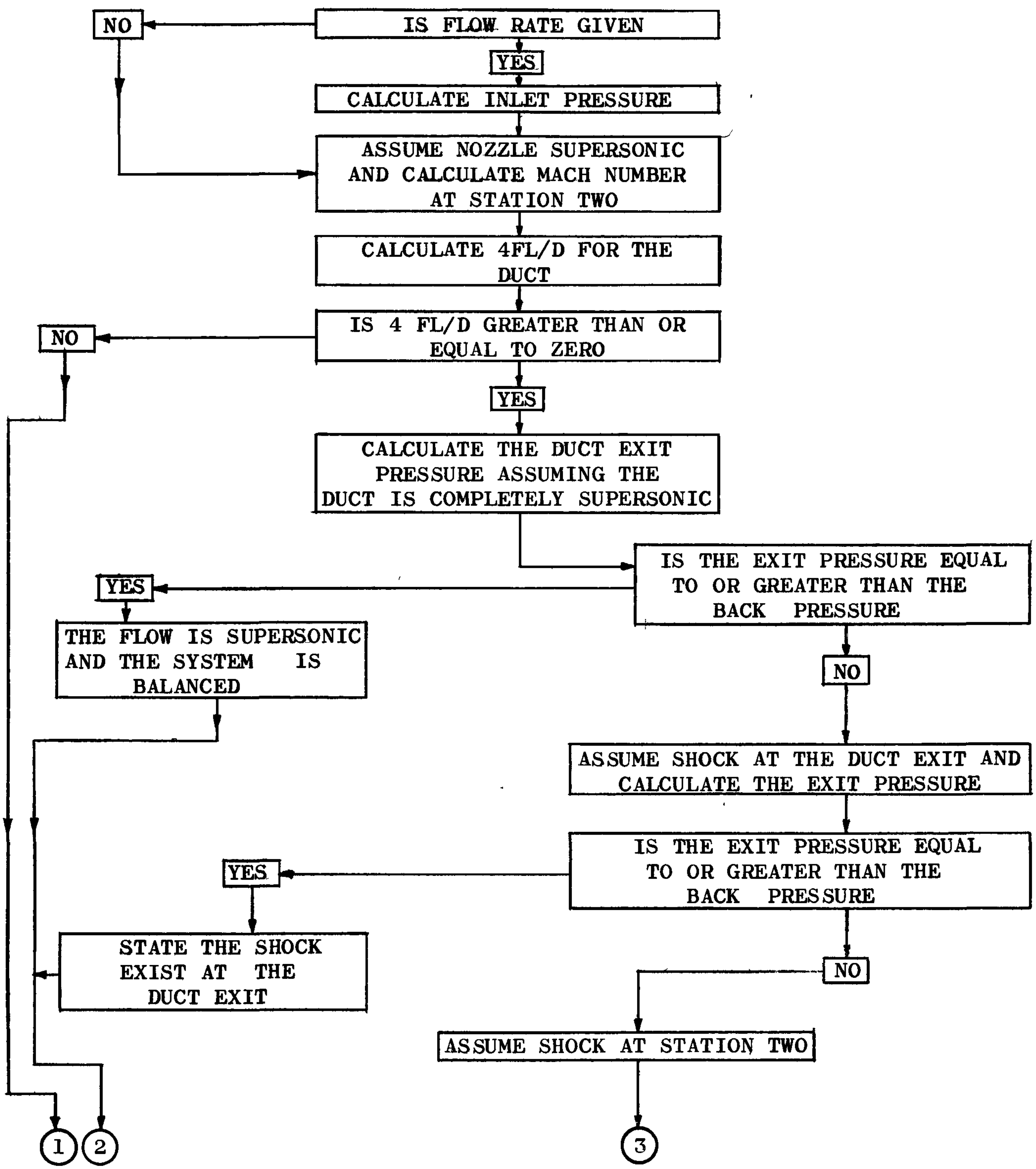
P	=	Pressure, psia	D	=	Duct diameter, in
T	=	Temperature, °R	M	=	Mach Number
A	=	Area, in	K	=	Ratio of specific hts.
L	=	Equivalent length, in	R	=	Gas Constant

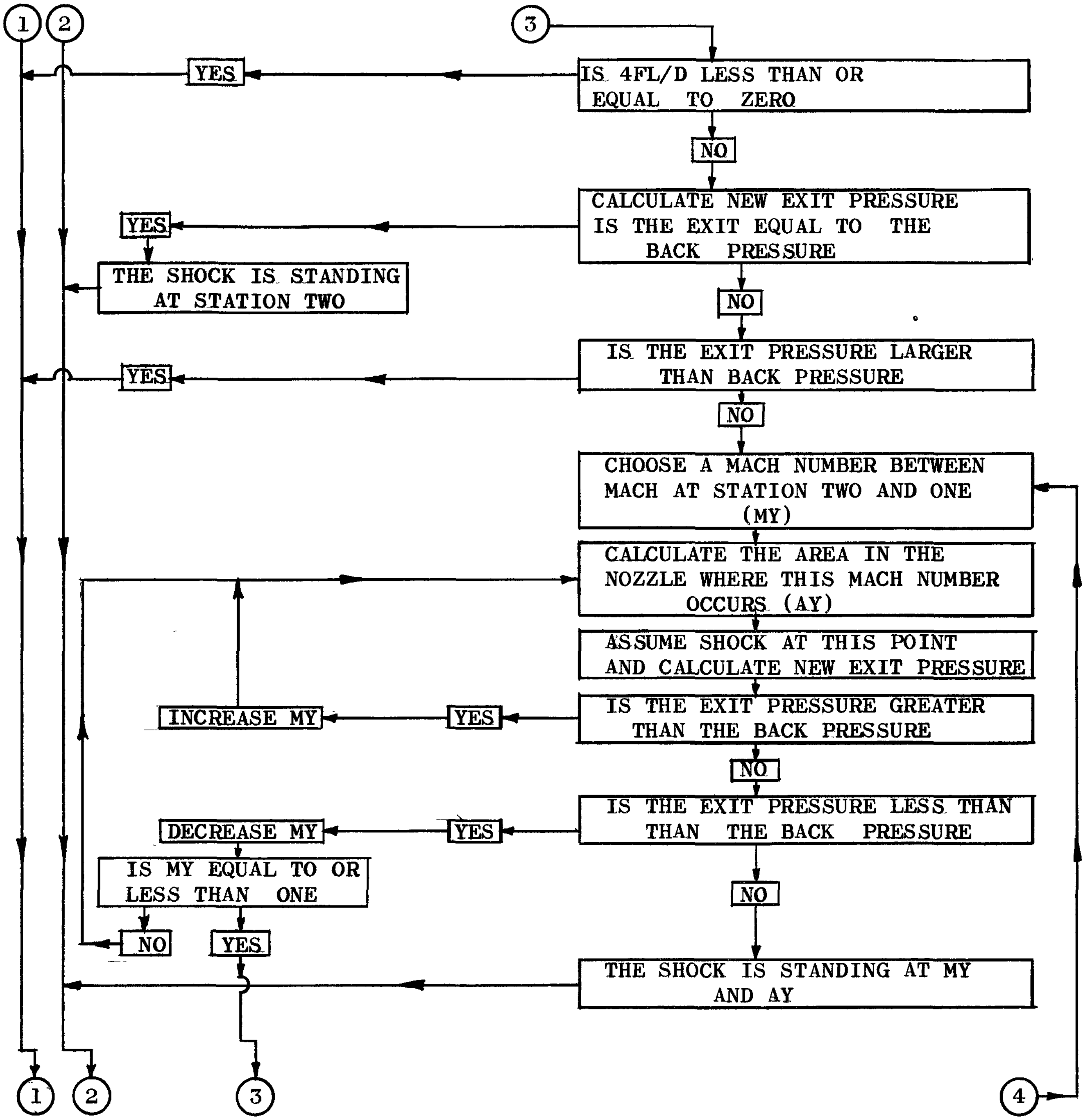
SUBSCRIPTS

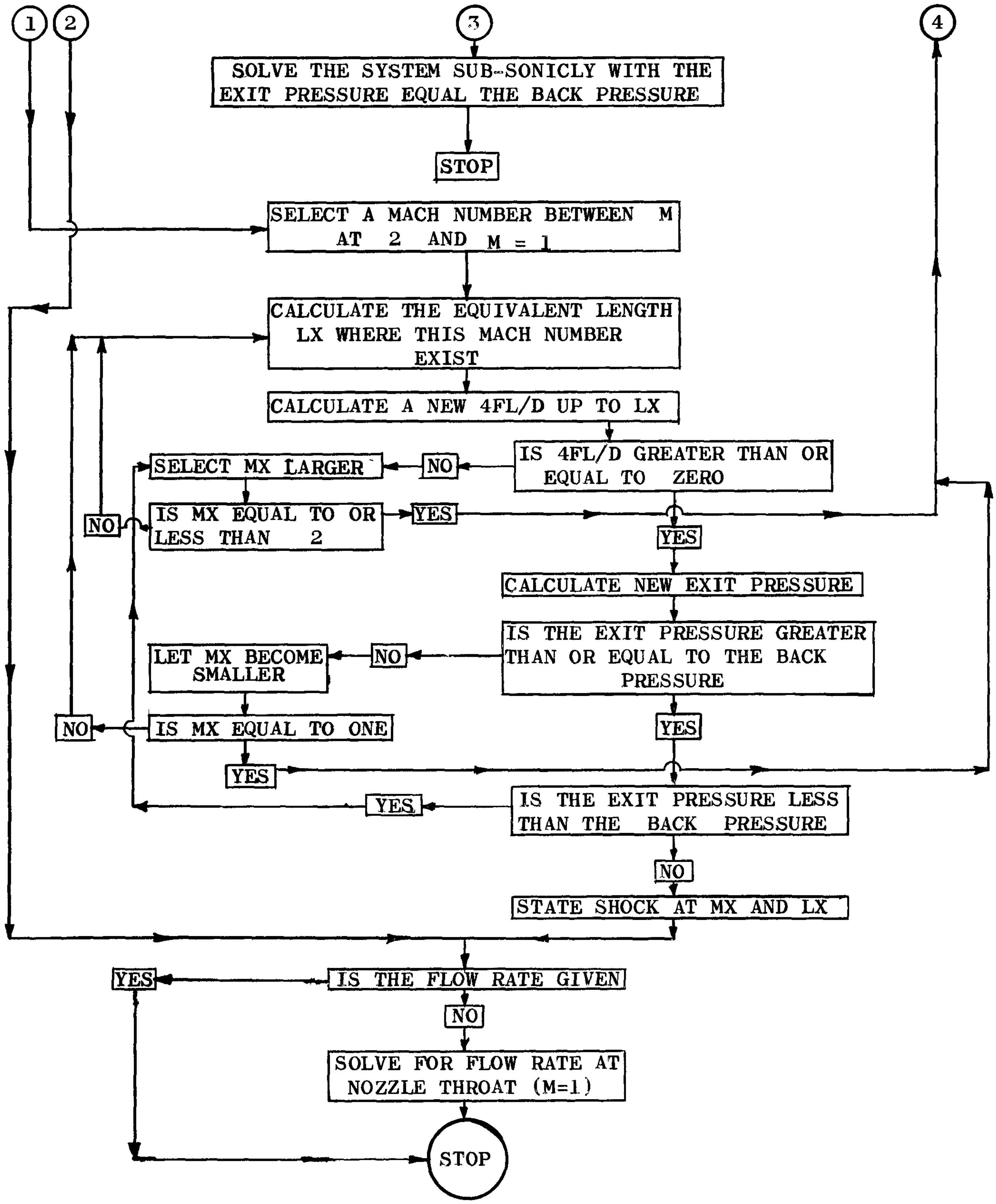
i	=	Initial	2	=	Duct entrance
*	=	Throat	X	=	Station X
Y	=	Station Y	3	=	Duct exit
			e	=	Ambient

LOGIC DIAGRAM

LONG DUCT SHOCK ANALYSIS




1
2
3
IS 4FL/D LESS THAN OR EQUAL TO ZERO
YES
NO
CALCULATE NEW EXIT PRESSURE IS THE EXIT EQUAL TO THE BACK PRESSURE
YES
THE SHOCK IS STANDING AT STATION TWO
NO
IS THE EXIT PRESSURE LARGER THAN BACK PRESSURE
YES
NO
CHOOSE A MACH NUMBER BETWEEN MACH AT STATION TWO AND ONE (MY)
CALCULATE THE AREA IN THE NOZZLE WHERE THIS MACH NUMBER OCCURS (AY)
ASSUME SHOCK AT THIS POINT AND CALCULATE NEW EXIT PRESSURE
IS THE EXIT PRESSURE GREATER THAN THE BACK PRESSURE
YES
INCREASE MY
NO
IS THE EXIT PRESSURE LESS THAN THAN THE BACK PRESSURE
YES
DECREASE MY
IS MY EQUAL TO OR LESS THAN ONE
NO
YES
NO
THE SHOCK IS STANDING AT MY AND AY
1
2
3
4


1
2
3
4
SOLVE THE SYSTEM SUB-SONICLY WITH THE EXIT PRESSURE EQUAL THE BACK PRESSURE
STOP
SELECT A MACH NUMBER BETWEEN M AT 2 AND M = 1
CALCULATE THE EQUIVALENT LENGTH LX WHERE THIS MACH NUMBER EXIST
CALCULATE A NEW 4FL/D UP TO LX
IS 4FL/D GREATER THAN OR EQUAL TO ZERO
NO
SELECT MX LARGER
IS MX EQUAL TO OR LESS THAN 2
YES
NO
YES
CALCULATE NEW EXIT PRESSURE
IS THE EXIT PRESSURE GREATER THAN OR EQUAL TO THE BACK PRESSURE
NO
LET MX BECOME SMALLER
IS MX EQUAL TO ONE
NO
YES
YES
IS THE EXIT PRESSURE LESS THAN THE BACK PRESSURE
YES
NO
STATE SHOCK AT MX AND LX
IS THE FLOW RATE GIVEN
YES
NO
SOLVE FOR FLOW RATE AT NOZZLE THROAT (M=1)
STOP

ANALYTICAL MODEL

1. Equations

0.) Is $W_i = 0$; yes, skip to 1.)

$$P_i^o = \frac{W_i \, (T_i^o)^{1/2}}{A^* \left[\frac{kgc}{R} \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}} \right]^{1/2}}$$

1.) Calculate $M_2 > 1$ by Newton's Iteration

$$\frac{A^*}{A_2} = \frac{\left(\frac{k+1}{2} \right)^{\frac{k+1}{2(k-1)}}}{\left(1 + \frac{k-1}{2k} M_2^2\right)^{\frac{k+1}{2(k-1)}}}$$

2.) $$4FL/D(MAX) = \left[\frac{k+1}{2\,k} \quad Ln \left(\frac{\left(1 + \frac{k-1}{2}\right) M_2^2}{1 + \frac{k-1}{2} M_2^2} \right) \right] + \frac{1 - M_2^2}{k \, M_2^2}$$

3.) $X = 4FL/D$

4.) $4FL/D(1) = 4FL/D(MAX) - X$

5.) a) If $4FL/D(1) > 0$ go to 6.)

b) If $4FL/D(1) < 0$ go to 13.)

6.) Solve for M_3 by Newton's Iteration

$M_2 > M_3 > 1$

$$4FL/D(1) = \left[\frac{k+1}{2k} \quad ln \frac{\left(1 + \frac{k-1}{2}\right) M_3^2}{1 + \left(\frac{k-1}{2}\right) M_3^2} \right] + \frac{1 - M_3^2}{k \, M_3^2}$$

7.) $$P_2 = P_i \left(1 + \frac{k-1}{2} M_2^2\right)^{\frac{k}{k-1}}$$

8.) $P_i^* = P_2 M_2 \left(\frac{k + 1}{2(1 + \frac{k - 1}{2} M_3^2)} \right)^{-1/2}$

9.) $P_3 = \frac{P_i^*}{M_3} \left(\frac{k + 1}{2(1 + \frac{k - 1}{2} M_3^2)} \right)^{1/2}$

10.) a) If $P_3 \geq P_e$ skip to 63.) and state No Shock

b) If $P_3 < P_e$ skip to 11.)

11.) $P_{3a} = P_3 \left(\frac{2kM_3^2 - (k - 1)}{k + 1} \right)$

12.) a) If $P_{3a} < P_e$ skip to 13.)

b) If $P_{3a} \geq P_e$ shock at exit of duct; skip to 63.)

13.) $M_{2a} = \left[\frac{(k - 1)\left(\frac{2kM_2^2 - (k - 1)}{k + 1} \right) + k + 1}{2\left(\frac{2kM_2^2 - (k - 1)}{k + 1} \right)} \right]^{1/2}$

14.) $4FL/D\ MAX(2) = \frac{k + 1}{2k} \ln \frac{(k + 1)M_{2a}^2}{2(1 + \frac{k - 1}{2} M_{2a}^2)} + \frac{1 - M_{2a}^2}{k M_{2a}^2}$

15.) $4FL/D(2) = 4FL/D\ MAX(2) - X$

16.) a) If $4FL/D(2) < 0$ skip to Eqn. 22.)

b) If $4FL/D(2) \geq 0$ skip to 17.)

17.) Solve for M_3' by Newton's Iteration

M_3' 1

$4FL/D(2) = \frac{K + 1}{} \ln \frac{(K + 1)M_3'^2}{2(1 + \frac{k - 1}{2} M_3'^2)} + \frac{1 - M_3'^2}{M_3'^2}$

18.) $P_{2a} = P_2 \frac{2kM_2^2 - (k - 1)}{k + 1}$

19.) $$P_{2a}{}^{*} = P_{2a} M_{2a} \left[\frac{k + 1}{2(1 + \frac{k - 1}{2} M_{2a}{}^{2})} \right]^{-1/2}$$

20.) $$P_3{}' = \frac{P_{2a}{}^{*}}{M_3{}'} \left[\frac{k + 1}{2(1 + \frac{k - 1}{2} M_3{}'^{2})} \right]^{1/2}$$

21.) a) If $\left| \frac{P_3{}'}{P_e} - 1 \right| < .0001$ Shock at Station 2; skip to 63.)

b) If $P_3{}' > P_e$ Shock in duct skip to 50.)

c) If $P_3{}' < P_e$ Shock in nozzle or flow is subsonic; skip to 22.)

22.) SET $$M_y = \frac{M_2 + 1}{2}$$

23.) $$A_y = \frac{A^*}{M_y} \left[\frac{2(1 + \frac{k - 1}{2} M_y{}^{2})}{k + 1} \right]^{\frac{k + 1}{2(k - 1)}}$$

24.) $$P_y = P_i \left(1 + \frac{k - 1}{2} M_y{}^{2}\right)^{\frac{k + 1}{2(k - 1)}}$$

25.) $$M_{ya} = \left[\frac{(k - 1)\left(\frac{2 My^2 - (k - 1)}{k + 1}\right) + (k + 1)}{2 \; \frac{2kMy^2 - (k - 1)}{k + 1}} \right]^{1/2}$$

26.) $$P_{ya} = P_y \left(\frac{2kMy^2 - (k - 1)}{k + 1} \right)$$

28.) Solve for M_{n2} by Newton's Method

$M_{n2} < 1$

$$\frac{A_y}{A_2} Mya \left(1 + \frac{k-1}{2} M_{ya}^2\right)^{-\frac{k+1}{2(k-1)}} = M_{n2} \left(1 + \frac{k-1}{2} M_{n2}^2\right)^{-\frac{k-1}{2(k-1)}}$$

29.) $$P_n^* = \frac{M_{n2} P_{ya}}{\left[\dfrac{k+1}{2(1 + \frac{k-1}{2k} M_{n2}^2}\right]^{1/2}} \left[\frac{1 + \frac{k-1}{2} M_{ya}^2}{1 + \frac{k-1}{2} M_{n2}^2}\right]^{\frac{k}{k-1}}$$

30.) $$4FL/D(MAX)(N) = \frac{k+1}{2k} \text{ in } \frac{(1 + \frac{k-1}{2}) M_{n2}^2}{1 + \frac{k-1}{2} M_{n2}^2} + \frac{1 - M_{n2}^2}{k M_{n2}^2}$$

31.) 4FL/DCN) = 4FL/DMAX(N) - X

a) If 4FL/D(N) > 0 skip to 32.)

b) If MY < MAXMY, MAXMY = MY

c) $MY = \frac{MAXMY + 1}{2}$

d) If MY $\cong$ 1 skip to 35.)

e) If MY > 1 skip to 23.)

32.) Solve for M_{n3} using Newton's Method $M_{n3} < 1$

$$4FL/DCN) = \frac{k+1}{2k} \ln \frac{(1 + \frac{k-1}{2} M_{n3}^2)}{1 + (\frac{k-1}{2}) M_{n3}^2} + \frac{1 - M_{n3}^2}{k M_{n3}^2}$$

33.) $$P_{3N} = \frac{P_n^*}{M_{N3}} \left(\frac{k+1}{2(1 + \frac{k-1}{2} M_{N3})}\right)^{1/2}$$

34.) a.) If $\left(\frac{P_{3N}}{P_e} - 1\right) < .0001$ Shock at A_Y. skip to 63.)

b.) If $P_{3N} < P_E$

1.) If MY-1. < .001 skip to 35.)

2.) $MY_L = \frac{MY_{i-1} + 1}{2}$

3.) If $MY_{i-1} <$ MAXMY

Set MAXMY = MY_{i-1}

4.) Skip to 34.)d.)

c.) If $P_{3N} > P_E$

1.) If $MY_{i-1} - M_2 < .001$ error

2.) If $MY_{i-1} >$ MINMY

set MINMY - MY_{i-1}

3.) $MY_i = \frac{MY_{i-1} + M_2}{2}$

4.) Skip to 34.)d.)

d.) If MINMY < MY_i < MAXMY Skip to 23.)

If not $MY_i = \frac{MINMY + MAXMY}{2}$ skip to 23.)

35.) Set MT = .7

36.)
$$A_C{}^* = \frac{A^*\left(\frac{k-1}{2}\right)^{\frac{k+1}{2(k-1)}} M_T}{\left(1 + \frac{k+1}{2} M_T{}^2\right)^{\frac{k+1}{2(k-1)}}}$$

37.) Solve for M_{2C} using Newton's Method $M_{2C} < 1$

$$\frac{A_C{}^*}{A_2} = \frac{\left(\frac{k+1}{2}\right)^{\frac{k+1}{2(k-1)}} M_{2C}}{\left(1 + \left(\frac{k-1}{2}\right) M_{2C}{}^2\right)^{\frac{k+1}{2(k-1)}}}$$

38.) $P_{2C} = P_{io}\ (1 + \frac{k-1}{2} M_{2C}^2)^{-k/k-1}$

39.) $P_C^* = P_{2C} \cdot M_{2C} \left[\frac{k-1}{2(1 + (\frac{k-1}{2}) M_{2C}^2)} \right]^{-1/2}$

40.) $4FL/D_{MAXC} = \frac{k+1}{2} \ln \frac{(1 + \frac{k-1}{2}) M_{2C}^2}{1 + \frac{k-1}{2} M_{2C}^2} + \frac{1 - M_{2C}^2}{k\ M_{2C}^2}$

41.) $4FL/D_{(C)} = 4FL/DMAXC - X$

42.) If 4FL/D(C) LO error, If not continue

43.) Solve for M_{3C} using Newton's Method $M_{3C} < 1$

$$4FL/D(c) = \frac{k+1}{2} \ln \frac{(1 + \frac{k-1}{2}) M_{3C}^2}{1 + \frac{k-1}{2} M_{3C}^2} + \frac{1 - M_{3C}^2}{k\ M_{3C}^2}$$

44.) $P_{3C} = \frac{P_C^*}{M_{3C}} \left(\frac{k+1}{2(1 + \frac{k-1}{2} M_{3C}^2)} \right)^{1/2}$

a.) If $\left| \frac{P_{3C}}{P_E} - 1. \right| < .0001$ skip to 45.)

b.) If $P_{3C} > P_E$

1.) If MT > MINMT
MINMT = MT, if not skip to 2.)

2.) $MT = \frac{MT + 1}{2}$

3.) Skip to 44d.)

c.) If $P_{3C} < P_e$

1.) If MT < MAXMT
MAXMT = MT, if not skip to 2.)

2.) $MT = \frac{MT}{2}$

3.) Skip to 44d.)

4.) If MINMT < MT < MAXMT skip to 36.)
If not $MT = \frac{MINMT + MAXMT}{2}$ skip to 36.)

45.) $T_{2C} = T_i \left(1 + \frac{k-1}{2} M_{2C}^2\right)^{-1}$

46.) $\hat{W} = \frac{P_{2C}}{T_{2C} R} \cdot M_{2C} (32.2\ k\ RT_{2C})^{1/2} \cdot A_2$

47.) Solve for M_{iC} by Newton's Iteration $M_{iC} < 1$

$$\frac{A^*_C}{A_1} = M_{iC} \left[\frac{2\left(1 + \frac{k-1}{2} M_{iC}^2\right)}{k+1}\right]^{-\frac{k+1}{2(k-1)}}$$

48.) $P_{iC} = P_o \left(1 + \frac{k-1}{2} M_{iC}^2\right)^{-k/k-1}$

49.) Print $\dot{W}$, P_{iC} and state flow **is** subsonic, end case

50.) $MX = \frac{M_2 + 1}{2}$, MAXMX $= M_2$, MINMX $= 1$

51.) $$4FL/D_{(MAX(X)} = \frac{k+1}{2k} \ln \frac{\left(1 + \frac{k-1}{2}\right) M_X^2}{1 + \frac{k-1}{2} M_X} + \frac{1 - M_X^2}{k\ M_X^2}$$

52.) $Y = 4FL/D_{MAX(1)} - 4FL/D_{(MAX(X)}$

If $Y < 0$ $MX = \frac{M_X + M_2}{2}$, if $M_X = M_2$ go to 22

If not go to 51.)

If > 0 go to 52a

52a) $L_X = \frac{DY}{4F}$

53.) $$M_{Xa} = \left[\frac{(k-1)\frac{2 M_4^2 - (k-1)}{k+1} + (k+1)}{2k\left(\frac{2 M_4^2 - (k-1)}{k+1}\right)}\right]^{1/2}$$

54.) $P_X = \frac{P_i^*}{M_X} \left(\frac{k + 1}{2\,(1 + \frac{k - 1}{2} M_4^2)} \right)^{1/2}$

54A.) $P_{Xa} = P_X \left(\frac{2\,M_4^2 - (k - 1)}{k + 1} \right)$

55.) $P_{Xa}^* = P_{Xa} \cdot M_{Xa} \left(\frac{k + 1}{2(1 + \frac{k - 1}{2} M_{Xa}^2)} \right)^{-1/2}$

56.) $4FL/D_{(MAX)(XA)} = \frac{k + 1}{2k} \text{ in } \frac{(1 + \frac{k - 1}{2}) M_{Xa}^2}{1 + \frac{k - 1}{2} M_{Xa}^2} + \frac{1 - M_{Xa}^2}{k\,M_{Xa}^2}$

57.) $Z = \frac{4F(L - L_X)}{D}$

58.) $4FL/D_{(Xa)} = 4FL/D_{(MAX(XA)} - Z$

59.) If $4Fl/D_{(Xa)} < 0$ set $M_X = \frac{M_X + M_2}{2}$, if $M_X = 1$ go to 66.)

a.) If $M_X = M_2$ error, if not skip to 51.)

b.) If $4Fl/D_{(Xa)} \geq 0$ continue

60.) Solve for M_{3X} using Newton's Method $M_{3X} < 1$

$$4FL/D_{(xa)} = \frac{k + 1}{2k} \ln \frac{(1 + \frac{k - 1}{2}) M_{3X}^2}{1 + \frac{k - 1}{2} M_{3X}^2} + \frac{1 - M_{3X}^2}{k\,M_{3X}^2}$$

61.) $P_{3X} = \frac{P_{4a}^*}{M_{3X}} \left(\frac{k + 1}{2(1 + \frac{k - 1}{2} M_{3X}^2)} \right)^{1/2}$

62.) a.) If $\left| \frac{P_{3X}}{P_E} - 1. \right| < .0001$ state shock at LX skip to 63.)

b.) If $P_{3X} > P_E$

1.) If M_X MAXMX set MAXMX = M_X

2.) $M_X = \frac{M_2 + 1}{2}$, if MX $\cong$ 1 go to 68.)

3.) Skip to 62d)

c.) If $P_{3X} < P_E$

1.) If MX < MINMX set MINMX = MX

2.) $MX = \frac{M_2 + M_X}{2}$, if MX $\cong$ M_2 go to 22.)

3.) Skip to 62d)

62A) If MINMX < MX < MAXMX skip to 51.)

If not $MX = \frac{MINMX + MAXMX}{2}$ skip to 51.)

63.) $T_i^* = \frac{T_o}{(\frac{k + 1}{2})}$

64.) $P^* = P_2 \left[\frac{k + 1}{2(1 + \frac{k - 1}{2})} \right]^{-k/k-1}$

65.) $\dot{W} = \rho^* A^* \sqrt{gc\ R\ k\ T_i^*}$

where ρ is function of para-hydrogen

66.) Print impossible physical condition.

[redacted]

CUSTOMER INSTRUCTIONS	KEYPUNCH INSTRUCTIONS	
1. ENTER DATA LEGIBLY WITHIN SPACES PROVIDED	X PUNCH 1 CARD PER HAND POSTED LINE ITEM	CUSTOMER: NERVA
2. DISTINGUISH BETWEEN I vs 1, Ø vs 0, Z vs 2, U vs V, S̄ vs 5	PUNCH ALL * LINES WHETHER POSTED OR NOT. IF NECESSARY PROVIDE BLANK CARDS	DATE:
	PUNCH ALL * LINES THAT ARE HAND POSTED	JOB NO.: 12007
	PAS INCLUDING SPACES	PROGRAMMER: R. Wick
	ALL SPACES MAY BE IGNORED	TITLE: LONG DUCT SHOCK ANALYSIS
	X ALL SPACES MAY BE IGNORED EXCEPT ON T CARD	FORM APPROVED (KEY PUNCH):
	ALL SPACES MAY BE IGNORED EXCEPT (Specify cols.)	DATE:
	X ALL SIGNS ON KEY PUNCH LINES MUST BE PUNCHED	
	DO NOT PUNCH PRE-PRINTED SIGNS SHOWN AFTER LAST HANDWRITTEN VALUE ENTRY	

Card					
	K	R	A_1	A*	A_2
L 0	+1.4	+9170.0	+505.0	+290.0	+2360.0
	L	F	D	P_1°	T_1°
L 5	+888.0	+.004	+24.0	+60.0	+280.0
	P_e	W DOT	DUMP FLAG		
L 1 0	+14.7	+0.0	+0.0		

REMARKS

T LONG DUCT ANALYSIS SAMPLE CASE

Card					
	K	R	A_1	A*	A_2
L 0	+	+	+	+	+
	L	F	D	P_1°	T_1°
L 5	+	+	+	+	+
	P_e	W DOT	DUMP FLAG		
L 1 0	+	+	+		

REMARKS

T

SAMPLE INPUT

B-1

AGC 2-411 (Master)

PLEASE PRINT CLEARLY - USE BLACK PENCIL

SAMPLE OUTPUT

LONG DUCT ANALYSIS   SAMPLE CASE

GAMMA	R	AI	A*	A2	L	F	D	PIO	TIO	PE	WDOT
1.4000	9170.00	505.00	290.00	2360.00	888.00	.004	24.000	60.00	280.00	14.70	.00

SHOCK STANDING AT AY = 1531.44 AND MY = 3.232

WDOT = 145.71