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DIVISION SNAP-8

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TECHNICAL MEMORANDUM

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TITLE: A STUDY OF A CONDENSER INVENTORY CONTROL FOR THE SNAP-8 SYSTEM

ABSTRACT

This report presents the results of a study to determine the effectiveness of a mercury inventory control system to regulate condensing pressure within limits bounded by mercury pump cavitation on the low side and turbine output power requirements on the high side.

The results show that the inventory control system can regulate condensing pressure within system limits although it is more effective in its ability to increase condensing pressure than to reduce it. Limitations exist involving system instability for narrow pressure regulation and the biasing effects which could result from vehicle acceleration.

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## I INTRODUCTION

This study was undertaken to determine the characteristics of a condenser inventory control system and its effectiveness in controlling mercury condensing pressure for all disturbances the SNAP-8 system is likely to encounter during a 10,000 hour mission. For the control system to be effective it is required to maintain the condensing pressure above a low limit dictated by the mercury pump minimum NPSH to prevent pump cavitation and below a high limit dictated by a failure to provide required turbine power output due to excessive back pressure. The control system was added to the analog computer simulation of the SNAP-8 flight reference system (Rev. B) and computer runs were made.

## II DESCRIPTION OF THE INVENTORY CONTROL SYSTEM

The condenser inventory control system as shown in Figure A consists of a metal cylinder which contains a metal bellows with precharged gas on one side and liquid mercury on the discharge side. The cylinder is connected to the condenser mercury discharge manifold such that a movement of the bellows due to pressure changes causes a shift in condenser inventory and therefore condensing length. Since the condensing pressure is a direct function of condensing length, an inventory system should be able to control the condensing pressure. As an example of how this system operates a sun-shade system transient can be examined. When the main radiator goes from a sun to a shade environment, the NaK temperature of the condenser drops approximately 20°F causing the condensing pressure of the mercury to drop. This causes a pressure unbalance across the control bellows which results in mercury being shifted into the condenser until pressure equilibrium is again established. The condensing pressure increases as the condensing length decreases until the inventory control stops injecting mercury. There is some offset of the condensing pressure from the original control set point due to:

1. The bellows spring gradient
2. Change in gas pressure with bellows volume changes
3. Change in condenser pressure drop with condensing length

The offset is minimized in the direction of decreasing spring gradient and increased gas volume.

An analysis of the dynamics of the control system is shown in the appendix along with the resultant transfer function for the system. This analysis contained the following assumptions:

1. The system is operating in an earth orbit under zero "G" conditions. (there are no vehicle acceleration forces)
2. The mercury in the inventory cylinder acts as one continuous mass.
3. Fluid damping is present due to the movement of the liquid mercury through a restricted area entering or leaving the cylinder.
4. The damping is viscous (proportional to the first power of velocity).

### III DESCRIPTION OF THE CONDENSER COMPUTER SIMULATION

The analog computer simulation of the SNAP-8 condenser was modified to reflect the latest information available from the "MECA" testing of the condenser. The condenser overall heat transfer coefficient was increased from 1000 to 1900 BTU/hr-ft<sup>2</sup>-°R and pressure drop vs. condensing length was inserted into the simulation. The latest -1 condenser tube geometry was used; tube area and volume equations were written to accurately describe the tapered tube. Since the computer simulation depicts the flight reference "B" mercury flow rate of 9100 lbs per hour, the number of tubes was reduced to 60 to provide the same flow per tube as the -1 condenser and, therefore, the same pressure drop. The condenser equations are as shown in the appendix.

### IV DESCRIPTION OF THE COMPUTER RUNS

The initial control system gain was found to be excessive for the system since the system became unstable when the control was switched into the loop. The initial gain was derived to provide for  $\pm 1$  psi pressure regulation (see appendix) for  $\pm 50$  lbs of inventory change. The gain was reduced to approximately  $\pm 5$  psi for  $\pm 50$  lbs of inventory change as shown in Figure B. This gain does not represent the highest gain which could be obtained since the

damping factor and natural frequency of the system could be changed to provide for increased stability margin. Figure B shows the locus of operation of the control with changes in condenser NaK outlet temperatures. The intersection of the control set point pressure and rated NaK temperature shows the nominal rated operating point of the condenser. The resultant condensing pressure for a change in NaK temperatures would correspond to the vertical intersection with the temperature curve if no inventory control were present. In other words, the locus of pressure with changes in NaK temperatures occurs at a constant condensing length for no control. With an inventory control, the condensing length varies with changes in control inventory and pressure is controlled along the slanted line which results in less total pressure deviation for given NaK temperature changes. The higher the control gain the more nearly horizontal the control line becomes and the smaller the resultant pressure variations for temperature changes. The control line in Figure B below the normal operating line shows the effect of 20 lbs loss of mercury from the inventory cylinder which includes 10 lbs of leakage past the TAA space seals and a 10 lb shift of mercury to the boiler. The drop in the operating line is caused by reduced gas pressure in the bellows when it expands to occupy the volume left by the 20 lbs of mercury. This variation in pressure could be minimized by sizing the gas volume larger initially since the pressure change is inversely proportional to initial gas volume. Leakage of 20 lbs without a control is represented by an increase in condensing length corresponding to the 20 lbs reduction in condenser inventory. The resultant condensing pressure is then the intersection of the new condensing length with the rated NaK temperature line. A limitation on the effectiveness of the inventory control is apparent on close examination of Figure B. The pressure profiles of the condenser approach a horizontal asymptote at long condensing lengths which coincide with the vapor pressure of mercury corresponding to the NaK outlet temperature. This occurs because the minimum mercury condensing temperature cannot be less than the NaK coolant temperature. Therefore the minimum condensing pressure obtainable is dictated by the coolant and not the control. Any attempt to reduce the pressure to that minimum would result in a complete evacuation of the mercury inventory in the condenser.

Computer runs which were made on the computer are summarized in Table I and include sun-shade, variations in NaK exit temperature of the condenser, and 20 lbs leakage from the control cylinder. Vehicle load changes of 35 kw were made but are not reported since the steady state changes in pressure are small with or without the control. A sun-shade computer run with and without the inventory control system is shown by Figures E and F respectively.

#### V SUMMARY AND CONCLUSIONS

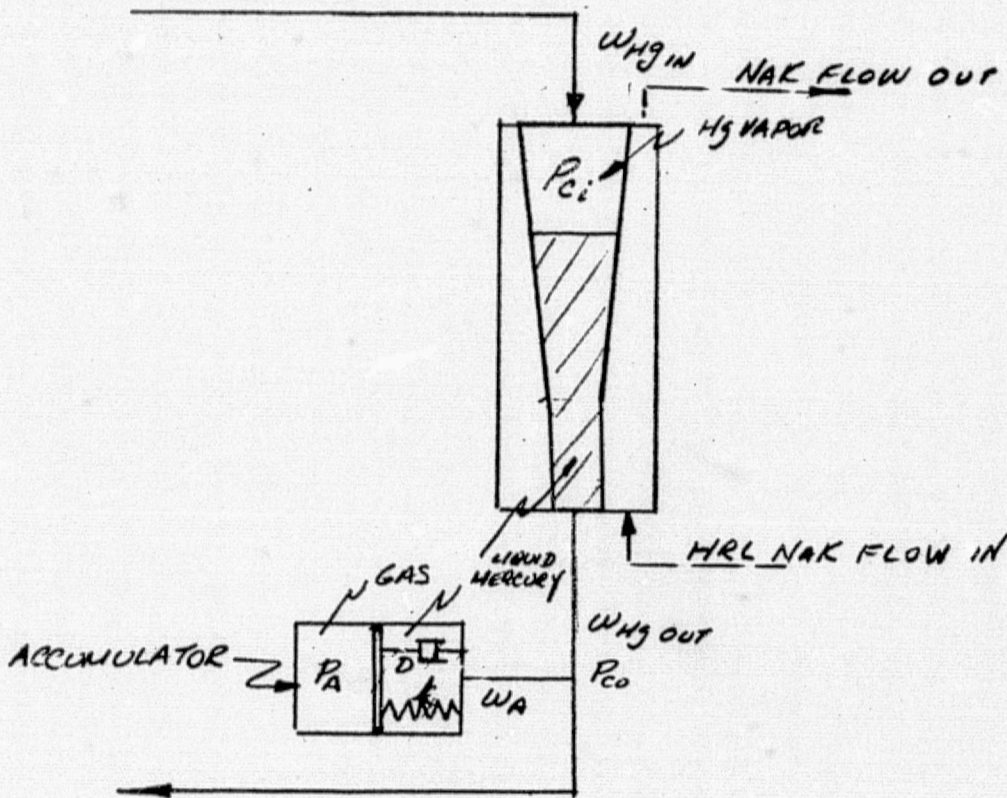
The condenser inventory control system is a feasible means of controlling condensing pressure although there are limitations on its effectiveness. These limitations involve the requirement of maintaining system stability which may require increased pressure regulation limits by a necessity to reduce the control gain. The lack of control of condenser NaK exit temperature also limits the minimum obtainable condensing pressure regardless of control gain. The inventory control therefore is more effective in increasing condensing pressure than reducing it. A biasing effect on the operation of the inventory control would be the effect of acceleration forces on the liquid mercury columns during orbit departures. This effect could be somewhat minimized by equalizing the column heights by proper location of the control cylinder in relation to the condenser nominal interface position of the mercury.

Advantages of the condenser inventory control involve its simplicity, reliability and ability to maintain a relatively fixed inventory in the condenser with mercury leakage and variable boiler inventory.



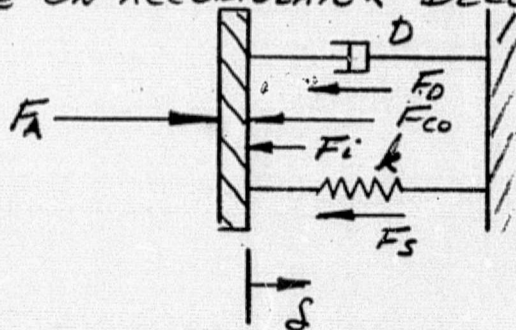
VI APPENDIX

DYNAMIC ANALYSIS OF A MERCURY INVENTORY CONTROL OF THE SNAP-8 CONDENSER PRESSURE



ACCUMULATOR DYNAMIC EQUATIONS

FORCE BALANCE ON ACCUMULATOR BELLOWS



- $F_i$  = INERTIA FORCE
- $F_d$  = DAMPING FORCE
- $F_s$  = SPRING FORCE
- $F_A, F_{Co}$  = PRESSURE FORCES

- $A$  = BELLOWS AREA
- $M$  = TOTAL MASS OF MERCURY LIQUID DISPLACED IN SYSTEM

$\Sigma F = 0$

$F_i + F_d + F_s = (F_A - F_{Co})$   
 $M\ddot{\delta} + D\dot{\delta} + k\delta = (P_A - P_{Co})A$

since  $W_A = \frac{dm}{dt} = \frac{d}{dt}(\rho A \delta) = \rho A \dot{\delta}$

$\dot{\delta} = \frac{W_A}{\rho A}$        $\delta = \frac{1}{\rho A} \int W_A dt$

$\ddot{\delta} = \frac{\dot{W}_A}{\rho A}$

FLOW OUT OF (+) OR INTO (-) ACCUMULATOR



$$\frac{1}{\rho A} [M \dot{w}_a + D w_a + k \int w_a dt] = (P_a - P_{c0}) A$$

TRANSPOSING TO THE LAPLACIAN DOMAIN

$$\frac{1}{\rho A} [M s + D + \frac{k}{s}] w_a(s) = [P_a(s) - P_{c0}(s)] A$$

$$\begin{aligned} \frac{w_a(s)}{P_a(s) - P_{c0}(s)} &= \frac{\rho A^2}{M s + D + \frac{k}{s}} \\ &= \frac{\rho A^2 s}{M s^2 + D s + k} \\ &= \frac{[\frac{\rho A^2}{M}] s}{s^2 + \frac{D}{M} s + \frac{k}{M}} \end{aligned}$$

$$\boxed{\frac{w_a(s)}{P_a(s) - P_{c0}(s)} = \frac{K_0 s}{s^2 + a s + b}}, \quad \frac{\text{LBS/SEC}}{\text{LB/FT}^2}$$

$\rho$  = DENSITY OF MERCURY LIQUID  $\approx 800 \text{ #/FT}^3$

$A$  = AREA OF BELLOWS =  $0.785 \text{ FT}^2$  (FOR  $D = 1.0 \text{ FT}$ )

$M$  = MASS OF MERCURY LIQUID IN ACCUMULATOR

$$M = \frac{50 \text{ LBS}}{32.2 \text{ FT/SEC}^2} = 1.55 \text{ SLUGS}$$

$D$  = DAMPING FACTOR =  $\text{LBS/FT/SEC}$

$k$  = SPRING RATE =  $\text{LBS/FT}$

$$F_{S \text{ MAX}} = k S_{\text{MAX}} = k (\Delta V_{\text{MAX}} / A) = k \left( \frac{W_{A \text{ MAX}}}{\rho A} \right)$$

$$k = \frac{F_{S \text{ MAX}} \times \rho \times A}{W_{A \text{ MAX}}} = \frac{113 \times 800 \times 0.785}{50 \text{ LBS}} = 1420 \text{ LBS/FT}$$

$$F_{S \text{ MAX}} = 144 \times 0.785 \text{ FT}^2 = 113 \text{ LBS} \quad \text{FOR 1 PSI STEADY STATE ERROR}$$



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$$b = \frac{k}{M} = \frac{1420}{1.55} = \underline{916} \text{ SEC}^{-2} = \omega_{ND}^2$$

NATURAL FREQUENCY =  $(916)^{1/2}$  30.3 RAD/SEC  
OF ACCUMULATOR

$$a = \frac{D}{M} = 2 f \omega_{ND}$$

FOR CRITICAL DAMPING (FASTEST RESPONSE WITH NO OVERSHOOT)  
LET  $f = 1.0$

$$a = \frac{D}{M} = 2(1.0)(30.3) = \underline{60.6 \text{ SEC}^{-1}} = a$$

$$D = 60.6(1.55) = 94 \text{ LBS/FT/SEC}$$

$$\frac{W_a(s)}{P_A(s) - P_{C0}(s)} = \frac{3185}{s^2 + 60.6s + 916}$$

$$\text{STATIC GAIN} = \frac{K_0}{\omega_{ND}^2} = \frac{318}{916} = 0.347 \frac{\text{LBS HG}}{\text{LB/FT}^2}$$

$$K_0 = \frac{\rho A^2}{M} = \frac{800(.785)^2}{1.55} = \underline{318}$$

LET  $W_A(s) = \frac{w_a}{s} = \int w_a dt = \text{CONTROL INVENTORY, LBS CHANGE.}$

$$\frac{W_A(s)}{P_A(s) - P_{C0}(s)} = \frac{318}{s^2 + 60.6s + 916} \quad \frac{\text{LBS HG}}{\text{LB/FT}^2}$$

ACCUMULATOR PRESSURE

$$P_A(V_{A0} + \Delta V_A) = P_{A0} V_{A0}$$

$$\text{OR } P_A = \frac{P_{A0} V_{A0}}{V_{A0} + \Delta V_A}$$

ASSUMING ISOTHERMAL  
EXPANSION ( $T=C$ )



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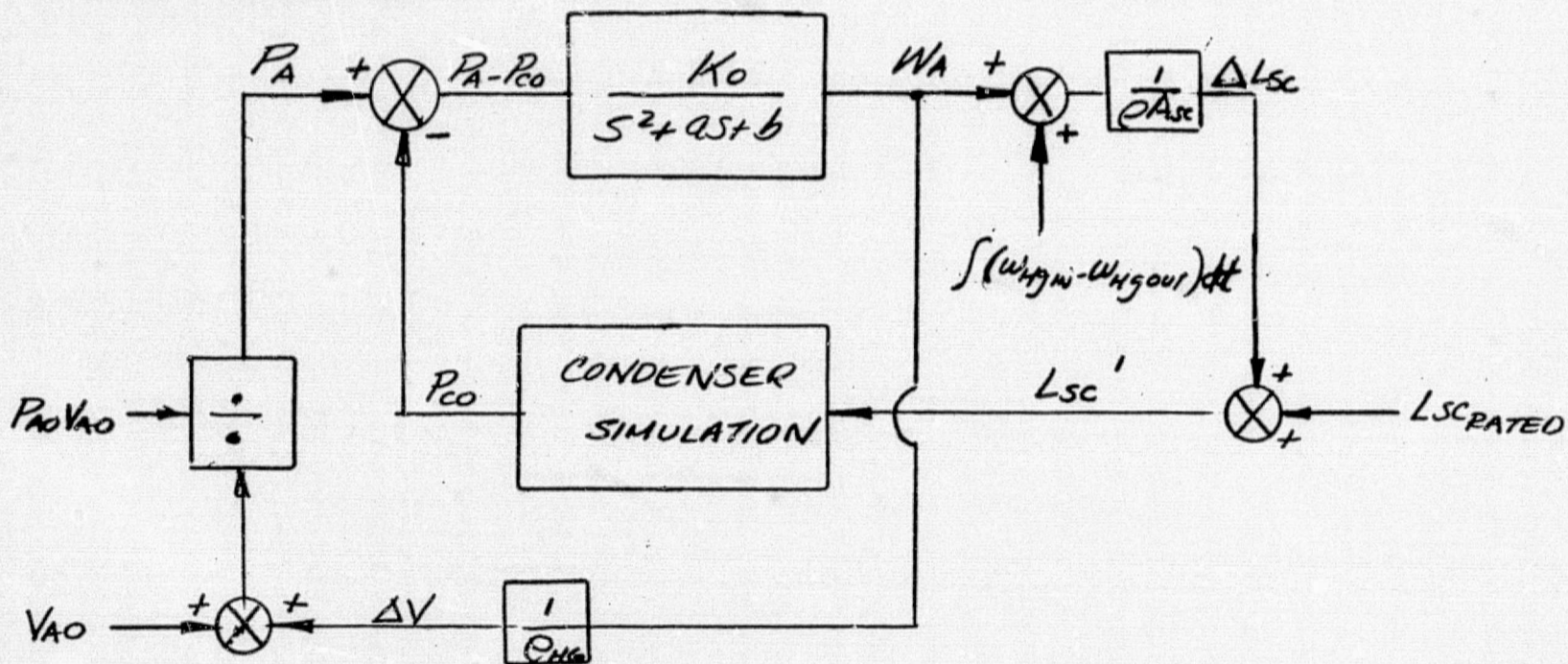
$$\Delta V_A = \frac{1}{\rho} \int W_A dt = \frac{W_A(s)}{\rho}$$

$$P_A(s) = \frac{P_{A0} V_{A0}}{V_{A0} + \frac{W_A(s)}{\rho}}$$

where  $P_{A0}$  = ORIGINAL ACCUMULATOR  
GAS PRESSURE

$V_{A0}$  = ORIGINAL ACCUMULATOR  
GAS VOLUME

BLOCK DIAGRAM



$$P_{A0} V_{A0} = 2230(1.24) = 2765 \text{ LB-FT}$$

$$P_A(s) = \frac{2765}{1.24 + \frac{W_A(s)}{800}} = \frac{2.21 \times 10^6}{992 + W_A(s)}$$

RESULT OF 20# OF MERCURY LEAKAGE FROM ACCUMULATOR

$$M' = \frac{30}{32.2} = 0.932 \quad M/M' = 1.55/0.932 = 1.665$$

$$a' = a \frac{M}{M'} = 60.6 \times 1.665 = 101$$

$$b' = b \frac{M}{M'} = 916 \times 1.665 = 1525$$

$$K_0' = K_0 \times \frac{M}{M'} = 318 \times 1.665 = 530$$

$$\frac{W_A}{P_A - P_{C0}} = \frac{530}{s^2 + 101s + 1525}$$

$$\text{STATIC GAIN} = 530/1525 = 0.347 \frac{\text{LBS Hg}}{\text{LB/FT}^2}$$

$$\text{NATURAL FREQUENCY} = (1525)^{1/2} = 39.1 \text{ RAD/SEC}$$

$$\text{DAMPING FACTOR} = \frac{101}{2(39.1)} = 1.29$$

RESULT: INCREASE IN STABILITY MARGIN FOR LOSS OF 20 # FROM ACCUMULATOR. THE OPERATING PRESSURE WOULD DECREASE 0.4 PSI.

where

$$P_A' = \frac{P_{A0} V_{A0}}{V_{A0} + \Delta V} = \frac{2765}{1.24 + \frac{20}{800}} = \frac{2765}{1.24 + 0.025} = 2185 \text{ PSF}$$

$$P_A' = 15.1 \text{ psi} \quad 1.265$$

$$\Delta P_A = 15.5 - 15.1 = 0.4 \text{ psi } \checkmark$$



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CONDENSER EQUATIONS

1.  $(LMTD)_c = \frac{C_1 X_T W_{216}}{A_c}$
2.  $(LMTD)_c = \frac{(T_{203} - T_{303}) - (T_{202} - T_{302})}{\ln \left( \frac{T_{203} - T_{303}}{T_{202} - T_{302}} \right)}$
3.  $T_{302} = \frac{C_2 A_c (LMTD)_c - C_3 W_3 (T_{302} - T_{303})}{C_4 L_c}$
4.  $T_{303} = \frac{C_6 W_{206} (T_{203} - T_{204}) - C_3 W_3 (T_{303} - T_{304})}{(C_4 + C_7) L_{SC}}$
5.  $P_{202} = f_1(T_{202})$  FROM SATURATION CURVE FOR MERCURY
6.  $P_{203} = P_{202} - \Delta P_c$
7.  $\Delta P_c = f_2(L_c)$  SEE FIG. 1
8.  $T_{203} = f_3(P_{203})$  FROM SATURATION CURVE FOR MERCURY
9.  $T_{204} = T_{304} + C_9$
10.  $L_c = C_5 - L_{SCT}$
11.  $L_{SCT} = \frac{\int (W_{216} - W_{206} + W_A) dt}{C_{10} \times [V_{TSC} / L_{SCT}]}$
12.  $\frac{V_{TSC}}{L_{SCT}} = f_4(L_{SCT})$  SEE FIG 2
13.  $A_c = f_5(L_c)$  SEE FIG 3
14.  $L_{SC} = C_8 + L_{SCT}$

SOLVE FOR  
 $T_{202}$



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CONSTANTS

$$C_1 = h_{fg}/u_c = \frac{126.4}{0.528} = \underline{\underline{239.5}} \text{ SEC-FT}^2\text{-}^\circ\text{F/LB}$$

$$C_2 = u_c = \underline{\underline{0.528}} \text{ BTU/SEC-FT}^2\text{-}^\circ\text{F}$$

$$C_3 = C_{PN} = \underline{\underline{0.21}} \text{ BTU/LB-}^\circ\text{F}$$

$$C_4 = \frac{(MCP)_{TOT}}{LT} = \frac{13.64}{4.295} = \underline{\underline{3.18}} \frac{\text{BTU}}{^\circ\text{F-FT}}$$

$$C_5 = \underline{\underline{3.215}} \text{ FT}$$

$$C_6 = C_{PML} = \underline{\underline{1.0324}} \frac{\text{BTU}}{\text{LB-}^\circ\text{F}}$$

$$C_7 = \frac{(MCP)_{HGL}}{LT} = \frac{2.98}{4.295} = \underline{\underline{0.694}} \frac{\text{BTU}}{^\circ\text{F-FT}}$$

$$C_8 = \underline{\underline{1.075}} \text{ FT}$$

$$C_9 = \underline{\underline{4}} \text{ }^\circ\text{F}$$

$$C_{10} = \rho_{HGL} = \underline{\underline{793}} \text{ LB/FT}^3$$



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RATED CONDITIONS

$$\begin{aligned}
 T_{202} &= 680^{\circ}\text{F} = 1140^{\circ}\text{R} \\
 T_{302} &= 665^{\circ}\text{F} = 1125^{\circ}\text{R} \\
 T_{203} &= 680^{\circ}\text{F} = 1140^{\circ}\text{R} \\
 T_{303} &= 503^{\circ}\text{F} = 963^{\circ}\text{R} \\
 T_{204} &= 499^{\circ}\text{F} = 959^{\circ}\text{R} \\
 T_{304} &= 495^{\circ}\text{F} = 955^{\circ}\text{R} \\
 W_A &= 0 \\
 \Delta P_c &= 0 \\
 P_{302} &= 15.5 \text{ psia} =
 \end{aligned}$$

$$\begin{aligned}
 W_{216} &= W_{201} = 2.53 \text{ LBS/SEC} \\
 W_3 &= 8.89 \text{ LBS/SEC} \\
 X_T &= 0.948 \\
 A_c &= 8.68 \text{ FT}^2 \\
 U_c &= 0.528 \frac{\text{BTU}}{\text{SEC-FT}^2\text{-OF}} \\
 L_c &= 1.44 \text{ FT} \\
 L_{SCF} &= 1.775 \text{ FT}
 \end{aligned}$$

STEADY STATE CHECK OF EQUATIONS

$$1. \quad LMTD_c = \frac{0.948(126.4)(2.53)}{0.528 \times 8.68} = 66^{\circ}\text{F}$$

$$\begin{aligned}
 2. \quad LMTD_c &= \frac{(680^{177} - 503^{15}) - (680 - 665)}{\ln \frac{177}{15}} = \frac{162}{\ln 11.8} \\
 &= \frac{162}{2.47} = 65.6^{\circ}\text{F} \quad \checkmark
 \end{aligned}$$

$$3. \quad \frac{0.528 \times 8.68 \times 66}{302} = \frac{0.21(8.89)(162)}{302} \quad \checkmark$$

$$4. \quad \frac{0.0324(2.53)(181)}{14.84} = \frac{0.21(8.89)(8)}{14.94} \quad \checkmark$$



### GLOSSARY OF TERMS

$T_{202}$	= Hg CONDENSER INLET TEMP	$^{\circ}F$
$T_{203}$	= " " EXIT "	$^{\circ}F$
$T_{204}$	= " SUBCOOLER " "	$^{\circ}F$
$T_{302}$	= NAK CONDENSER " "	$^{\circ}F$
$T_{303}$	= " " INLET "	$^{\circ}F$
$T_{304}$	= " SUBCOOLER " "	$^{\circ}F$
$W_{216}$	= Hg FLOW INTO CONDENSER	LBS/SEC
$W_{206}$	= Hg FLOW FROM PUMP	LBS/SEC
$h_{fg}$	= Hg HEAT OF CONDENSATION	BTU/LB
$X_T$	= Hg QUALITY AT CONDENSER INLET	—
$A_c$	= CONDENSER HEAT TRANSFER AREA	FT <sup>2</sup>
$(LMTD)_c$	= LOG MEAN TEMP. DIFF. FOR CONDENSER	$^{\circ}F$
$W_3$	= NAK FLOW	LBS/SEC
$L_c$	= CONDENSING LENGTH	FT
$L_{SC}$	= SUBCOOLING LENGTH	FT
$L_{SCT}$	= SUBCOOLER TAPERED LENGTH	FT
$P_{202}$	= CONDENSER PRESSURE CORRESPONDING TO $T_{202}$	LBS/FT <sup>2</sup>
$P_{203}$	= " " " " " " $T_{203}$	LBS/FT <sup>2</sup>
$\Delta P_c$	= CONDENSER PRESSURE DROP ( $P_{202} - P_{203}$ )	LBS/FT <sup>2</sup>
$V_{TSC}$	= VOLUME OF TAPERED SECTION OF SUBCOOLER	FT <sup>3</sup>
$U_c$	= OVERALL HEAT TRANSFER COEFFICIENT FOR CONDENSER	$\frac{BTU}{SEC-FT^2-^{\circ}F}$
$C_{PN}$	= SPECIFIC HEAT AT CONSTANT PRESS. FOR NAK	$\frac{BTU}{LB-^{\circ}F}$
$C_{PL}$	= " " " " " " " Hg LIQUID	$\frac{BTU}{LB-^{\circ}F}$
$L_T$	= TOTAL CONDENSER + SUBCOOLER LENGTH	FT
$(MCP)_T$	= TOTAL NAK & CONDENSER METAL CAPACITANCE	$\frac{BTU}{^{\circ}F}$
$(MCP)_{HgL}$	= TOTAL POSSIBLE Hg LIQUID CAPACITANCE	$\frac{BTU}{^{\circ}F}$
$\rho_{HGL}$	= DENSITY OF MERCURY LIQUID	LB/FT <sup>3</sup>

# TABLE I

## TABULATED RESULTS OF COMPUTER RUNS

DISTURBANCE TO CONDENSER	CONDENSING PRESSURE CHANGES	
	WITHOUT CONTROL	WITH CONTROL $K_s \approx .07 \frac{\text{LBS}^4}{\text{LB} \cdot \text{SQ} \cdot \text{FT}}$
SUN-SHADE	- 3.0 psi	- 1.4 psi
NAK EXIT TEMP. OF COND. = 680°F	+ 2.2 psi	+ 1.2 psi
NAK EXIT TEMP OF COND. = 620°F	- 5.0 psi	- 2.5 psi
20 LBS LEAKAGE	- 1.5 psi	- 1.6 psi



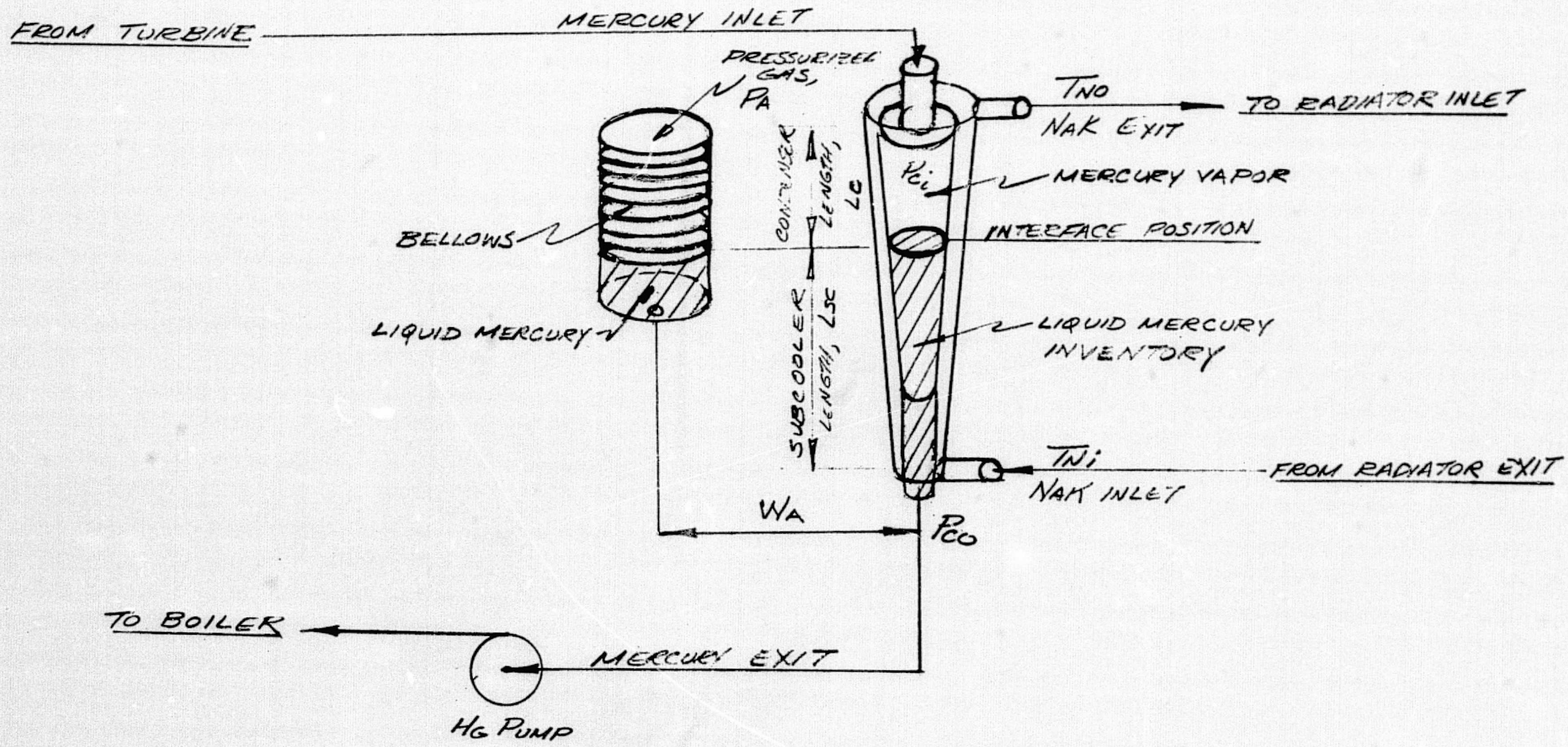
SNAP-8 DIVISION

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VON KARMAN CENTER

FIG. A

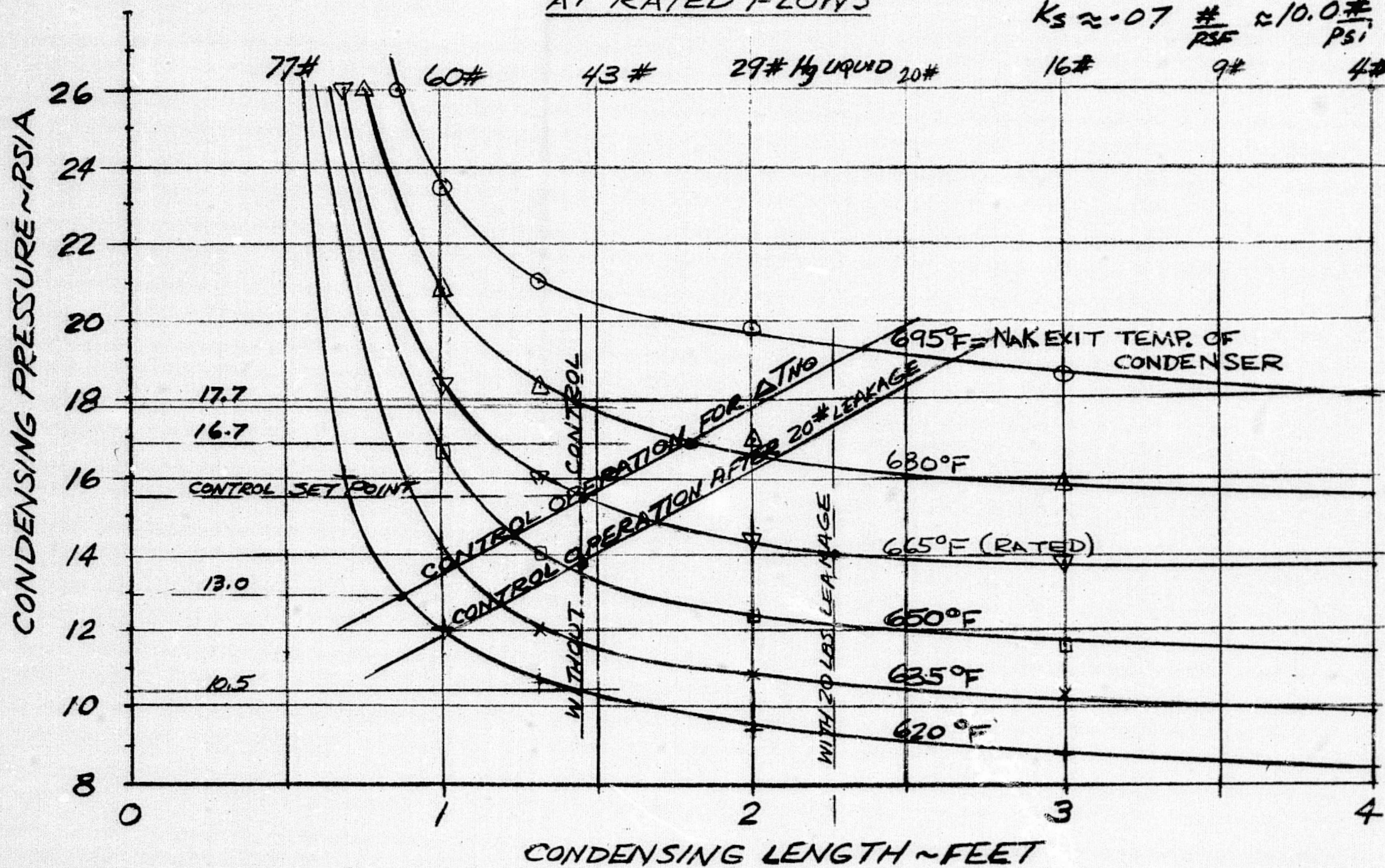
INVENTORY CONTROL SYSTEM



# FIG. B

## CONDENSING PRESSURE VS CONDENSING LENGTH AT RATED FLOWS

$$K_s \approx -0.7 \frac{\#}{\text{PSE}} \approx 10.0 \frac{\#}{\text{PSI}} = \frac{\Delta W}{\Delta P}$$



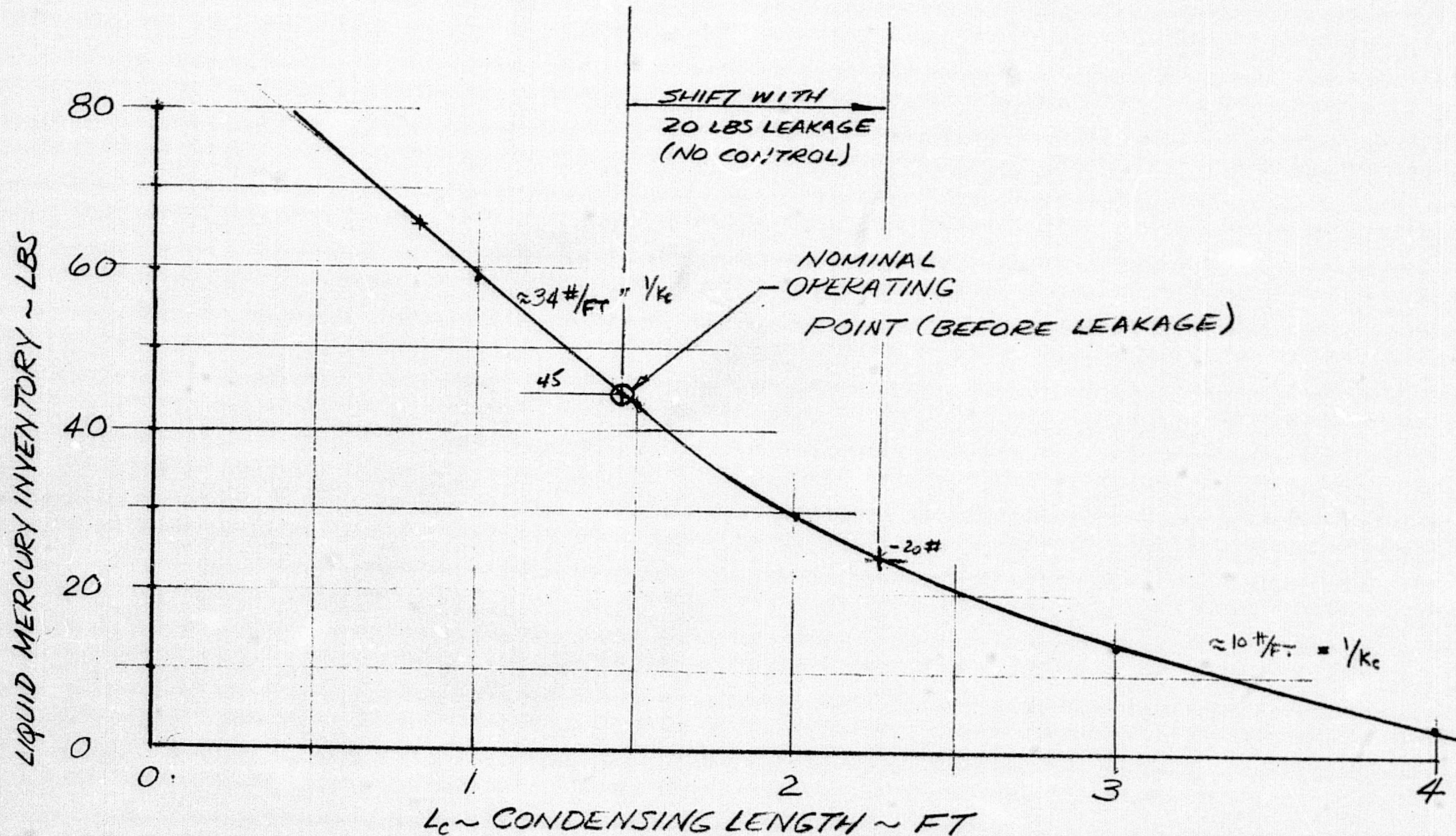
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# FIG. C

## CONDENSOR INVENTORY VS CONDENSING LENGTH

NOTE: 60 TUBES

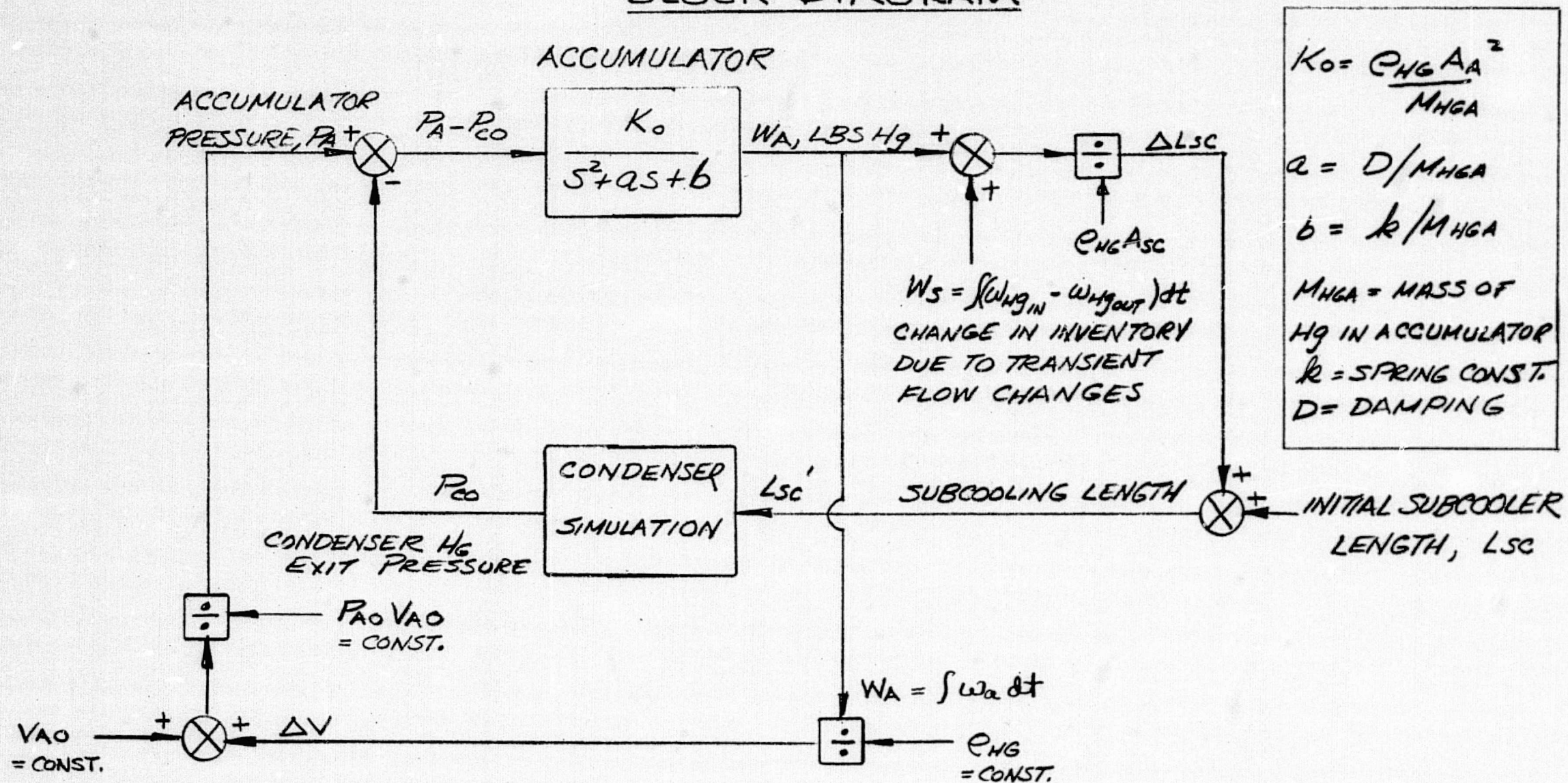


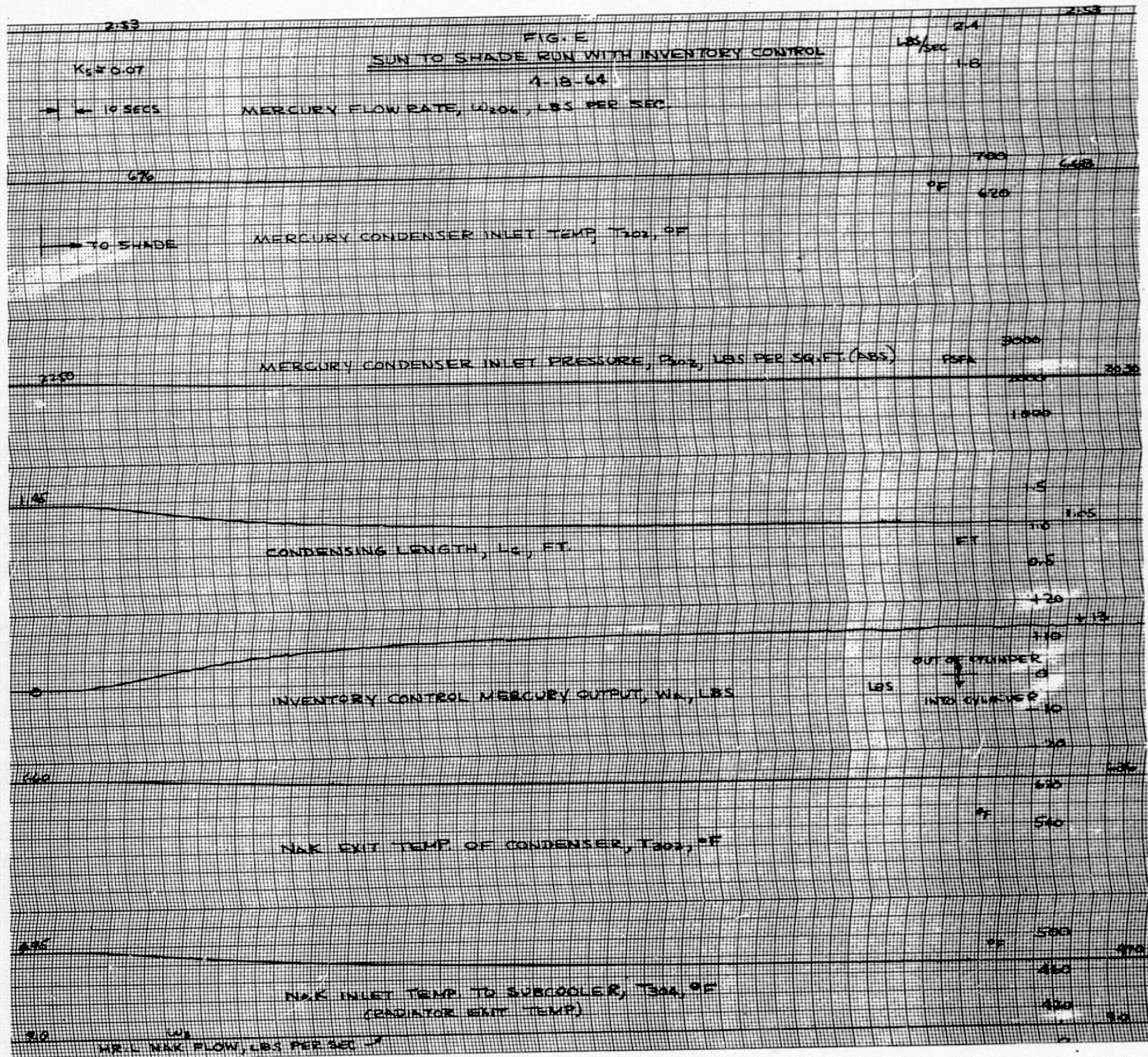
SNAP-8 DIVISION

VON KARMAN CENTER

# FIG. D

## CONDENSER INVENTORY CONTROL SYSTEM BLOCK DIAGRAM





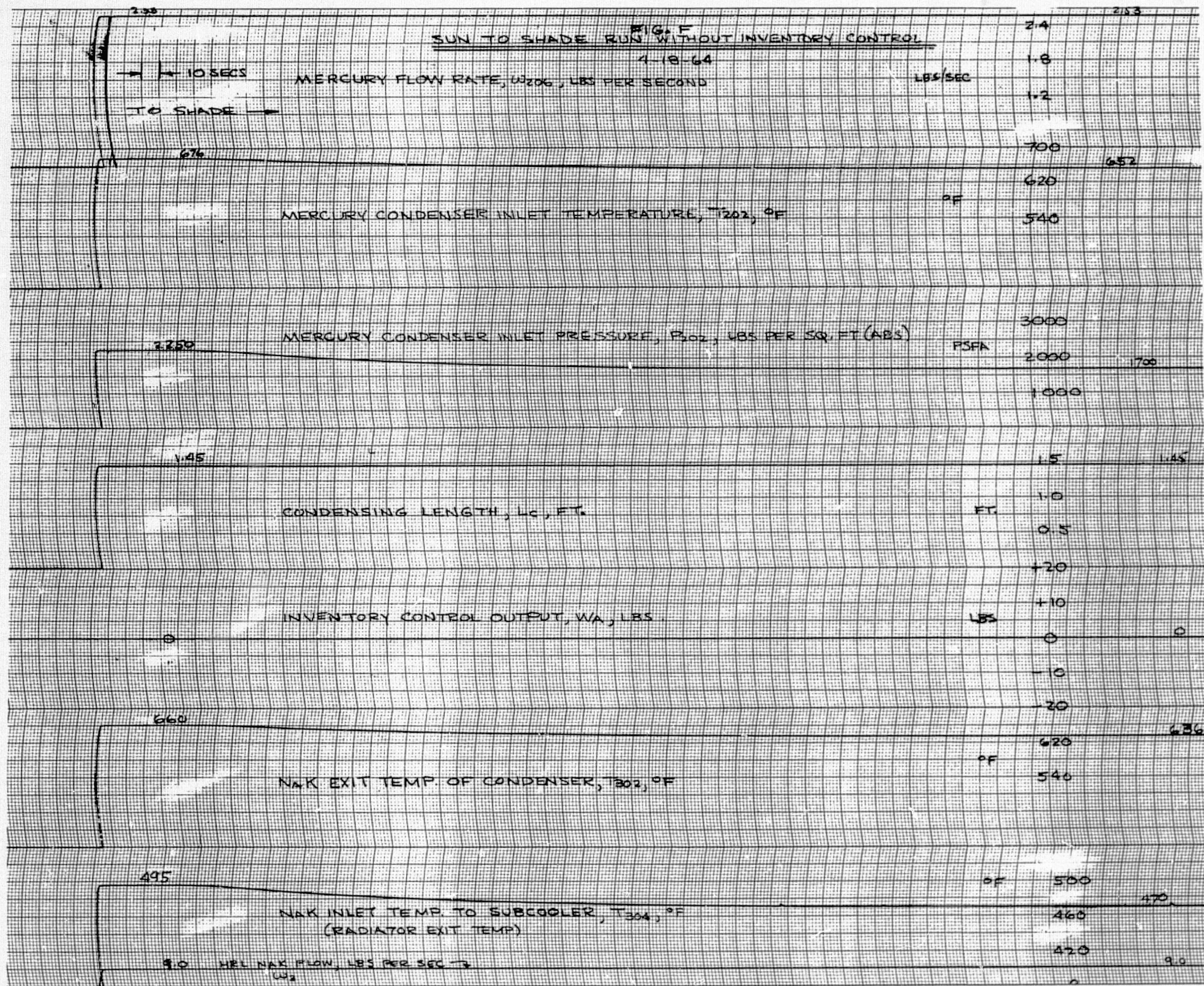
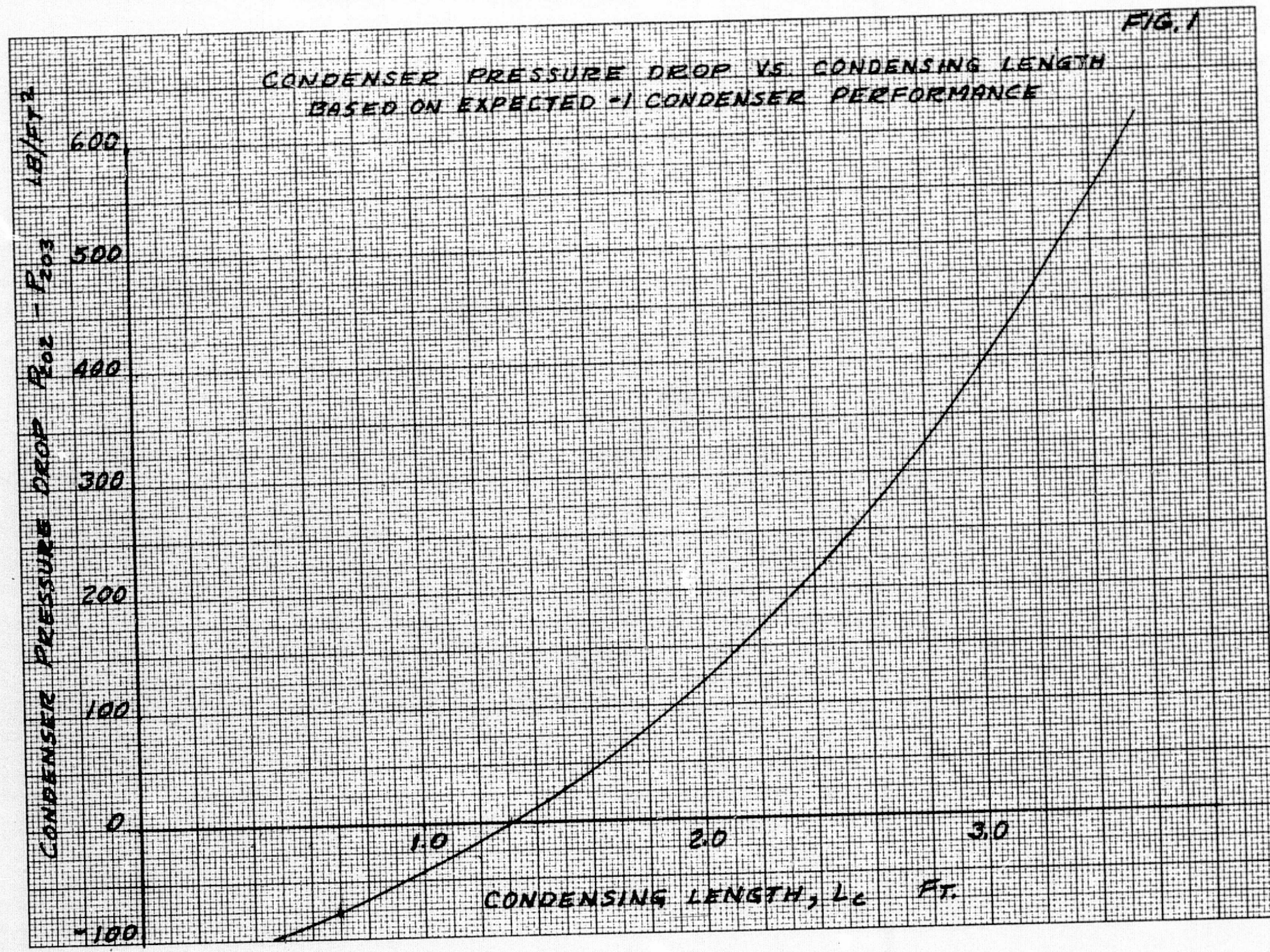


FIG. 1

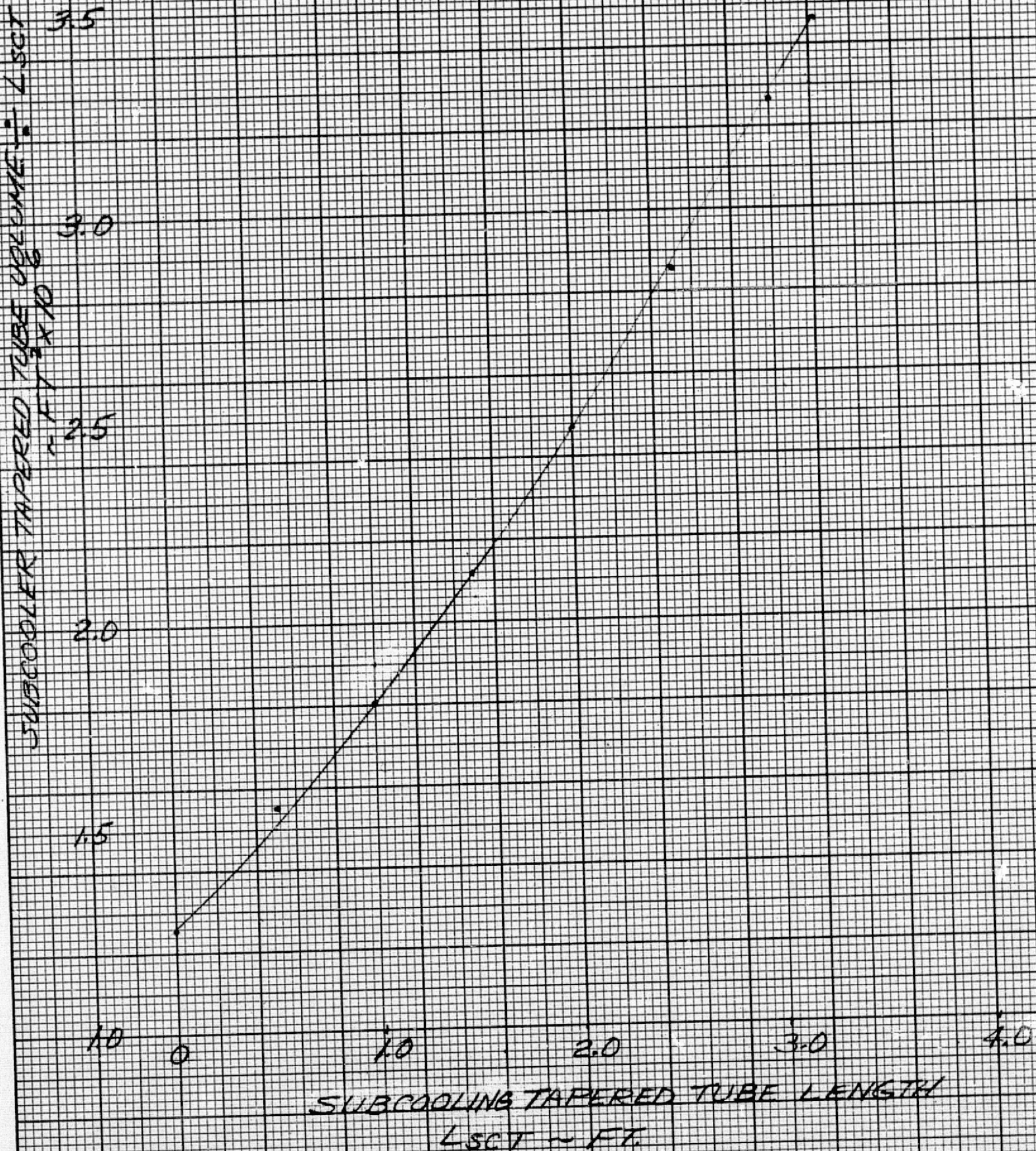
CONDENSER PRESSURE DROP VS. CONDENSING LENGTH  
BASED ON EXPECTED -1 CONDENSER PERFORMANCE



SUBCOOLER TAPERED TUBE  
 VOLUME ÷ LENGTH VS LENGTH

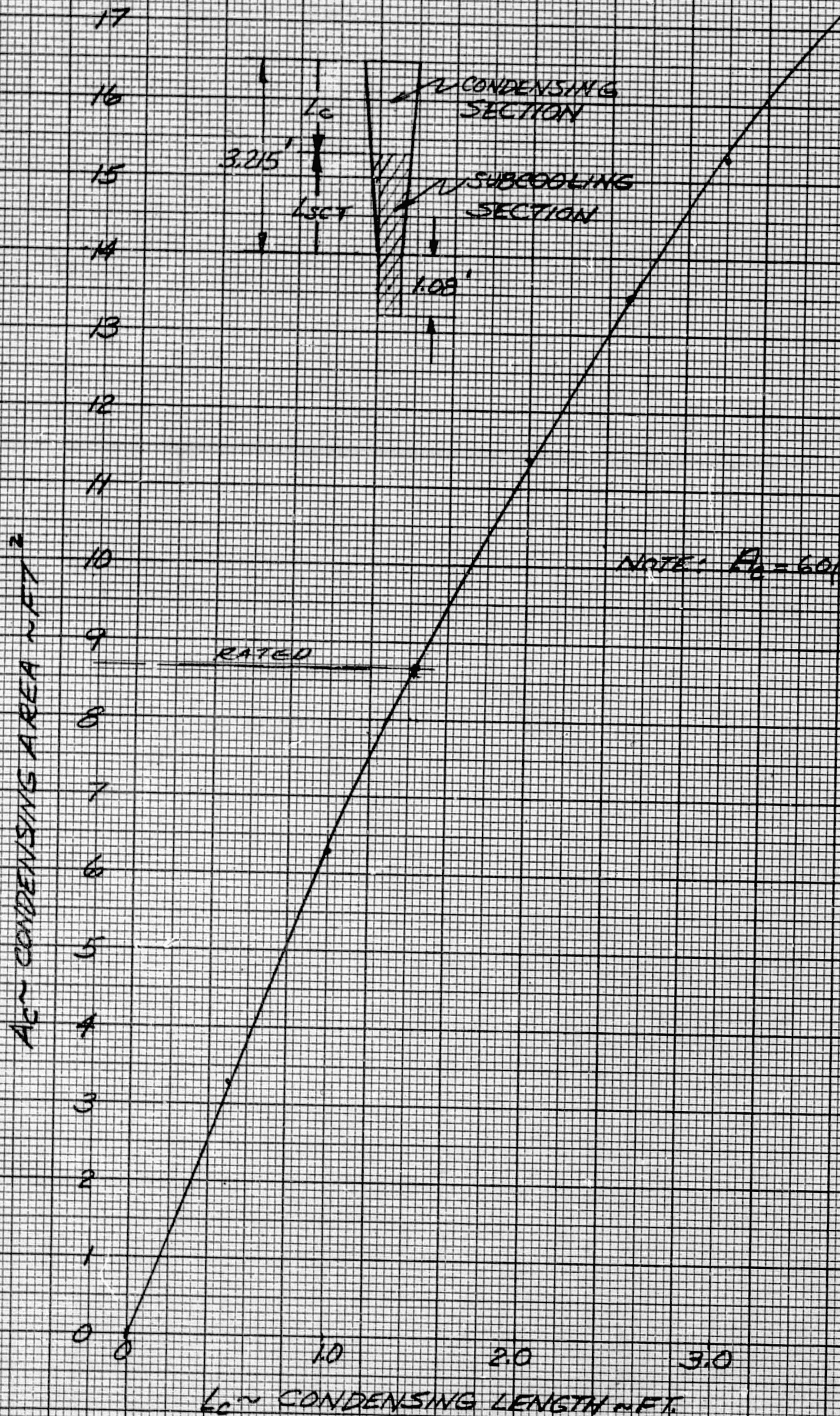
FIG. 2

NOTE:  $\frac{V_{SC}}{L_{SCT}} = \frac{60 \times \pi}{3} \times 10^{-4} (2 + 0.777 L_{SCT} + 0.1 L_{SCT}^2)$



CONDENSING AREA VS LENGTH

FIG. 3



NOTE:  $A_c = 60(.115L_c - 1.08/L_c^2)$

(IPW)