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BASIC PERFORMANCE CHARACTERISTICS OF THE STEAM TURBINE-COMPRESSOR-JET AIRCRAFT PROPULSION CYCLE

By

Arthur P. Fraas
George Cohen

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BASIC PERFORMANCE CHARACTERISTICS OF THE STEAM TURBINE-COMPRESSOR-JET AIRCRAFT PROPULSION CYCLE

by

Arthur P. Fraas
and
George Cohen*

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BASIC PERFORMANCE CHARACTERISTICS OF THE STEAM TURBINE-COMPRESSOR-JET AIRCRAFT PROPULSION CYCLE

Introduction

Recently much interest has been expressed in utilizing the supercritical water cycle for aircraft nuclear propulsion. One of the most widely-advocated methods of accomplishing this is to use the compressor-jet propulsion cycle. This involves adding pressure energy to the air stream in a low compression ratio blower, then adding heat in a radiator or condenser, and finally allowing the air to expand in a jet to generate an impulse for propulsion. The supercritical steam from the reactor expands through a turbine which drives the air blower and the feed water pump. The turbine exhaust steam is fed to the condenser where it loses its heat of vaporization to the air stream from the blower.

Among the advantages of this cycle is the use of water, a familiar and a relatively non-corrosive substance, for both coolant and moderator. The disadvantages include an inherently low specific impulse and the necessity of developing an entirely new type of aircraft engine.

The purpose of the work covered by this report was to analyze the fundamental cycle and discover some of the relations among the many basic parameters involved. In particular, the condenser air inlet face area, the condenser weight, and the impulse were evaluated per pound of air flow in terms of the temperature and pressure of the steam leaving the reactor and the condenser pressure. This was accomplished for flight at 45,000 feet altitude at Mach numbers of 0.9 and 1.5.

[redacted]

Reasonable values were assumed for component efficiencies and actual test data used for the condenser performance. The results should give attainable performance of the fundamental cycle at the two design points investigated. Somewhat better performance can probably be obtained through a program of optimization of the cycle and equipment. However, the data presented here should give performance not far from the optimum and hence should be useful for preliminary design studies of the system.

Summary of Results

The results of this investigation as summarized in Figure 1 indicate that, for reactor outlet steam conditions ranging from 1000 to 1500 $^{\circ}$F and pressures from 5000 to 10,000 psi, the following statements can be made:

1. The specific impulse was found to be low in all cases considered; i.e., from 15 to 20 lb/lb air/sec at a flight Mach No. = 0.9 and from 9 to 14 lb/lb air/sec at a flight Mach No. = 1.5.

2. Increasing reactor outlet steam temperature or pressure or condenser pressure effects some improvement in all cases and in all parameters considered; i.e., specific impulse, specific heat consumption, and specific condenser weight and frontal area.

3. Increasing steam condenser pressures above 400 psi gives relatively little improvement in performance.

4. Increasing the reactor steam outlet pressure from 5000 to 10,000 psi gives very little improvement in performance.

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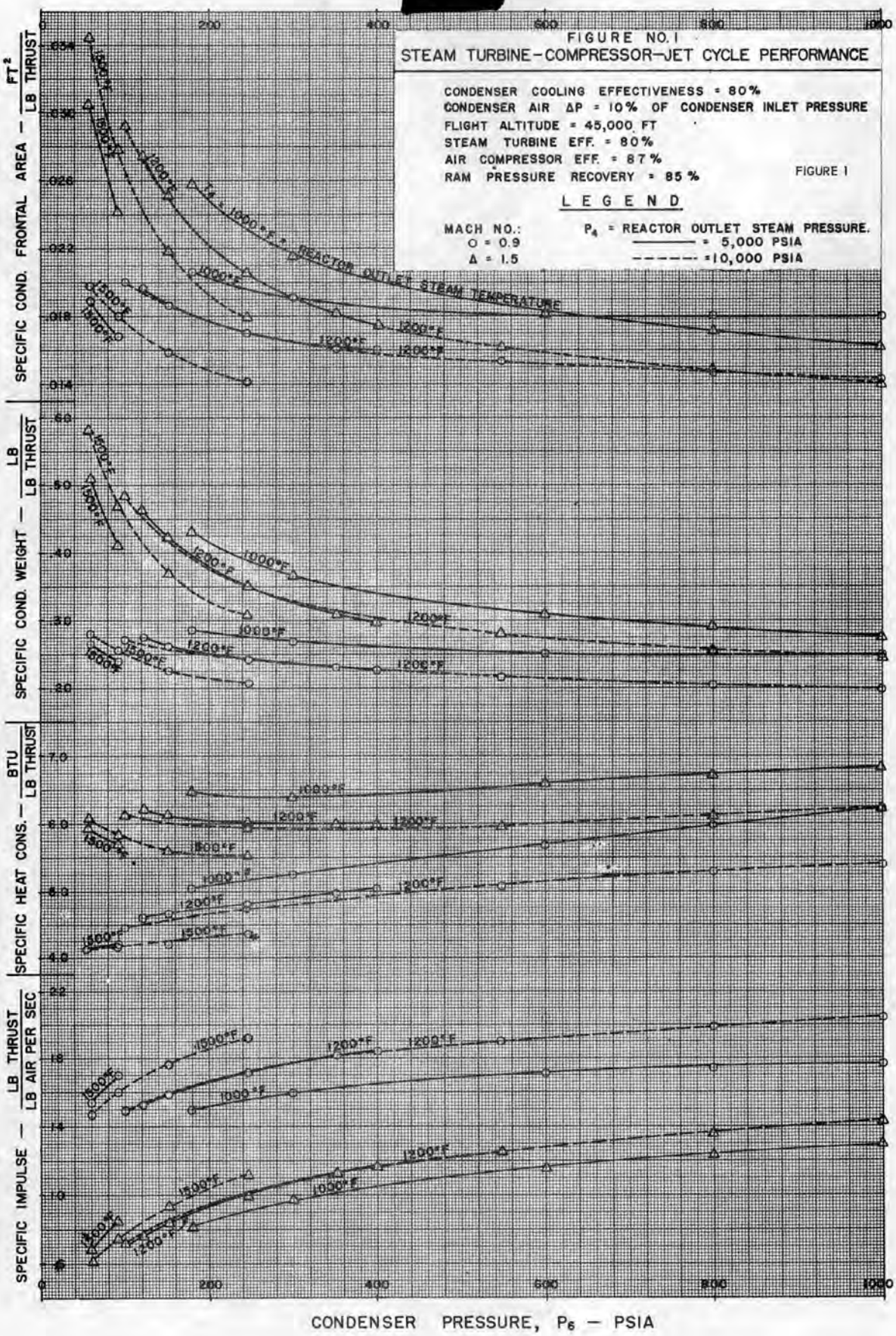


FIGURE NO. I
STEAM TURBINE-COMPRESSOR-JET CYCLE PERFORMANCE
CONDENSER COOLING EFFECTIVENESS = 80%
CONDENSER AIR ΔP = 10% OF CONDENSER INLET PRESSURE
FLIGHT ALTITUDE = 45,000 FT
STEAM TURBINE EFF. = 80%
AIR COMPRESSOR EFF. = 87%
RAM PRESSURE RECOVERY = 85%
FIGURE I
LEGEND
MACH NO.:
O = 0.9
Δ = 1.5
P4 = REACTOR OUTLET STEAM PRESSURE.
= 5,000 PSIA
= 10,000 PSIA
REACTOR OUTLET STEAM TEMPERATURE
SPECIFIC COND. FRONTAL AREA — FT² / LB THRUST
SPECIFIC COND. WEIGHT — LB / LB THRUST
SPECIFIC HEAT CONS. — BTU / LB THRUST
SPECIFIC IMPULSE — LB THRUST / LB AIR PER SEC
CONDENSER PRESSURE, P6 — PSIA

[redacted]

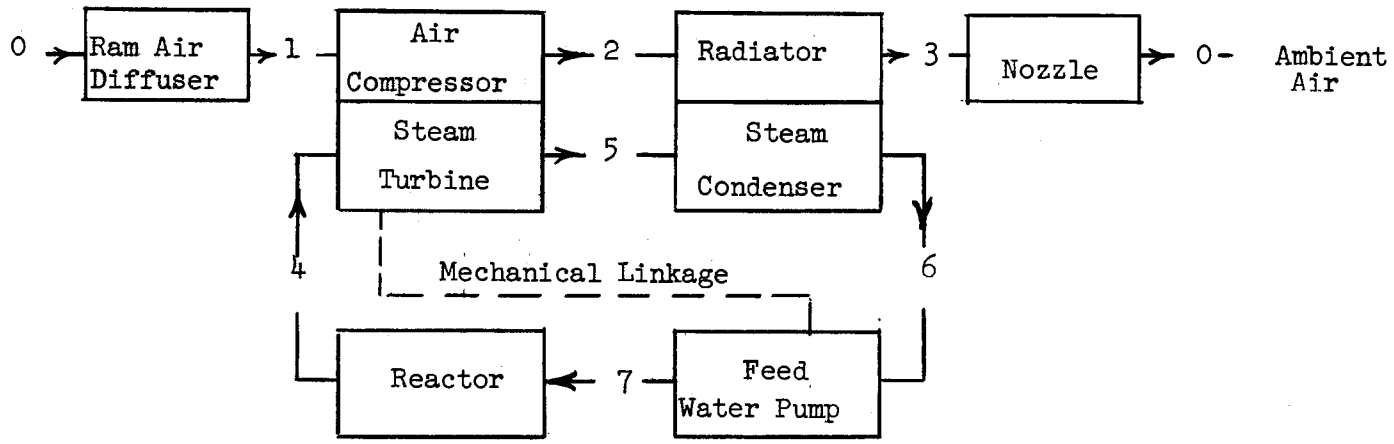


Figure 2

SCHEMATIC FLOW SHEET SHOWING THE MAJOR ITEMS OF EQUIPMENT REQUIRED FOR THE STEAM TURBINE-COMPRESSOR-JET CYCLE.

(The subscripts used in the text of this report indicate the same points in the cycle as the corresponding numerals in this diagram.)

Description of Cycle:

While there are many type of aircraft power plant that might be designed around a steam generating reactor, the type considered here is one in which the steam is generated at supercritical pressures and fed through the turbine, condenser, and feed water pump back to the reactor. Modification of this basic cycle can be made; e.g., a fuel oil burner could be employed to boost the temperature of the air ahead of the jet nozzle, but such elaborations were not considered in the cycle performance calculations made in this study.

[redacted]

The proposed cycle is illustrated in Figure 2. Air compression owing to ram takes place in the air inlet and diffuser. Further compression takes place in the turbine-driven axial flow blower, or compressor. The air then flows to the radiator, or condenser, where it is heated by the exhaust steam from the turbine. The high velocity resulting from expansion of the air through the nozzle in discharging to the atmosphere gives an impulse, or thrust.

On the steam side of the cycle, water enters the reactor from the feed pump at supercritical pressure, i.e., above 3206 psia. The high pressure prevents boiling in the reactor and preserves sufficient density for effective moderation. After gaining heat energy in the reactor, the steam drives the turbine and then transfers its heat of vaporization to the air in the condenser-radiator. The condensed water is then raised to reactor pressure by the turbine-driven feed water pump.

There are a multitude of parameters involved in the system. Obviously basic are the turbine inlet conditions, T_4 and P_4, and the condenser pressure, P_5 (see Figure 2). No pressure drop is assumed in the condenser on the steam side, so $P_5 = P_6$. The condenser outlet temperature, T_6, was taken as the saturation temperature corresponding to P_5. (Actually the water would have to be cooled below this temperature to avoid feed pump cavitation). P_7 is assumed equal to P_4. T_5 may be superheated or saturated with some moisture.

On the air side, the blower compression ratio, P_2/P_1, and the air pressure drop in the condenser, $(P_2-P_3)/P_2$, must be considered. The nozzle temperature, T_3, is found to be directly related to the heat exchanger <u>cooling effectiveness</u>, a widely-used heat exchanger performance parameter.

[redacted]

The cooling effectiveness, η , is normally defined as:

$$\eta = \frac{\text{Temperature rise in coolant}}{\text{Initial temperature difference}}$$

It is usually expressed as a percentage.

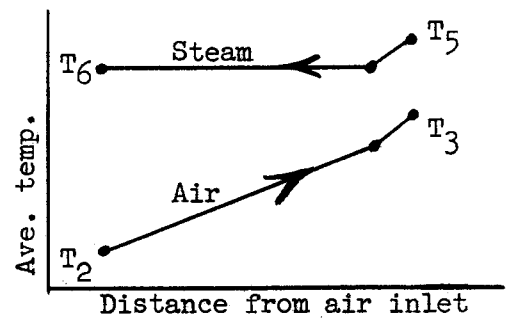


Figure 3. Temperature Distribution in Condenser

The application of this expression is quite straight forward when there is no change in state in a fluid passing through the heat exchanger, or when only condensation or boiling occur. If superheated steam is fed to a condenser, however, the peculiar temperature distribution shown in Figure 3 results. In order to use available heat exchanger performance data, it was necessary to redefine cooling effectiveness for this special case. A reasonable approximation was taken to be the following:

$$\eta = \frac{T_3 - T_2}{\Delta T_{effective}} \quad (100\%)$$

where

$$\Delta T_{eff} = (T_6 - T_2) + \frac{\Delta h \text{ superheat}}{\Delta h \text{ total}} (T_5 - T_6)$$

The relations are such that selection of T_4, P_4, P_5, $(P_2 - P_3)/P_2$, and T_3 identify a cycle. With values of these parameters known, the following can be evaluated also:

[redacted]

a) Blower compression ratio

b) Heat exchanger cooling effectiveness = η

c) Specific impulse = $\frac{\text{lb of thrust}}{\text{lb of air per sec}}$

d) Condenser airflow rate = $\frac{\text{lb air per sec}}{\text{ft}^2 \text{ air inlet face area}}$

e) Specific condenser area = $\frac{\text{ft}^2 \text{ of air inlet face area}}{\text{lb of thrust}}$

f) Condenser depth in direction of air flow - inches

g) Specific condenser weight = $\frac{\text{lb}}{\text{lb of thrust}}$

h) Specific heat consumption = Btu/lb of thrust

The first step in the study was an attempt to select optimum values for two of the five identifying variables. If this could be done, these two parameters could be fixed at their optimum values and the calculations required would be greatly reduced.

The optimization was accomplished by plotting (b) through (h) against T_3 for a particular combination of T_4, P_4, and P_5. This was done for several values of $(P_2 - P_3)/P_2$. The results are presented in Figures 4 to 9.

These plots revealed that a pressure drop across the condenser of $\Delta P/P = .10$ seems to be the most reasonable pressure drop. They show that going to $\Delta P/P = .20$ reduces the specific area very little, but increases the specific weight substantially. On the other hand, $\Delta P/P = .05$ gives a quite severe increase in specific area, with only a slight decrease in specific weight. The specific weights for .05 and .10 generally converge in the region of interest.

The plots also revealed a minimum in specific condenser area. This minimum occurs at practically the same point for each cycle. With the selection of

$\Delta P/P = .10$, the minimum specific area is obtained at approximately 80% cooling effectiveness. It seems reasonable to select this as the optimum value for η .

The identity of the cycle could now be established by T_4, P_4, and P_5, since $\Delta P/P = .10$ and $\eta = 80\%$. Selection of $\eta = 80\%$ is equivalent to selection of T_3, because the plots reveal a linear variation between the two parameters.

The next step was to select values for T_4 and P_4 and vary P_5 for each combination. The principal parameters were then plotted versus P_5 in Figure 1 for five different combinations at Mach = 0.9 and 1.5. The remaining parameters are tabulated in Tables I, II, and III.

The lower limit imposed on P_5 was that pressure at which the steam contained 10% moisture at the turbine exit. The upper limit was either arbitrarily taken as 1000 psi, or that pressure at which the heat from the superheat of the exhaust steam was 10% of the total heat given up in the condenser by the exhaust steam. The heat exchanger data were based on condensing coefficients and should not be extended into the superheat range. It was felt that the approximation for cooling effectiveness given on Page 6 should be fairly good if limited to small amounts of steam superheat at the condenser inlet, especially since the major temperature drop is from the metal to the air rather than from the steam to the metal. A special 2-pass condenser would, of course, be required with the superheated steam coursing across the air outlet end first before entering the main part of the condenser.

Calculation Methods

The method of performing the calculations can be best explained by carrying through the entire procedure for an illustrative cycle.

TABLE I

CALCULATED PERFORMANCE OF A STEAM-TURBINE-COMPRESSOR-JET CYCLE FOR A CONDENSER COOLING EFFECTIVENESS OF 80%, AN ALTITUDE OF 45,000 FT., AND A FLIGHT MACH NO. OF .9

Cycle No.	T_4, Steam Temp. at Turbine Inlet-°F	P_4, Steam Press. at Turbine Inlet-psia	P_6, Steam Press. at Condenser-psia	T_6, Saturated Steam Temp. in Condenser-°F	R = Ratio of Energy to Condenser to Energy to Blower	Steam out of Turbine % Moist., or Degrees Superheat and $\Delta h_{SH}/\Delta h_{TOT}$	Specific Condenser Area-ft²/lb air/sec	Specific Condenser Weight-lb/lb air/sec	Specific Impulse lb/lb air/sec	Airflow Rate-lb. Air/lb Steam	Condenser Depth-Inches	T_3, Air Temp. out of Condenser - °R	P_2/P_1, Compressor Pressure Ratio
C-1	1000	5000	1000	545	6.50	43°, 6.6%	.0180	.250	17.61	3.16	7.91	910	1.47
C-3	1000	5000	800	518	5.90	26°, 3.5%	.0181	.252	17.35	3.19	7.93	887	1.49
C-5	1000	5000	600	486	5.23	Dry Satd.	.0181	.254	17.08	3.24	7.97	861	1.51
C-7	1000	5000	300	417	4.17	5.2% M	.0192	.270	16.00	3.25	7.98	806	1.53
C-9	1000	5000	180	373	3.67	7.7% M	.0206	.289	14.95	3.25	7.98	771	1.53
B-1	1200	10000	1000	545	4.86	53°, 7.8%	.0143	.203	20.48	3.42	8.08	914	1.64
B-3	1200	10000	800	518	4.55	35°, 4.6%	.0148	.210	19.80	3.42	8.08	891	1.64
B-5	1200	10000	550	477	4.06	5°, 0.7%	.0154	.219	19.00	3.41	8.08	857	1.64
B-7	1200	10000	247	400	3.32	5.1% M	.0170	.242	17.25	3.41	8.08	795	1.64
B-9	1200	10000	100	328	2.80	8.9% M	.0200	.274	14.94	3.35	8.02	736	1.59
B-11	1200	7000	800	518	4.65	105°, 11.3%	.0148	.207	19.90	3.39	8.05	898	1.62
B-13	1200	7000	550	477	4.12	72°, 7.0%	.0152	.217	19.20	3.42	8.09	863	1.64
B-15	1200	7000	247	400	3.55	8°, 0.7%	.0178	.251	16.75	3.36	8.02	795	1.60
B-17	1200	5000	400	445	3.94	120°, 9.4%	.0160	.228	18.35	3.40	8.07	840	1.63
B-19	1200	5000	350	432	3.78	108°, 8.3%	.0162	.230	18.10	3.41	8.08	828	1.64
B-21	1200	5000	247	400	3.48	82°, 5.9%	.0172	.245	17.15	3.38	8.06	800	1.62
B-23	1200	5000	150	358	3.12	43°, 2.9%	.0188	.265	15.85	3.36	8.02	762	1.60
B-25	1200	5000	120	341	3.00	29°, 1.9%	.0196	.277	15.22	3.35	8.02	748	1.59

TABLE II

CALCULATED PERFORMANCE OF A STEAM-TURBINE-COMPRESSOR-JET CYCLE FOR A CONDENSER COOLING EFFECTIVENESS OF 80%, AN ALTITUDE OF 45,000 FT., AND A FLIGHT MACH NO. OF .9

Cycle No.	T_4, Steam Temp. at Turbine Inlet-°F	P_4, Steam Press. at Turbine Inlet-psia	P_6, Steam Press. at Condenser-psia	T_6, Saturated Steam Temp. in Condenser-°F	R = Ratio of Energy to Condenser to Energy to Blower	Steam out of Turbine % Moist. or Degrees Superheat and $\Delta h_{SH}/\Delta h_{TOT}$	Specific Condenser Area-ft^2/lb air/sec	Specific Condenser Weight-lb/lb air/sec	Specific Impulse lb/lb air/sec	Airflow Rate-lb Air/lb Steam	Condenser Depth-Inches	T_3, Air Temp. out of Condenser - °R	P_2/P_1, Compressor Pressure Ratio
A-1	1500	10000	247	400	2.78	135°, 9.0%	.0142	.211	19.23	3.60	8.23	807	1.78
A-3	1500	10000	150	358	2.54	98°, 6.1%	.0158	.228	17.70	3.57	8.20	768	1.74
A-5	1500	10000	90	320	2.42	73°, 4.3%	.0182	.260	15.97	3.46	8.18	735	1.67
A-7	1500	10000	58	290	2.23	31°, 1.8%	.0200	.284	14.65	3.41	8.08	708	1.64
A-9	1500	7000	150	358	2.59	180°, 10.4%	.0152	.220	18.23	3.59	8.20	779	1.76
A-11	1500	7000	90	320	2.41	144°, 7.9%	.0174	.250	16.42	3.50	8.17	742	1.70
A-13	1500	7000	58	290	2.27	112°, 5.9%	.0197	.282	14.90	3.41	8.18	713	1.64
A-15	1500	5000	90	320	2.49	220°, 11.4%	.0167	.240	16.95	3.53	8.18	754	1.72
A-17	1500	5000	58	290	2.33	188°, 9.4%	.0189	.269	15.35	3.45	8.10	722	1.67

TABLE III

CALCULATED PERFORMANCE OF A STEAM-TURBINE-COMPRESSOR-JET CYCLE FOR A CONDENSER COOLING EFFECTIVENESS OF 80%, AN ALTITUDE OF 45,000 FT., AND A FLIGHT MACH NO. OF 1.5

Cycle No.	T_4, Steam Temp. at Turbine Inlet-°F	P_4, Steam Press. at Turbine Inlet-psia	P_6, Steam Press. at Condenser-psia	T_6, Saturated Steam Temp. in Condenser-°F	R = Ratio of Energy to Condenser to Energy to Blower	Steam out of Turbine % Moist. or Degrees Superheat and $\Delta h_{SH}/\Delta h_{TOT}$	Specific Condenser Area-ft²/lb air/sec	Specific Condenser Weight-lb/lb air/sec	Specific Impulse lb/lb air/sec	Airflow Rate-lb Air/lb Steam	Condenser Depth-Inches	T_3, Air Temp. out of Condenser - °R	P_2/P_1, Compressor Pressure Ratio
C-2	1000	5000	1000	545	6.50	43°, 6.6%	.0163	.275	12.88	4.75	9.56	930	1.29
C-4	1000	5000	800	518	5.90	26°, 3.5%	.0172	.290	12.24	4.75	9.56	907	1.29
C-6	1000	5000	600	486	5.23	Dry Satd.	.0182	.308	11.46	4.78	9.60	880	1.30
C-8	1000	5000	300	417	4.17	5.2%M	.0216	.364	9.71	4.78	9.60	826	1.30
C-10	1000	5000	180	373	3.67	7.7%M	.0257	.430	8.25	4.71	9.50	790	1.28
B-2	1200	10000	1000	545	4.86	53°, 7.8%	.0141	.244	14.35	4.94	9.82	935	1.38
B-4	1200	10000	800	518	4.55	35°, 4.6%	.0149	.254	13.52	4.97	9.70	910	1.38
B-6	1200	10000	550	477	4.06	5°, 0.7%	.0163	.281	12.40	4.94	9.80	877	1.38
B-8	1200	10000	247	400	3.32	5.1%M	.0205	.354	10.00	4.88	9.80	815	1.35
B-10	1200	10000	100	328	2.80	8.9%M	.0291	.489	7.25	4.75	9.56	755	1.29
B-18	1200	5000	400	445	3.94	120°, 9.4%	.0175	.299	11.66	4.91	9.72	860	1.36
B-20	1200	5000	350	432	3.78	108°, 8.3%	.0182	.312	11.18	4.91	9.72	848	1.36
B-22	1200	5000	247	400	3.48	82°, 5.9%	.0206	.351	9.99	4.87	9.70	818	1.34
B-24	1200	5000	150	358	3.12	43°, 2.9%	.0251	.424	8.30	4.80	9.60	780	1.31
B-26	1200	5000	120	341	3.00	29°, 1.9%	.0275	.465	3.10	7.60	9.60	766	1.30
A-2	1500	10000	247	400	2.78	135°, 9.0%	.0179	.311	11.15	5.00	9.85	825	1.41
A-4	1500	10000	150	358	2.54	98°, 6.1%	.0218	.374	9.30	4.93	9.75	785	1.37
A-6	1500	10000	90	320	2.42	73°, 4.3%	.0279	.473	7.46	4.80	9.62	751	1.32
A-8	1500	10000	58	290	2.23	31°, 1.8%	.0345	.580	6.10	4.75	9.56	724	1.29
A-16	1500	5000	90	320	2.49	220°, 11.4%	.0243	.418	8.45	4.88	9.80	770	1.35
A-18	1500	5000	58	290	2.33	188°, 9.4%	.0305	.516	6.82	4.80	9.60	738	1.31

Cycle B-3 will be used for this purpose. Its identifying qualities are:

$$M = 0.9 \text{ at } 45{,}000 \text{ ft}$$

$$T_4 = 1200^{\circ}F$$

$$P_4 = 10{,}000 \text{ psi}$$

$$P_6 = P_5 = 800 \text{ psi}$$

With the assumption of turbine adiabatic efficiency = 80%, it is possible to specify the conditions and the energy at each point of the steam side of the cycle.

From extrapolated steam data contained in TAB-78:

$$h_4 = 1447 \text{ Btu/lb}; \; S_4 = 1.396$$

Using the Mollier Diagram, the enthalpy after isentropic expansion to condenser pressure is:

$$h_5 = 1179 \text{ Btu/lb}$$

$$\Delta h_{isent} = (h_4 - h_5)_{isentropic} = 268 \text{ Btu/lb}$$

Application of the 80% turbine efficiency gives the true enthalpy drop:

$$\Delta h = (.8)(h_4 - h_5)_{isent} = 214 \text{ Btu/lb}$$

$$h_5 = h_4 - 214 = 1233 \text{ Btu/lb}$$

From Mollier Diagram at $h_5 = 1233$, $P_5 = 800$ psi:

$$T_5 = 553^{\circ}F$$

Saturation temperature at 800 psi is $518^{\circ}F$, so the steam is entering the condenser with 35° superheat. The water leaves the condenser saturated so:

$$T_6 = 518^{\circ}F$$

$$V_6 = .0209 \text{ ft}^3/\text{lb}$$

$$h_6 = 510 \text{ Btu/lb}$$

The heat given up in the condenser is:

$$h_5 - h_6 = 1233 - 510 = 723 \text{ Btu/lb}$$

The feed pump work to return the water to the reactor, assuming 65% efficiency and incompressibility is:

$$h_7 - h_6 = \frac{V_6 (P_7 - P_6)}{(\text{Eff}) J}$$

$$= \frac{(.0209)(10{,}000 - 800)(144)}{(.65)(778)} = 55 \text{ Btu/lb}$$

A useful parameter is now defined:

$$R = \frac{\text{Heat to condenser}}{\text{Energy to blower}}$$

$$= \frac{h_5 - h_6}{(h_4 - h_5)-(h_7 - h_6)} = \frac{h_3 - h_2}{h_2 - h_1}$$

$$= \frac{723}{214 - 55} = 4.55$$

(All values of enthalpy so far are per pound of <u>water</u>.)

Turning to the air side of the cycle, standard atmospheric conditions at 45,000 feet are:

$$T_o = 393^{\circ}R; \quad P_o = 2.14 \text{ psia}$$

The Air Tables give the isentropic pressure ratio at Mach = 0.9:

$$P_o/P_1' = .59126 \qquad \text{(Primes represent isentropic)}$$

$$P_1' = 2.14/.59126 = 3.62$$

$$P_1 - P_o' = 1.48$$

The diffuser is assumed to achieve 85% of the isentropic pressure recovery.

$$P_1 - P_o = .85(1.48) = 1.26$$

$$P_1 = 2.14 + 1.26 = 3.40 \text{ psia}$$

The temperature is the stagnation temperature for Mach = 0.9.

$$T_1 = 393/.86058 = 457^{\circ}R; \quad h_1 = 109.2 \text{ Btu/lb of air}$$

It is now possible to select one more condition, T_3, against which the major performance parameters may be plotted. To illustrate the procedure, T_3 is selected as:

$$T_3 = 891^{\circ}R$$

$$h_3 = 214.05 \text{ Btu/lb}$$

The jet velocity, and therefore the thrust, can be calculated if P_3 is determined. It is first necessary to determine the compression ratio of the blower.

The energy added in the blower and condenser is:

$$h_3 - h_1 = 214.1 - 109.2 = 104.9 \text{ Btu/lb}$$

Since R is known from the steam side:

$$(h_2 - h_1) + R(h_2 - h_1) = h_3 - h_1$$

$$h_2 - h_1 = \frac{h_3 - h_1}{1 + R} = \frac{104.9}{1 + 4.55} = 18.9 \text{ Btu/lb}$$

$$h_2 = h_1 + 18.9 = 109.2 + 18.9 = 128.1 \text{ Btu/lb}$$

From the Air Tables at this h:

$$T_2 = 536^{\circ}R$$

Knowing the blower inlet conditions, and assuming an adiabatic efficiency = 87%, it is possible to plot T_2 against P_2/P_1. This has been done in Figure 15. Entering this plot at $T_2 = 536^{\circ}$, P_2/P_1 is found to be = 1.64.

$$P_2 = 1.64\ P_1 = (1.64)(3.4) = 5.58 \text{ psia.}$$

It is now necessary to select an air pressure drop in the radiator. Three different values were used originally, but for this illustration the optimum will be used:

$$\frac{P_2 - P_3}{P_2} = 0.10$$

$$P_3 = 0.9\ P_2 = (0.9)(5.58) = 5.02 \text{ psia}$$

$$\frac{1}{r} = \frac{P_3}{P_o} = \frac{5.02}{2.14} = 2.35$$

$$r = 0.426 = \text{pressure ratio across jet nozzle.}$$

The jet velocity is:

$$V_j = \sqrt{\frac{T_3}{\bar{m}}} \sqrt{\frac{2\ g\ n\ \bar{R}}{n - 1}} \sqrt{(1 - r^{\frac{n-1}{n}})}$$

$$\bar{m} = \text{molecular weight}$$

$$\bar{R} = 1545 \qquad n = 1.4 = \frac{c_p}{c_v}$$

$$V_j = 109.6 \sqrt{T_3} \sqrt{(1 - r^{\frac{n-1}{n}})}$$

The last term is tabulated in Table 25 of Keenan and Kaye Gas Tables.

$$V_j = (109.6) \sqrt{891} \quad (.465) = 1522 \text{ ft/sec}$$

The airplane velocity is:

$$V_a = Ma = (0.9)(49.1) \sqrt{393^\circ} = 876 \text{ ft/sec}$$

The impulse is equal to the change in momentum:

$$J_t = W/g\ (V_j - V_a)$$

$$W = \text{weight of air, lb}$$

With a weight flow of one pound of air per sec, the specific impulse is:

$$I = \frac{V_j - V_a}{g} = \frac{1522 - 876}{32.2} = 20.1 \ \frac{\text{lb - sec}}{\text{lb}}$$

[redacted]

The total heat added per pound of air is:

$$h_3 - h_1 = 214.1 - 109.2 = 104.9 \ \frac{\text{Btu}}{\text{lb of air}}$$

The specific heat consumption is:

$$\text{Sp. Ht. Consumption} = \frac{h_3 - h_1}{I} = \frac{104.9}{20.1} = 5.22 \ \frac{\text{Btu/sec}}{\text{lb of thrust}}$$

It is necessary to calculate condenser cooling effectiveness and $\sigma \Delta P$ in order to specify the size, airflow, and weight of the condenser. Cooling effectiveness, η, has previously been defined as:

$$\eta = \frac{T_3 - T_2}{(T_6 - T_2) + \frac{\Delta h_{superheat}}{\Delta h_{total}} (T_5 - T_6)} \ (100\%)$$

All of these quantities have been found except $\frac{\Delta h_{SH}}{\Delta h_{total}}$. The enthalpy of saturated steam at condenser pressure = 800 psi is h_g = 1199 Btu/lb.

$$\frac{\Delta h_{SH}}{\Delta h_{TOT}} = \frac{h_5 - h_g}{h_5 - h_f} = \frac{1233 - 1199}{1233 - 510} = .047$$

$$\eta = \frac{(891 - 536)(100\%)}{(978 - 536) + .047\ (1013 - 978)} = 80\%$$

σ is the ratio of the density of the air entering the condenser to the density of air at standard sea level conditions.

$$\sigma = \frac{\rho_2}{\rho_o} = \frac{\left(\frac{P_2}{R\ T_2}\right)}{\left(\frac{P_o}{R\ T_o}\right)} = \left(\frac{T_o}{P_o}\right)\left(\frac{P_2}{T_2}\right)$$

$$\sigma = \frac{519}{14.69} \ \frac{P_2}{T_2} = 35.3 \ \frac{P_2}{T_2}$$

$$\sigma = 35.3 \ \frac{5.58}{536} = .367$$

[redacted]

$$\sigma \Delta P = (.367)(.10)(P_2) = (.0367)(5.58) = .204 \text{ psi}$$

Entering the chart in Figure 10 at this η and ΔP:

$$\text{Airflow} = 3.42 \frac{\text{lb/sec}}{\text{ft}^2 \text{ condenser frontal area}}$$

Condenser depth = 8.08 inches

The specific condenser area is

$$\text{Sp. cond. area} = \frac{1}{(I)(\text{airflow})} \frac{1}{(20.1)(3.42)} = .0146 \frac{\text{ft}^2}{\text{lb of thrust}}$$

The condenser in NACA RME7J01 is 8.75 inches deep and weighs 15.4 pounds per square foot of frontal area. Assuming that the condenser weight is directly proportional to its volume:

$$\text{Sp. cond. weight} = \frac{15.4}{8.75} (\text{condenser depth})(\text{Sp. area})$$

$$= (1.75)(8.08)(.0146) = .208 \frac{\text{lb}}{\text{lb of thrust}}$$

Calculations Using Graphical Working Charts

Graphical working charts have been devised to expedite the cycle calculations. The charts are used in conjunction with calculation sheets of the form shown in Table IV . Use of these aids will be illustrated by once again calculating cycle B-3.

$\frac{P_2 - P_3}{P_2}$, R, $\frac{\Delta h_{SH}}{\Delta h_{total}}$, T_6 and T_5 are selected or calculated just as before. Thus lines 1, 3, 7, 8, 10, and 11 in the calculation sheet can be filled in. A range of values of T_3 can be selected and placed in line 2. For this example, $T_3 = 891^{\circ}R$. Entering the chart in Figure 12 at $T_3 = 891$ and R = 4.55, it is possible to read $P_2/P_1 = 1.64$ and specific impulse = 19.80.

[redacted]

TABLE IV

Sample Calculation Sheet

Line No.	Quantity	Cycle No. B-3		
1	Condenser air $\Delta P \div$ inlet air pressure $= (P_2 - P_3)/P_2$	.10		
2	Condenser air outlet temperature, T_3, ^{o}R	891		
3	R factor (from Figure 12)	4.55		
4	Compressor pressure ratio = P_2/P_1	1.64		
5	Compressor air outlet temperature, T_2, ^{o}R	536		
6	Condenser air ΔT rise = $T_3 - T_2$ = (2)-(5) ^{o}F	355		
7	Ratio of steam condenser superheat Δh to total Δh	.047		
8	Steam saturation temp. in condenser, T_6, ^{o}R	978		
9	$T_6 - T_2$ = (8) - (5), ^{o}F	442		
10	Degrees of superheat = T_5 - (8), ^{o}F	35		
11	(7) x (10)	2		
12	Effective temp. diff. in condenser = (9) + (11), ^{o}F	444		
13	Cooling effectiveness = η = 100 x (6)/(12)	80		
14	Condenser air inlet press. = P_2 = 3.4 x (4), psia	5.58		
15	Condenser air inlet density ratio = σ = 35.3 x (14)/(5)	.367		
16	Condenser $\sigma \Delta P$ = (1) x (14) x (15), lb/ft^2	.204		
17	Condenser depth, in	8.08		
18	Condenser air flow, $lb/sec\text{-}ft^2$ inlet face area	3.42		

[redacted]

[redacted]

TABLE IV (Cont'd)

Sample Calculation Sheet

Line No.	Quantity	Cycle No.		
		B-3		
19	Specific impulse, lb/lb of air/sec	19.8		
20	Specific Condenser area = $\frac{1}{(18) \times (19)}$ = ft^2/lb thrust	.0148		
21	Specific condenser weight = 1.76 x (17) x (20) = lb/lb thrust	.210		
22	Air Δ h through compressor and condenser, Btu/lb (Figure 16)	105.0		
23	Specific heat consumption = (22)/(19), Btu/sec-lb thrust	5.30		

Then the chart of Figure 15 reveals that $T_2 = 536^{\circ}R$ if $P_2 = 1.64\ P_1$.

With the information now available, the calculation sheet can be completed through line 16. Then entering the chart of Figure 10 at $\eta = 80\%$ and $\sigma\Delta P = .204$, the condenser depth is found to be 8.08 inches and the airflow is 3.42 lb/ft^2-sec. Combinations of calculated numbers provide the specific condenser area = .0148 and weight = .210 for lines 20 and 21.

Chart 7 (Figure 16) gives $h_3 - h_1$ as a function of T_3. Thus $h_3 - h_1 =$ 105.0. Dividing this by specific impulse yields specific heat consumption = 5.30.

After learning the otpimum value for η, it is only necessary to guess two or three values of T_3 until this value of η is obtained. The remainder of the calculation sheet can then be filled out for this T_3 only.

[redacted]

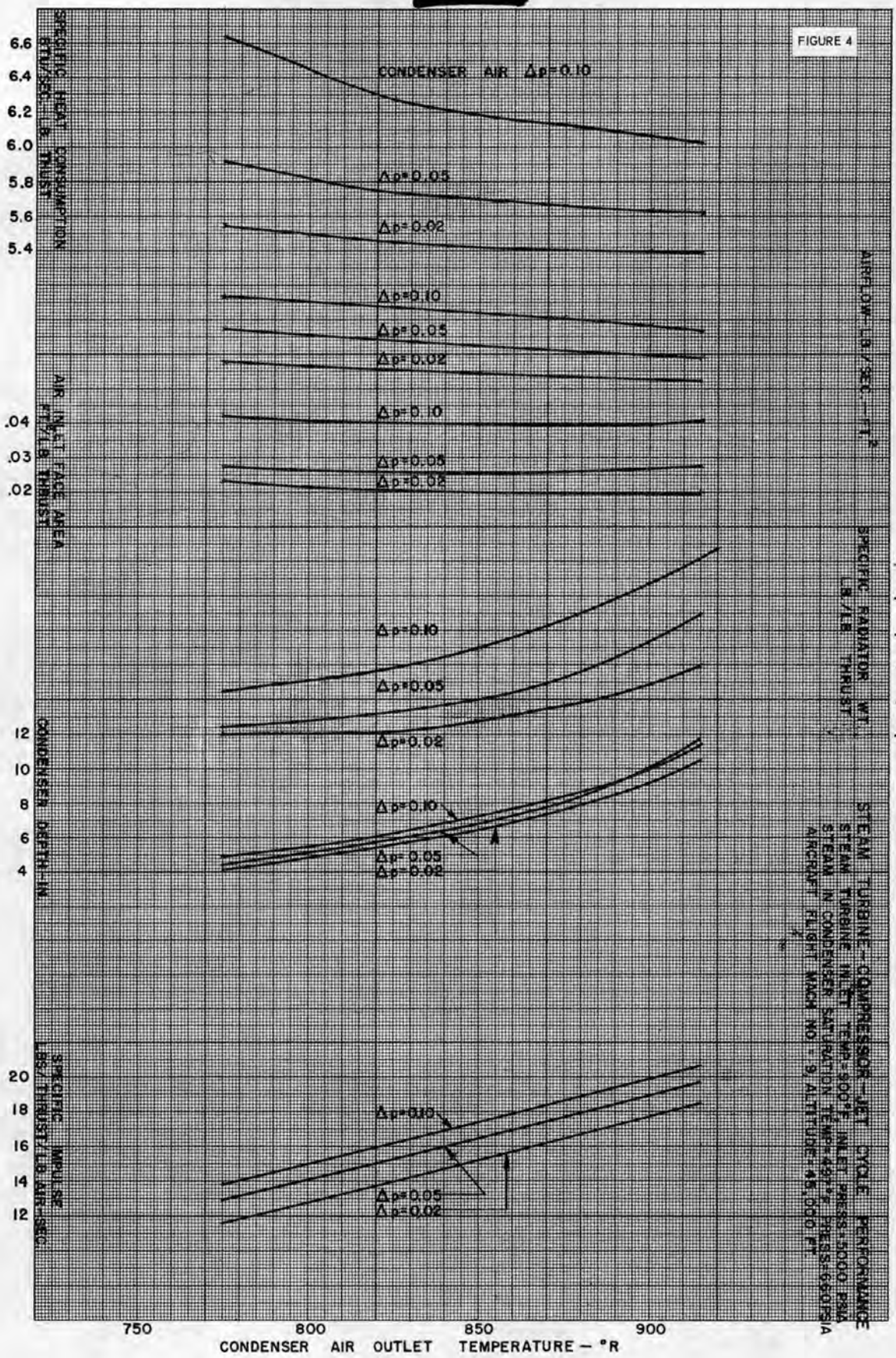


FIGURE 4
SPECIFIC HEAT CONSUMPTION BTU/SEC.-LB. THRUST
6.6
6.4
6.2
6.0
5.8
5.6
5.4
CONDENSER AIR Δp=0.10
Δp=0.05
Δp=0.02
AIRFLOW-LB./SEC.-FT.²
4
3
2
1
Δp=0.10
Δp=0.05
Δp=0.02
AIR INLET FACE AREA FT.²/LB THRUST
.04
.03
.02
Δp=0.10
Δp=0.05
Δp=0.02
SPECIFIC RADIATOR WT. LB./LB THRUST
.7
.6
.5
.4
.3
.2
Δp=0.10
Δp=0.05
Δp=0.02
CONDENSER DEPTH-IN.
12
10
8
6
4
Δp=0.10
Δp=0.05
Δp=0.02
STEAM TURBINE-COMPRESSOR-JET CYCLE PERFORMANCE
STEAM TURBINE INLET TEMP=900°F, INLET PRESS=5000 PSIA
STEAM IN CONDENSER SATURATION TEMP=497°F, PRESS=660 PSIA
AIRCRAFT FLIGHT MACH NO.=9, ALTITUDE=45,000 FT.
SPECIFIC IMPULSE LBS./THRUST/LB. AIR-SEC.
20
18
16
14
12
Δp=0.10
Δp=0.05
Δp=0.02
750
800
850
900
CONDENSER AIR OUTLET TEMPERATURE — °R

[redacted]

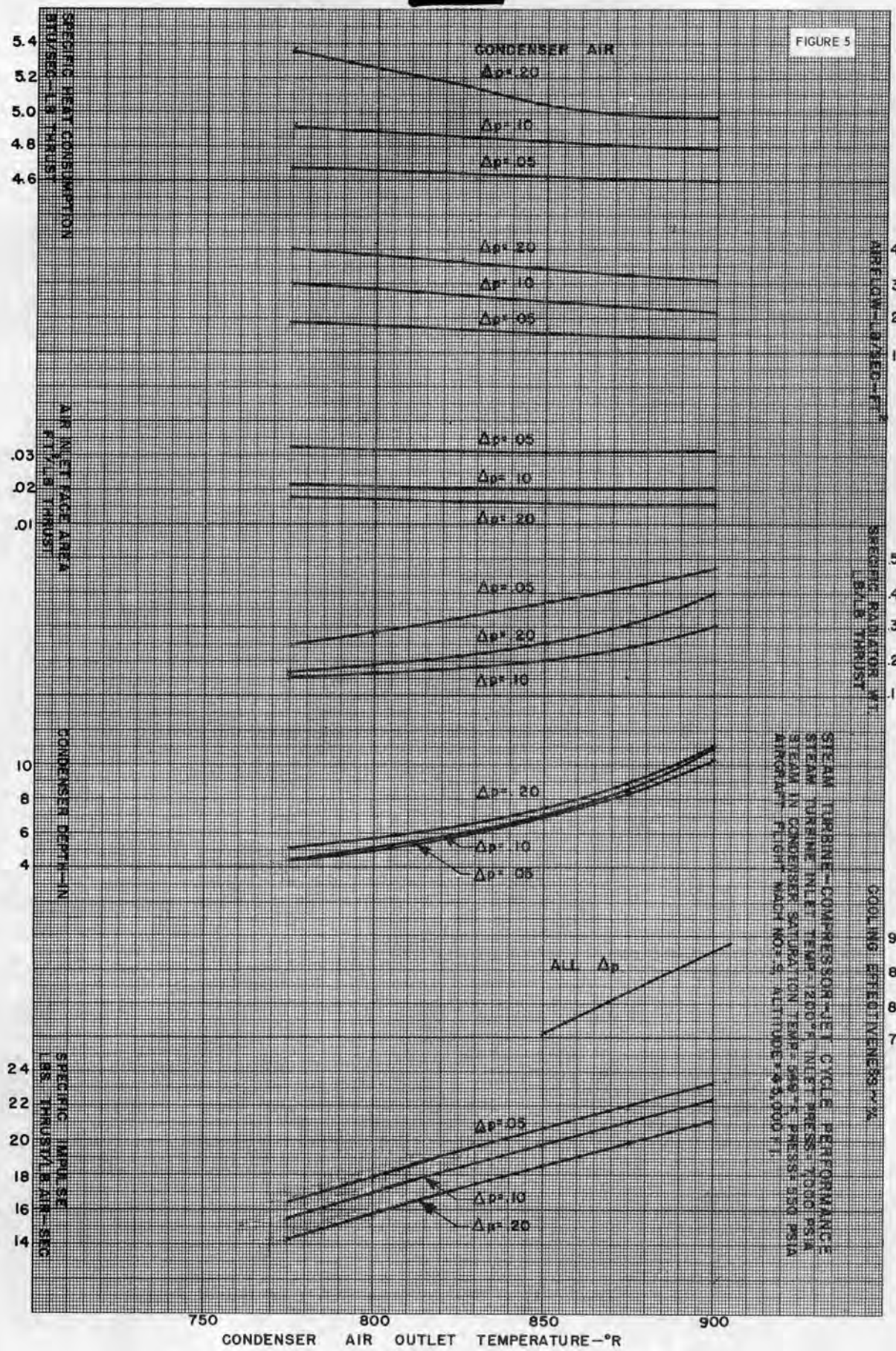


FIGURE 5
SPECIFIC HEAT CONSUMPTION BTU/SEC-LB THRUST
5.4
5.2
5.0
4.8
4.6
CONDENSER AIR
Δp=.20
Δp=.10
Δp=.05
AIRFLOW-LB/SEC-FT²
4
3
2
1
Δp=.20
Δp=.10
Δp=.05
AIR INLET FACE AREA FT²/LB THRUST
.03
.02
.01
Δp=.05
Δp=.10
Δp=.20
SPECIFIC RADIATOR WT. LB/LB THRUST
.5
.4
.3
.2
.1
Δp=.05
Δp=.20
Δp=.10
CONDENSER DEPTH—IN
10
8
6
4
Δp=.20
Δp=.10
Δp=.05
COOLING EFFECTIVENESS-%
90
85
80
75
ALL Δp
SPECIFIC IMPULSE LBS. THRUST/LB AIR-SEC
24
22
20
18
16
14
Δp=.05
Δp=.10
Δp=.20
STEAM TURBINE-COMPRESSOR-JET CYCLE PERFORMANCE
STEAM TURBINE INLET TEMP.=1200°F, INLET PRESS.=1000 PSIA
STEAM IN CONDENSER SATURATION TEMP.=949°F, PRESS.=550 PSIA
AIRCRAFT FLIGHT MACH NO.=.9 ALTITUDE=45,000 FT.
750
800
850
900
CONDENSER AIR OUTLET TEMPERATURE—°R

[redacted]

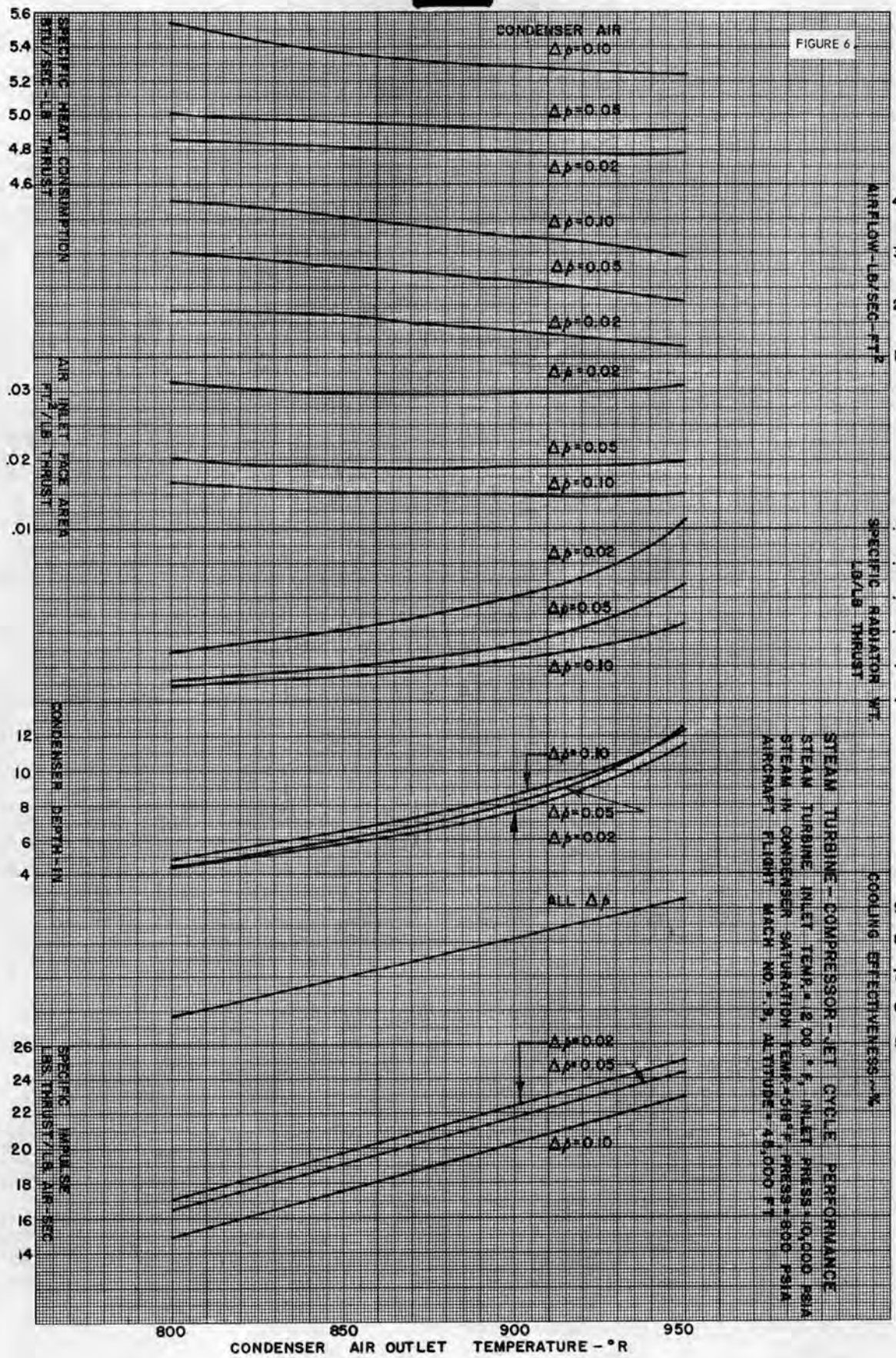


FIGURE 6
STEAM TURBINE-COMPRESSOR-JET CYCLE PERFORMANCE
STEAM TURBINE INLET TEMP.=1200°F, INLET PRESS.=10,000 PSIA
STEAM IN CONDENSER SATURATION TEMP.=518°F, PRESS.=800 PSIA
AIRCRAFT FLIGHT MACH NO.=.9, ALTITUDE=45,000 FT
CONDENSER AIR
Δp=0.10
Δp=0.05
Δp=0.02
ALL Δp
SPECIFIC HEAT CONSUMPTION BTU/SEC-LB THRUST
AIR INLET PROJ. AREA FT²/LB THRUST
CONDENSER DEPTH-IN
SPECIFIC IMPULSE LBS THRUST/LB AIR-SEC
AIRFLOW LB/SEC-FT²
SPECIFIC RADIATOR WT. LB/LB THRUST
COOLING EFFECTIVENESS-%
CONDENSER AIR OUTLET TEMPERATURE - °R
800
850
900
950

[redacted]

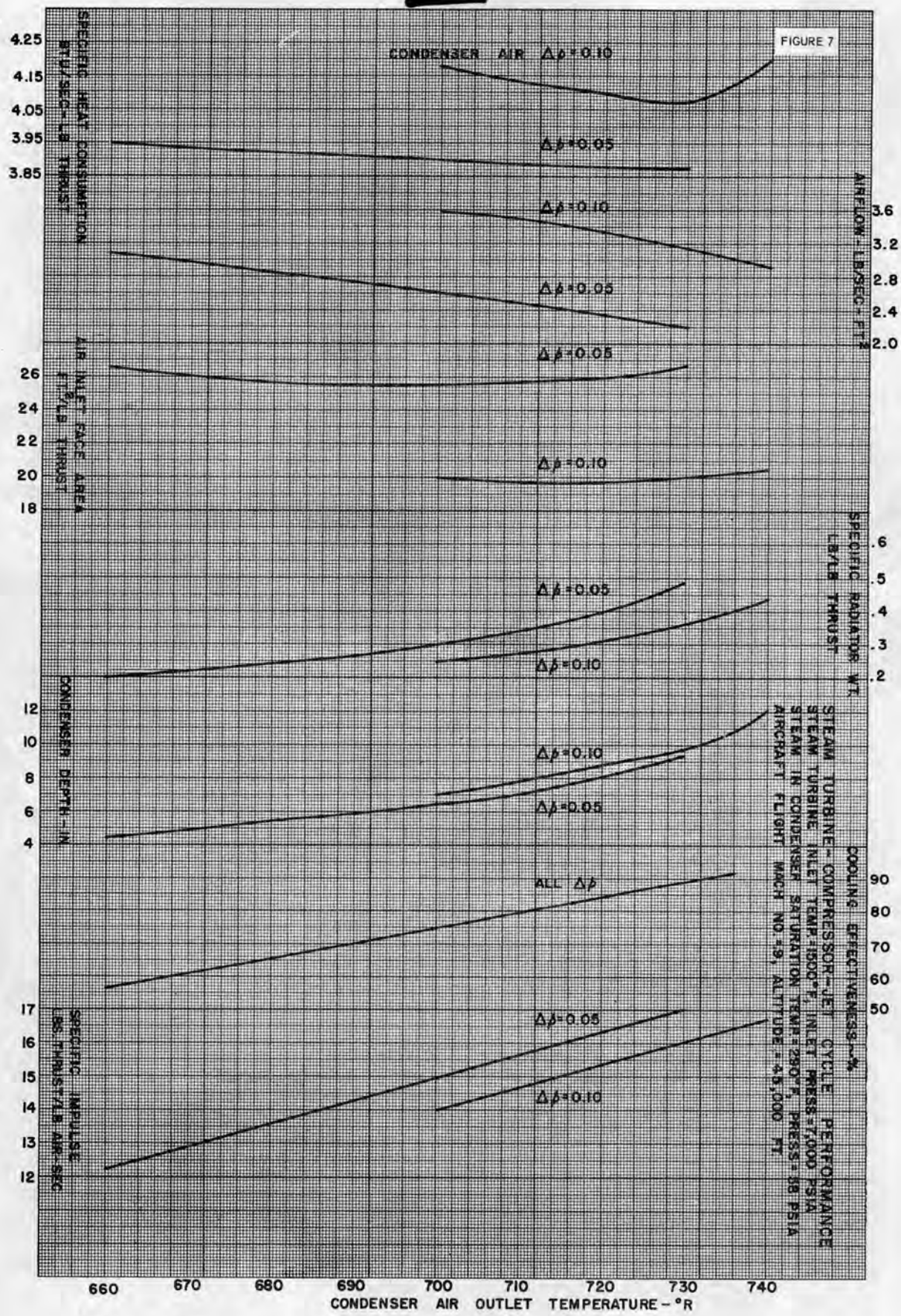


FIGURE 7
CONDENSER AIR Δp=0.10
Δp=0.05
Δp=0.10
Δp=0.05
Δp=0.05
Δp=0.10
Δp=0.05
Δp=0.10
Δp=0.10
Δp=0.05
ALL Δp
Δp=0.05
Δp=0.10
SPECIFIC HEAT CONSUMPTION BTU/SEC-LB THRUST
4.25
4.15
4.05
3.95
3.85
AIRFLOW-LB/SEC-FT²
3.6
3.2
2.8
2.4
2.0
AIR INLET FACE AREA FT²/LB THRUST
26
24
22
20
18
SPECIFIC RADIATOR WT. LB/LB THRUST
.6
.5
.4
.3
.2
CONDENSER DEPTH-IN
12
10
8
6
4
COOLING EFFECTIVENESS-%
90
80
70
60
50
SPECIFIC IMPULSE LBS THRUST/LB AIR-SEC
17
16
15
14
13
12
660
670
680
690
700
710
720
730
740
CONDENSER AIR OUTLET TEMPERATURE-°R
STEAM TURBINE-COMPRESSOR-JET CYCLE PERFORMANCE
STEAM TURBINE INLET TEMP=1500°F, INLET PRESS=7000 PSIA
STEAM IN CONDENSER SATURATION TEMP=280°F, PRESS=38 PSIA
AIRCRAFT FLIGHT MACH NO=.9, ALTITUDE=45,000 FT

[redacted]

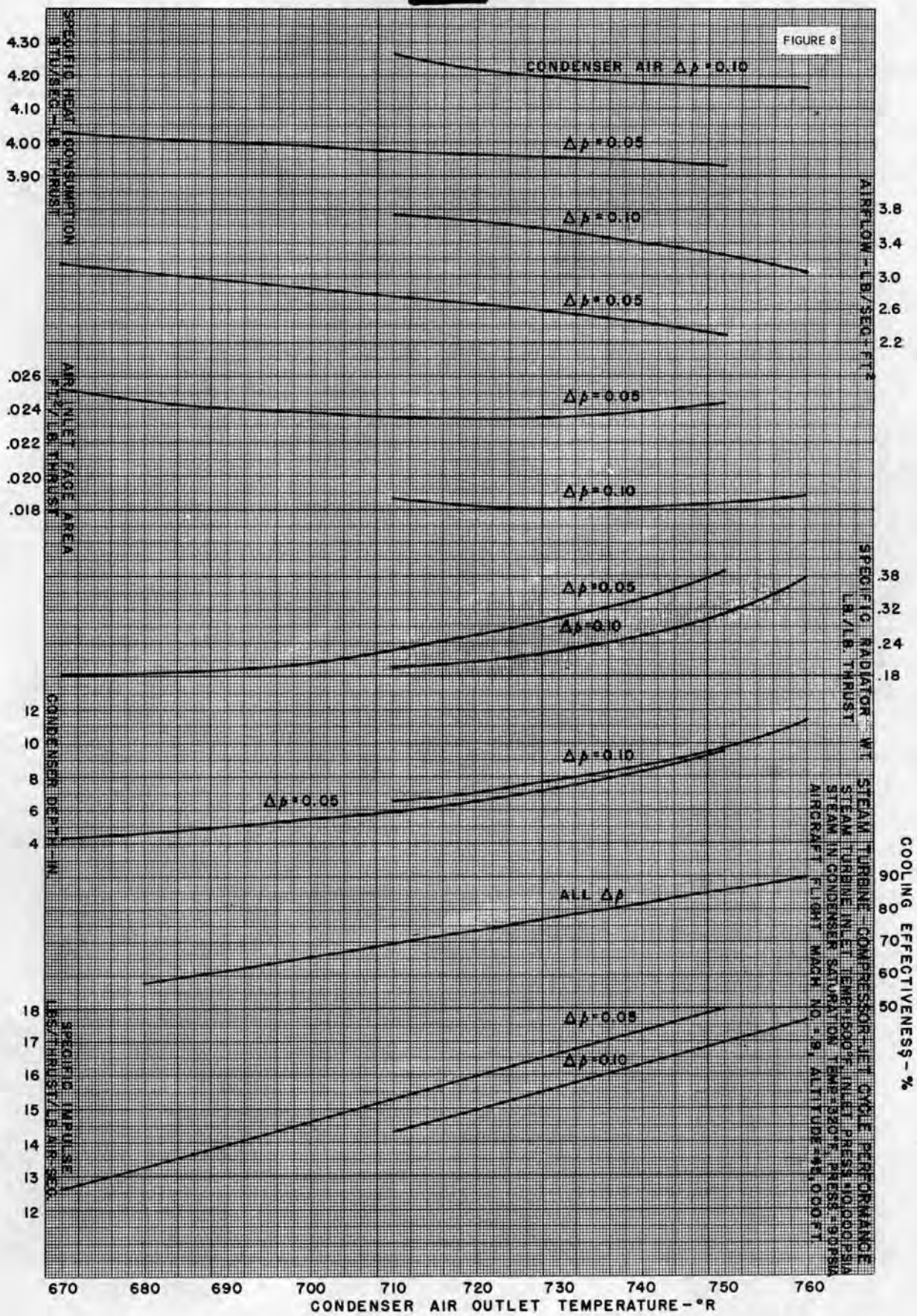


FIGURE 8
SPECIFIC HEAT CONSUMPTION BTU/SEC-LB THRUST
4.30
4.20
4.10
4.00
3.90
CONDENSER AIR Δp = 0.10
Δp = 0.05
Δp = 0.10
Δp = 0.05
AIRFLOW - LB/SEC-FT²
3.8
3.4
3.0
2.6
2.2
AIR INLET FACE AREA FT²/LB THRUST
.026
.024
.022
.020
.018
Δp = 0.05
Δp = 0.10
SPECIFIC RADIATOR WT LB/LB THRUST
.38
.32
.24
.18
Δp = 0.05
Δp = 0.10
CONDENSER DEPTH - IN.
12
10
8
6
4
Δp = 0.10
Δp = 0.05
STEAM TURBINE-COMPRESSOR-JET CYCLE PERFORMANCE
STEAM TURBINE INLET TEMP = 800°F, INLET PRESS 100,000 PSIA
STEAM IN CONDENSER SATURATION TEMP = 520°F, PRESS = 90 PSIA
AIRCRAFT FLIGHT MACH NO = .9, ALTITUDE = 45,000 FT
COOLING EFFECTIVENESS - %
90
80
70
60
50
ALL Δp
SPECIFIC IMPULSE LBS/THRUST/LB AIR SEC.
18
17
16
15
14
13
12
Δp = 0.05
Δp = 0.10
670
680
690
700
710
720
730
740
750
760
CONDENSER AIR OUTLET TEMPERATURE - °R

[redacted]

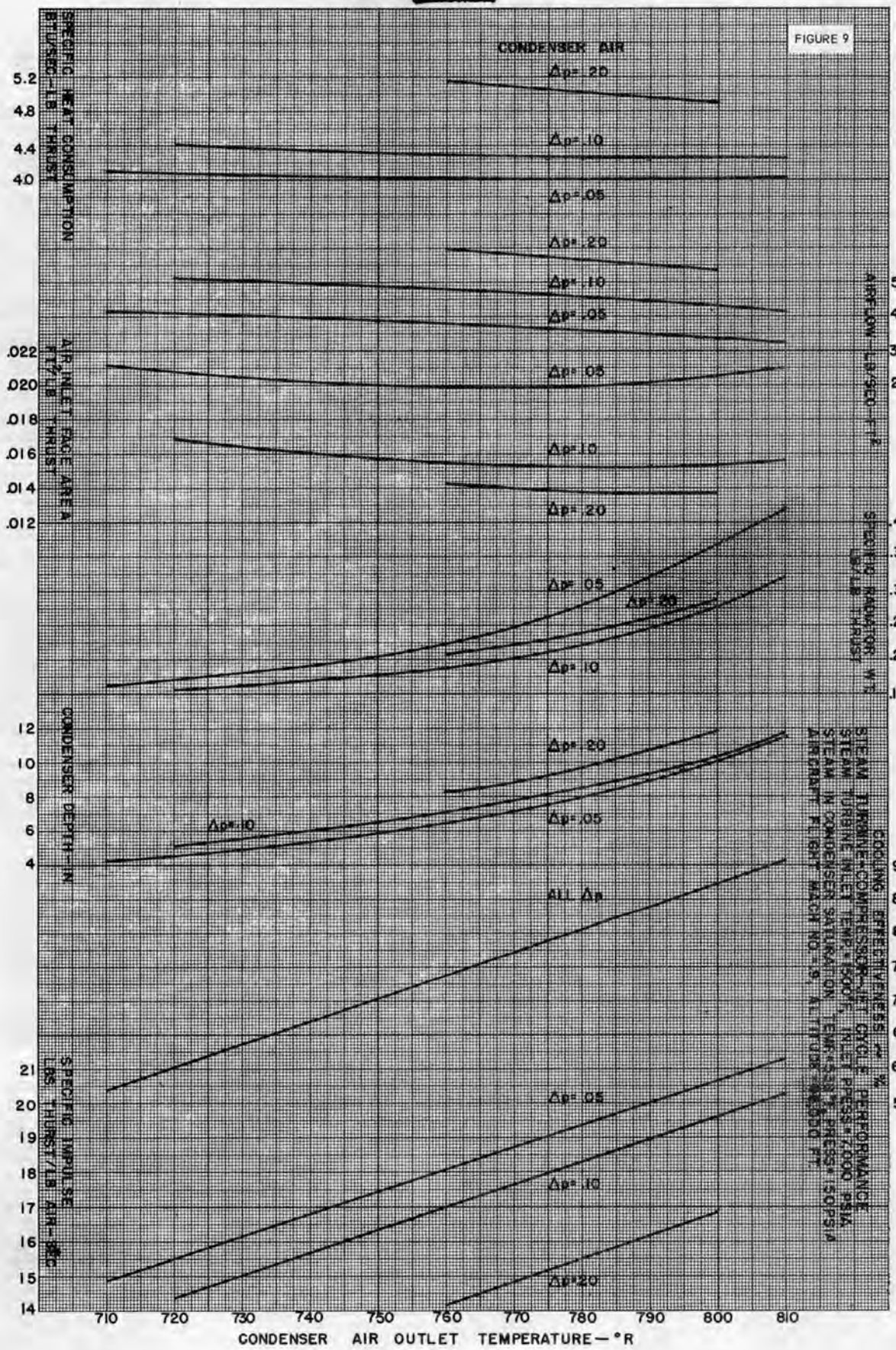


FIGURE 9
CONDENSER AIR
SPECIFIC HEAT CONSUMPTION BTU/SEC-LB THRUST
AIR INLET FACE AREA FT²/LB THRUST
CONDENSER DEPTH-IN
SPECIFIC IMPULSE LBS THRUST/LB AIR-SEC
AIRFLOW-LB/SEC-FT²
SPECIFIC RADIATOR WT. LB/LB THRUST
COOLING EFFECTIVENESS ~ %
STEAM TURBINE-COMPRESSOR-JET CYCLE PERFORMANCE
STEAM TURBINE INLET TEMP.=1500°F, INLET PRESS.=7,000 PSIA
STEAM IN CONDENSER SATURATION TEMP.=538°F, PRESS.=150 PSIA
AIRCRAFT FLIGHT MACH NO.=.9, ALTITUDE=40,000 FT.
Δp=.20
Δp=.10
Δp=.05
ALL Δp
CONDENSER AIR OUTLET TEMPERATURE—°R

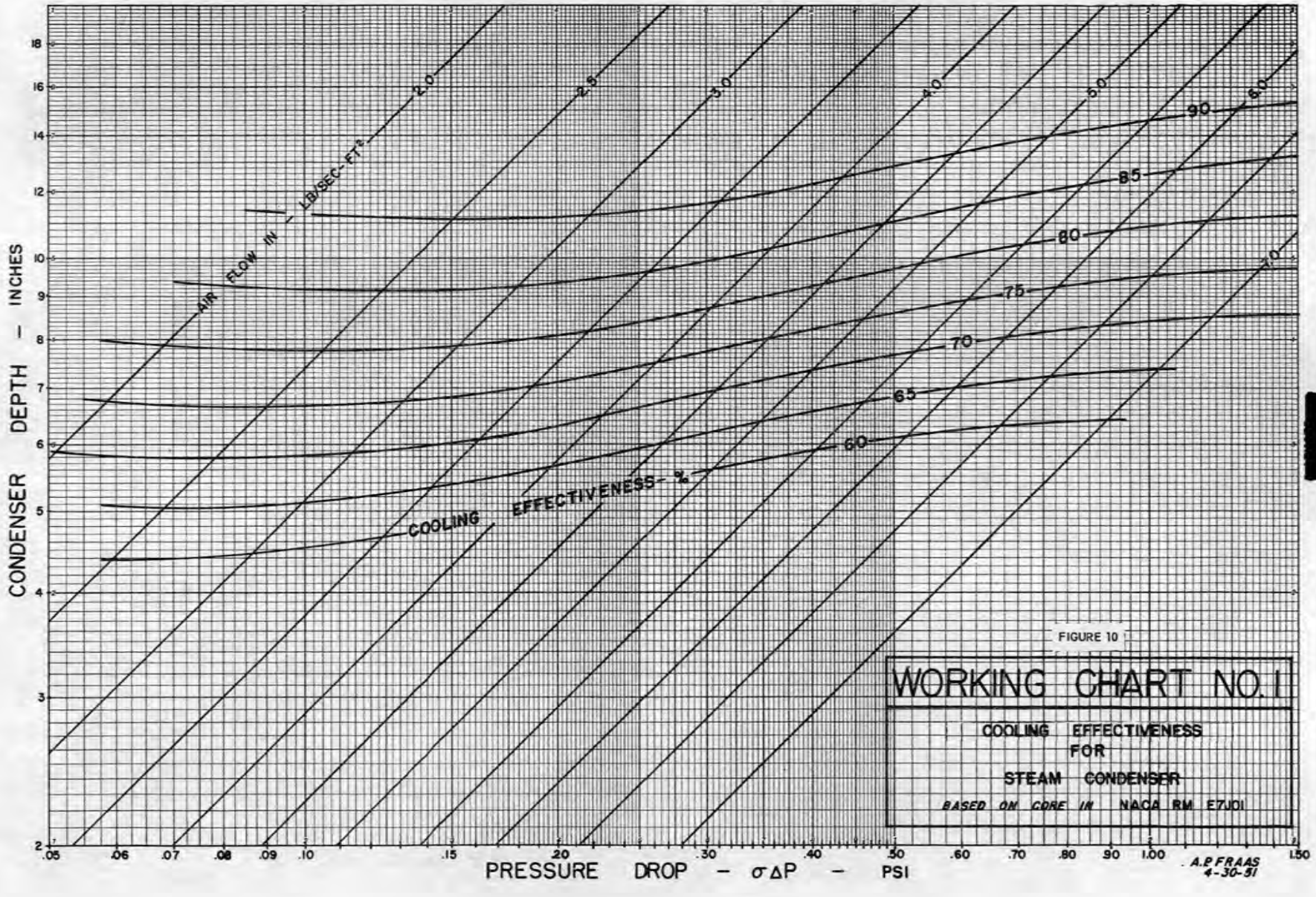


FIGURE 10

WORKING CHART NO. I

COOLING EFFECTIVENESS FOR STEAM CONDENSER

BASED ON CORE IN NACA RM E7J01

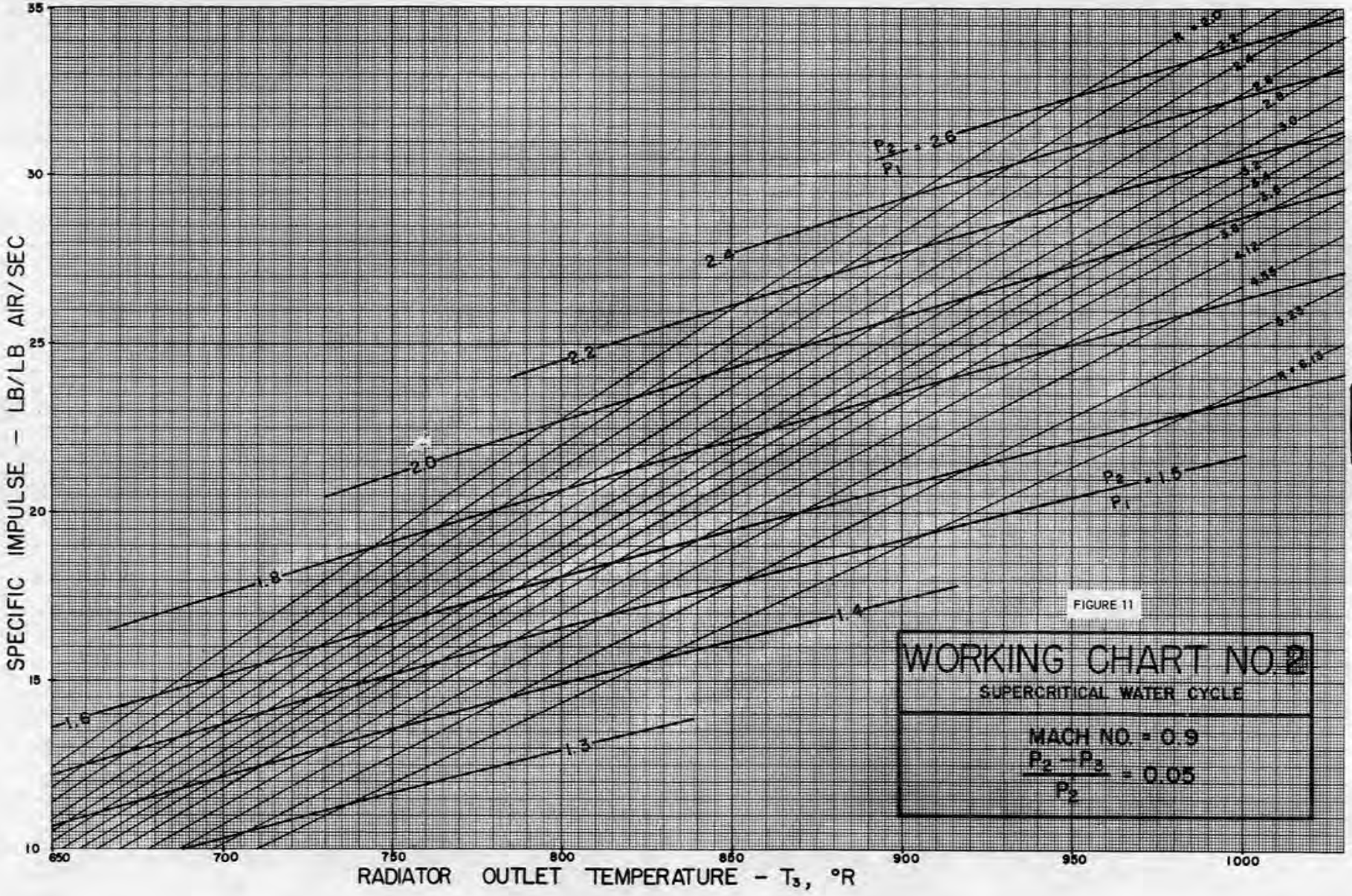

SPECIFIC IMPULSE - LB/LB AIR/SEC
RADIATOR OUTLET TEMPERATURE - T_3, °R
35
30
25
20
15
10
650
700
750
800
850
900
950
1000
$\frac{P_2}{P_1}$ = 2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.3
$\frac{P_3}{P_1}$ = 1.5
WORKING CHART NO. 2
SUPERCRITICAL WATER CYCLE
MACH NO. = 0.9
$\frac{P_2 - P_3}{P_2}$ = 0.05

FIGURE 11

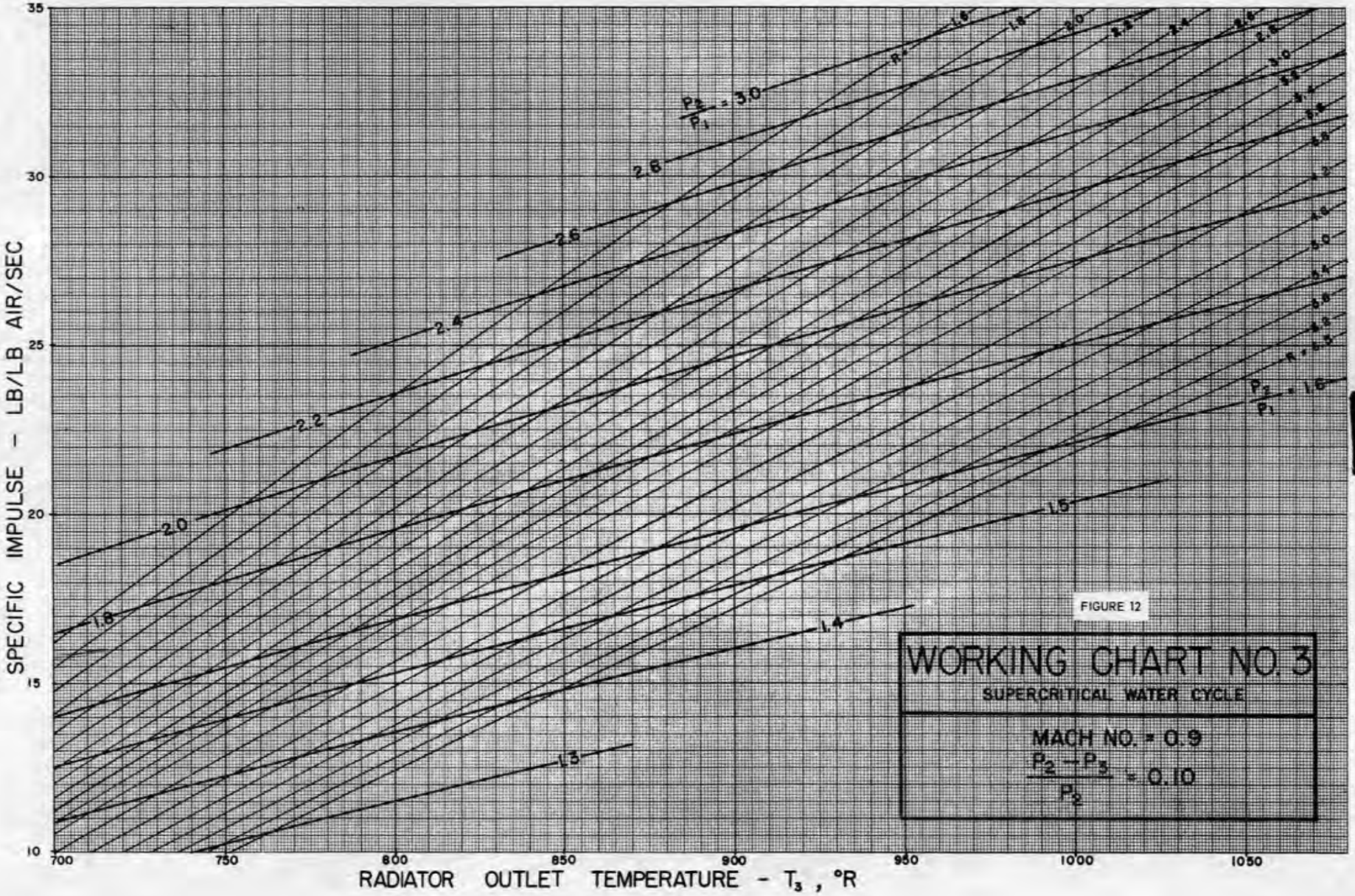

SPECIFIC IMPULSE - LB/LB AIR/SEC
RADIATOR OUTLET TEMPERATURE - T_3, °R
35
30
25
20
15
10
700
750
800
850
900
950
1000
1050
$\frac{P_2}{P_1} = 3.0$
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.5
1.4
1.3
$\frac{P_2}{P_1} = 1.6$
WORKING CHART NO. 3
SUPERCRITICAL WATER CYCLE
MACH NO. = 0.9
$\frac{P_2 - P_3}{P_2} = 0.10$

FIGURE 12

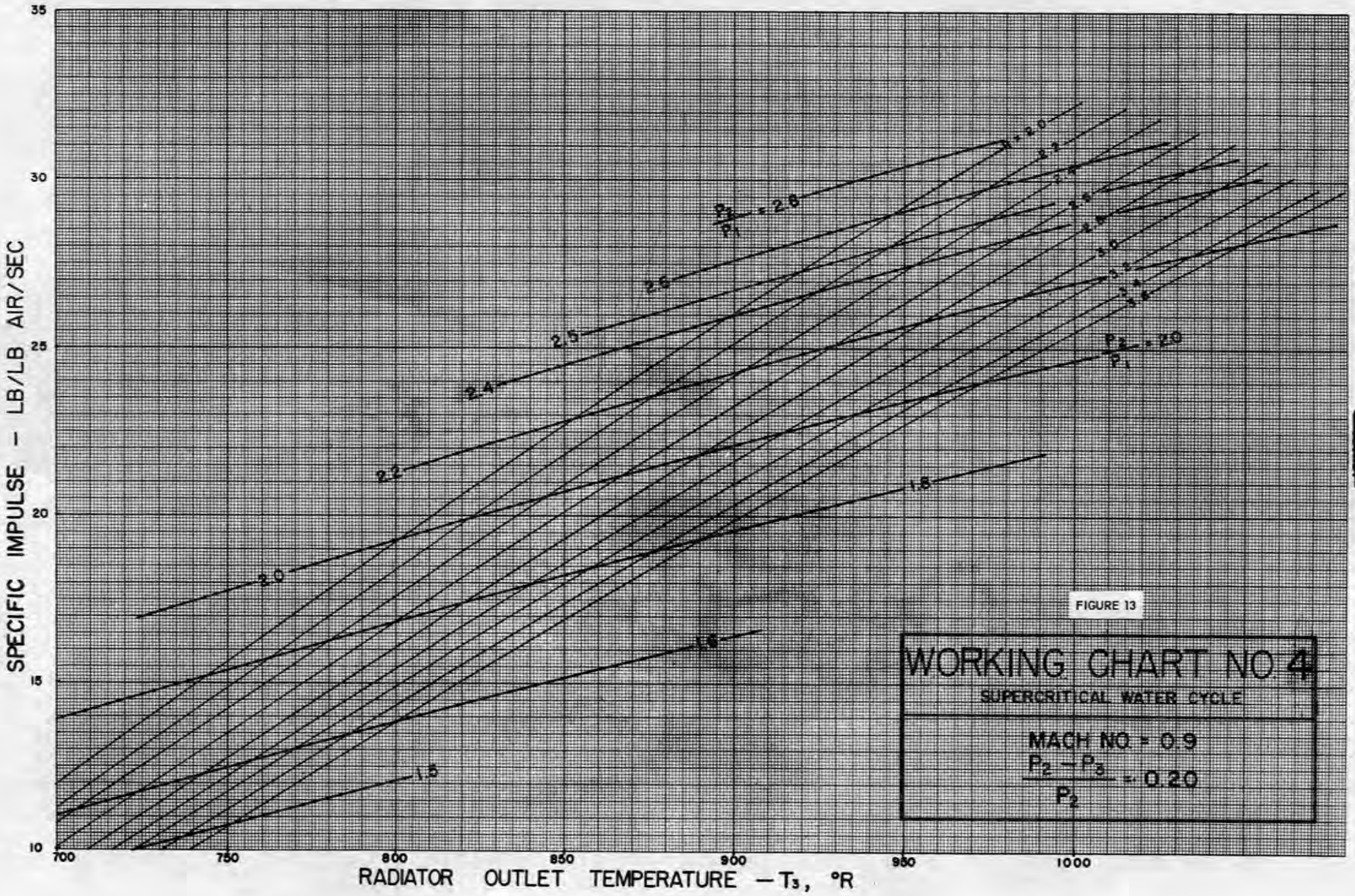

SPECIFIC IMPULSE – LB/LB AIR/SEC
RADIATOR OUTLET TEMPERATURE – T3, °R
35
30
25
20
15
10
700
750
800
850
900
950
1000
P3/P1 = 2.8
2.5
2.4
2.2
2.0
1.8
1.6
1.5
P2/P1 = 2.0
WORKING CHART NO. 4
SUPERCRITICAL WATER CYCLE
MACH NO. = 0.9
(P2 – P3)/P2 = 0.20

FIGURE 13

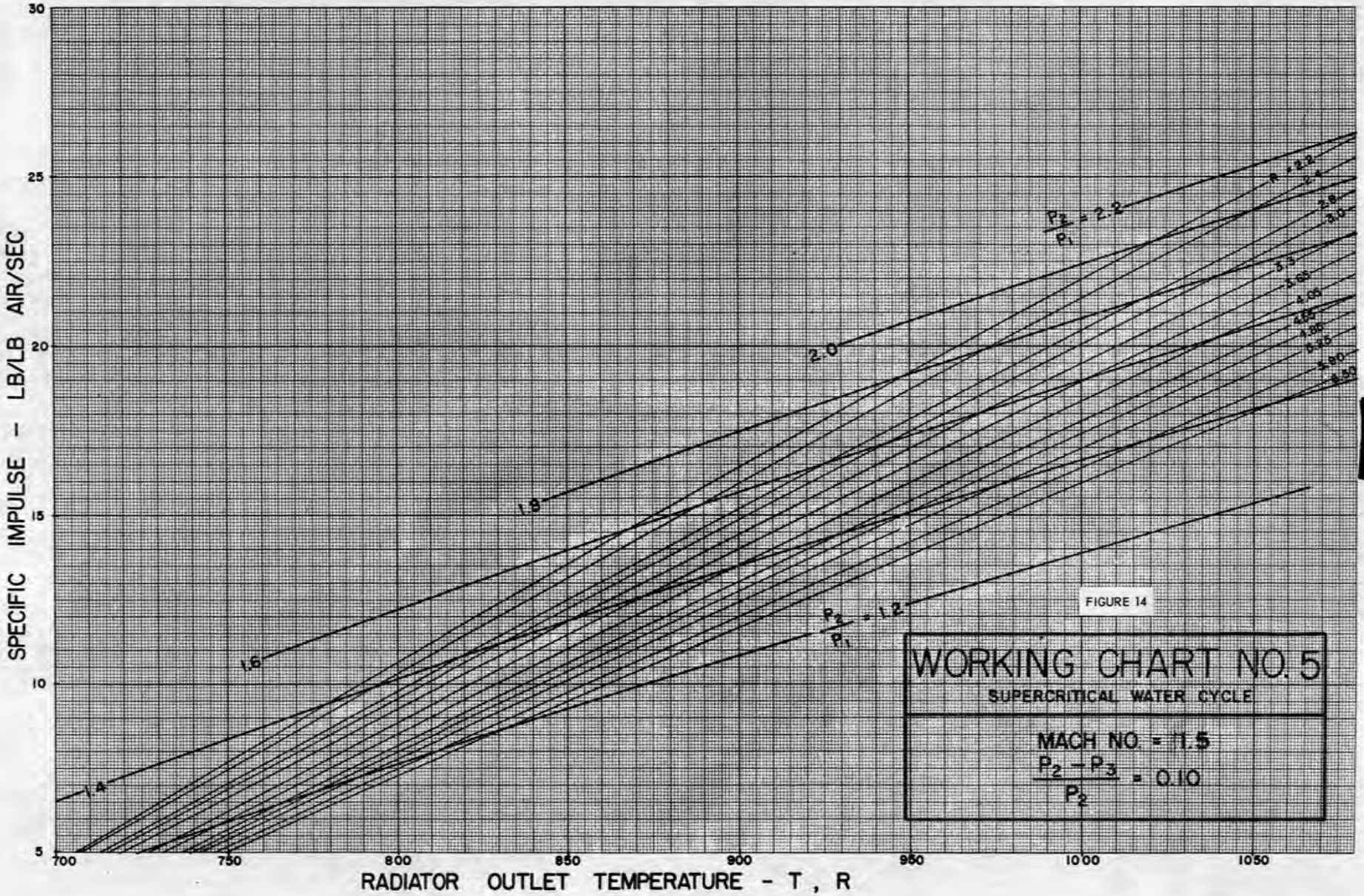
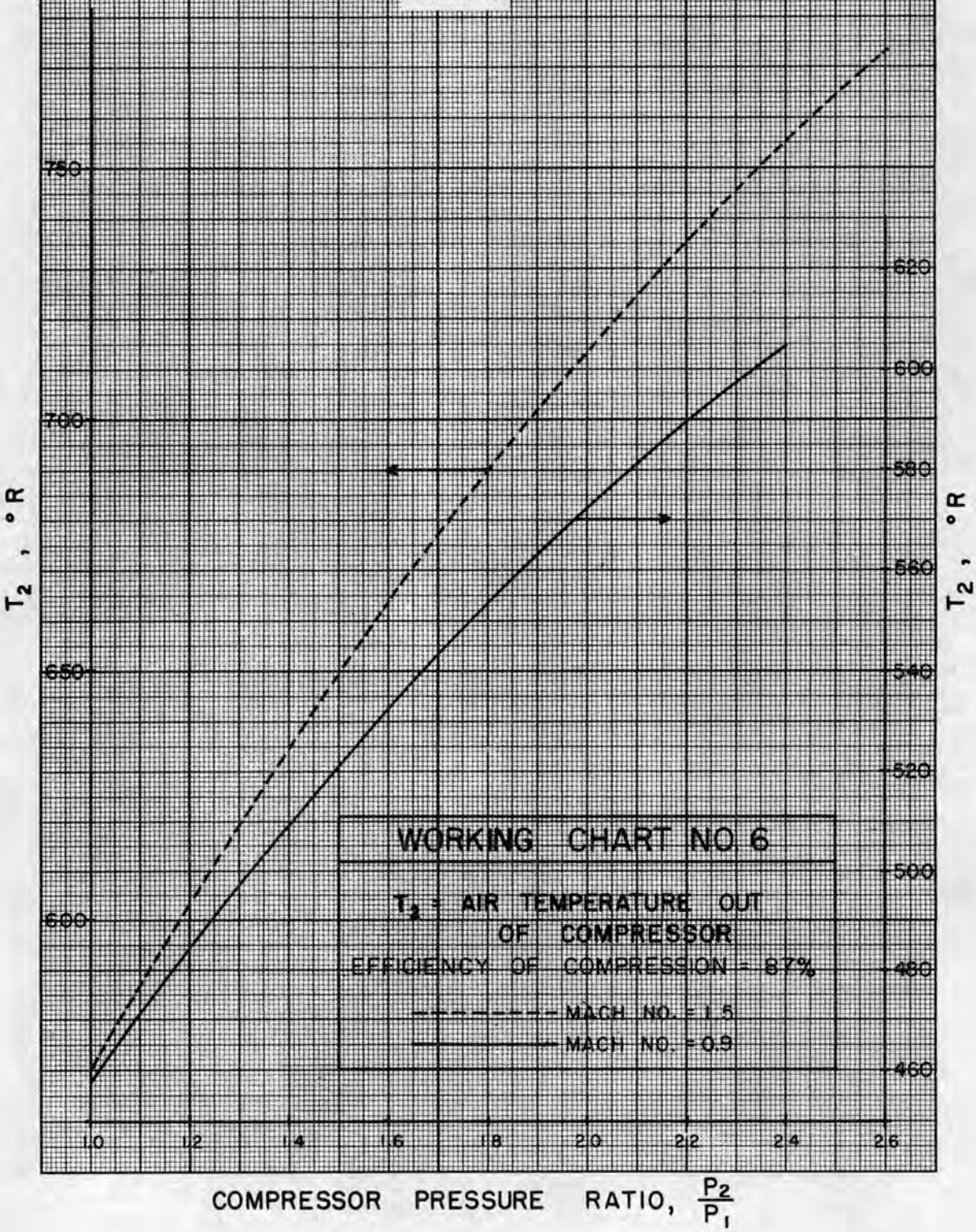

SPECIFIC IMPULSE - LB/LB AIR/SEC
RADIATOR OUTLET TEMPERATURE - T , R
30
25
20
15
10
5
700
750
800
850
900
950
1000
1050
$\frac{P_2}{P_1} = 2.2$
2.0
1.8
1.6
1.4
$\frac{P_2}{P_1} = 1.2$
R = 2.0
2.4
2.8
3.0
3.5
3.65
4.00
4.65
4.85
5.25
5.90
6.50
WORKING CHART NO. 5
SUPERCRITICAL WATER CYCLE
MACH NO. = 1.5
$\frac{P_2 - P_3}{P_2} = 0.10$

FIGURE 14

[redacted]

FIGURE 15



[redacted]

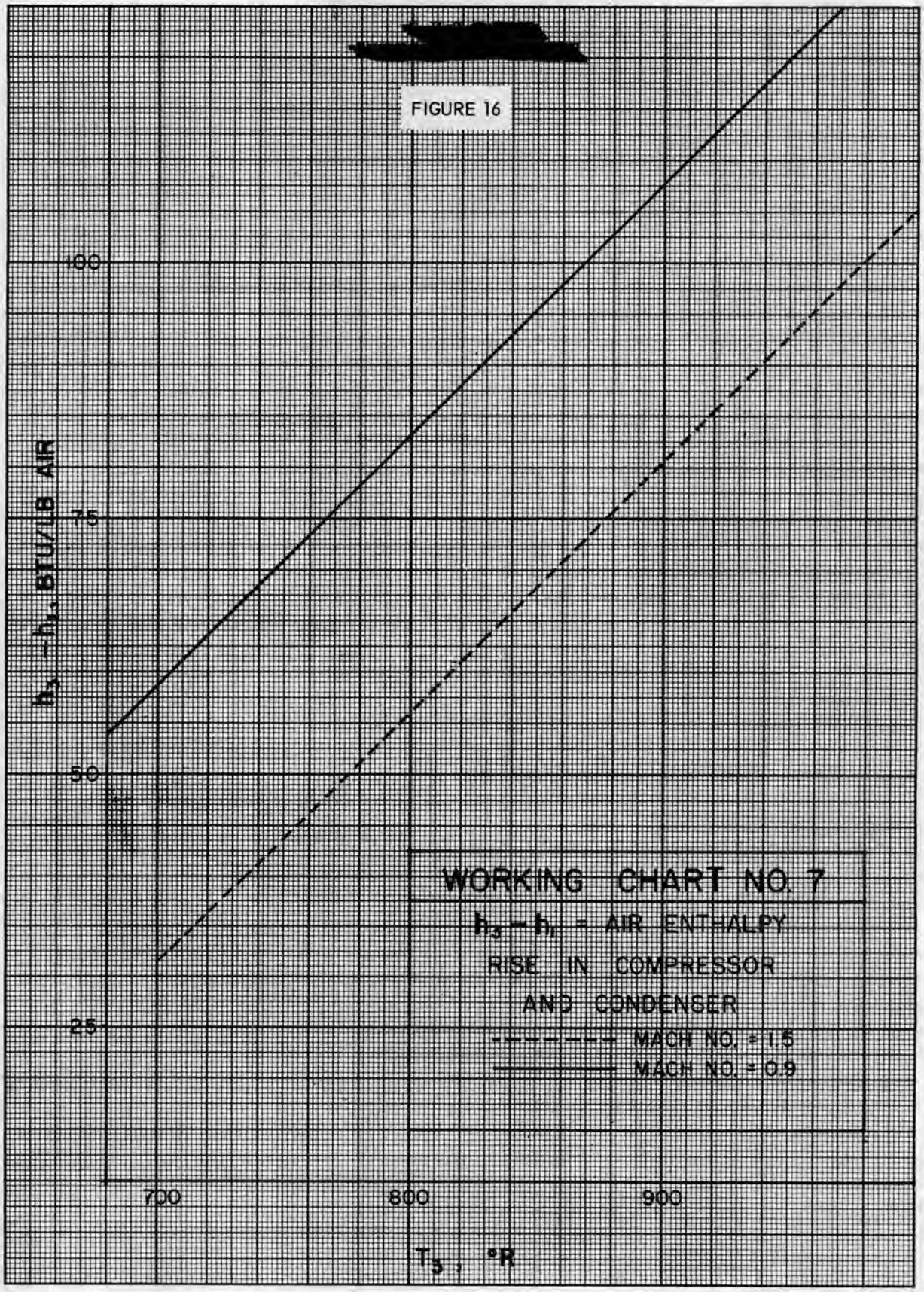



FIGURE 16