R. MILEY [redacted]

Bendix

Aerospace
Systems Division

Development of a Power Dissipation Model for the Power Conditioning Unit (PCU)

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ATM 783	

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This memorandum summarizes the effort to develop a mathematical model of the power dissipation within the PCU and to adapt that model to assist in the central station power/thermal analytical studies that have been required during ALSEP system development.

Prepared by: F. E. Wilburn

Prepared by: H. W. Wilson

Approved by: O. Neau

7-12-68

1. Introduction and Summary

Throughout the ALSEP Program, ATM 449 (Power Budget) has provided a catalog of power availability and power demand associated with the various equipment items of the system. This type of power budgeting has been essential to system power management and to the forecasting of system performance in terms of:

- permissible experiment power demands
- thermal support power availability
- maintenance of voltage regulation under all operational modes
- thermal control of central station electronics.

This budget process was simplified by the fact that all units except the Power Conversion Unit (PCU) have, at most, two or three operational modes in which their power demands differ appreciably. Hence, although the number of operational modes is relatively large, the associated power demands at the output of the PCU are normally predictable. The power dissipation (W) associated with the PCU requires a knowledge of this system power demand as well as the power coming in to the system from the RTG, and is determined by summing the electrical dissipations associated with the two PCU functions of power conversion and voltage regulation, viz. :

$$W = P_{rt} + P_c \tag{1}$$

where

P_{rt} = Reserve power dissipated within PCU

P_c = Voltage conversion losses.

It is the purpose of this memorandum to discuss the history of development of the model used for the prediction of PCU power dissipation and to discuss the application of this model during ALSEP system test and lunar surface operation.

2. Mathematical Modelling of PCU Dissipation

The distribution of power in the ALSEP system can be described in terms of the subdivisions shown in Figure 1 to be

$$P_{in} = P_o + P_c + P_r \tag{2}$$

where

P_{in} = Power into PCU (RTG OUTPUT)

P_o = Power out of PCU (ALSEP LOAD)

P_c = Power used in voltage conversion (CONVERSION LOSS)

P_r = Power dissipated in shunt regulator (RESERVE POWER)

The last two items are determined by the performance of the PCU. Hence, it is necessary to be able to establish the power usage of the PCU in order to evaluate the balance of power throughout the system. A first approximation of the PCU conversion loss was made during engineering model testing of that unit. At that time it was assumed that the power consumed in the PCU for voltage conversion and associated functions varied linearly with PCU power output in the following manner:

$$P_c = C + K\,P_o \tag{3}$$

where

C = 5.0 watts

K = 0.08

The reserve power dissipated within the PCU is simply stated as:

$$P_{rt} = P_r - P_{rr} \tag{4}$$

where

P_r = Total reserve power

P_{rr} = Reserve power external to PCU

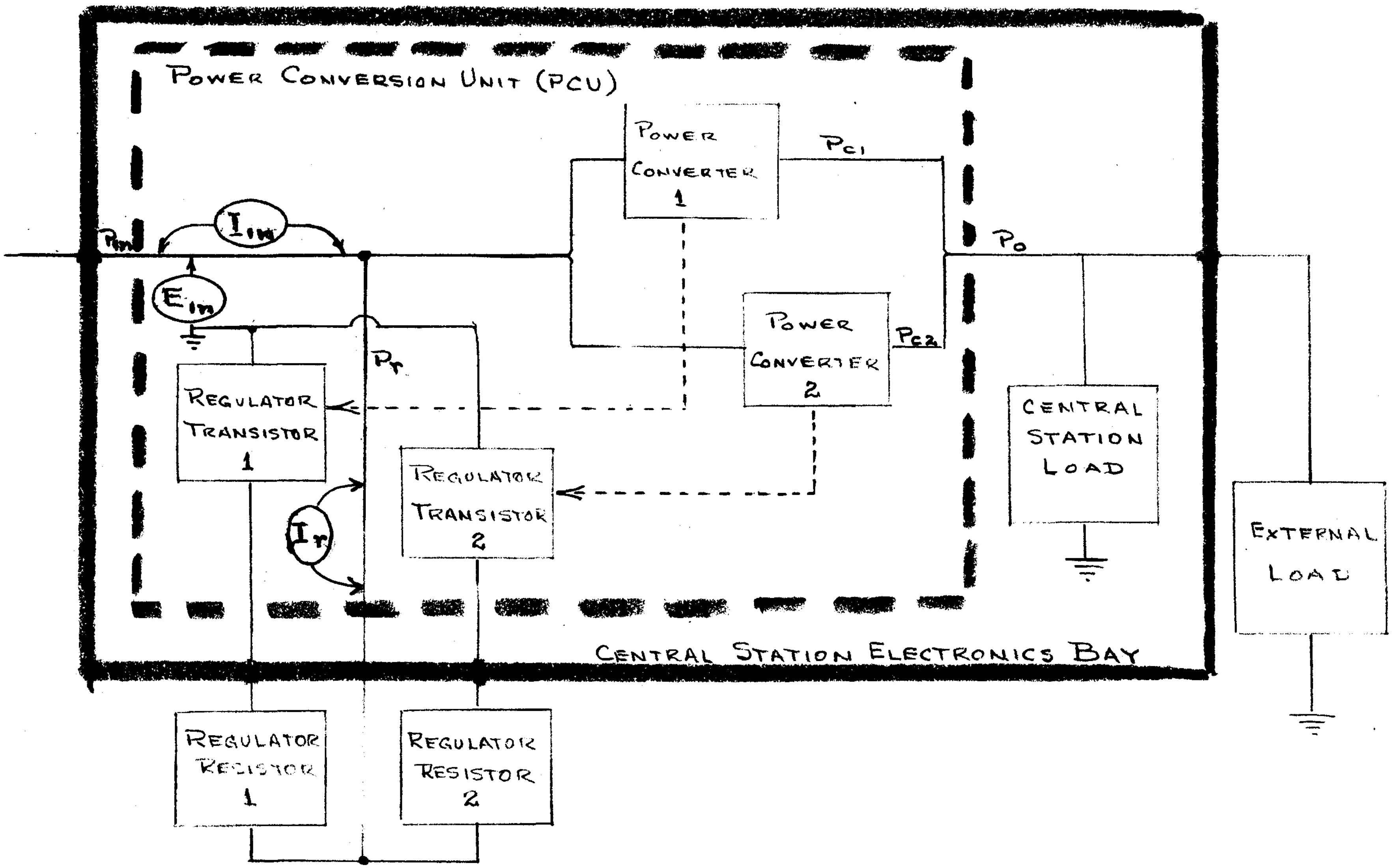


Figure 1: Simplified Diagram of Power Distribution

Since $$P_{rr} = I_r^2 \cdot R_{ext}$$

or $$P_{rr} = \left(\frac{P_r}{E_{in}}\right)^2 \cdot R_{ext}$$

then $$P_{rr} = \frac{P_r^2}{P_v} \tag{5}$$

where

I_r = Current in shunt regulator

R_{ext} = Shunt regulator circuit resistance external to PCU

E_{in} = Voltage at PCU input

$$P_v = \frac{E_{in}^2}{R_{ext}}$$

Substituting (5) into (4) yields

$$P_{rt} = P_r \left(1 - \frac{P_r}{P_v}\right) \tag{6}$$

By definition, the sum of equations (3) and (6), represent the total electrical dissipation within the PCU and can be written as

$$W = P_r \left(1 - \frac{P_r}{P_v}\right) + C + K P_o \tag{7}$$

When the system parameters other than reserve power (P_r) and output power (P_o) are available, this model can be expressed in alternate, but equivalent, forms such as,

$$W = P_s - \frac{\left(P_s - P_c\right)^2}{P_v} \qquad (8)\,(8)$$

where

$$P_s = P_{in} - P_o$$

and

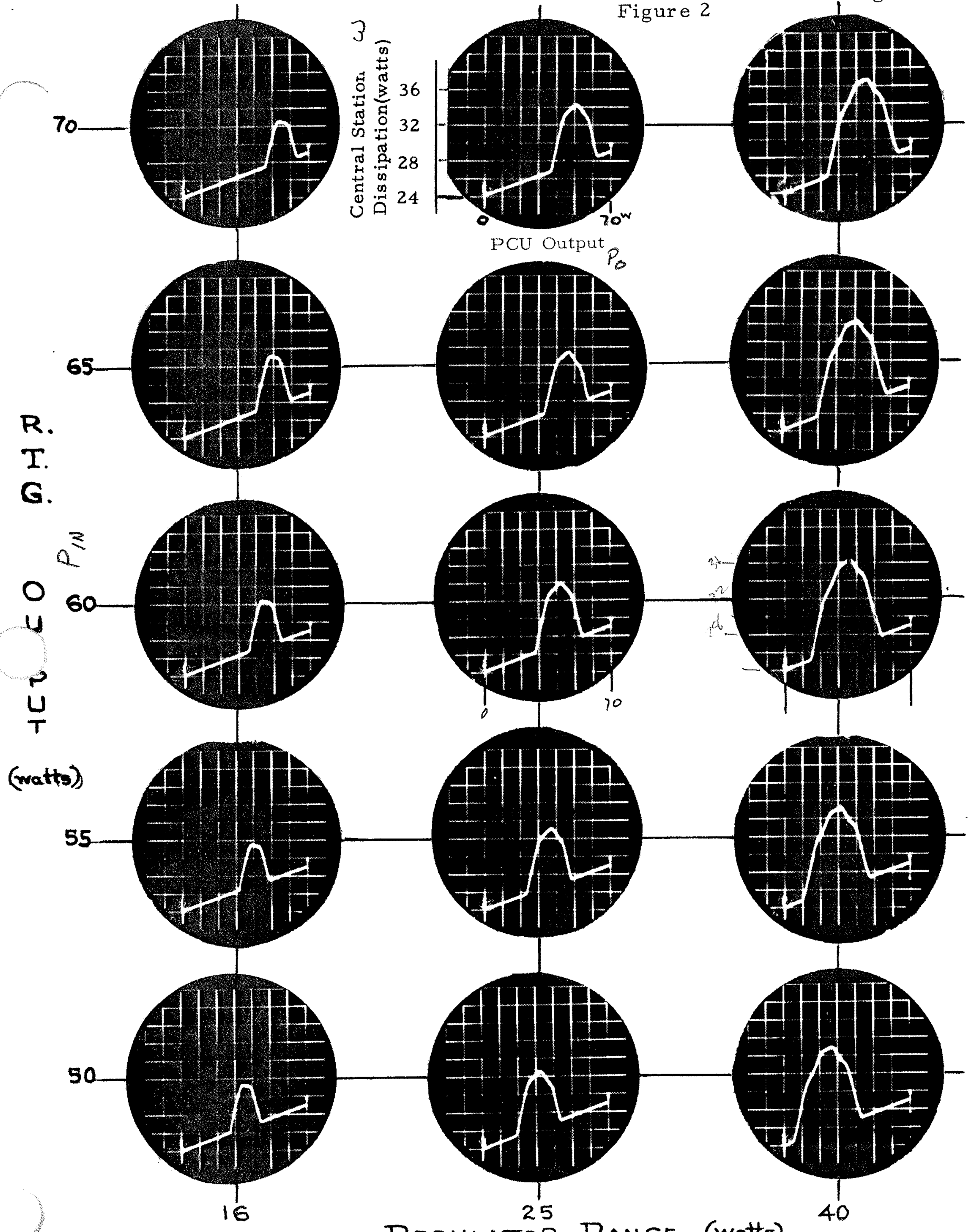
$$W = \frac{\left(P_{in} - C - (1+K)\,P_o\right)\left(P_v - P_{in} + C + (1+K)\,P_o\right)}{P_v} + C + KP_o \qquad (9)$$

This last equation was investigated for the effect of changes in P_{in}, P_o and P_v by use of an analog computer. The results of this analog modelling effort were published in ATM 675, and are reproduced in Figure 2.

To improve the flexibility and accuracy of these calculations, a digital computer program was written which provided a tabulated, printed output of the calculation of W for selected values of the primary parameters. This program was extended to provide plots of W vs P_o in several forms (see Figures 3 and 4) to aid in the analysis of various power distribution problems.

As a result of data obtained from tests performed on both the qualification, back-up and prototype Power Conversion Units, the need for modifying this preliminary model of PCU dissipation became evident. These tests were reported in ATM 753 and revealed, among other things, that P_c is actually a nonlinear function of P_o. Figures 5 and 6 are reproduced from that report. Since a change in the dissipation model was necessary to reflect this new information, it was decided to also change the parameters used in the model so that it would be useful in the analysis of test and operational data. The only power parameters telemetered in the housekeeping data are:

Figure 2



$$P_V = \frac{(AE3)^2}{4.2\Omega} = 60 \text{ WATT REGULATOR}$$

FIGURE 3

PCU DISIPATION VS PCU OUTPUT (IN WATTS)

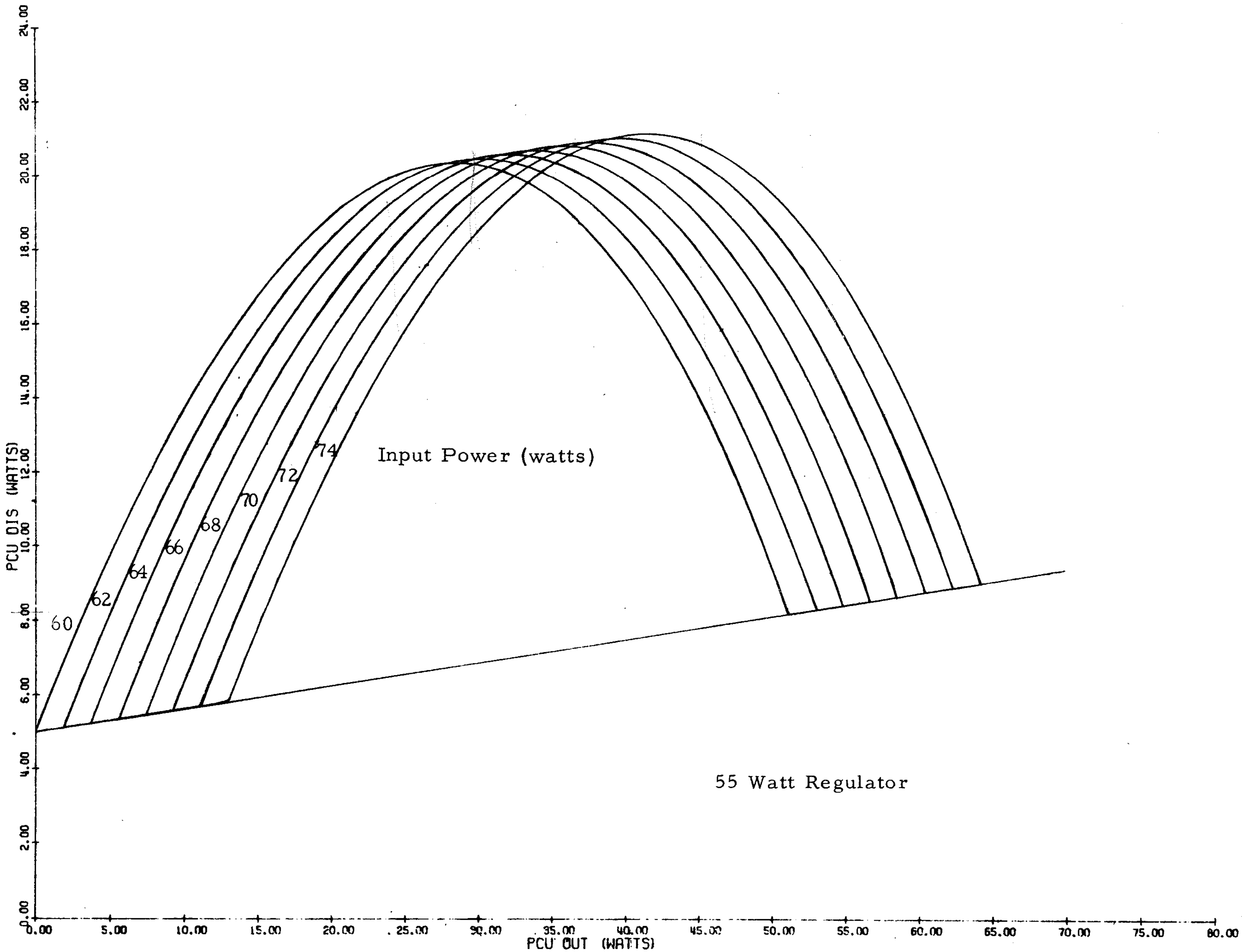


Figure 4

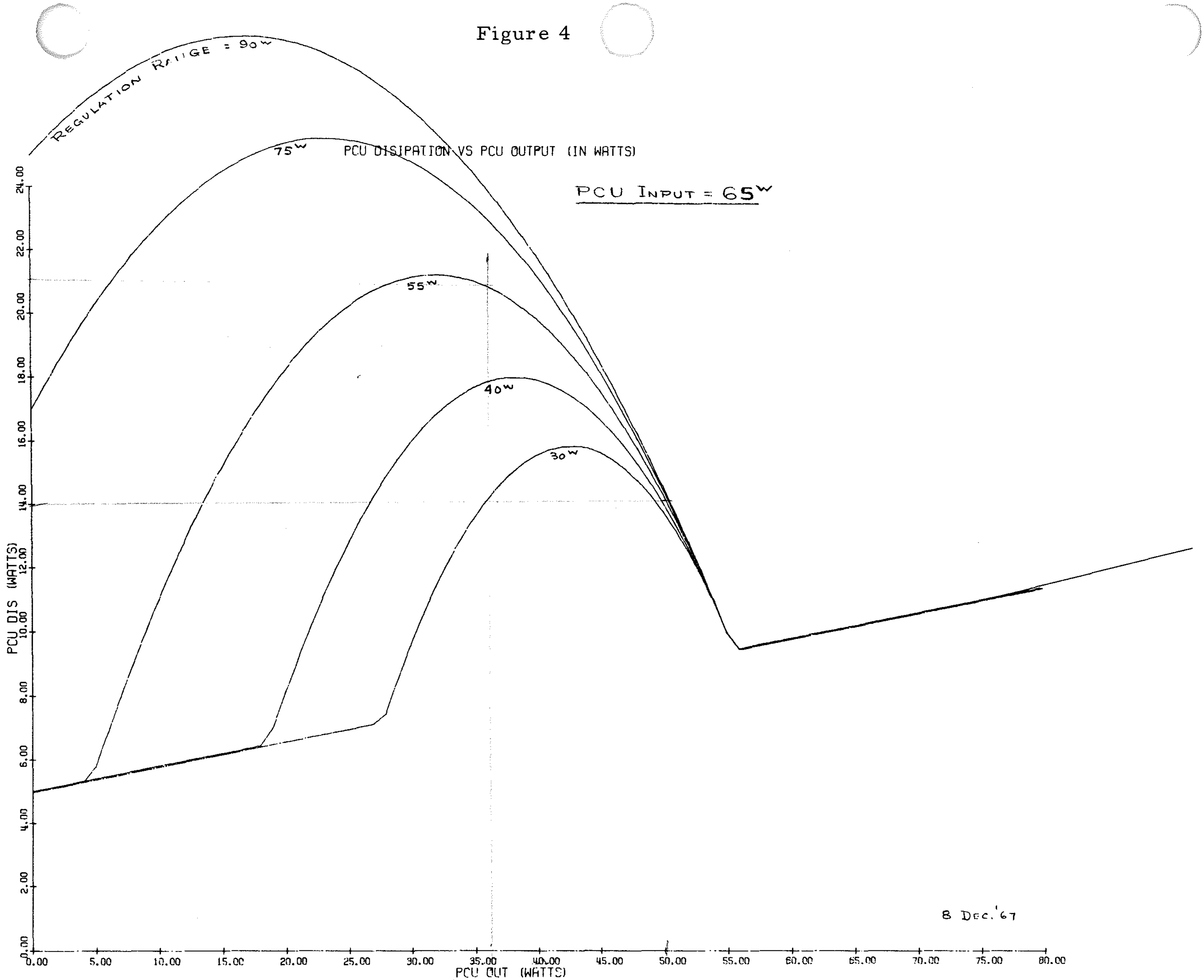

REGULATION RANGE = 90W
75W
PCU DISIPATION VS PCU OUTPUT (IN WATTS)
PCU INPUT = 65W
55W
40W
30W
PCU DIS (WATTS)
PCU OUT (WATTS)
8 Dec. '67
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
55.00
60.00
65.00
70.00
75.00
80.00

Figure 5
DISSIPATION WITHIN PCU Vs PCU OUTPUT POWER
33 WATT REGULATOR

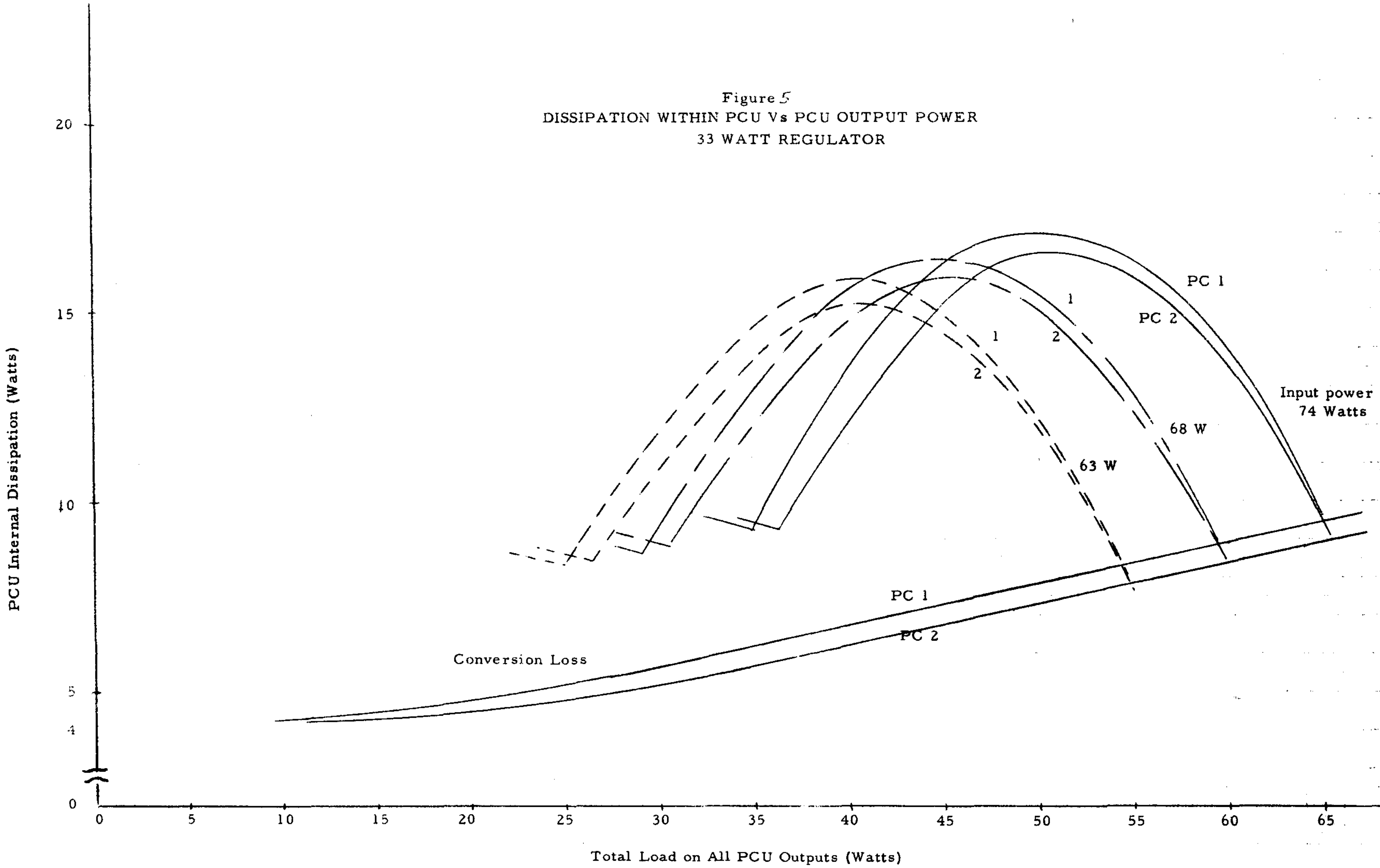
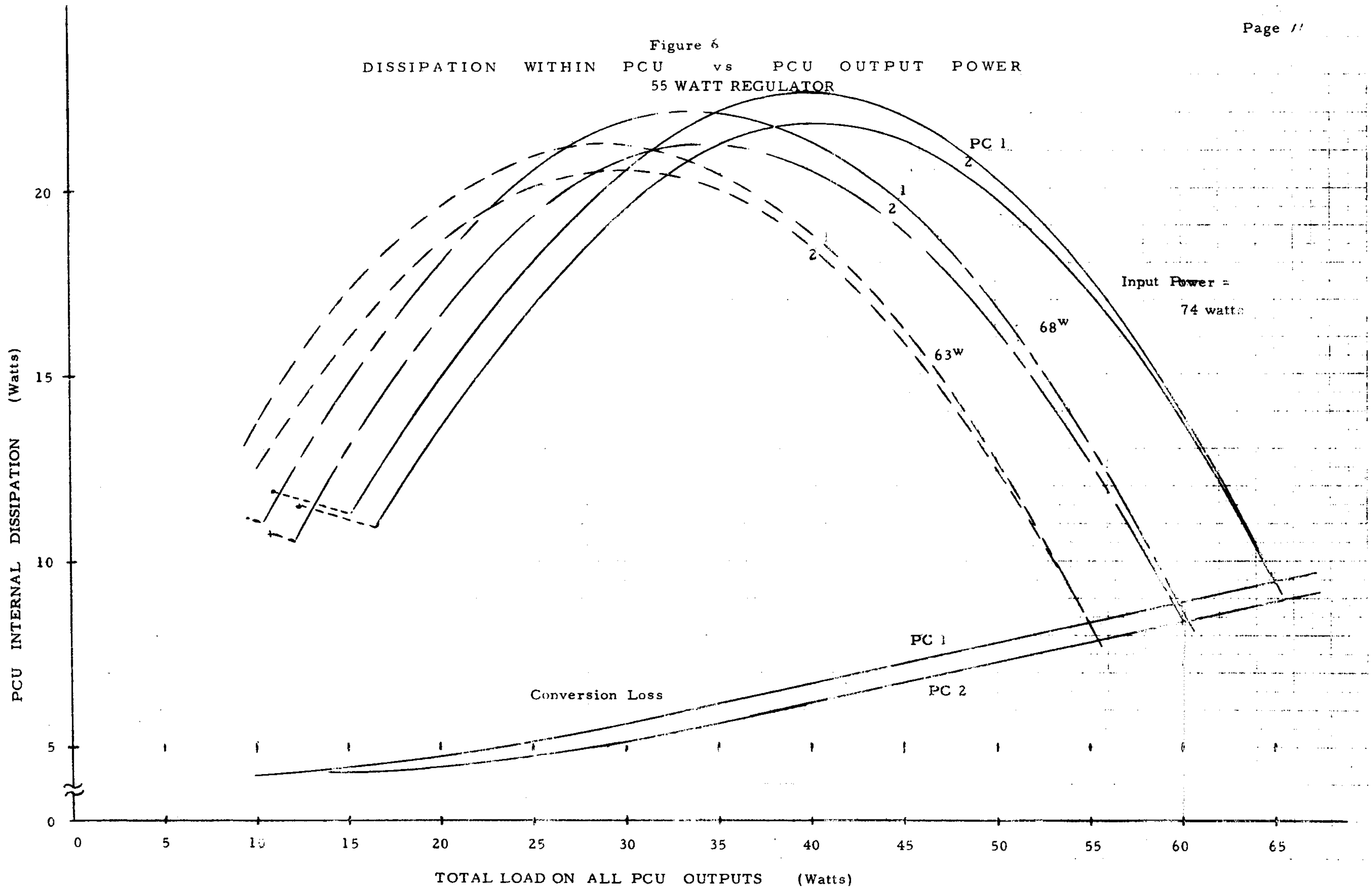


Figure 6

DISSIPATION WITHIN PCU vs PCU OUTPUT POWER

55 WATT REGULATOR



Input Voltage: E_{in}

Input Current: I_{in}

Reserve Current: I_r

This model was thus modified to express the test-derived values of PCU dissipation in terms of these input parameters.

The amount of reserve power dissipated inside the PCU, (i.e., P_{rt}) was already derivable from these parameters using equation (4). The relation between PCU conversion loss and the input power parameters was derived by empirical curve-fitting techniques. The details of this effort are given in Appendix A. The revised PCU dissipation model now has the form

INT DISS + (PCU CONV LOSS)

$$W = I_r (E_{in} - I_r R_{ext}) + A + B (P_{in}') + c (P_{in}')^2 \tag{10}$$

where

Ir = SHUNT CURRENT
EIN = RTG INPUT

$P_{in}' : E_{in} (I_{in} - I_r)$

REXT = 4.2Ω PCU1 PIN' = RTG INPUT PWR – RESERVE PWR
A = 3.893 (PCU1)
B = 0.0205 (PCU1)
C = 000759 (PCU1)

A digital computer program has been written for this relation which provides tabulated and/or analog plotted presentations of the PCU dissipation as a function of P_{in}'. Typical plots are presented in Figure 7.

A4

EIN 15.90 V

REXT 4.2 Ω

IIN 3.77 A

RTG INPUT 60W

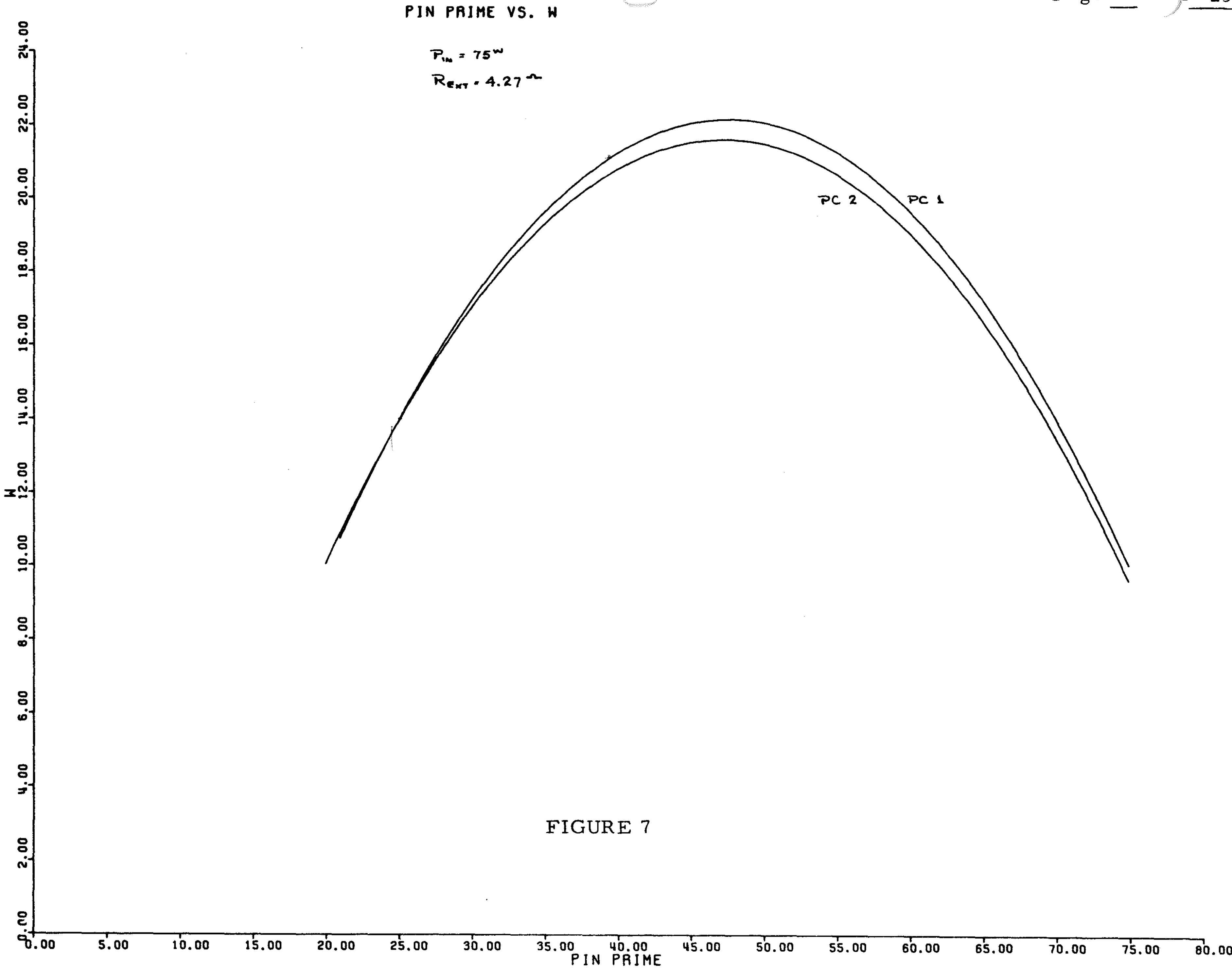

PIN PRIME VS. W
P_{IN} = 75 W
R_{EXT} = 4.27 Ω
PC 2
PC 1
W
PIN PRIME
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
55.00
60.00
65.00
70.00
75.00
80.00

FIGURE 7

3. Application of the Revised Model

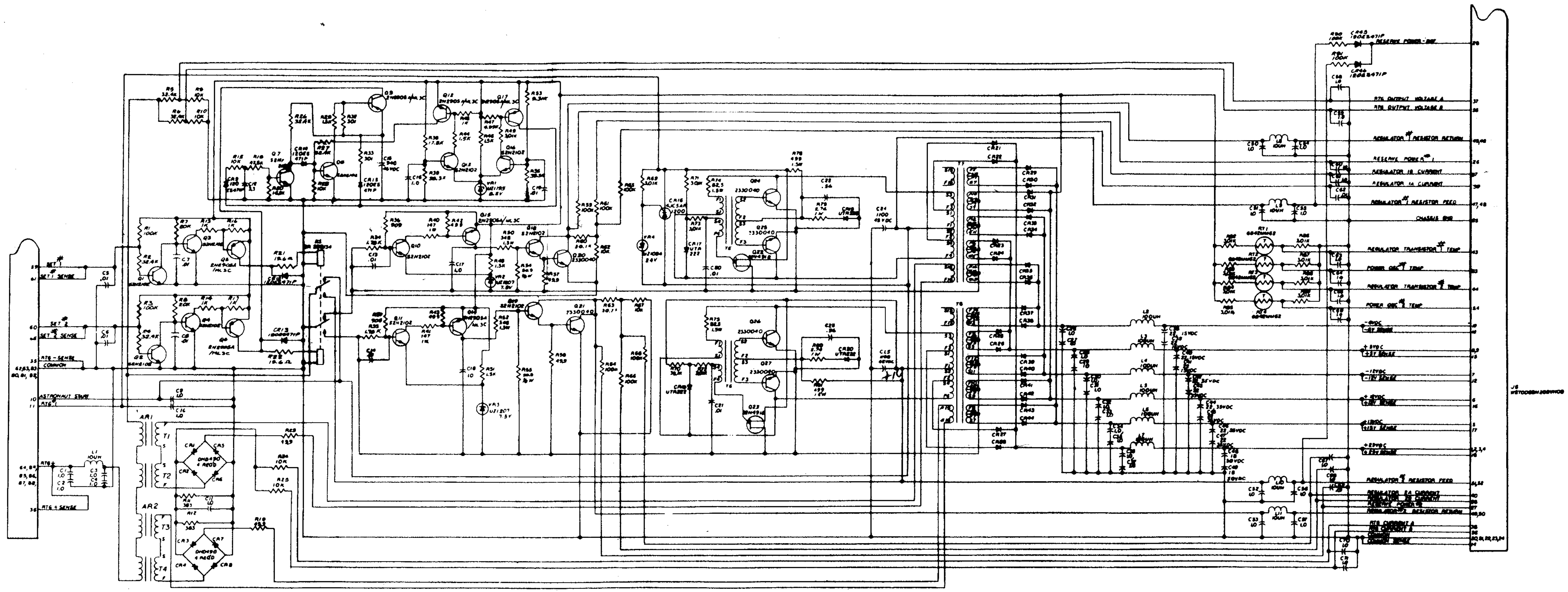
When substituting specific values for the parameters in this model it is, of course, important to properly interpret the definition of each parameter. Figure 1 illustrates the assumed distribution of power and emphasizes the assignment of all PCU power to "conversion" losses or "reserve power" dissipation. When considering the real PCU (Figure 8) it is necessary to be more specific in the definition of the P_c and P_{rt} terms in the mathematical model. As stated above, the P_c term in the revised model was molded to suit the results of a specific test designed to measure the PCU conversion losses. To make these measurements under a range of load conditions it was necessary to establish the meaning of "conversion loss" so that the test data would be consistent. For purposes of this test the operating point of the regulator servo was set to "cut-off". This point was set by varying the voltage of the power source in such a manner as to yield a maximum voltage drop across the regulator transistor. This establishes a unique condition of power system operation where the regulator is imposing minimum load on the power source and the supply voltages are on the verge of dropping due to excessive load. Hence the measurements of power consumed within the PCU under this condition (and herein designated P_c) represent the total PCU dissipation when reserve current is at a minimum.

When the above test measurements were made the data was correlated in terms of input power using a measurement of E_{in} made at the PCU connector. When values of E_{in}, obtained during system test or operation (from the System Test Set or from the telemetered data) are substituted into this math model, it must be recognized that these voltage readings may require some correction to represent the voltage at the input connector. The resolution of the telemetered input power parameters introduces an additional uncertainty into the results obtained by this model. To illustrate, the resolution of these parameters at a typical power operating point, in terms of the possible change in the parameter without a change in octal representation, is as follows:

Input Voltage Resolution:	0.08^V @ 16^V
Input Current Resolution:	0.0275^A @ 4.25^A
Reserve Current Resolution:	0.0172^A

TRAN HR 8.5
PSE 4.5
SWS 3.0
SIDE 2.0
LSM 0.0
18.0

47



NOTES:
1. LAST DESIGNATION USED: C71, CR46, K1, Q27, R91, RT4, L11, AR8, T8, VR4
2. EXCEPT AS NOTED:
ALL RESISTORS ARE IN OHMS AND ARE 1/10 WATT
ALL CAPACITORS ARE IN MICROFARADS.
3. "A" SIGNALS GO TO D33.
4. "B" SIGNALS GO TO ACTIVE SEISMIC.
5. CAPACITORS:
10MFD CAPACITORS ARE C3R136105KP
.01MFD CAPACITORS ARE CKR12BX103KM.
6. COMPONENTS NOT USED: R30, R31, R76 & R77
CR10, CR11

DIODE CHART (PARTIAL)		
CR DESIGNATION	TYPE	QTY
21-28	28800394	8
29-44	UTR 222	16

Figure 8 - PCU Electrical Schematic, Complete

This uncertainty is provided solely by the digitizing process and does not include any of the measurement errors imposed by voltage and temperature changes. These measurement uncertainties, if multiplied together in the most adverse combinations to determine power, yield the following typical resolution products:

$$\Delta \text{ Input Power} = +(16.08 \times 4.2775) - (15.92 \times 4.2225)$$

$$= 68.7822 - 67.2221$$

$$= 1.56^{W} (@68^{W})$$

$$\Delta \text{ Reserve Power} = +(16.08 \times 0.3275) - (15.92 \times 0.2725)$$

$$= 5.2662 - 4.3382$$

$$= 0.928 (@5^{W})$$

APPENDIX A

Curve-Fitting to PCU Conversion Loss Test Results

On 9 May 1968, a test was performed on the Qualification Back-up Model of the PCU (Part No. 2330000-3, Serial No. 2) to determine the electrical power consumed by the PCU when the regulator is inactive. The procedure for this test was the first 62 pages of the Thermal Mapping Test Procedure for the PCU. The results of this test are plotted in Figure 9 against input power, P_{in}. Using the measurement data shown in Table I, rather than these hand-fitted curves, a series of equations of the form

$$P_{cn} = A_n + B_n (P_{in}') + C_n (P_{in}')^2$$

$$\text{where } P_{in}' = P_{in} - P_r$$

$$= P_{in} \text{ (when } P_r = 0\text{)}$$

n: relevant power converter (1 or 2)

were fitted numerically using simple curvilinear regression techniques.* This curve-fitting process yielded the following relations which are the ones being used to compute the PCU conversion loss, P_c, in the revised model:

$$P_{c1} = 3.893 + 0.0205\, P_{in}' + 0.000759\, (P_{in}')^2$$

$$P_{c2} = 3.97 + 0.0234\, P_{in}' + 0.000605\, (P_{in}')^2$$

The following paragraphs detail the method for determining the coefficients of these relations.

*REFERENCE:
Ezekiel and Fox, "Methods of Correlation and Regression Analysis", Third Edition, Wiley.

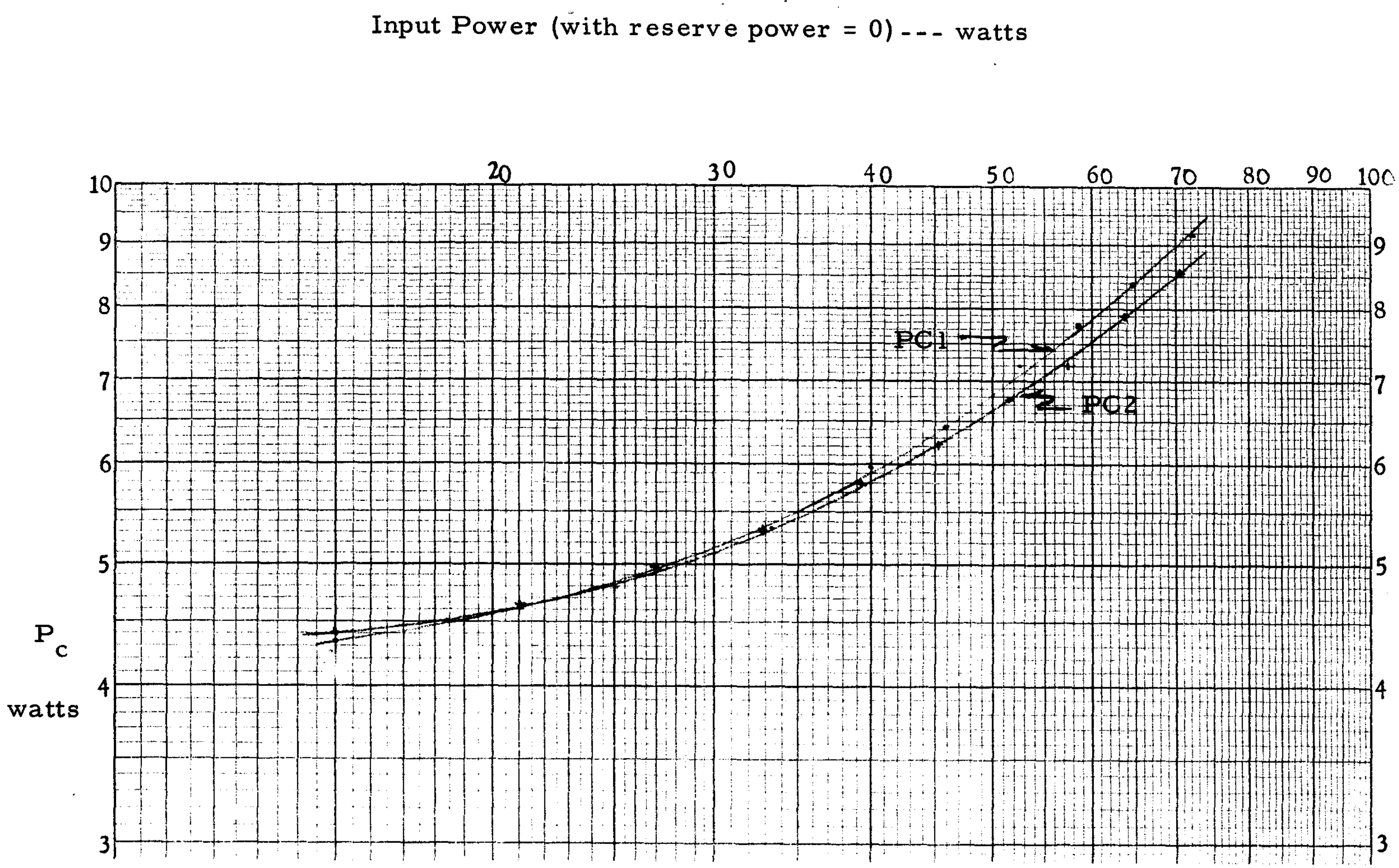


Figure 9: PCU Conversion Loss Test Results.

Power Converter 1		Power Converter 2	
Pin	Pc	Pin	Pc
15.009	4.336	14.997	4.406
21.148	4.645	21.004	4.647
27.044	4.955	26.930	4.984
33.201	5.348	32.980	5.322
39.921	5.975	39.271	5.700
45.939	6.430	45.343	6.224
52.437	7.197	51.530	6.769
58.637	7.766	57.419	7.197
64.719	8.408	63.760	7.904
71.964	9.184	70.519	8.562

TABLE I:
PCU CONVERSION LOSS TEST DATA

Assuming a quadratic curve fit for the data and using a simple curvilinear regression technique, then

$$P_1 = a + b\,(P_{in}') + \quad (P_{in}')^2$$

In the following table $Y = P_1$, $X = P_{in}$, $U = X^2$

Tabulation for P_1 Equation

TABLE II

X	Y	X^2	XU	U^2	XY	UY
15.009	4.336	225.27	3,381.0	$5.07(10^4)$	65.08	976.77
21.148	4.645	447.24	9,458.2	$20.00(10^4)$	98.23	2,077.43
27.044	4.955	731.38	19,779.4	$53.5\ (10^4)$	134.00	3,624.00
33.201	5.348	1102.31	36,597.8	$1.22(10^6)$	177.56	5,895.52
39.921	5.975	1593.69	63,621.7	$2.54(10^6)$	238.53	9,522.30
45.939	6.430	2110.39	96,949.2	$4.45(10^6)$	295.39	13,569.81
52.437	7.197	2749.64	144,182.9	$7.56(10^6)$	377.39	19,789.16
58.637	7.766	3438.30	201,611.6	$11.82(10^6)$	455.16	26,701.84
64.719	8.408	4188.55	271,078.8	$17.54(10^6)$	544.16	35,217.33
71.964	9.184	5178.82	372,688.6	$26.82(10^6)$	660.92	47,562.28
$\sum X=430.02$	$\sum Y=64.27$	$\sum U=21{,}765.60$	$\sum XU=1{,}219{,}349$	$\sum U^2=72.73(10^6)$	$\sum XY=3{,}046.63$	$\sum UY=164{,}936$

Determine the following auxiliary relations in order to find the parameters a, b, & c;

$$M_x = \frac{\sum X}{n} = \frac{430.02}{10} = 43 \qquad M_y = \frac{\sum Y}{n} = \frac{64.27}{10} = 6.427 \qquad M_u = \frac{21{,}765.6}{10} = 2{,}176$$

$$\sum x^2 = \sum X^2 - nM_x^2 = 3{,}275.6$$

$$\sum xu = \sum XU - nM_xMu^2 = 283{,}669$$

$$\sum u^2 = \sum U^2 - nM_u^2 = 25.43(10^6)$$

$$\sum xy = \sum XY - nM_xM_y = 282$$

$$\sum uy = \sum UY - nMuM_y = 25{,}085$$

b and c can now be found by solving the following equations simultaneously.

$$(\sum x^2)b + (\sum xu)\ c = \sum xy$$

$$(\sum xu)b + (\sum u^2)\ c = \sum uy$$

Then

$$c_i = .000759$$

$$b_i = .0205$$

and the following relationship is used to determine a;

$$a_i = My - bMx - cMu$$

$$a_i = 3.893$$

Therefore,

$$P_{c_i} = 3.893 + 0.0205\ P_{in}' + 0.000759\ (P_{in}')^2$$

Using the same assumptions given in Appendix A-1, then

$$P_{c2} = a + b(P_{in}') + c(P_{in}')^2$$

Tabulation for P_{c2} Equation

TABLE III

X	Y	U	XU	U^2	XY	UY
14.997	4.406	225	3,375.0	$5.06(10^4)$	66.09	991.35
21.004	4.647	441	9,262.8	$19.45(10^4)$	97.60	2,049.33
26.930	4.984	725.22	19,530.2	$52.59(10^4)$	134.22	3,614.50
32.980	5.322	1,087.7	35,872.3	$1.183(10^6)$	175.52	5,788.74
39.271	5.700	1,542.2	60,563.7	$2.378(10^6)$	223.84	8,790.54
45.343	6.224	2,056.0	93,225.2	$4.227(10^6)$	282.21	12,796.54
51.530	6.769	2,655.3	136,827.6	$7.050(10^6)$	348.8	17,973.73
57.419	7.197	3,296.9	189,304.7	$10.869(10^6)$	413.24	23,727.79
63.760	7.904	4,065.5	259,216.3	$16.528(10^6)$	503.96	32,133.71
70.519	8.562	4,972.9	350,683.9	$24.730(10^6)$	603.78	42,577.97
$\sum X=423.74$	$\sum Y=61.73$	$\sum U=21{,}067.7$	$\sum XU=1{,}157{,}861.7$	$\sum U^2=67.74(10^6)$	$\sum XY=2{,}849.26$	$\sum UY=150{,}444$

$M_x = \frac{\sum X}{n} = 42.374$ $\quad M_y = \frac{\sum Y}{n} = 6.173$ $\quad M_u = \frac{\sum U}{n} = 2,106.8$

$$\sum x^2 = \sum X^2 - nM_x^2 = 3,112.2$$

$$\sum xu = \sum XU - nM_xM_u = 265,842$$

$$\sum u^2 = \sum U^2 - nM_u = 23.35(10^6)$$

$$\sum xy = \sum XY - nM_xM_y = 233.8$$

$$\sum uy = \sum UY - nM_uM_y = 20,391$$

$$(\sum x^2)b + (\sum xu)c = \sum xy = 233.8$$

$$(\sum xu)b + (\sum u^2)c = \sum uy = 20,391$$

Solving Simultaneously,

$$c_2 = .000605$$

$$b_2 = .0234$$

and

$$a_2 = My - bM_x - cMu = 3.97$$

Then

$$P_{C2} = 3.97 + 0.0234\, P_{in}' + .000605\, (P_{in}')^2$$