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TECHNICAL REPORT NO. 10774

Army Vehicle Power System and Load Study

Final Report
December 1970

by J. G. Nell

Westinghouse Electric Corporation
Aerospace Electrical Division
Lima, Ohio

DAAE07-67-C-1563 Amendment II

TACOM

VEHICULAR COMPONENTS & MATERIALS LABORATORY

U.S. ARMY TANK AUTOMOTIVE COMMAND Warren, Michigan

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SUMMARY

The study summarized in this report has compiled a band of power system data so that, given an electric power profile for an army vehicle, an optimum power system approach can be selected. The basis for the selection are four parameters; weight, volume, efficiency, and life cycle cost.

The major power system components included in the study were a gas turbine, fuel for a 24 hour and a 48 hour mission, a generator, a voltage regulator, system controls, and protection.

Three types of electric power were investigated; 28 volts d-c, 56 volts d-c and 115/200 volts, 3 phase, 400 Hz a-c.

The study indicates that the type of electric power selected should be a function of what is best for the loads since fuel weight is quite large compared with the other components. Also, a method of determining life cycle cost for a vehicle electric power system is described.

TABLE OF CONTENTS AND ILLUSTRATIONS

I. Contract Objectives and Guidelines

The purpose of the APU study program defined on Amendment II of Contract DA AE07-67C 1563 was to establish a method of systematic study for applying electric power to army vehicles.

The study indicated that power system application should be approached from two standpoints. First, the loads of the vehicle should be analyzed, grouped by usage with respect to operating mode, and arranged into power profiles for each operating mode. Second, different types of auxiliary power supplies should be investigated to determine characteristic data over a wide band of possible operating conditions and power output levels. The requirements defined by the power profiles determine the level of power and the type of power required. When the power level is established the following information can be derived from data generated by the power system analysis: weight, volume, efficiency, and life cycle cost.

As an axample of the type of analysis required for application of power systems to army vehicles, the loads of the M60A1E2 were plotted in power profiles for each vehicle operating mode.

Also, power supply data was generated such that effects of power system weight volume, efficiency, and life-cycl cost could be evaluated for different mission times and different output power levels.

The prime mover for all the systems was a gas turbine engine. Types of electrical power considered were 28 volt dc, 56 volt dc, and 115/200 volt 3 phase, 400 Hz ac.

II Load Analysis

Information about M60A1E2 tank loads was obtained from Chrysler Corporation, Defense Engineering, drawings and from discussions with vehicle users at the Armor Agency, Combat Development Command (CDC), Fort Knox, Kentucky. The major loads on the M60A1E2 are listed on Chrysler drawing 11591511. This drawing, a schematic of the turret and cupola, identifies each load by a designator. The designators can be associated with part numbers on the interconnecting wiring diagram 11607959. Knowledge of the part numbers gives access to the product specifications for each part number.

Only a few of these product specifications were made available for this study; however, enough were available to establish the general guidelines for the loads.

Load data was not available in sufficient detail to engage a comprehensive load analysis. Power profiles for the M60A1E2 were formulated from the data obtained on the product specifications and from CDC. Profiles have been drawn for the normal, standby, and battlefield day operating modes.

ATAC defined the operating modes for the M60A1E2 as:

Normal	Gun tied down, driving vehicle
Standby	Ready for action but not in action. Alert condition.
Battlefield Day	Silent watch included; vehicle in action. For the M60A1E2, the battlefield day can be broken down as follows:

24 Hour Stated	24 Hour Interpretation
40% Idling	(Equivalent 18-25 miles wear)
40% Cross-Country from 2-1/2 to 10 MPH	(Approximately 37.5 odometer Miles)
20% Secondary Roads at 15-20 MPH	(Approximately 37.5 odometer miles)

Comparatively, the 24 hour version can be expressed as the equivalent of approximately 93-100 miles of wear on the vehicle or 75 odometer miles.

48 Hour Stated	48 Hour Interpretation
32 hours intensified	
40% Idling	(Equivalent 25-35 miles engine wear)
40% Cross-Country 2-1/2 to maximum safe	(Approximately 50 odometer miles)
20% Secondary Roads at 15 to maximum safe	(Approximately 50 odometer miles)
16 Hours Minimized	
At least 12 hours light time operation of components to maintain operational readiness.	(Equivalent to 10-15 miles of engine wear)

Comparatively, the 48 hour version can be expressed as the equivalent of approximately 150 miles of wear on the vehicle or 100 odometer miles.

The loads are listed and identified on the following pages. The power profiles for the three operating modes follow the list of loads (figures 1, 2, and 3). These profiles indicate that a 28 volt dc system (battery-generator) rated at 300 amperes with a three per-unit short-time overload rating will be adequate for the present M60 vehicle. Selection of this rating was based on the most severe profile, the battle field day. Continuous loads were between 300 and 325 amperes with pulsed loads adding 25 amperes to the continuous loads. The hydraulic pump operation is the most severe of any load; adding 600 amperes for 5 to 10 seconds. This would be serviced by the generator overload capacity and the battery.

Battery charging was not added into the power profiles because of the irregularity of the amount of amperes required for battery charging. With a normally charged battery short periods of high current will be experienced immediately after start-up, especially after resumption of engine operation after a silent watch period or a long idle period; and after any operation of the hydraulic pump. The battery should be used, as a voltage source, in these high current instances, to assist the system voltage regulator. Current limiting the generator output may be required to limit peak load and battery charging currents to a level safe for the rectifier.

Xenon Searchlight	-	Consumes 2.2 kw continuously and operates in two modes:
White Light	-	observation while driving in standby, normal, or battlefield-day modes.
Infrared	-	observation during silent watch.
Grenade Launcher	-	Launch igniter; consists of a small solenoid pulse of about 12 amperes. Used in battlefield-day mode.
Breech Motor	-	Used in large gun/missile launcher to open and close breech - battlefield day.
Scavenging System	-	A compressor which provides a blast of air to clear the breech of unconsumed cartridge material. Used after firing during battlefield-day.
Master Relay	-	Continuous operation during vehicle operation. All modes.
Radio-Receive and Transmit	-	Used during all modes.
Batteries	-	Used for startup and during silent watch. Could possibly reduce number of batteries if silent APU is applied.
Dome Lamp	-	Used full time.
Blasting Machine	-	Manual ba 'kup for electric igniter. No requiremen electric power.
Transmitter Door	-	Used during day or night firing.
Grenade Launcher Power Supply	-	D-C to D-C Converter

Firing Probe	-	Consumes no electric power
Cupola	-	Used during all modes
Passive Night Vision	-	D-C to D-C converter consumes 96 watts during all three modes at night.
Turret	-	Used when firing, during search, and for target acquisition. Necessary for standby, normal and battlefield-day operation.
Blower Assembly	-	Heater-blower used when environment dictates.
Amplifier	-	Both turret and cupola. Search, target acquisition, and firing aid; used for stabilization during battlefield day, standby, and normal modes.
CBR (Chemical, Biological, Radiation).	-	These are continuous loads. The air from these may be heated by operating the blower assembly when environmental condition dictates.
Gyro	-	Search, target acquisition and firing aid used for stabilization during battlefield-day, standby and normal modes.
Rate Sensor	-	Same as Gyro and amplifier above.
Laser Range Finder	-	Consumes 500 watts average during battlefield-day, standby and normal modes.
Optical Tracker	-	Used for following missile after firing - battlefield-day.
Infrared Transmitter	-	Used in conjunction with tracker to communicate with missile. Two operating modes - standby and battlefield-day.
Modulator and Signal Data Converter	-	Operational link between optical tracker and transmitter. Battlefield-day and standby.

Intercom Set	-	Consumes 2 amperes when in use. Unit on standby (no current drain) whenever vehicle in operation.
Frequency Control	-	Consumes no appreciable electric power.
Antenna Matching Unit	-	Stepping relay used when changing frequency. Used any time during all modes.
Receiver/Transmitter	-	Receiver consumes 80 watts. Receiver and transmitter combination consumes 300 watts. Used any time during all modes except minimum transmit during silent watch.

SKETCH SHEET
FORM 28577

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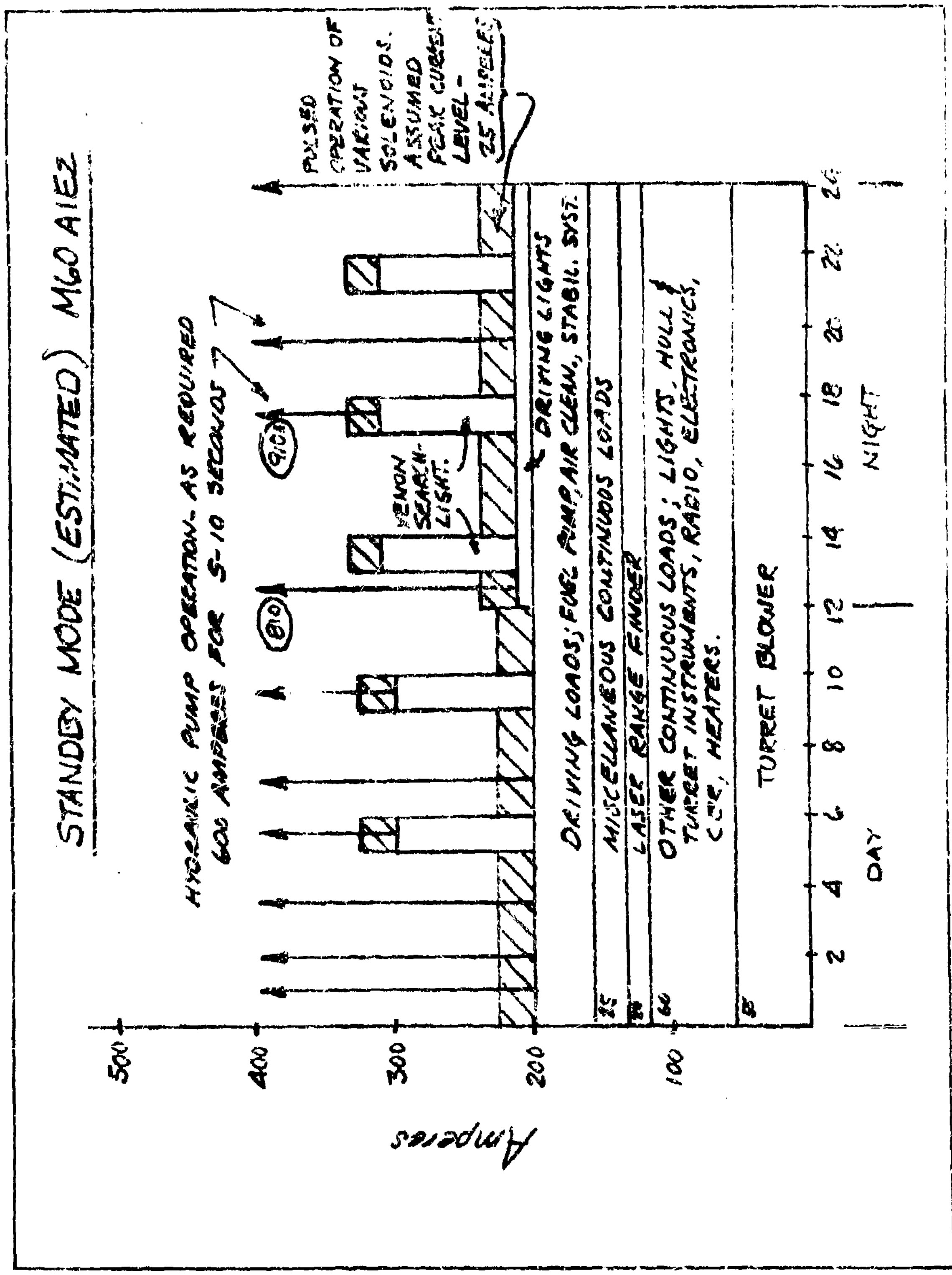

FIGURE 1

SKETCH SHEET
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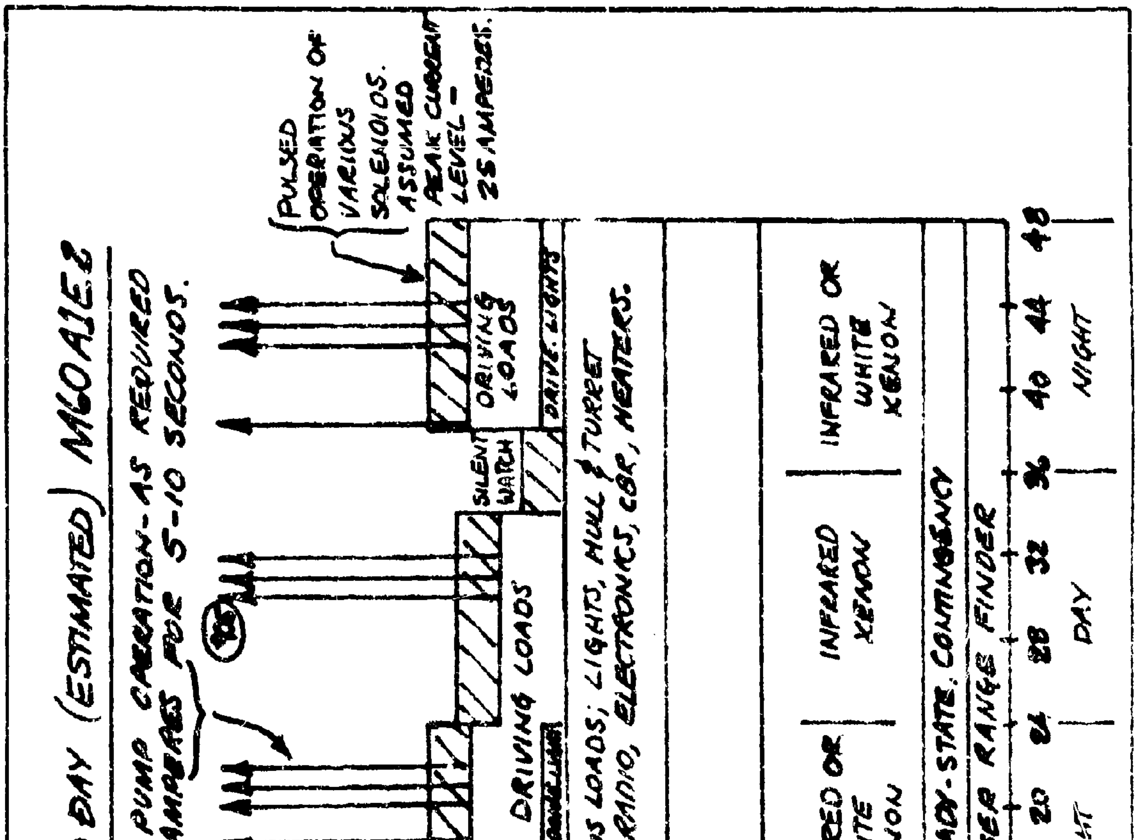

FIGURE 2

SKETCH SHEET
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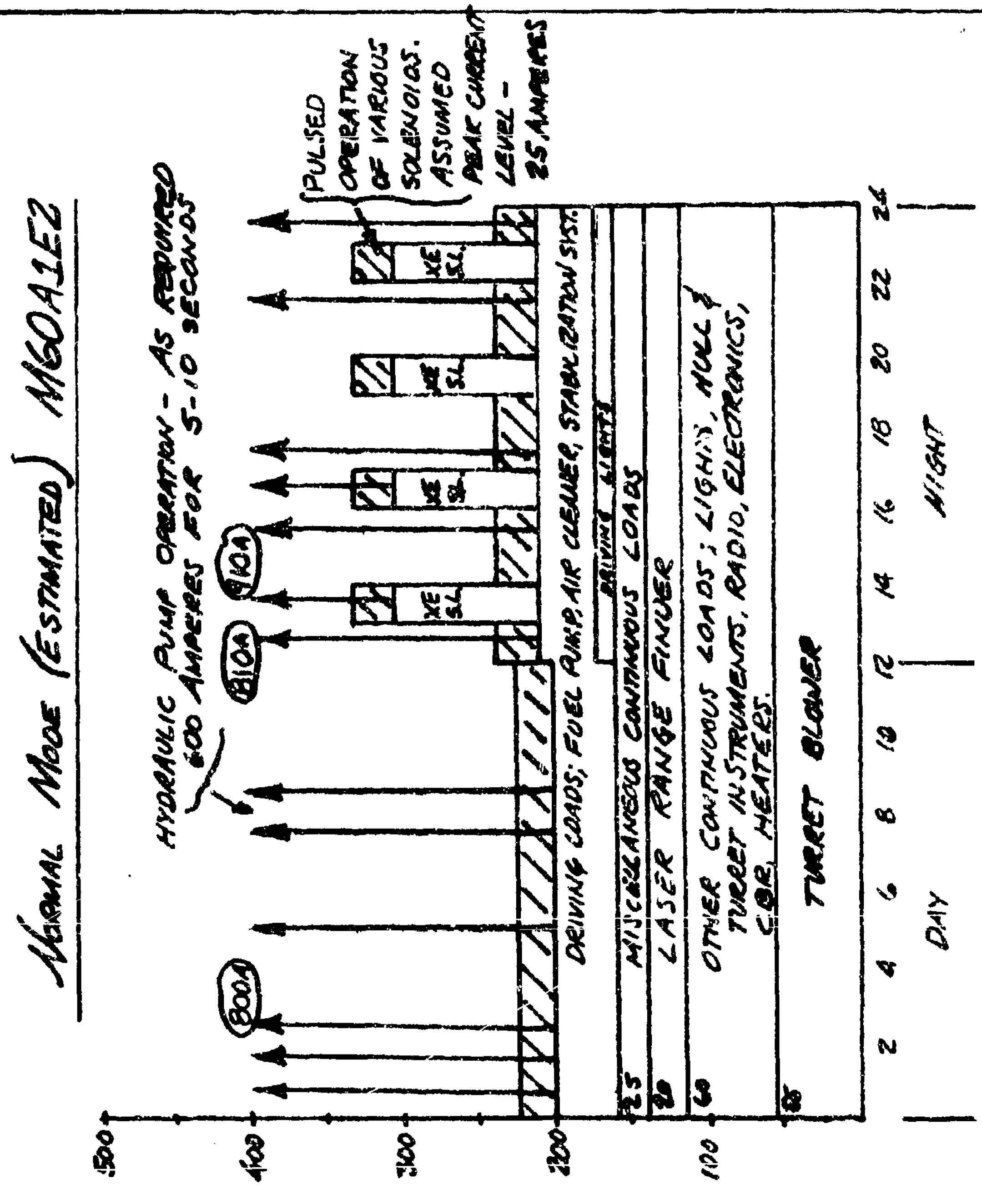

FIGURE 3

III Power System Analysis

The systems considered in this study are to be applied as self-powered units for mounting outside the vehicle. The systems include the gas turbine, the generator, the voltage regulator, controls, and protection. Fuel weight is also considered for the different system concepts; however, the tankage, since its characteristics are so dependent on individual vehicle constraints, is not included.

Power systems have been investigated at four ratings which will give a band of data that would hopefully encompass both present and future vehicle needs. The ratings are 10 kw, 25 kw, 40 kw, and 60 kw. Three types of systems have been considered, the standard 28 volt brushless d-c system, a three-wire 56 volt d-c system and a 400 Hz, 3 phase 120/208 volt a-c system.

The desirability of the different power systems are compared over the load range with respect to weight, volume, efficiency, and life-cycle cost. More detailed discussions of the equipment studied follows under the appropriate subheadings later in the report. Please note, however, that data presented was not intended to be firm for quotation purposes but was derived more to show relative differences in power system characteristics.

Power system weight and volume data are plotted on Figures 4 and 5, respectively. Supporting data are shown on Table 1 which follows the curves. The turbine and fuel weight analysis, and the electrical component weights are given in Section V. The lightest turbine-fuel combination was used as turbine data on the power system curves. This way the lightest and smallest system over the load range is shown on the system weight curves.

The data is plotted over a temperature range of $-65^{\circ}F$ to $+130^{\circ}F$; a 24 hour mission and a 48 hour mission; and a power output range of 10 kw to 60 kw. Although calculations were made for a-c and d-c systems the differences in weight and volume of these two systems were overwhelmed by the fuel weight making the decision of what type of power is best, a decision of what is best for the loads inside the vehicle.

The effects of system efficiency versus power output and type of system is shown on Figure 6 and Table 2. Whereas the total system weights and volumes are plotted at a constant electrical system efficiency of 75%, efficiency curves utilized the generator efficiency predictions on Table 8 in the generator data section of this report. The curves show the a-c system to provide a small weight advantage mostly due to the improved fuel consumption rate made possible by the lower power demand of the more efficient systems.

IV Life Cycle Cost

The cost and reliability evaluation will be combined into a cost effectiveness concept defined as availability. This section explains the derivation of the life cycle cost used in this study.

The life cycle cost of a component of a larger system equals the total dollar value of procuring, maintaining, operating, and replacing that component. The object is to develop a dollar cost per hour for each component. This cost would include labor, material, training, spares administration, technical data, tools, test equipment, and original procurement.

Costs occurring during the life cycle of system components can be divided into four groups:

1. Scheduled Maintenance Costs

   Includes parts, materials, and labor costs.
   Scheduled maintenance costs are a function of the mean-time-between- maintenance and the degree of difficulty of the scheduled maintenance; or, the mean scheduled maintenance down time.

2. Failure or Unscheduled Maintenance Cost

   Parts, materials, and labor costs. Failure maintenance cost is a function of mean-time-between-failure and the mean failure maintenance down time.

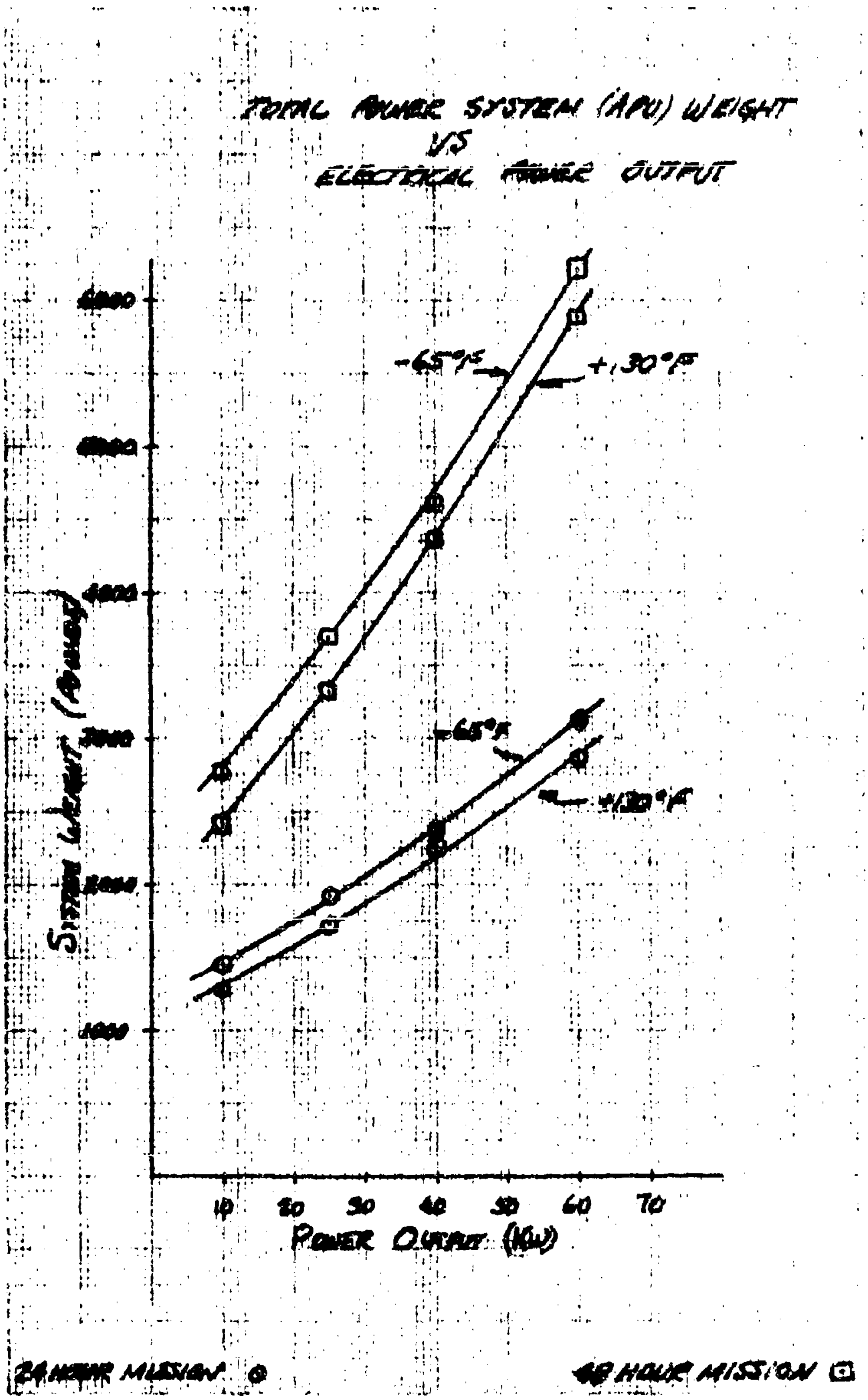

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FIGURE 4

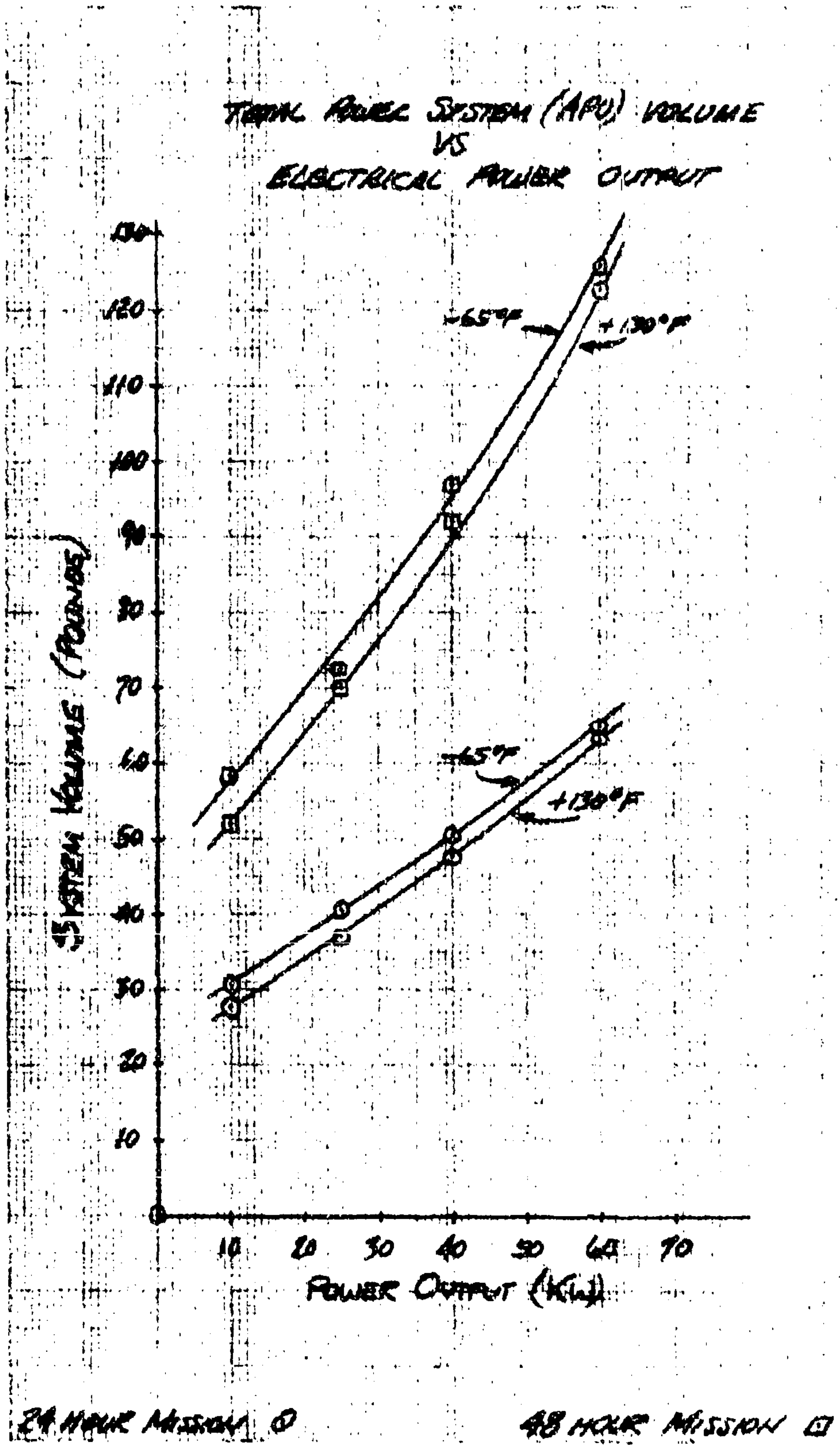

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TABLE 1

TOTAL POWER SYSTEM WEIGHT AND VOLUME DATA

KW Power Output	Lightest Turbine & Fuel	Mission Time	Mission Temp.	Weight Turbine & Fuel	Weight Elect. ac/28v dc/56v dc	Total Weight (Pounds) ac /28v dc /56v dc	Volume Turbine & Fuel	Volume Elect. ac /28v dc/56v dc	(Cubic Feet) Total Volume ac /28v dc /56v dc
10	T1	24	- 65	1409	39/ 40/ 43	1448/1449/1452	30.4	.26/.41/.41	30.7/30.8/30.8
	T1	48	- 65	2729	39/ 40/ 43	2768/2769/2772	58.0		58.3/58.4/58.4
	T2	24	+130	1237		1276/1277/1280	27.5		27.8/27.9/27.9
	T2	48	+130	2389		2428/2429/2432	51.7		52 /52.1/52.1
25	T1	24	- 65	1865	49/ 56/ 57	1914/1921/1922	39.9	.30/.44/.44	40.2/40.3/40.3
	T1	48	- 65	3641		3690/3697/3698	72.2		72.5/72.6/72.6
	T2	24	+130	1669		1718/1725/1726	36.6		36.9/37 /37
	T2	48	+130	3253		3302/3309/3310	69.8		70.1/70.2/70.2
40	T2	24	- 65	2317	58/ 66/ 67	2375/2383/2384	50.3	.32/.48/.48	50.6/50.8/50.8
	T2	48	- 65	4549		4607/4615/4616	96.7		97 /97.2/97.2
	T2	24	+130	2197		2255/2263/2264	47.4		47.7/47.9/47.9
	T2	48	+130	4309		4367/4375/4376	91.7		92 /92.2/92.2
60	T3	24	- 65	3048	69/ 85/ 86	3117/3133/3134	64.3	.34/.73/.73	64.6/65 /65
	T3	48	- 65	5952		6021/6037/6038	125.3		125.6/126 /126
	T3	24	+130	2796		2865/2881/2882	62.8		63.1/63.5/63.5
	T3	48	+130	5808		5877/5893/5894	122.3		122.6/123 /123

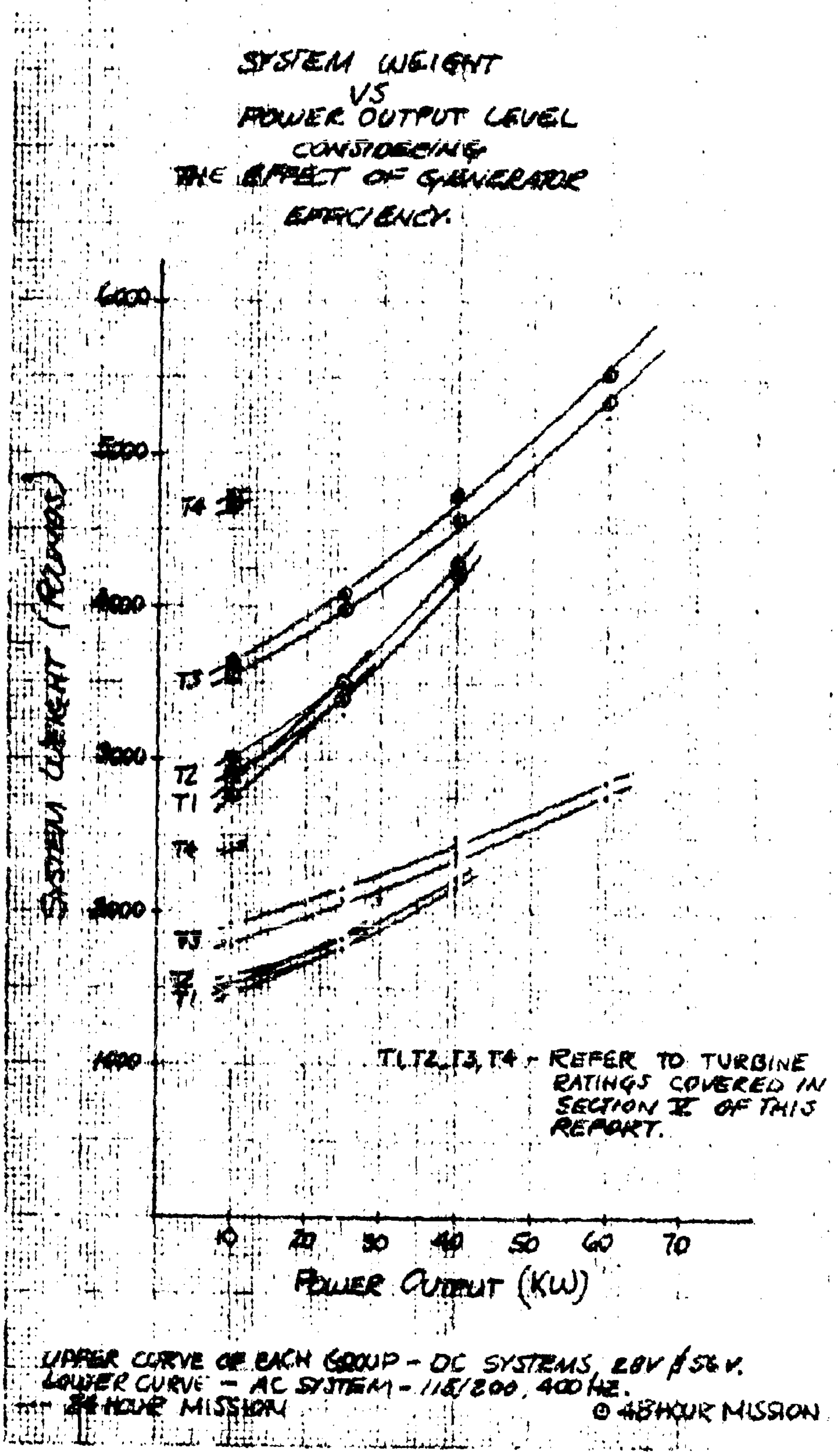

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FIGURE 6

TABLE 2

SYSTEM EFFICIENCY DATA

KW	Turbine	Mission Time	Elect. System	-65°F #/Hr. HP Reqd	-65°F #/Hr.	Fuel Weight	Fixed Weight Elect.& Turb. Total	Fixed Weight Elect.& Turb. Tu.	Fixed Weight Elect.& Turb. El.	Total System Wt.
10	T4	24	ac	19	94	2260	134	85	49	2394
		24	dc	22	96	2300	127		42	2427
		48	ac	19	94	4520	134		49	4654
		48	dc	22	96	4600	127		42	4727
10	T2	24	ac	19	58	1390	124	85	39	1514
		24	dc	22	60	1440	127		42	1567
		48	ac	19	58	2780	124		39	2904
		48	dc	22	60	2880	127		42	3007
10	T1	24	ac	19	55	1320	128	89	39	1448
		24	dc	22	57	1370	131		42	1501
		48	ac	19	55	2640	128		39	2768
		48	dc	22	57	2740	131		42	2871
10	T3	24	ac	19	70	1680	183	144	39	1763
		24	dc	22	72	1730	186		42	1916
		48	ac	19	70	3360	183		39	3543
		48	dc	22	72	3460	186		42	3646
25	T1	24	ac	40	67	1620	138	89	49	1758
		24	dc	43	69	1660	146		57	1806
		48	ac	40	67	3240	138		49	3378
		48	dc	43	69	3320	146		57	3466
25	T2	24	ac	40	68	1630	134	85	49	1764
		24	dc	43	70	1680	142		57	1822
		48	ac	40	68	3260	134		49	3394
		48	dc	43	70	3360	142		57	3502

TABLE 2

SYSTEM EFFICIENCY DATA

KW	Turbine	Mission Time	Elect. System	-65°F #/Hr. HP Reqd		Fuel Weight	Fixed Weight Elect. & Turb. Total	Tu.	El.	Total System Wt.
25	T3	24	ac	40	79	1900	193	144	49	2093
		24	dc	43	81	1940	201	↓	57	2141
		48	ac	40	79	3800	193	↓	49	3993
		48	dc	43	81	3880	201	↓	57	4081
40	T2	24	ac	65	84	2020	143	85	53	2163
		24	dc	70	86	2060	152	↓	67	2212
		48	ac	65	84	4040	143	↓	58	4183
		48	dc	70	86	4120	152	↓	67	4272
40	T3	24	ac	65	91	2180	202	144	58	2382
		24	dc	70	95	2280	211	↓	67	2491
		48	ac	65	91	4360	202	↓	58	4562
		48	dc	70	95	4560	211	↓	67	4771
60	T3	24	ac	94	107	2570	213	144	69	2783
		24	dc	100	110	2640	230	↓	86	2870
		48	ac	94	107	5140	213	↓	69	5353
		48	dc	100	110	5280	230	↓	86	5510

3. Procurement Costs

The dollar cost of equipment procurement.

4. Operating Costs

Cost to operate equipment i.e. fuel costs: For this evaluation operating costs are neglected. The components in question do not use fuel directly and the relative power consumption should be studied as part of a total vehicle weight-efficiency-mission time optimization. The life cycle cost will be defined as:

Life Cycle Cost = Scheduled Maintenance Cost
+ Unscheduled Maintenance Cost
+ Procurement Cost

Determination of Maintenance Costs - Maintainability & Availability

To state maintenance costs accurately, there must be a value assigned to the maintenance actions which permits a prediction of the frequency of maintenance required and the duration of a maintenance action. The concepts of maintainability and availability provide techniques to do this.

Academically, maintainability is the probability that a device will be restored to operational effectiveness within a given period of time when the maintenance action is performed in accordance with prescribed procedures. Mathematically, maintainability, M. may be expressed in terms of the mean-time-to-repair, MTTR, and the allowable maintenance time constraint, t:

$$M = 1 - e^{-\left(\frac{t}{MTTR}\right)}$$

This equation shows that the longer the time constraint or the shorter the mean-time-to-repair, the greater the maintainability will be.

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Equipment availability is the probability that a stated percent of equipment or missions will provide adequate performance <u>during a mission</u> with no down-time interval exceeding the maintenance time constraint, t. Good availability can be achieved in two ways: (1) Increase reliability and reduce the probability of failure; and/or (2) Design equipment for rapid maintenance. Thus,

Availability = Probability of survival + maintainability.

This concept of availability is basically a reliability concept in that it is tied to a mission time constraint. That is, it is a probability of survival through a mission time with no failure requiring more time than t hours to repair.

There is another measure of availability which is commonly applied to <u>continuously operable maintained</u> systems. This is called the up-time ratio or time availability. The up-time ratio consists of a steady state component and a transient component. The steady state is merely the ratio of the up, or operable, time to the sum of the up and down time. If the mean-time-between-failure is the up time and mean-time-to-repair the down time, the steady state equation for the up-time ratio is:

$$UTR = \frac{MTBF}{MTBF + MTTR} = 1\text{-down time ratio} = 1\text{-}DTR$$

$$DTR = \frac{MTTR}{MTTR + MTBF}$$

At the beginning of a mission it is obvious that the probability of an equipment operating at the end of the mission is higher at the beginning of an equipment's life than at the end. It can be shown that the complete expression for the UTR is*:

$$UTR = \frac{u}{\lambda + u} + \frac{\lambda}{T(\lambda + u)^2} - \frac{\lambda}{T(\lambda + u)^2} \exp\left[-(\lambda + u)T\right]$$

where

T = mission time

$\lambda = \frac{1}{MTBF}$ = failure rate (failure/hour)

$u = \frac{1}{MTTR}$ = maintenance action rate (action/hour)

*R. E. Barlow, L. C. Hunter; <u>Mathematical Models For Systems Reliability</u>; The Sylvania Technologist; Vol. 13, January 1960.

As T approaches infinity the transient state disappears and the equation reduces to the steady-state component.

For this analysis the mission time, T, will be assumed to be the time until scheduled maintenance. Since the time until scheduled maintenance is almost as long as the total vehicle life, the transient portion of the UTR equation will be neglected.* For this study then, the availability, hence the unscheduled maintenance cost of equipment will be defined by 1 - UTR or:

$$DTR = \frac{MTTR}{MTTR + MTBF}$$

The percentage of the mission time which the equipment is estimated to be down will be multiplied by the maintenance hourly costs to find the unscheduled maintenance cost portion of life cycle cost. Figure 7 and Tables 3 and 3A on the following pages present the life cycle cost data for this study.

*With a T of 3000 hours, an MTBF of 300 hours and an MTTR of 50 hours the steady state component calculates to be .87 and the transient component calculates to .002.

Table 3 and 3A depict the development of the cost numbers plotted on Figure 7. Explanation of the life cycle cost calculation process used will be by defining the make-up of each column.

<u>System</u> - Three systems were considered at each power level; an a-c system, a 56 volt d-c system, and a 28 volt d-c system.

<u>Original Cost</u> - The estimated procurement costs for each system component are listed to get comparative system costs. These costs were not intended to be firm selling prices but relative comparisons between systems. Quantities greater than 1000 units were assumed.

<u>Scheduled Maintenance Cost</u> - Essentially these are based on overhaul costs. Vehicle usage was based on the assumption that tank life is approximately 6 years and it is utilized at the rate of 2000 miles/year or 200 hours per year. Although system mean-time-between-overhauls are 3000 hours, it was assumed that the tank would be completely overhauled at the end of the third year.

<u>Compounded Scheduled Maintenance</u> - The cost of overhaul was compounded at the rate of 3-1/2%/year to conservatively account for inflation. In making the future expenditure calculations it was further assumed that there will be no cost of capital or alternative uses for funds considered. Thus the value of a dollar today equals the value of a dollar next year plus an inflation rate of 3-1/2%.

<u>Maintenance Rate per Hour</u> - This was assumed to be $10 per hour.

<u>Unscheduled Maintenance Cost</u> - These are derived on Table 3A explained below.

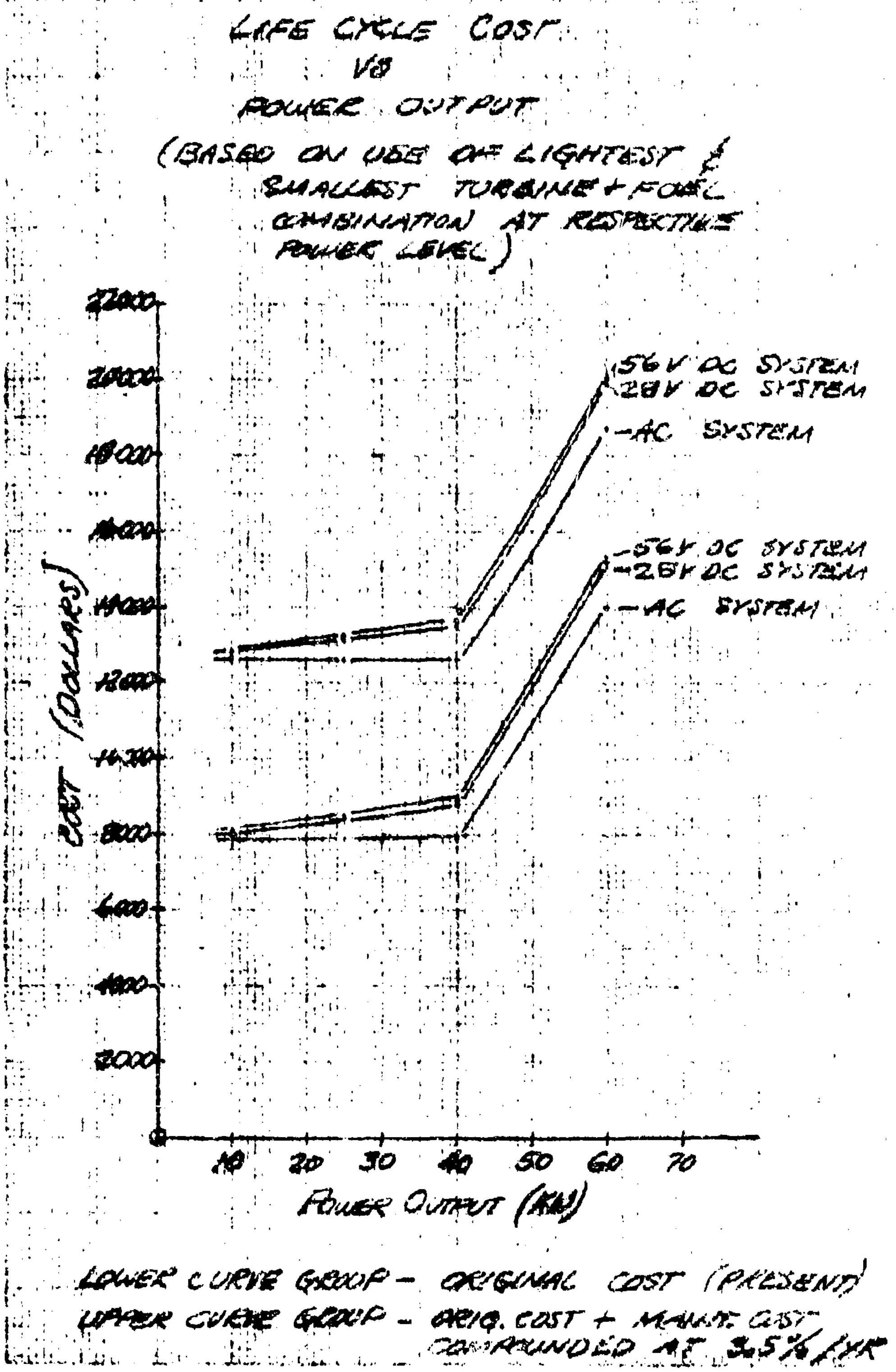

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TABLE 3

LIFE CYCLE COST ANALYSIS (USEFUL LIFE 6 YEARS)

System	Orig. Cost	Sch. Maint. Cost Overhaul	Compounded Scheduled Maint.	Maint. Rate/Hr.	Unsched Maint. Cost 1 Yr.	Total Unsched Maint. 6 Yr.	Compounded Total Maint.	Total Cost
10 KW								
Generator, 28 vdc	$1,550	$ 500						
GCU	503	-						
Turbine	6,000	1,600						
	$8,053	$ 2,100	$ 2,411	$ 10	$ 290.78	$2,261	$ 4,672	$12,725
Generator, 56 vdc	$1,580	$ 500						
GCU	606	-						
Turbine	6,000	1,600						
	$8,186	$ 2,100	$ 2,411	$ 10	$ 289.24	$2,250	$ 4,661	$12,847
Generator, ac	$1,200	$ 500						
GCU	742	-						
Turbine	6,000	1,600						
	$7,942	$ 2,100	$ 2,411	$ 10	$ 290.68	$2,260	$ 4,671	$12,613
25 KW								
Generator, 28 vdc	$1,930	$ 500						
GCU	503	-						
Turbine	6,000	1,600						
	$8,433	$ 2,100	$ 2,411	$ 10	$ 290.86	$2,263	$ 4,674	$13,107
Generator, 56 vdc	$1,970	$ 500						
GCU	606	-						
Turbine	6,000	1,600						
	$8,576	$ 2,100	$ 2,411	$ 10	$ 290.94	$2,263	$ 4,674	$13,250
Generator, ac	$1,220	$ 500						
GCU	742	-						
Turbine	6,000	1,600						
	$7,962	$ 2,100	$ 2,411	$ 10	$ 290.68	$2,260	$ 4,671	$12,633

TABLE 3

LIFE CYCLE COST ANALYSIS (USEFUL LIFE 6 YEARS)

System	Orig. Cost	Sch. Maint. Cost	Compounded Scheduled Maint.	Maint. Rate/Hr.	Unsched Maint.Cost	Total Unsched Maint.	Compounded Total Maint.	Total Cost
40 KW								
Generator, 28 vdc	$2,320	$ 500						
GCU	503	-						
Turbine	6,000	1,600						
	$8,823	$2,100	$ 2,411	$ 10	$ 290.82	$2,262	$ 4,673	$13,496
Generator, 56 vdc	$2,370	$ 500						
GCU	606	-						
Turbine	6,000	1,600						
	$8,976	$2,100	$ 2,411	$ 10	$290.90	$2,263	$ 4,674	$13,650
Generator, ac	$1,240	$ 500						
GCU	742	-						
Turbine	6,000	1,600						
	$7,982	$2,100	$ 2,411	$ 10	$ 290.68	$2,260	$ 4,671	$12,653
60 KW								
Generator, 28 vdc	$2,720	$ 500						
GCU	503	-						
Turbine	12,000	11,600						
	$15,223	$2,[illegible]	$ 2,411	$ 10	$ 290.90	$2,263	$ 4,674	$19,897
Generator, 56 vdc	$ 2,780	$ 500						
GCU	606	-						
Turbine	12,000	1,600						
	$15,386	$2,100	$ 2,411	$ 10	$ 290.98	$2,264	$ 4,675	$20,061
Generator, ac	$ 1,270	$ 500						
GCU	742	-						
Turbine	12,000	1,600						
	$14,012	$2,100	$ 2,411	$ 10	$ 290.68	$2,260	$ 4,671	$18,683

TABLE 3A

DEVELOPMENT OF UNSCHEDULED MAINTENANCE COST FOR TABLE 3

MTBF	MTTR	MTBF & MTTR	UTR	DTR	Yearly Hrs. Maint. x $10/Hr.
11,520	10	11,530	.99913		
31,400	4	31,404	.99987		
300	51	351	.85547		
			.85461	.14539	$290.78
11,200	10	11,210	.99911		
23,300	4	23,304	.99983		
300	51	351	.85547		
			.85538	.14462	$289.24
12,240	9	12,249	.99926		
18,700	4	18,704	.99979		
300	51	351	.85547		
			.85466	.14534	$290.68
10,880	10	10,890	.99908		
31,400	4	31,404	.99987		
300	51	351	.85547		
			.85457	.14543	$290.86
10,800	10	10,810	.99907		
23,300	4	23,304	.99983		
300	51	351	.85547		
			.85453	.14547	$290.94
12,240	9	12,249	.99926		
18,700	4	18,704	.99979		
300	51	351	.85547		
			.85466	.14534	$290.6

TABLE 3A

DEVELOPMENT OF UNSCHEDULED MAINTENANCE COST FOR TABLE 3

MTBF	MTTR	MTBF & MTTR	UTR	DTR	Yearly Hrs. Maint. x $10/Hr.
11,040	10	11,050	.99910		
31,400	4	31,404	.99987		
300	51	351	.85547		
			.85459	.14541	$290.82
11,040	10	11,050	.99910		
23,300	4	23,304	.99983		
300	51	351	.85547		
			.85455	.14545	$290.90
12,240	9	12,249	.99926		
18,700	4	18,704	.99979		
300	51	351	.85547		
			.85466	.14534	$290.66
10,560	10	10,570	.99905		
31,400	4	31,404	.99987		
300	51	351	.85547		
			.85455	.14545	$290.90
10,560	10	10,570	.99905		
23,300	4	23,304	.99983		
300	51	351	.85547		
			.85451	.14549	$290.98
12,240	9	12,249	.99926		
18,700	4	18,704	.99979		
300	51	351	.85547		
			.85466	.14534	$290.68

Total Unscheduled Maintenance Expense - These are based on a useful life of 6 years for the M60A1E2. Unscheduled maintenance is compounded at 3-1/2% per year for 6 years. Essentially this is the present cost of unscheduled maintenance.

Compounded Total Maintenance - This is the sum of compounded scheduled maintenance and compounded unscheduled maintenance. This is the present value of maintenance.

Total Cost - The sum of original cost plus present value of maintenance expense. Total cost is plotted as an ordinate of Figure 7.

Table 3A on which the annual costs of unscheduled maintenance are determined, is described below:

The up-time rates for each component is determined so that system availability can be calculated.

A = (UTR Gen) (UTR GCU) (UTR Turbine)

1-A = DTR System

MTBF - The MTBF for each system component is listed. The turbine MTBF includes all other auxiliary components and controls except the generator and the generator control unit. These are predicted achieved MTBF's.

MTTR - Based on field experience.

UTR - Product of three component UTR's.

DTR - 1 - System UTR.

Yearly Hours of Maintenance - 200 hours usage per year times the DTR times $10.00/hr maintenance labor cost.

V Power System Components

Information for the following presentations are based on data from the component manufacturers. The turbine data were calculated from information supplied by the AiResearch Manufacturing Company, Phoenix, Arizona; and Solar, San Diego, California. Electric component data were generated by Westinghouse at the Aerospace Electrical Division, in Lima, Ohio.

Turbine Prime Mover

Westinghouse has assembled information on engine-fuel systems which will be applicable to any vehicle presently or within 2 years. Conditions which were established for operating the turbine are:

- Duty Cycle: Continuous, 3-4 starts per day.
- General Environmental Rest Requirements - Climatic conditions per MIL-STD-210A and MIL-STD-810A.
- Output Pad - One pad for spline-driven generator.
- Power Profile - 1.0 per unit continuous load with 1.5 per unit load occurring for 5 minutes once every hour. (This is a simplification of the power profiles and turbine load is shared with the battery load.)

Two gas turbine manufacturers were especially helpful by supplying necessary parametric data and supporting information. The engines appearing most suited for this type of application are:

Rating	20 HP 10 KW	50 HP 25 KW	80 HP 40 KW	120 HP 60 KW
Manufacturers:				
AiResearch	GTP30-67	GTCP30-92	GTP30-106	GTP36-60
Solar	T-62T-33	T-62T-33	T-62T-32	T-62T-32

Since the comparison of different manufacturers' turbines is not an objective of this contract, Westinghouse will define a standard-composite turbine for each rating studied. Turbine information is based on equipment that is fully developed and in production. These turbines will be directly applicable as prime movers for vehicle ground power in the 10 kw to 60 kw range.

The turbine output speed will be a function of the turbine gearbox. Since output speeds up to direct drive can be easily accommodated, and since the generator operates best at 12, 000 RPM, a 12,000 RPM gearbox is assumed.

All of the engines are simple-cycle, single-shaft gas turbines.

By-products are available from these turbines. Briefly these are: clean compressed air, auxiliary shaft power, and hot gases.

Typically, small gas turbine engines do not require any maintenance for operational periods of up to 250-300 hours. At this time it is normal to replace filters, check the ignition system, oil level, etc. Depending on the application, lube oil may be replaced at the 300 hour point or at about 1000 hours. Except for these maintenance items, turbine engines are generally operated on an "on-condition" basis.

Gas Turbine Application Data

Figures are plots of turbine and fuel, weights and volumes over the load range and temperature range anticipated. The data is plotted for two profiles, one for 24 hours and the other for 48 hours.

The curves show plots of various available turbine ratings identified only by T1, T2, T3, and T4. The dry weight of individual turbines was combined with the fuel consumption at $-65^{O}F$ or $+130^{O}F$ and for the 24 or 48 hour profile. A generator efficiency of 75% was used for all calculations.

The fuel volume was calculated by determining the average of the specific gravities of gasoline and kerosene. This figure was 6.4 pounds per cubic foot. The turbine volumes were estimated from envelope drawings supplied by the turbine manufacturers.

Generators

Generators for the following three types of systems were investigated:

1. 120/208 volt, 400 Hz, 3 phase, 4 wire system
2. 28 volt d-c, 2 wire system
3. 56 volt d-c, 3 wire system

For each type of system, data on 10 kw, 25 kw, 40 kw, and 60 kw rated generators was calculated. The generator requirements and characteristics which form the basis upon which this study was conducted are shown in Table 3.

The electrical portion of all the generators in this study consists of a main machine from which the output power is obtained, an exciter which supplies power to the rotor of the main machine, a rotating rectifier assembly which converts the exciter output to d-c, and a permanent magnet generator for supplying control and excitation power. In the case of the d-c machines, a three-phase, full-wave stationary rectifier assembly is included to rectify the output of the main machine to d-c. The main machine is of the salient-pole, synchronous design.

The output diode rating for the d-c machines was established on the basis that the rectifier assembly must be capable of carrying 3.0 per unit short circuit current while operating at a diode case temperature of 160°C (30°C over the maximum oil inlet temperature of 130°C). Available diode ratings considered and their current carrying capability at 160°C are shown in Table 4. The number of diodes and diode rating required for each d-c machine in this study are presented in Table 5 along with other data pertinent to rectifier selection.

The electrical components are housed in an aluminum casting. The rotor is supported at each end by oil lubricated bearings.

Generator weight and size reductions were accomplished through the use of spray oil cooling. Spray oil cooling, a relatively new concept in cooling generators, is more effective at removing heat from the generator windings than other methods such as air cooling or oil cooling through conduction. Spray cooling permits higher current densities, reduced diameters, and, therefore, weight and size reductions. In a spray oil cooled generator, oil is sprayed directly on the generator windings through nozzles that are specially designed so that proper atomization of the oil can be obtained to

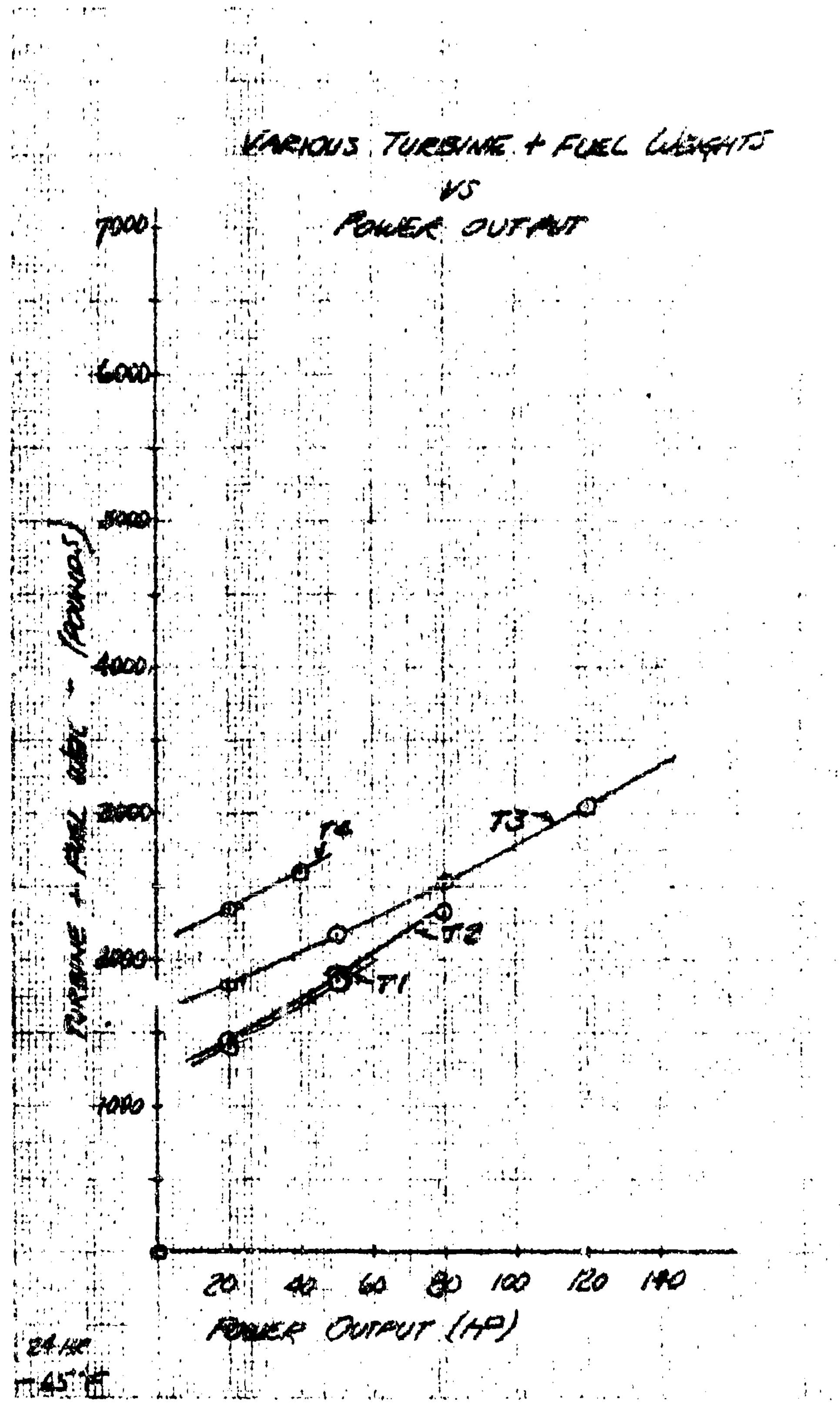
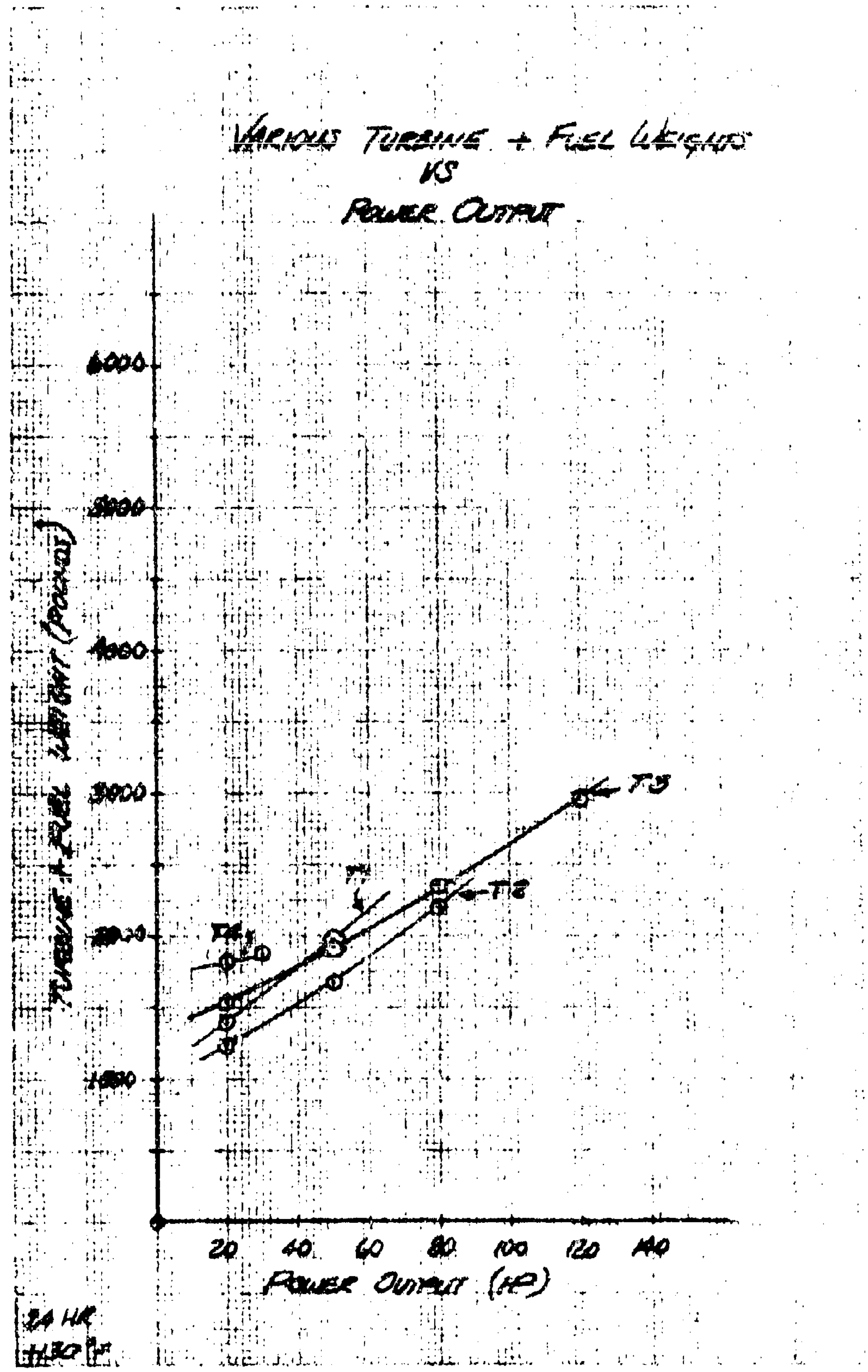

VARIOUS TURBINE + FUEL WEIGHTS
VS
POWER OUTPUT
TURBINE + FUEL WGT. - (POUNDS)
7000
6000
5000
4000
1000
T4
T3
T2
T1
20
40
60
80
100
120
140
POWER OUTPUT (HP)
24 HP
45

FIGURE 8



SIGNATURE

FIGURE 9

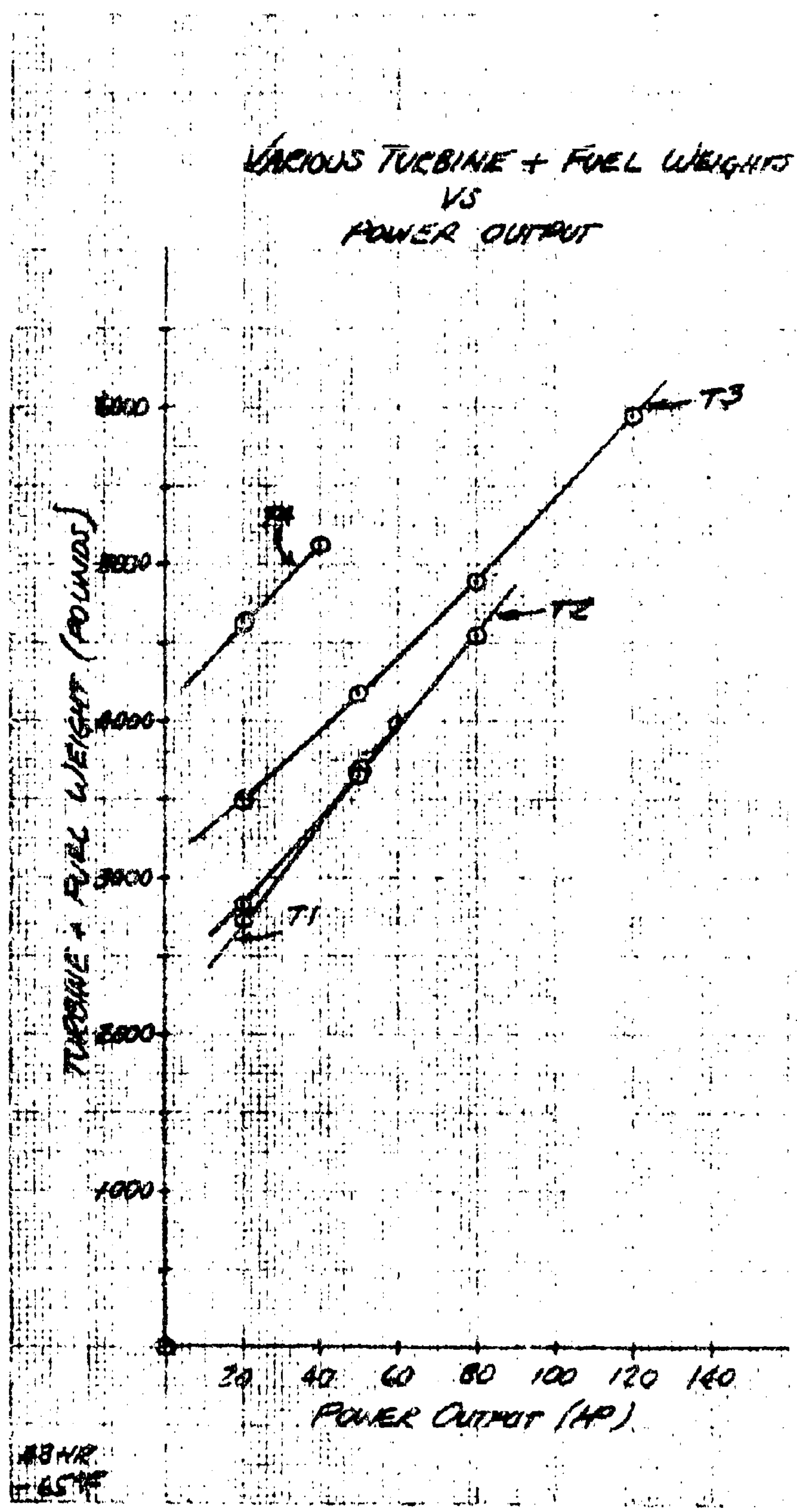

VARIOUS TURBINE + FUEL WEIGHTS
VS
POWER OUTPUT
TURBINE + FUEL WEIGHT (POUNDS)
POWER OUTPUT (HP)
T1
T2
T3
1000
2000
3000
4000
20
40
60
80
100
120
140

FIGURE 10

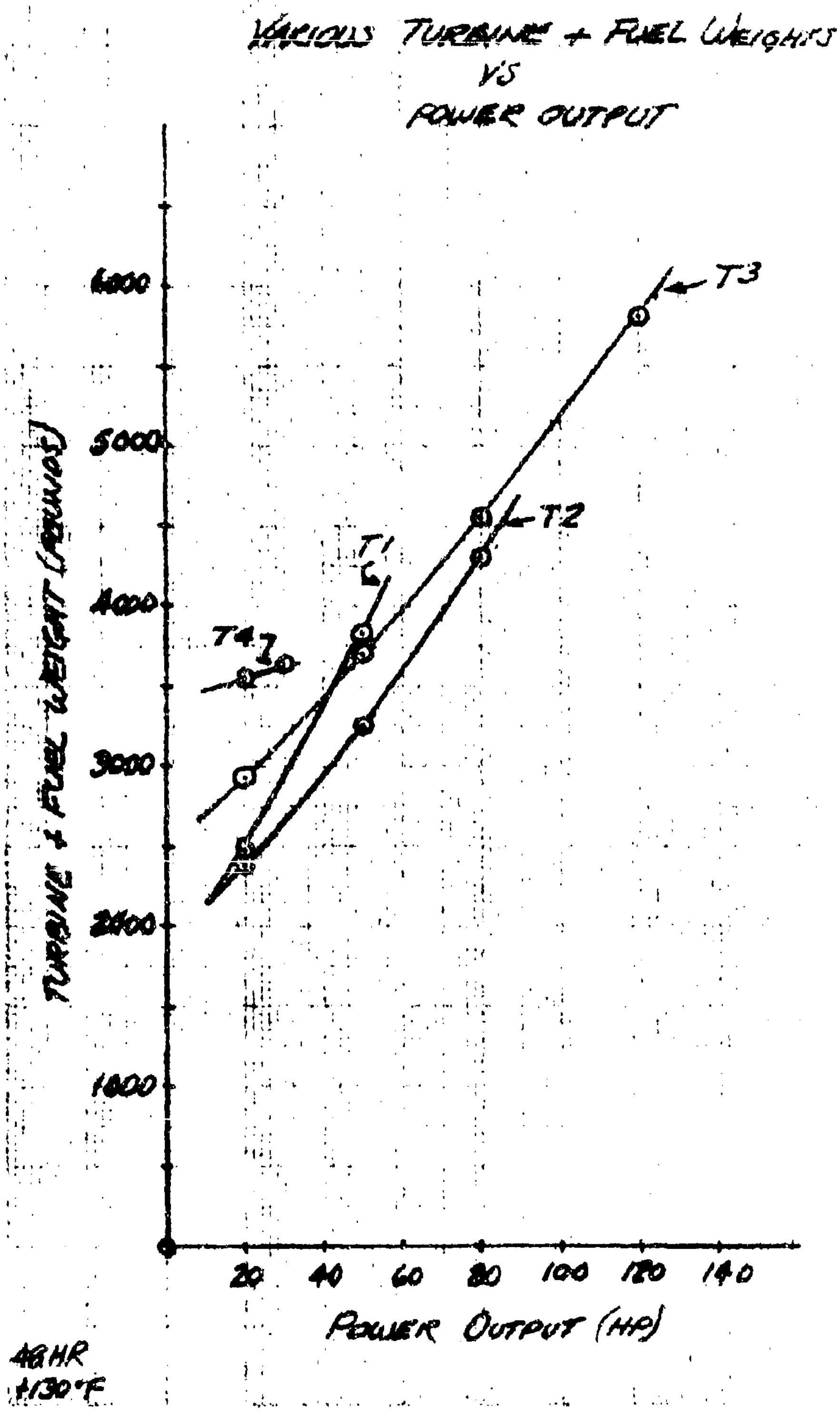
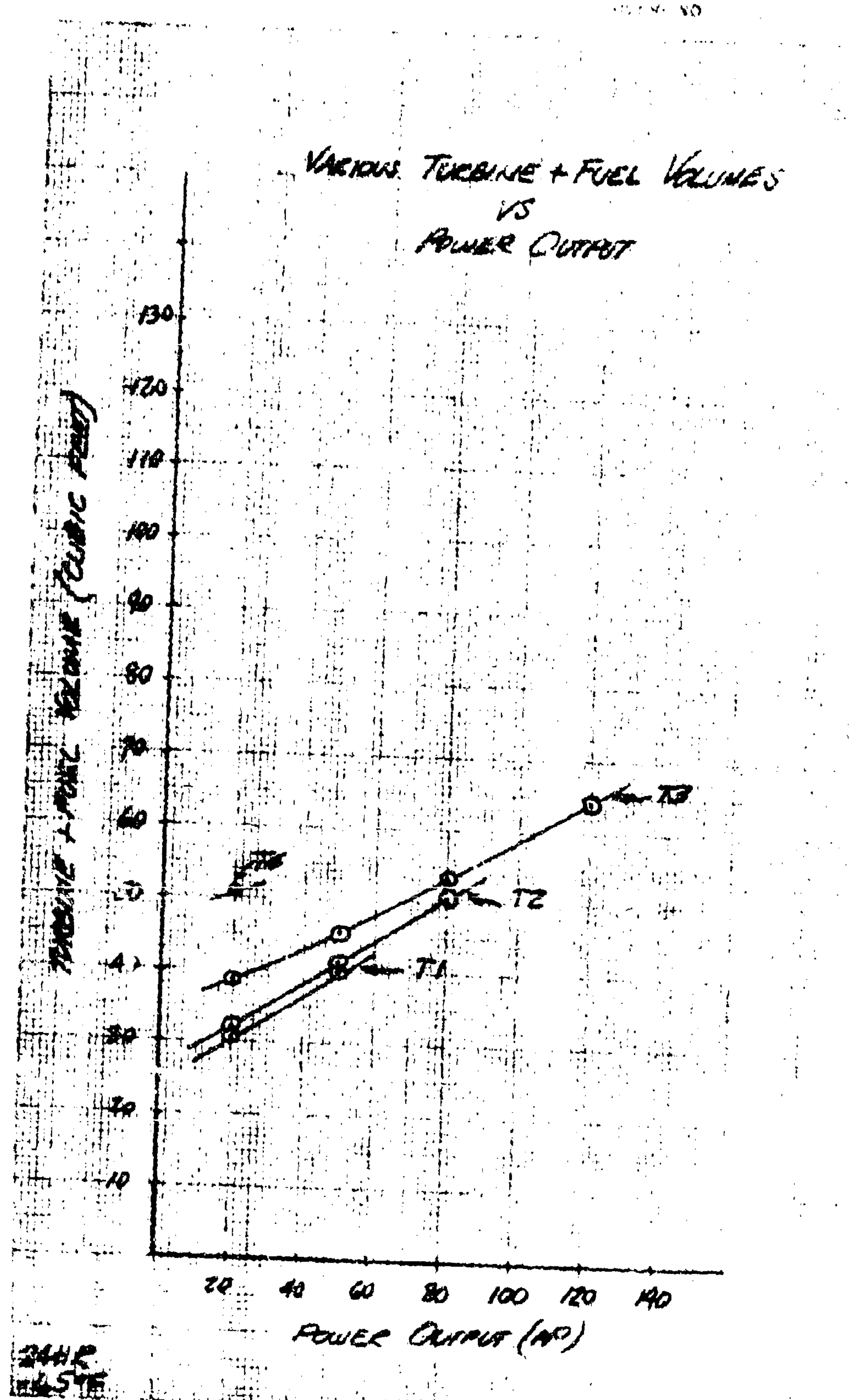
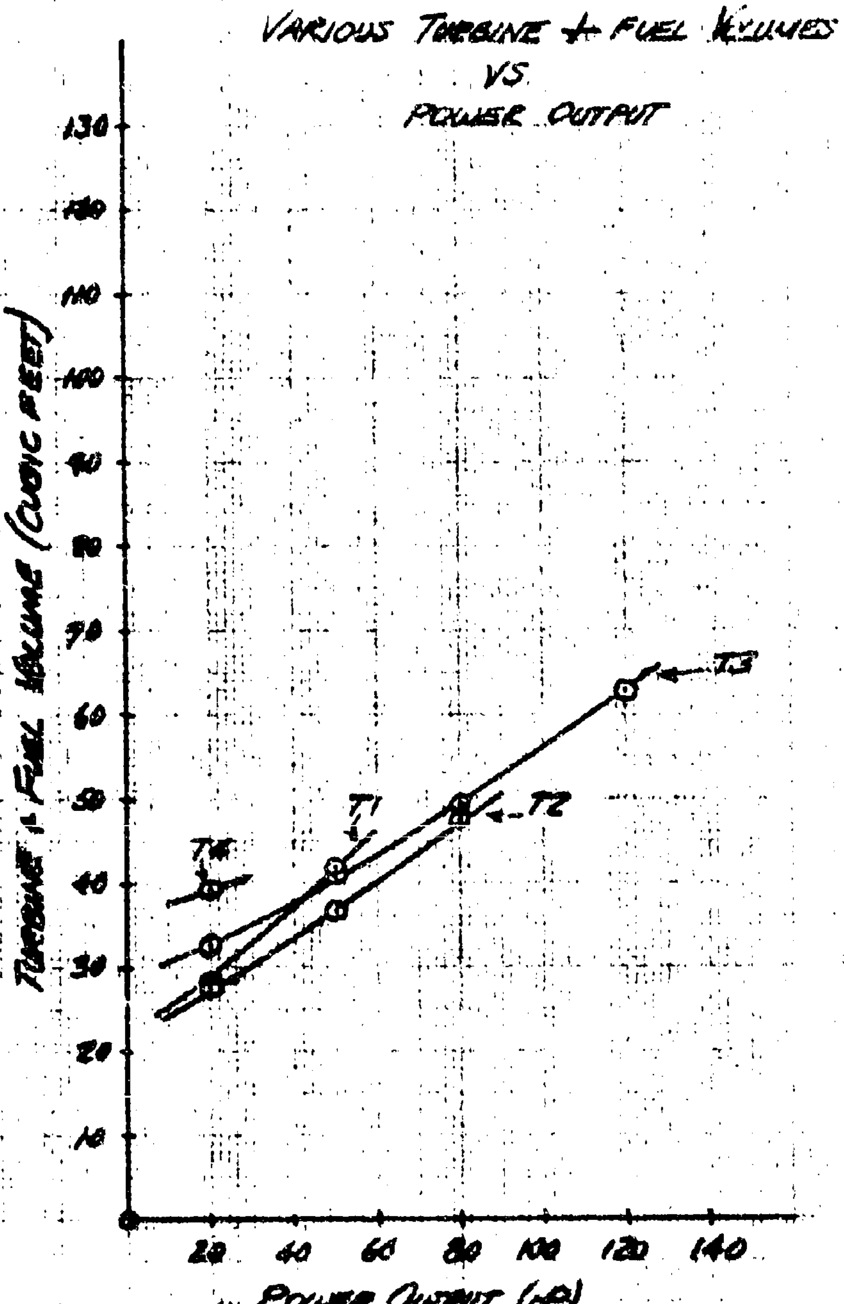

VARIOUS TURBINE + FUEL WEIGHTS
VS
POWER OUTPUT
TURBINE + FUEL WEIGHT (POUNDS)
6000
5000
4000
3000
2000
1000
20
40
60
80
100
120
140
POWER OUTPUT (HP)
T1
T2
T3
T4
48 HR
+130°F

FIGURE 11



SIGNATURE DATE CURVE NO FIGURE 12



24 HR
-130°F

SIGNATURE

FIGURE 13

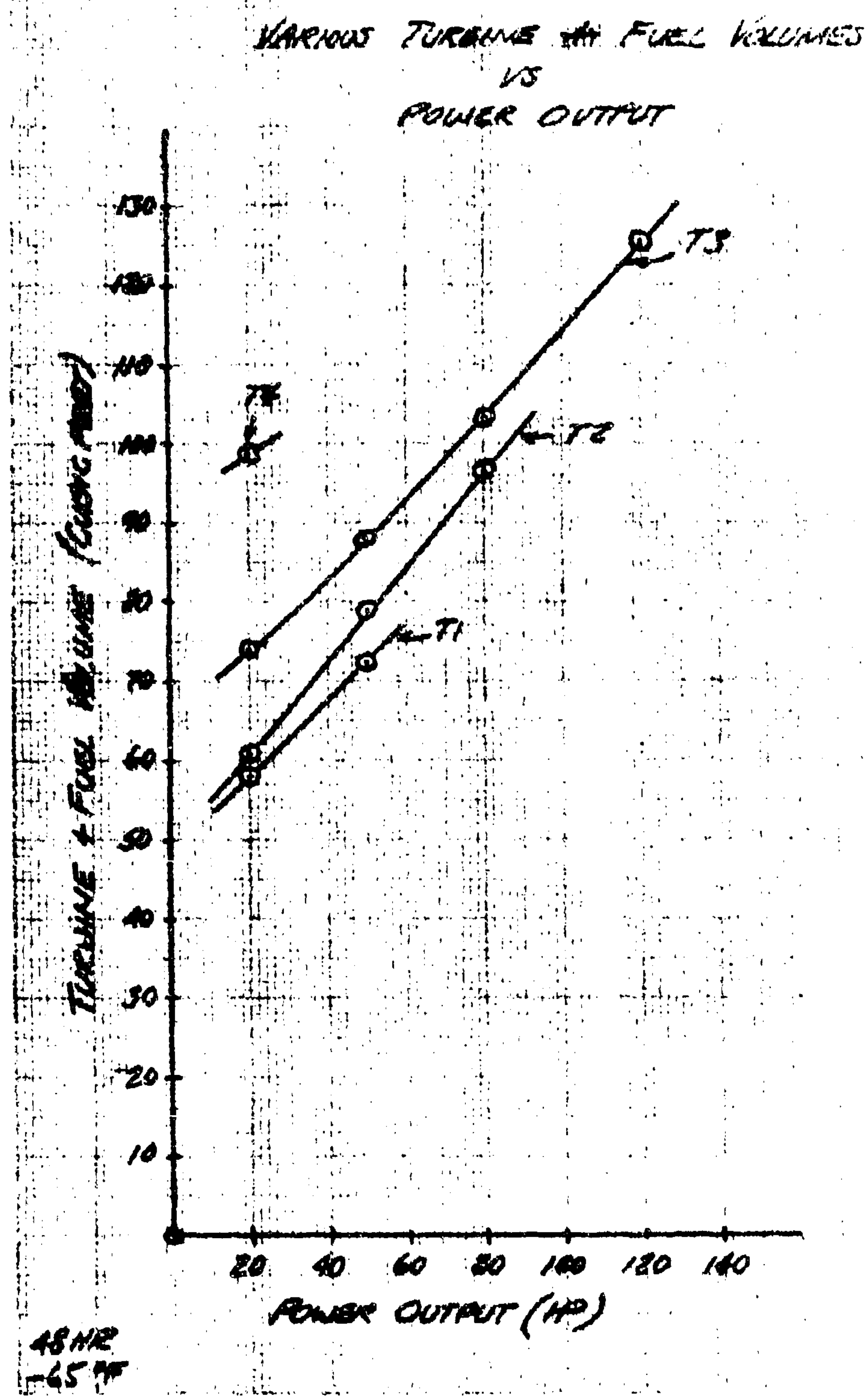
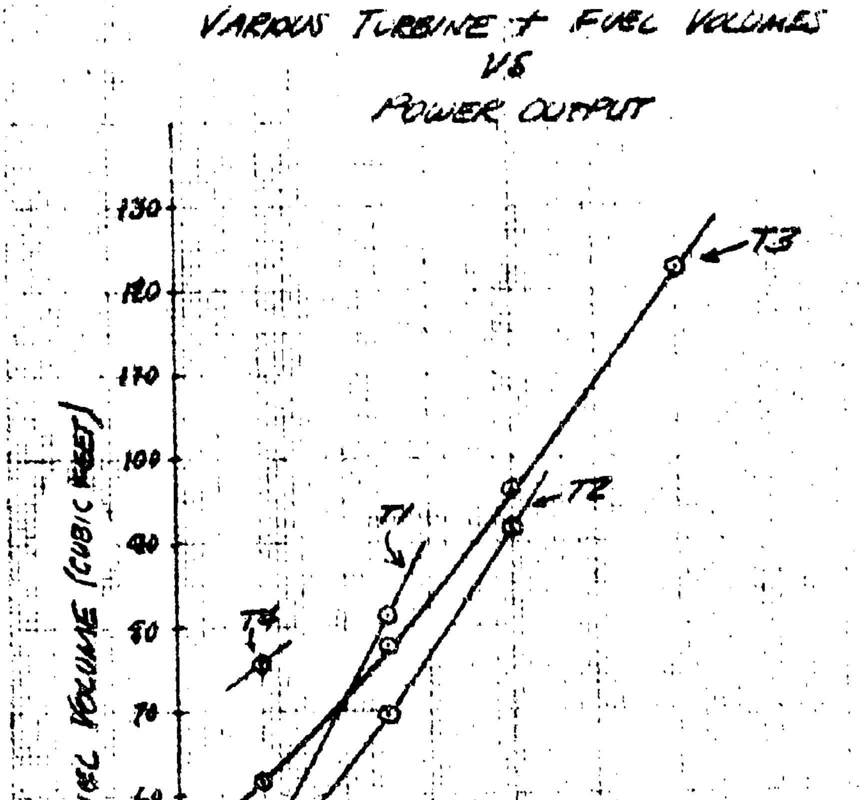

VARIOUS TURBINE & FUEL VOLUMES
VS
POWER OUTPUT
T3
T2
T1
TURBINE & FUEL VOLUME (CUBIC FEET)
POWER OUTPUT (HP)
10
20
30
40
50
60
70
80
90
100
110
120
130
20
40
60
80
100
120
140
48 HR
-65 °F

FIGURE 14



VARIOUS TURBINE + FUEL VOLUMES
VS
POWER OUTPUT
TURBINE + FUEL VOLUME (CUBIC FEET)
POWER OUTPUT (HP)
T1
T2
T3
T4
130
120
110
100
90
80
70
60
50
40
30
20
10
20
40
60
80
100
120
140
48 HOUR
+130°F

FIGURE 15

TABLE 4

TURBINE WEIGHT & VOLUME DATA

HP	Turbine	Mission Time	Temp. °F	#/Hr.	Fuel Weight	Total Weight	Tot.Vol. Ft.^{3}	Fuel Vol. Ft.^{3}	Tot.Vol. Ft.^{3}
20	T4 85 Pounds	24	- 65	95	2280	2365	2.8	47.9	50.7
		48	- 65	95	4560	4645	2.8	95.8	98.6
		24	+130	72	1728	1813	2.8	36.3	39.1
		48	+130	72	3456	3541	2.8	72.6	75.4
20	T2 85 Pounds	24	- 65	57	1368	1453	3.3	28.7	32.0
		48	- 65	57	2736	2821	3.3	57.5	60.8
		24	+130	48	1152	1237	3.3	24.2	27.5
		48	+130	48	2304	2389	3.3	48.4	51.7
20	T1 89 Pounds	24	- 65	55	1320	1409	2.6	27.8	30.4
		48	- 65	55	2640	2729	2.6	55.4	58.0
		24	+130	50	1200	1289	2.6	25.2	27.8
		48	+130	50	2400	2489	2.6	50.4	53.0
20	T3 144 Pounds	24	- 65	70	1680	1824	3.3	35.3	38.6
		48	- 65	70	3360	3504	3.3	70.6	73.9
		24	+130	58	1392	1536	3.3	29.2	32.5
		48	+130	58	2784	2928	3.3	58.5	61.8
50	T1 89 Pounds	24	- 65	74	1776	1865	2.6	37.3	39.9
		48	- 65	74	3552	3641	2.6	74.6	72.2
		24	+130	78	1872	1961	2.6	39.3	41.9
		48	+130	78	3744	3833	2.6	78.6	81.2
50	T2 85 Pounds	24	- 65	75	1800	1885	3.3	37.8	41.1
		48	- 65	75	3600	3685	3.3	75.6	78.9
		24	+130	66	1584	1669	3.3	33.3	36.6
		48	+130	66	3168	3253	3.3	66.5	69.8

TABLE 4

TURBINE WEIGHT & VOLUME DATA

HP	Turbine	Mission Time	Temp. °F	#/Hr.	Fuel Weight	Total Weight	Tot. Vol. Ft.^{3}	Fuel Vol. Ft.^{3}	Tot. Vol. Ft.^{3}
50	T3 144 Pounds	24	- 65	84	2016	2160	3.3	42.3	45.6
		48	- 65	84	4032	4176	3.3	84.7	88.0
		24	+130	74	1776	1920	3.3	37.3	40.6
		48	+130	74	3552	3696	3.3	74.6	77.9
80	T2 85 Pounds	24	- 65	93	2232	2317	3.0	47.3	50.3
		48	- 65	93	4464	4549	3.0	93.7	96.7
		24	+130	88	2112	2197	3.0	44.4	47.4
		48	+130	88	4224	4309	3.0	88.7	91.7
80	T3 144 Pounds	24	- 65	99	2376	2520	3.3	49.9	53.2
		48	- 65	99	4752	4896	3.3	99.8	103.1
		24	+130	92	2208	2352	3.3	46.4	49.7
		48	+130	92	4416	4560	3.3	92.8	96.1
120	T3 144 Pounds	24	- 65	121	2904	3048	3.3	61	64.3
		48	- 65	121	5808	5952	3.3	122	125.3
		24	+130	118	2832	2976	3.3	59.5	62.8
		48	+130	118	5664	5808	3.3	119	122.3

prevent winding insulation erosion and to obtain the proper oil velocity over the coils. The surface temperature of the windings is held to below 200°C to prevent oil coking on the windings. A sump pump must be provided to remove the spray oil and oil leakage. For the d-c machines in this study, a combination of spray and conduction cooling is used in the area of the output rectifier assembly to insure adequate cooling of the diodes under all operating conditions.

The calculated data on the various generators is shown in Table 6. A brief discussion of the parameters tabulated in Table 6 is presented below:

1. Weight

The weight shown in the total weight of the generator, including the output rectifier assembly in the case of the d-c machines. In arriving at the weights shown, the weight of the electrical components (main a-c portion, exciter, permanent magnet generator, and output diodes for d-c machines) was calculated. The remaining mechanical weight was estimated based on that of similar generators.

2. Approximate Outline Dimensions

These figures are approximate since no layouts of the machines were made. The diameters shown are the basic machine diameters and do not take into account localized projections such as terminals, oil tubes, etc., which have some flexibility as to location and can usually be positioned to avoid interferences with other vehicle components. For the d-c generators with more than twelve output diodes, the diameter of the portion of the generator containing the diodes is increased to 12" to permit the nesting of the exciter and permanent magnet generator under the output rectifier assembly, thereby reducing the overall machine length and weight.

3. Efficiency

The efficiency was calculated based on the following operating conditions: 100% rated load, minimum rated speed

(11400 RPM), and maximum oil inlet temperature (130°C). In addition, for the a-c machines minimum rated power factor (0.8 lagging) was assumed. For the d-c generators, the losses associated with the output rectifier assembly were included in the efficiency calculation, the result being lower efficiencies for these machines.

4. Life

The life of the generators is based on the life of the polyimide insulation system used.

5. MTBF

The mean-time-between-faulure was calculated from failure rates based on field data on in-service aircraft generators and MIL-HDBK-217A where possible. The MTBF values are predicted achieved MTBF which is 80% of the calculated inherent values.

6. Costs

The costs shown are Engineering estimates based on the assumptions that approximately 50 units per month are being produced and adequate production tooling is available.

As can be seen, costs for the d-c machines are higher, reflecting the cost of the output rectifier assembly. The cost of the output rectifier assembly is directly affected by the severity of the overload requirement on the generator. For example, if the maximum overload required of the 60 kw, 28 volt d-c machine was 1.5 per unit instead of 3.0 per unit short circuit, the total cost of the generator would be reduced by approximately 25%.

TABLE 5

GENERATOR REQUIREMENTS AND CHARACTERISTICS

	120/208 Volt 400 Hz	28 Volt DC	56 Volt DC
Speed (rpm)	12000 ± 5%	12000 ± 5%	12000 ± 5%
Power Factor (min.)	0.8 lagging	-	-
Cooling			
1. Medium	130°C Oil	130°C Oil	130°C Oil
2. Method	Spray	Spray plus Conduction	Spray plus Conduction
Overloads			
1. 1.5 per unit	2 minutes	2 minutes	2 minutes
2. 2.0 per unit	5 seconds	5 seconds	5 seconds
3. 3.0 per unit short circuit	5 seconds	5 seconds	5 seconds
Excitation (max.)			
1. Continuous	2 amps	2 amps	2 amps
2. Overload	4 amps	4 amps	4 amps
Output Rectifier Assembly	None Req'd	Integral part of machine	Integral part of machine

Other Requirements and Characteristics (applicable to generators for all three types of systems):

1. Brushless design to be used.
2. Two bearing design to be used.
3. Single-phase permanent magnet generator to be included for control and excitation power.
4. Conventional silicon steel (AISI M-15) to be used.

TABLE 6

RECTIFIER CAPABILITY

Diode Rating	Forward Current Capacity @ 160°C Case Temperature
160 a.	115 a.
240 a.	170 a.
400 a.	260 a.
650 a.	430 a.

TABLE 7 - OUTPUT RECTIFIER DESCRIPTION (DC MACHINES ONLY)

Generator Rating	Max. D-C Current @ 3.0 P.U. S.C.	Parallel Paths in Main Stator	Matched Diodes per Rect. Leg	Current per Diode	Diode Rating Required *	Total No. of Diodes
A. 28 Volt d-c, 2-wire Designs						
1. 10 KW	1070 a.	1	1	357 a.	650 a.	6
2. 25 KW	2680 a.	4	1	224 a.	400 a.	24
3. 40 KW	4286 a.	4	1	357 a.	650 a.	24
4. 60 KW	6440 a.	4	2	268 a.	650 a.	48
B. 56 Volt d-c, 3-wire Designs (2 series connected bridges req'd)						
1. 10 KW	535 a.	1	1	179 a.	400 a.	12
2. 25 KW	1339 a.	2	1	224 a.	400 a.	24
3. 40 KW	2145 a.	2	1	357 a.	650 a.	24
4. 60 KW	3220 a.	4	1	268 a.	650 a.	48

* Selected from Table 4

TABLE 8 - CALCULATED GENERATOR DATA

RATING	WEIGHT	APPROX. OUTLINE (Length x dia.)	EFF.	LIFE	MTBF (Predicted Achieved)	COST
A. 120/208 Volt, 400 Hz Designs						
1. 12.5 KVA, 0.8 p.f.	36 lbs	9.0" x 7.0"	78.1%	20,000 hrs.	12240 hrs.	$1200
2. 31.3 KVA, 0.8 p.f.	46 lbs	10.7" x 7.0"	83.4%	"	"	$1220
3. 50 KVA, 0.8 p.f.	55 lbs	11.6" x 7.0"	86.6%	"	"	$1240
4. 75 KVA, 0.8 p.f.	66 lbs	13.1" x 7.0"	87.6%	"	"	$1270
B. 28 Volt d-c Designs						
1. 10 KW	36 lbs	11.2" x 8.0"	69.2%	20,000 hrs.	11520 hrs.	$1550
2. 25 KW	52 lbs	12.1" x 8.0"/12.0"*	78.6%	"	10880 hrs.	$1930
3. 40 KW	62 lbs	13.2" x 8.5"/12.0"*	80.7%	"	11040 hrs.	$2320
4. 60 KW	81 lbs	20.9" x 9.25"/12.0"*	80.8%	"	10560 hrs.	$2720
C. 56 Volt d-c Designs						
1. 10 KW	39 lbs	14.2" x 8.0"	69.2%	20,000 hrs.	11200 hrs.	$1580
2. 25 KW	53 lbs	12.1" x 8.0"/12.0"*	78.6%	"	10880 hrs.	$1970
3. 40 KW	63 lbs	13.2" x 8.5"/12.0"*	80.7%	"	11040 hrs.	$2370
4. 60 KW	[illegible] lbs	20.9" x 9.25"/12.0"*	80.8%	"	10560 hrs.	$2780

* 12" diameter applies to portion of machine containing output rectifiers

Dual 28 VDC GCU (Reference: EDSK-349668)

The dual voltage GCU is operationally identical to the single voltage GCU. The only differences are in the voltage regulator, Current Limit, OV Trip, and UV Warning Circuits.

For the dual voltage system it is necessary for the voltage regulator to sense line-to-line voltage instead of line-to-neutral. This is accomplished by means of a converter which changes the line-to-line voltage to an equivalent line-to-neutral voltage for the regulator.

The Current Limit must limit both positive and negative generator output currents so two current transformers are required instead of one.

The OV Trip and UV Warning Circuits monitor each battery individually to ensure that both voltages are within normal limits.

115 VAC GCU (Reference: EDSK-349669)

The 115 V GCU has five indicated functions - GCR Open, Abnormal Frequency (AF) Trip, Overcurrent (OC) Trip, OV Trip, and UV Trip. All four trip signals will cause the GCR to open unless the Commit Switch is closed. The appropriate trip indicator will light as a warning even if the GCR does not open.

The AF circuit senses whether the frequency of the generator output is within normal limits. This is important because magnetic components, such as motors and transformers, can be damaged by improper frequency.

The OC circuit senses generator output current by means of three current transformers in the three A-C lines. The circuit produces an output signal if any one of the three lines is carrying excessive current.

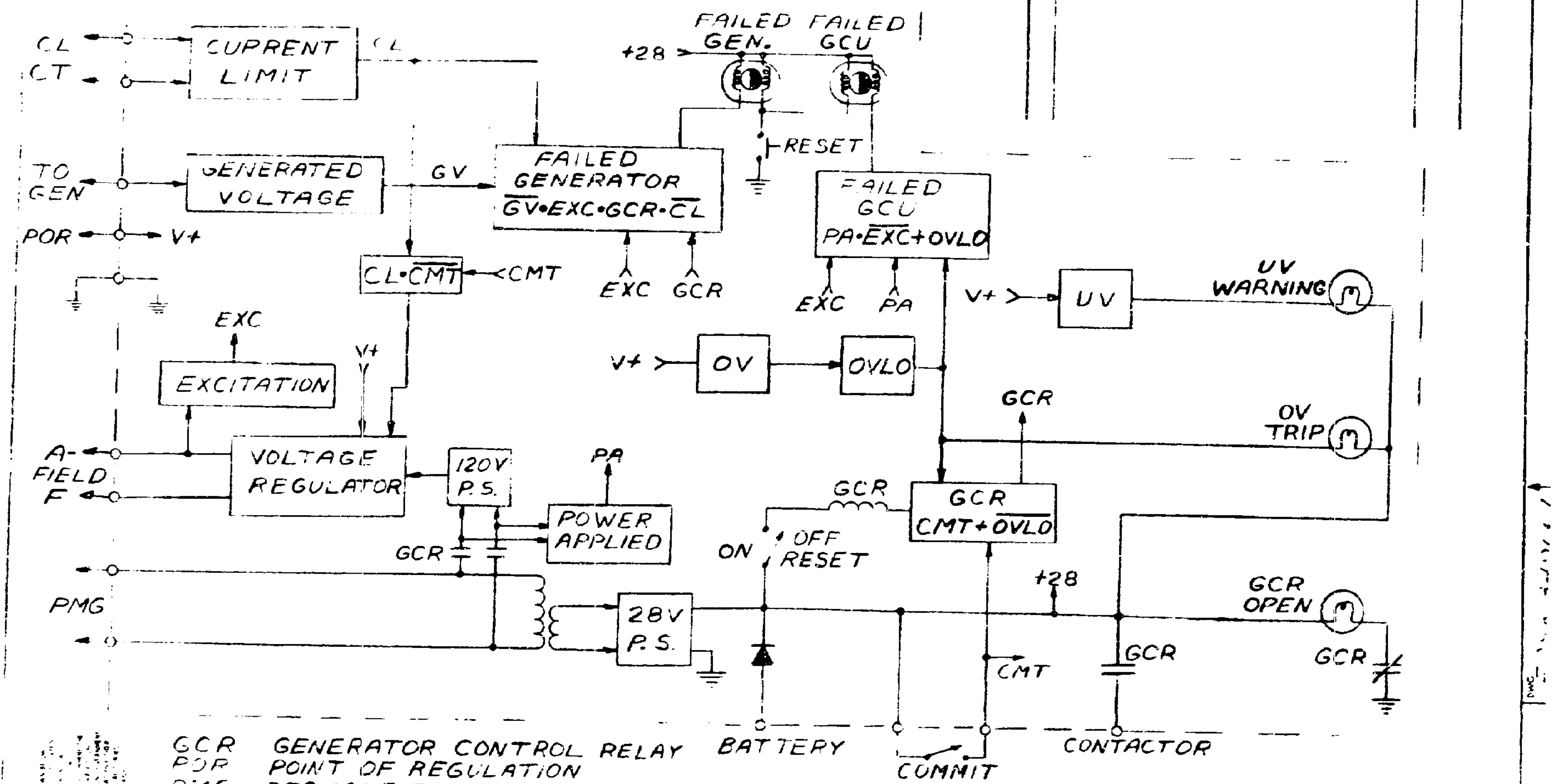
The OV and UV circuits produce output signals if any one of the three phase voltages is above or below normal limits.

Summary

The following table summarizes the estimated size, weight, cost, and reliability for the three GCU's.

	Size* HXWXL (in.)	Wt* (lb)	Cost ($)	MTBF Inherent (hr.)	MTBF Predicted Achieved
28V	3 x 5 x 7	2.9	503	39,200	31,400
Dual	3 x 6 x 8	3.7	606	29,100	23,300
115V	3 x 6 x 8	3.9	742	23,400	18,700

*Figures based on a bolt-down, fabricated aluminum, rectangular package.



GCR GENERATOR CONTROL RELAY
POR POINT OF REGULATION
PMG PERMANENT MAGNET GENERATOR
OV OVERVOLTAGE
UV UNDERVOLTAGE
PS POWER SUPPLY
LO LOCKOUT

QTY REQD PN	SYM	NOMENCLATURE OR DESCRIPTION	PART NO OR IDENT NO	SPECIFICATION	CODE IDENT NO	INTERNAL INFORMATION	ITEM NO

LIST OF MATERIAL OR PARTS LIST

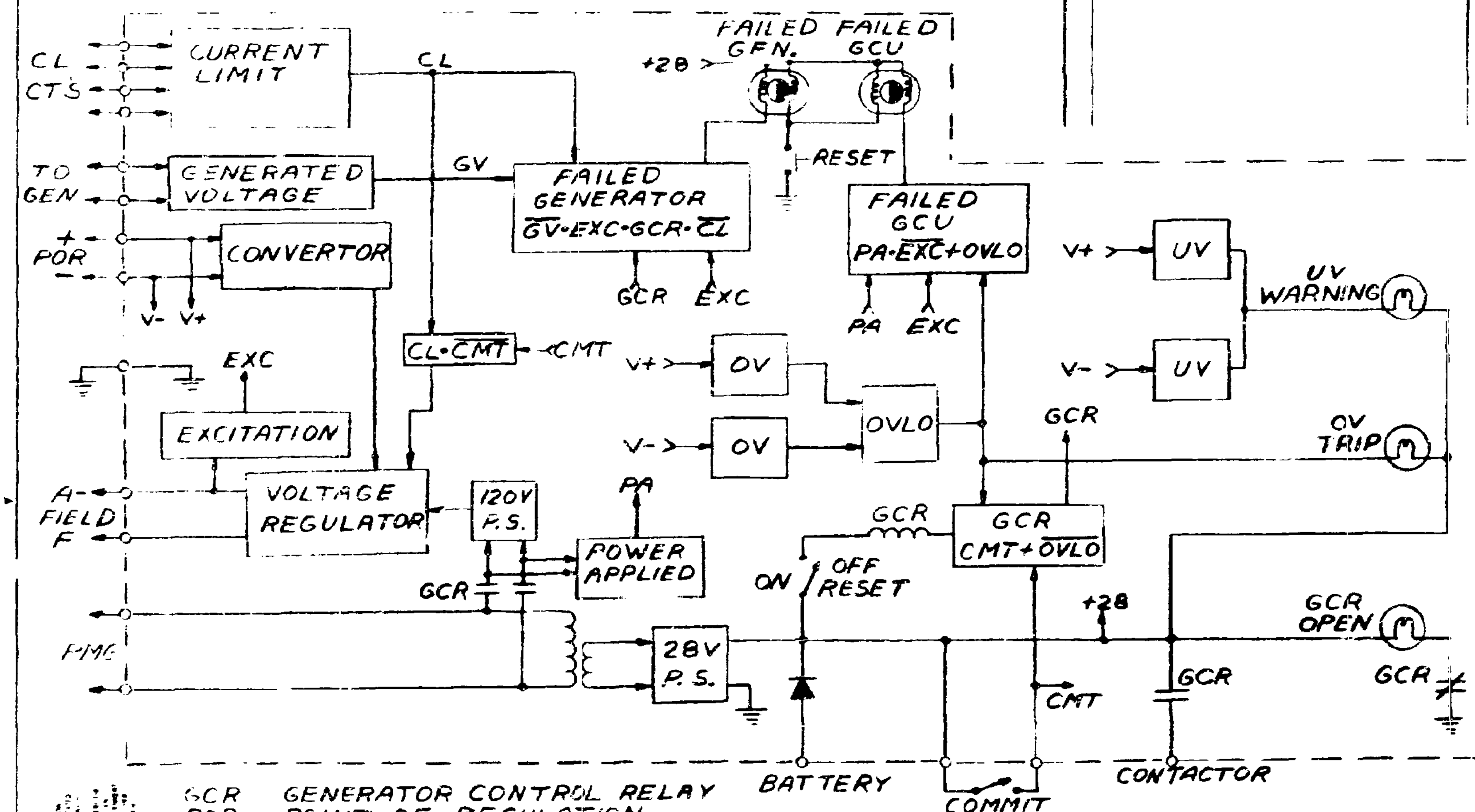
AEROSPACE ELECTRICAL DIVISION
WESTINGHOUSE ELECTRIC CORP
LIMA, OHIO U.S.A.

ENGR David O. Fox 1-22-

TITLE LOGIC DIAGRAM 28VDC GCU

SIZE C CODE IDENT NO 83843 DRAWING NO EDSK 343667

FIGURE 4



GCR GENERATOR CONTROL RELAY
POR POINT OF REGULATION
PMG PERMANENT MAGNET GENERATOR
OV OVERVOLTAGE
UV UNDERVOLTAGE
P.S. POWER SUPPLY
LO LOCKOUT

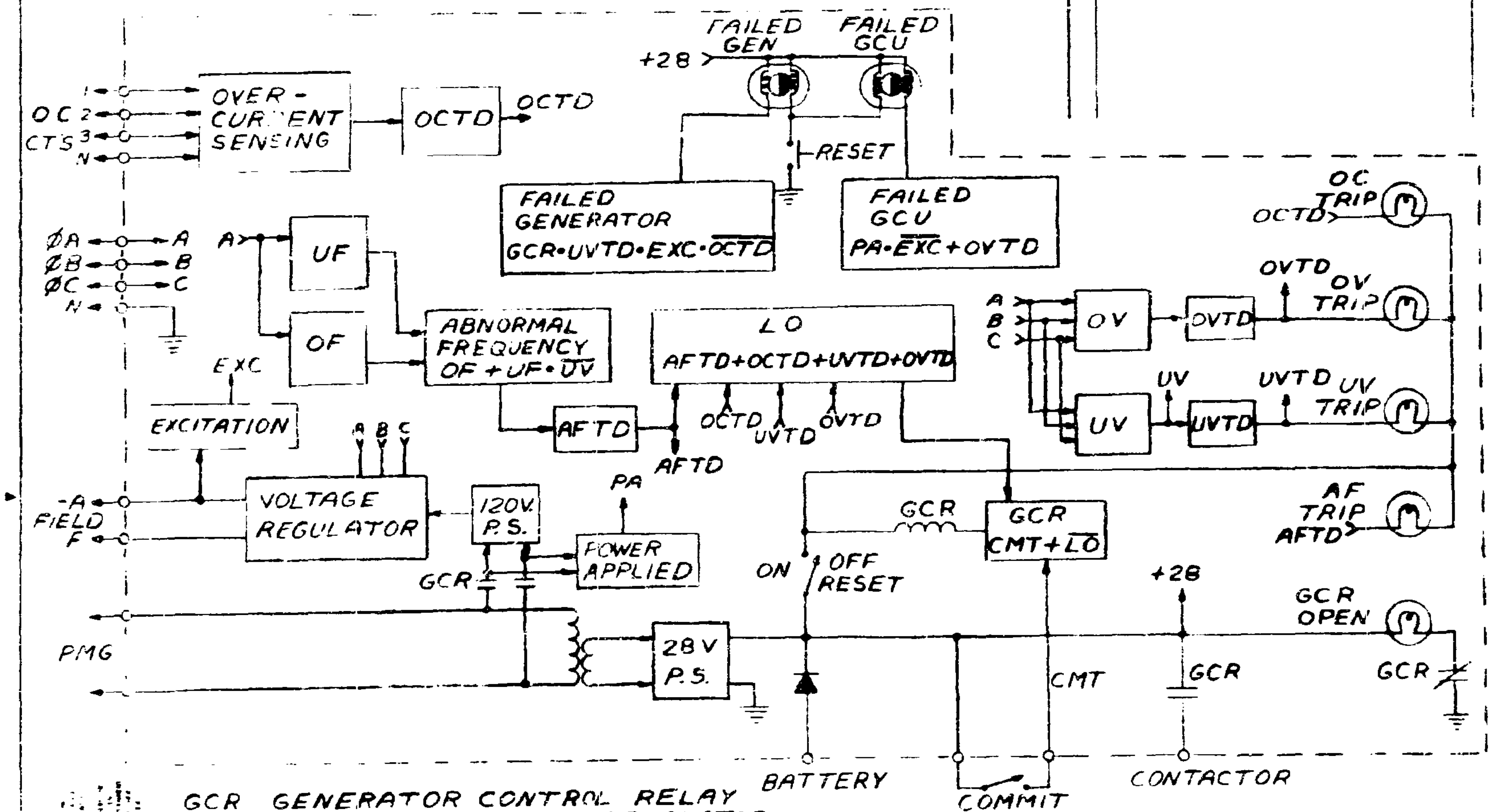
LIST OF MATERIAL OR PARTS LIST

AEROSPACE ELECTRICAL DIVISION
WESTINGHOUSE ELECTRIC CORP.
LIMA, OHIO U.S.A.

TITLE LOGIC DIAGRAM ±28VDC GCU

C 83843 EDSK 349668

FIGURE 15



GCR	GENERATOR CONTROL RELAY
PMG	PERMANENT MAGNET GENERATOR
OV	OVERVOLTAGE
UV	UNDERVOLTAGE
OF	OVERFREQUENCY
UF	UNDERFREQUENCY
TD	TIME DELAY
PS	POWER SUPPLY
LO	LOCKOUT

LIST OF MATERIAL OR PARTS LIST

AEROSPACE ELECTRICAL DIVISION
WESTINGHOUSE ELECTRIC CORP
LIMA OHIO U.S.A.

TITLE: LOGIC DIAGRAM 115 VAC GCU

SIZE C — CODE IDENT NO 93643 — DRAWING NO EDSK 349669

FIGURE 16

Unclassified
Security Classification

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(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

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13. ABSTRACT

This study ~~has~~ compiled a band of power system data so that, given an electric power profile for an army vehicle, an optimum power system approach can be selected. The basis for the selection are four parameters; weight, volume, efficiency, and life cycle cost.

The major power system components included in the study were a gas turbine, fuel for a 24 hour and a 48 hour mission, a generator, a voltage regulator, system controls, and protection.

Three types of electric power were investigated; 28 volts d-c, 56 volts d-c and 115/200 volts, 3 phase, 400 Hz a-c.

The study indicates that the type of electric power selected should be a function of what is best for the loads since fuel weight is quite large compared with the other components. Also, a method of determining life cycle cost for a vehicle electric power system is described.

DD FORM 1 NOV 65 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Weight						
Volume						
Efficiency						
Life Cycle Cost						
Power System						

END

Unclassified
Security Classification

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