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FLYWHEEL-POWERED MOBILE X-RAY GENERATOR
FINAL REPORT
(1 January 1982 - 31 October 1985)

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October 15, 1985

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AD-A188 686

Supported by
U. S. ARMY MEDICAL RESEARCH AND DEVELOPMENT COMMAND
Ft. Detrick, Frederick, Maryland 21701-5012

Contract No. DAMD17-82-C-2050

University of Wisconsin
Madison, Wisconsin 53706

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
1a. REPORT SECURITY CLASSIFICATION Unclassified		1b. RESTRICTIVE MARKING <i>AD-1188 686</i>			
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited			
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S)		5. MONITORING ORGANIZATION REPORT NUMBER(S)			
6a. NAME OF PERFORMING ORGANIZATION University of Wisconsin		6b. OFFICE SYMBOL (if applicable)		7a. NAME OF MONITORING ORGANIZATION	
6c. ADDRESS (City, State, and ZIP Code) 750 University Avenue Madison, WI 53706		7b. ADDRESS (City, State, and ZIP Code)			
8a. NAME OF FUNDING/SPONSORING ORGANIZATION U.S. Army Medical Research & Development Command		8b. OFFICE SYMBOL (if applicable)		9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAMD17-82-C-2050	
8c. ADDRESS (City, State, and ZIP Code) Fort Detrick Frederick, MD 21701-5012		10. SOURCE OF FUNDING NUMBERS			
		PROGRAM ELEMENT NO. 62772A	PROJECT NO. 3S1 62772A874	TASK NO. BA	WORK UNIT ACCESSION NO. 260
11. TITLE (Include Security Classification) (U) Flywheel-Powered Mobile X-Ray Generator					
12. PERSONAL AUTHOR(S) Melvin P. Siedband					
13a. TYPE OF REPORT Final		13b. TIME COVERED FROM 1/1/82 TO 10/31/85		14. DATE OF REPORT (Year, Month, Day) 1985 October 15	
15. PAGE COUNT 110					
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB GROUP	X-Ray, Energy Storage ←		
06	12		Flywheel Powered,		
06	02				
19. ABSTRACT (Continue on reverse if necessary and identify by block number)					
<p>Medical x-ray machines require high power for good images without motion artifacts. Power requirements are 5 kWp for small image fields and 15 kWp for larger fields, beyond the capacity of a small field generator. Conventional batteries and high voltage capacitors can be used to accumulate energy but have practical limitations of size or affect x-ray beam quality. Circuits and mechanical components have been developed which use small flywheels with certain alternators. Aircraft alternators were used as both motors and generators to accumulate energy at a slow rate and release the energy in a short burst suitable for operating a diagnostic x-ray machine. The flywheel alternator assembly accumulated energy from a 0.5 kW source and released it in bursts in excess of 35 kWp (regulated) and 50 kWp (unregulated).</p> <p><i>Keywords:</i></p>					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input type="checkbox"/> UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL Mary Frances Bostian		22b. TELEPHONE (Include Area Code) 301-663-7325		22c. OFFICE SYMBOL SGRD-RMI-S	

E. High Tension Transformer Assembly	43
High voltage transformer	43
Rectifier bridge	43
Filament circuit	46
Mechanical assembly	46
F. Tube Rotor Control	47
Circuit timing operation	47
Exposure interlock operation	49
G. Tube Filament Control Circuit	50
Circuit operation	50
Calibration	52
H. Fluoroscopic Circuits	53
Purpose	53
Fluoroscopic inverter	53
Circuit design	54
I. Fluoroscopic Control	57
Automatic brightness stabilizer	57
PMT power supply	59
J. Mechanical Assembly	60
Equipment cabinet	60
Column and tube arm assembly	61
Wheels and brakes	61
III. MICROPROCESSOR CONTROL	63
A. Introduction	63
B. X-Ray Machine Specifications	64
C. Microcontroller Tasks	65
Operator's commands	65
Front panel displays	67
Status signals	68
Control signals	69

D. Microcontrolller System Block Diagram	74
E. Microprocessor and Memory Components	77
Intel 8748 single component 8-bit microprocessor	77
Intel 8156 RAM with I/O ports and timer	79
2716 2-kbyte EPROM	80
F. Analog Signal Processing	82
National DAC08 8-bit D/A converter	82
National ADC0809 Data Acquisition system	82
G. Intel 8243 Input/Output Expander	84
H. Front Panel Interface	85
National 74C922 16 key encoder	85
Intersil 7218C 8 digit LED driver system	88
Pilot light drivers	91
I. Software Overview	92
Section 1: Symbol definition and macros	92
Section 2: Interrupts and initialization	92
Section 3: Push button and LED display	93
Section 4: Rad mode routine	93
Section 5: Fluoro mode routine	93
Section 6: LED display routines	94
Section 7: Signal inputting routines	94
Section 8: Signal outputting routines	94
Section 9: Mathematics routines	94
J. Concluding Remarks	95
IV. PERFORMANCE MEASUREMENTS	97
A. Dummy Load Tests	97
B. Fluoroscopic Tests	105
References	108
Distribution List	109

LIST OF FIGURES

	PAGE
1) Present flywheel mounting design	14
2) Previous flywheel mounting design	15
3) Critical frequency vs. shaft diameter	17
4) Whirling frequency vs. shaft radius	18
5) Power supply printed circuit board	24
6) Motor generator power control circuit	26
7) Motor control block diagram	27
8) Six-step drive waveforms	29
9) Three phase motor logic board	31
10) DC power supply	33
11) Motor driver opto-coupling board	36
12) Motor driver board	38
13) Exciter control board	40
14) High tension transformer assembly	44
15) Tube rotor control board	48
16) Tube filament control board	51
17) Fluoroscopic inverter circuit	55
18) Automatic brightness stabilizer board	58
19) Front panel of X-ray unit	66
20) Rad exposure timing diagram	69
21) Microcontroller system block diagram	75
22) Interface board	76
23) Microprocessor system schematic	78
24) Front panel push button and pilot lights	86
25) Rad display schematic	89
26) Fluoro display schematic	90
27) Anode waveform from improper adjustments	98
28) Anode to cathode waveform showing proper adjustments	98
29) Rectified alternator output across a 2.2 ohm dummy load	100
30) Typical 100 msec exposure at 8200 RPM	101
31) Example of significant output capability even at relatively low flywheel speed of 7200 RPM	102
32) Typical 220 msec exposure at 8200 RPM	102
33) Example of no droop even during relatively long exposure time of 750 msec	103

- | | |
|--|-----|
| 34) Plot of Dies and Dieb settings vs. V_{op} using a
dummy load | 104 |
| 35) Output of fluoroscopic inverter circuit across two
100W light bulbs | 106 |
| 36) Inverter waveforms | 107 |

Acknowledgements

It is proper to recognize the important contributions of many people to the success of this project. Dr. Donald Showers performed much of the analysis and design of the flywheel assembly. Mr. Alan Kutchera was the jack of all trades obtaining all of the component parts, building PC boards, and wiring the system. Graduate students David Trumble, Joseph Kidder and Scott Biederwolf did much of the electronic breadboard testing and the design. Mr. L. Burke O'Neil, Mr. Al Hanson and Mr. Robert Anderson of the Instrumentation Systems Center assisted in design, and machine fabrication of important parts of the assembly. Electrical Engineering students, Frank Grenzow, Tom Ray, Craig Heilman and Man-Kit Yau, performed many of the final tests, programming and frequent repairs of the system and also prepared portions of the Final Report. Dr. Steven Goetsch reviewed the text and assisted in the editing of the Report. Ms. Colleen Schutz was very important for her help in the preparation of the scientific papers, correspondence and progress reports.

FOREWORD

Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

I. INTRODUCTION

The contract between the University of Wisconsin and the U.S Army Medical Research and Development Command, Contract No. DAMD17-82-C-2050, was for the study and development of a flywheel-powered x-ray system. The final objective will be the general application of flywheel-powered x-ray generators in rugged, transportable systems of moderate power requirements.

The first phase of the program was to study and obtain information required for the design of practical flywheel systems. A demonstration apparatus was constructed comprising a flywheel-powered motor generator set, a high voltage transformer, an x-ray tube and the necessary control circuits. The details of the designs of certain critical components and the test results were described in the Interim Technical Progress Report published 18 March 1983.

The second phase consisted of the design of a demonstration unit packaged in the form of a complete mobile x-ray machine. The ratings were to be 20 kWp, 125 kVp, 200 mA, with fluoroscopic controls and configured for use as a conventional radiographic-fluoroscopic unit. Line power was to be less than 1.0 kWp, with a goal of 500 W or less. The details of that design and the test results are described in this report.

Other mobile x-ray generators have been made using nickel-cadmium storage batteries or large electrolytic capacitors. While these machines perform well under controlled conditions, they are heavy, cannot work under extremes of temperature, require charging or conditioning before use, and have limited output. One excellent commercial machine weighs about 370 kg and has a peak output of 12 kWp. The flywheel demonstration model has achieved 40 kWp during tests and weighs less than 200 kg.

The central idea of energy accumulator systems is that they acquire

energy at low rates, accumulate it and release the stored energy at high rates. A good stop-motion X-ray requires 10 to 50 kWp and a small power line or field power supply is capable of less than 1.5kW. Most small power supplies do not have a high ratio of peak to average power. Storage batteries or capacitors can be charged at low rates and release their charge at high rates. A flywheel can accept energy to slowly increase its speed and then release the stored energy in a powerful burst to a suitable alternator.

Capacitor energy storage has two disadvantages: the voltage of the capacitor decreases during the discharge and there is some danger of a catastrophic failure releasing the stored energy in a sudden and dramatic discharge as a cable or socket fails. These systems usually use two series capacitors of $2.0\mu\text{F}$ each with the pair charged to the initial kVp value. A new type of capacitor energy storage uses a bank of electrolytic capacitors, 0.33F at 350 Vdc to accumulate energy and feed the energy to a solid state inverter. The output of the inverter feeds a high frequency-high voltage transformer which supplies power to the X-ray tube. The circuit variables are controlled by a microcomputer and the results appear to be quite good.

Storage battery systems are in use with special batteries of modest capacity but of very low impedance. Sufficient energy is stored for up to 100 exposures. Since the impedance of the cells determines their size, systems would not be much smaller if their capacity were reduced. Unfortunately, NiCd cells have memory and must be completely discharged and recharged several times each year in order to keep their high capacity. They cannot withstand extremes of temperature, vibration or shock and must be charged fully before use. They have a limited lifetime.

The advantages of the use of an aircraft alternator-flywheel combination over other devices are: low power input and very high power output, high

reliability through the use of Mil-spec components, operation at extremes of temperature and vibration, capability of long-term storage followed by immediate use without "reconditioning", operation from a variety of poor power sources, capability of being designed with moderate size and weight. The essential idea is that the flywheel assembly accumulates energy at a rate of, say, 500 W until the kinetic energy of the wheel exceeds 30 kJ. The circuits are then switched from a motor mode to the alternator mode, for short bursts of controlled power of up to 40 kW. A 40 kW x-ray system could be operated from a very small camping generator or two car batteries rather than requiring heavy-duty wiring and a special distribution transformer or a field generator of 50 kW capacity.

Other advantages of the flywheel-powered system and the characteristics of other types of x-ray generators are discussed in the interim report and in other publications and papers.^{1,2}

II. APPLIED RESEARCH PROGRAM

During the past two years progress has been made in a number of areas. The original flywheel design was modified to place ball bearings on both sides of the flywheel, modifying the original cantilever design. This configuration allowed the use of smaller bearings and lead to a more compact and stable design. Peak kVp, mA and power loads achieved are discussed later.

A. ALTERNATORS

The flywheel/alternator is the heart of this X-ray system. Use of this novel flywheel energy storage device eliminates the need for bulky lead-acid batteries with their associated hydrogen gas and longevity problems. No massive, hazardous capacitors are needed as found in a number of commercial devices.

The ideal flywheel would be minimal in mass with the highest possible rotational speed. Counter-balancing these desirable characteristics is the risk of a breakdown of the flywheel/shaft assembly with subsequent ejection of high-speed projectiles and the need to use special wheel materials and bearings. A strong case surrounding the rotating flywheel is therefore necessary. Nevertheless, a working prototype has been tested at 11,000 RPM (corresponding to about 30,000 Joules). This device draws only about 500 Watts, or about 1/3 of the average domestic coffee maker. In order to successfully utilize the energy stored in this flywheel, a suitable alternator had to be found. The ideal machine for this purpose must function efficiently as a motor while the flywheel is being brought up to speed and also as an alternator when power is being taken out and X-rays are being generated.

CHARACTERISTICS OF AUTOMOBILE ALTERNATORS

Automotive alternators were initially considered for this purpose. Their advantages are that they are small, light, inexpensive, durable, common and capable of functioning in the required power range. The previous contract discussed the evaluation of alternators from Chrysler Corporation, Leece-Neville Corporation and Motorola Corporation. These units were capable of supplying 100 to 175 amperes at 12 to 24 volts (1.2 to 4.2kVA). Larger units are available up to 10kVA.

Automotive alternators are generally constructed in a multi-pole design using cast iron polepieces and multi-pole stators. While this is a space-efficient design suitable for a confined motor compartment, these units can only achieve low flux densities and have the additional drawback of a high series reactance. Since the flux maximizes quickly, the time derivative of flux (proportional to the electromotive force) also maximizes quickly. Higher rotational speeds increase output frequency, but since the high series reactance is proportional to frequency there is little additional output.

CHARACTERISTICS OF AIRCRAFT ALTERNATORS

Two aircraft alternators were also evaluated in the previous contract period. Each unit was rated at 20kVA at 208 volts, three-phase. The maximum rated rotational velocity of the Bendix Model 28B262-35B is 15,000 RPM. These alternators, like many aircraft alternators, use a more sophisticated design than automotive models. They are "brushless," unlike the automotive alternators, and use magnetic coupling. While this is useful in preventing arcing at high altitudes (and consequent low vapor pressure), it is of no advantage for this project. These alternators do, however, use a great deal more iron than the automotive models, which leads to much higher flux

densities with low series reactance. A great deal of power is developed at high RPM's, making them much more suitable for this application. While the peak to average power rating of an automotive alternator is about 1.25, for the aircraft alternators the ratio is greater than 4.

B. FLYWHEEL ASSEMBLY

The energy storage device for the mobile X-ray unit is a high-speed flywheel. The flywheel assembly consists of the flywheel along with its shaft, bearings and housing. This assembly is the main support unit for both the flywheel and the alternator.

The present design uses a symmetric bearing mount for the flywheel shaft. The original design used a cantilevered suspension. The shaft was cut to receive the spline of the alternator while the bearings supported the flywheel (see Figures 1 and 2).

REASONS FOR INDEPENDENT SUSPENSION

A consideration of vibrational modes lead to the realization that it is important to de-couple the flywheel from the alternator by means of an independent suspension system. Among the most important sources of vibration are rotor unbalance, obliquity in the flywheel and bearing mounting, and deflection of the rotor shaft. The vibrational modes driven by these sources include whirling, torsional and frame modes associated with the system support.

VIBRATIONAL STATES

Torsional modes may arise from the mounting of two rotors, i.e., flywheel and alternator rotor on the same shaft. An estimate of the critical torsional frequency is given by:

$$\omega = \left[\frac{GJ2E_0}{[\omega_0^2 d(2E_0/\omega_0^2 - I_r)I_r]} \right]^{1/2}$$

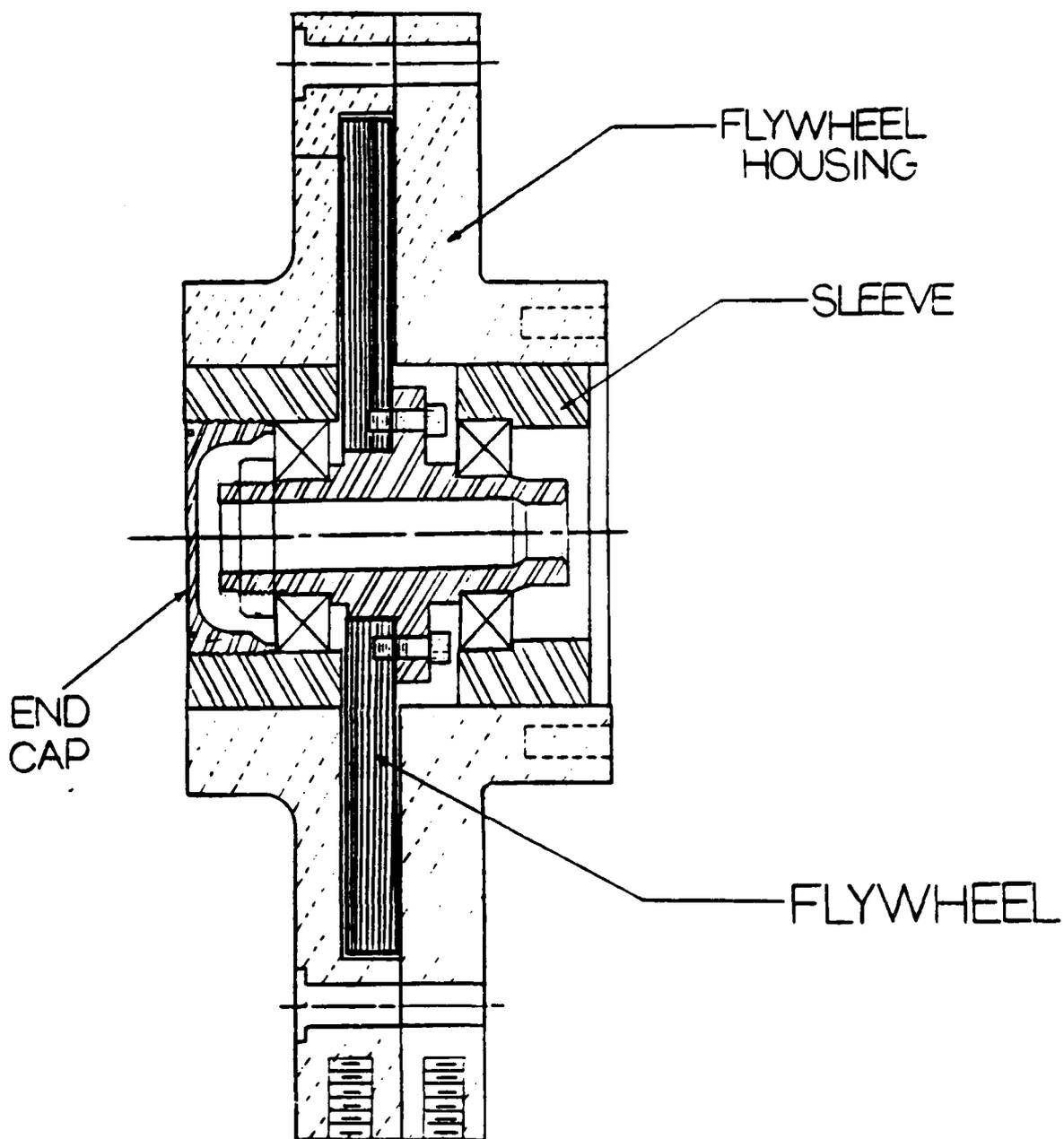


FIG. 1
PRESENT FLYWHEEL MOUNTING DESIGN

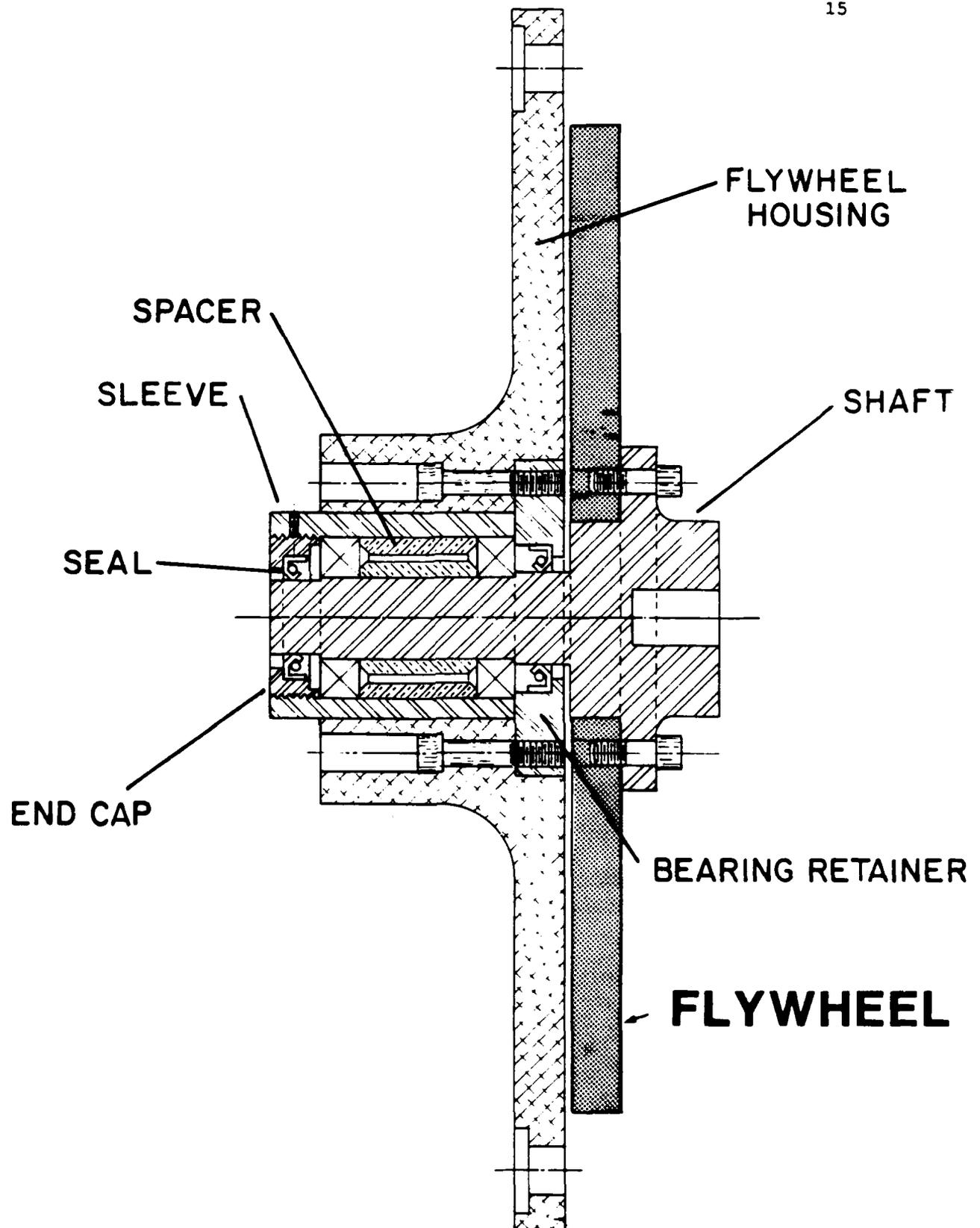


FIG. 2
PREVIOUS FLYWHEEL MOUNTING DESIGN

where G is the shear modulus, J the area moment of the shaft, E_0 is the initial energy stored in the rotating system, I_r is equal to the moment of the rotor, and d is the distance between the rotor and the flywheel. The expression indicates that the critical frequency varies as the square of the shaft diameter (see Figure 3).

Whirling occurs first when the restorative force due to the shaft stiffness equals the centrifugal force caused by an unbalance. Estimates of the critical frequency are greatly affected by the specific geometry of the shaft. Methods of analysis include Stodola's iteration technique, Holzer's method, and Macaulay's moment analysis for thin rotors.^{3,4} Using the latter technique, the whirling critical frequency of a 30-cm shaft with a 6-kg flywheel, and a 9-kg rotor placed at 5 and 18 cm along the shaft is easily computed as a function of shaft radius. The relation is plotted in Figure 4. The range of values includes the operating point of the alternator and thus care would be required to provide sufficient shaft stiffness to avoid vibration in a long shaft design.

This analysis of vibrational modes indicated two distinct possible design approaches. A long shaft design supporting two rotors was rejected in favor of a separately supported flywheel. The coupling between the flywheel and alternator is by a precision broach using a spline with a torsional damping plate. The unit was designed to store approximately 30kJoules at 10,000 rpm with a maximum stress less than 20,000 psi (140 MN/m^2). When dynamically balanced to a limit of 0.004 oz in. ($2.8 \times 10^{-5} \text{ N/m}$), no mechanical characteristic resonant states are observed during its operation.

STRENGTH OF MATERIALS

The present flywheel system emphasizes energy storage through higher

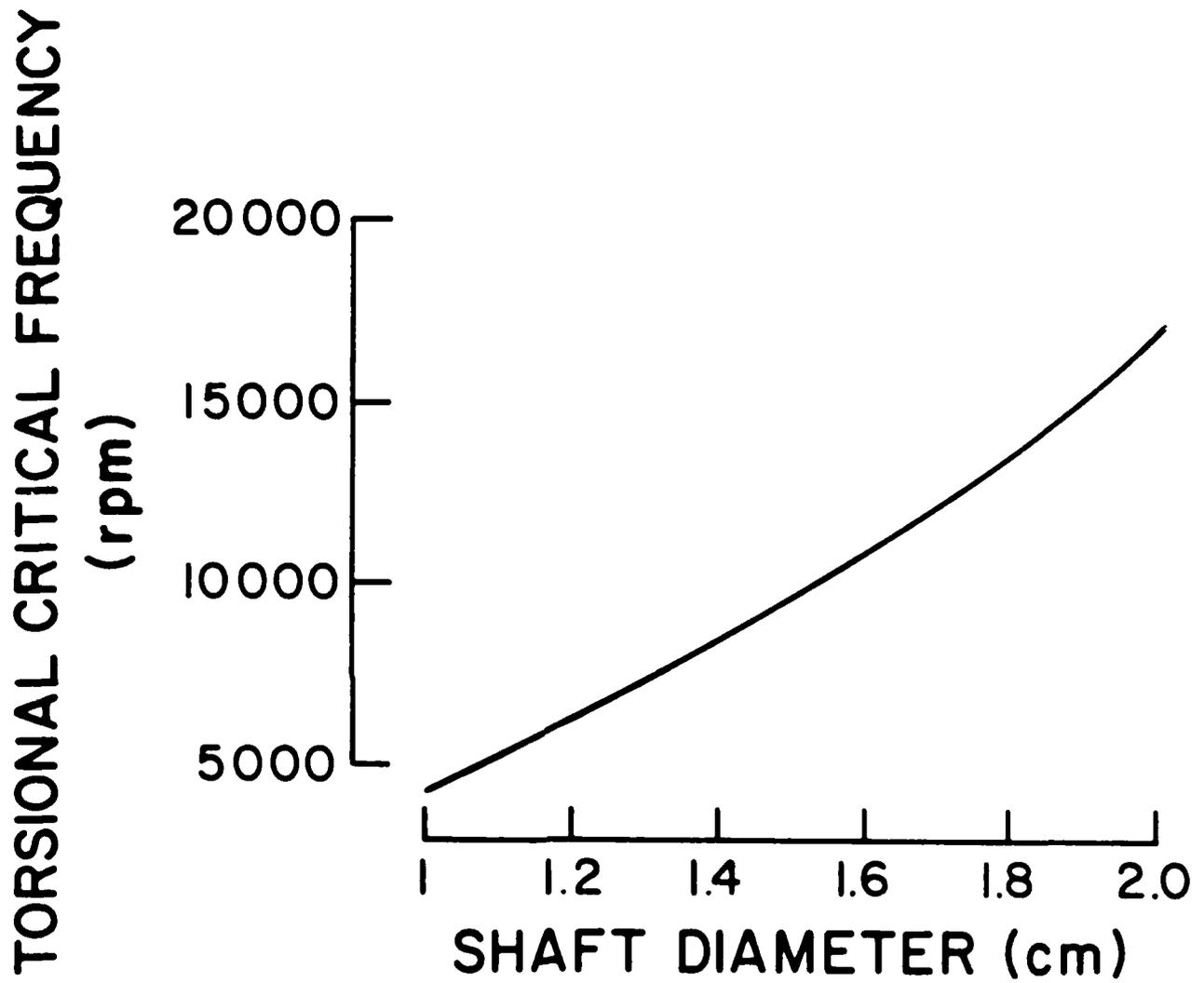


FIG. 3
CRITICAL FREQUENCY VS. SHAFT DIAMETER

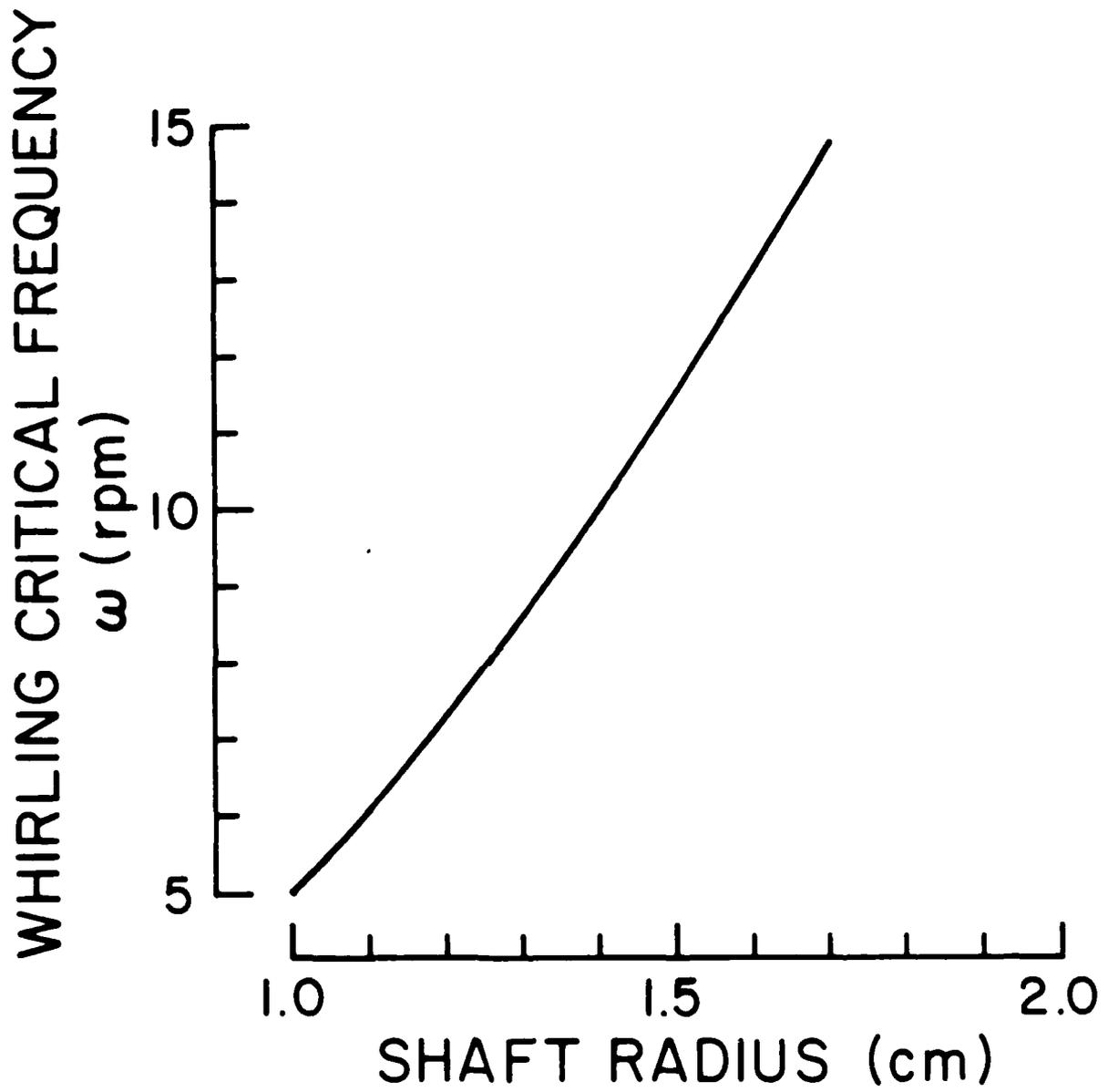


FIG. 4
WHIRLING FREQUENCY VS. SHAFT RADIUS

angular velocity rather than using a large flywheel. From first principles, the energy E stored in the flywheel is given by:

$$E = I \omega^2 / 2$$

where I is the moment of inertia and ω is the angular velocity. Differentiation and division by the original expression gives:

$$\frac{dE}{E} = 2 \frac{d\omega}{\omega}$$

Thus, a 10% change in energy gives a 5% change in speed. During an exposure, the power, P , withdrawn for the exposure is related to the energy by:

$$\begin{aligned} P &= dE/dT \\ &= I \omega d\omega/dt \end{aligned}$$

The reactive torque, T is given by:

$$T = P/\omega$$

For a given power level, the reactive torque is reduced by using a higher angular velocity.

Using the above relations, the energy stored by a 5 kg flywheel 30cm in diameter at 10,000 rpm is over 25kJ. At exposure levels of 100 kVp and 300mA for 50mS, the X-ray system requires approximately 30kW and 1500 Joules. The exposure will reduce the stored energy by 5% and the flywheel will slow approximately 2.5% while the reactive force on the system is about 28

Newton-meters (approximately 7 foot-pounds). As the reactive force is low enough, complicated schemes of paired counter-rotating flywheels are clearly not needed.

Flywheel stress also places limits on the rotational velocity and flywheel radius. For a rotating disc with a hole, the maximum stress, σ_{\max} , may be estimated by:

$$\sigma_{\max} = \frac{3}{4} \Sigma R^2 \omega^2$$

where $\Sigma = 7.8 \times 10^3 \text{ kg/m}^2$ for steel. For a radius R of 0.15m and $\omega = 10 \text{ krpm}$, then:

$$\sigma = 1.4 \times 10^8 \text{ N/m}^2$$

and $\sigma = 22,000 \text{ lb/in}^2$ (approximately).

Common steel plate has a yield point of about 50,000 lb/in², well above this value. Although localized stresses, due to machining and mounting can increase this load, specialized steel alloys can still offer a wide margin for safety. The present flywheel uses a 4340 alloy steel, normalized and tempered with a yield point of approximately 125,000 lbs/in². The risk of material failure can be reduced still further with high speed testing and low housing clearance. Since conventional grease-packed bearings have a ball speed limited to about 18m/sec, the shaft speed is limited to between 12,000 and 15,000 rpm, depending on the shaft diameter. At these speeds, the use of high grade bearings and close tolerances are necessary for low levels of unbalance.

ORIGINAL ASSEMBLY AND NEW CONFIGURATION

The original flywheel assembly used the cantilevered design with all bearings on the same side of the flywheel. During the present contract period a new assembly was designed and constructed in which bearings were placed on both sides of the flywheel. The advantage of the new configuration is that it allowed the use of smaller bearings. This, in turn, permitted a smaller overall size and a more stable operation.

OTHER POSSIBLE CONFIGURATIONS

Experience has indicated that the original design contained a protective shield (surrounding the flywheel) that was far stronger than necessary. No events have been observed in which the flywheel failed catastrophically. In any event, the close tolerance of the shield surrounding the flywheel provides a safety margin. Should the flywheel begin to oscillate or wobble on the shaft, the wheel would almost immediately contact the shield, thus providing a natural braking action. The resulting noise would certainly provoke the operator to turn off the unit. A reduction in the thickness of the shield would provide significant overall weight reduction of the unit.

NEW MATERIALS

The energy stored in a flywheel is directly proportional to the mass of the flywheel and to the square of the angular velocity. Doubling the angular velocity thus results in four times the stored energy. It is therefore attractive to consider a low mass, high speed alternative to the present design. While the present flywheel design has been tested at 12krpm, other workers have successfully tested flywheels at rotational velocities of up to 50krpm. It is possible to build flywheels with materials of extremely high

tensile strength, such as graphite or Kevlar which can withstand the stresses imposed by these velocities. However, ordinary ball bearings would not survive at these levels for very long, if at all. It might become necessary to use exotic forms of bearings such as fluid bearings or air bearings. These components are not as well tested or reliable as conventional bearings and may not be suited for field use.

Design emphasis in the present unit has been placed on reliability with some sacrifice from ultimate limits of performance. The present steel flywheel, for example, is being used at about one-fifth of the working strength of the steel used, and at about one-twenty-fifth of its yield strength. The ball bearings chosen were selected in part because of their expected 20,000 hour operational life. If a decision were made to increase the power levels by use of exotic materials and construction techniques, there would necessarily be some loss of the presently expected reliability.

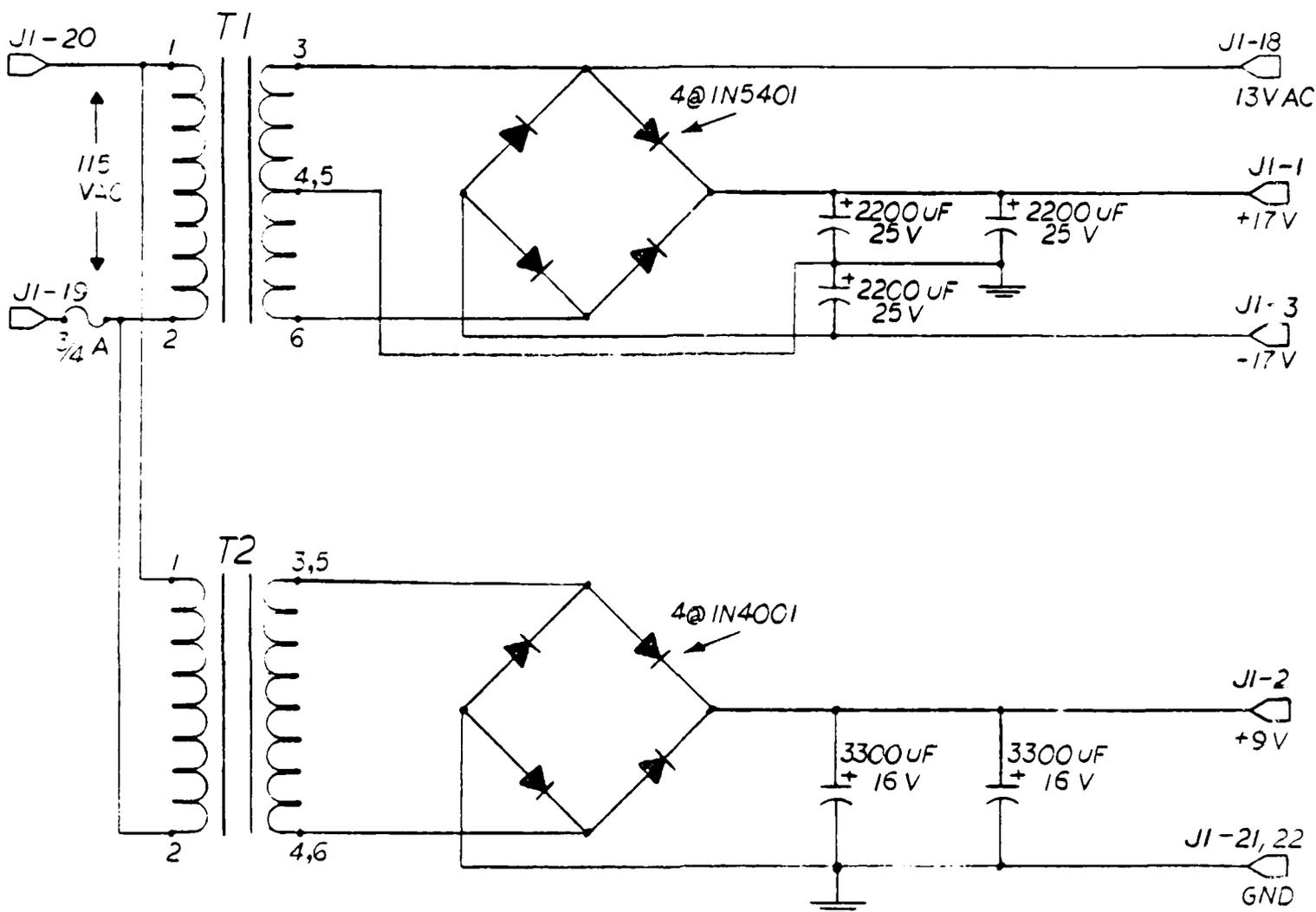
BEARINGS, SEALS AND HOUSING

Problems were experienced at first with seals. Lip seals were used in several mountings without success and it was thought that a carbon-faced seal or other form of low-friction seal might be necessary. However, further work with the previous system has demonstrated that careful machining of the O-ring grooves allows the seals to be made successfully.

C. POWER SUPPLIES

The main power supply consists of two transformers having their primaries in parallel and their secondaries in series feeding a diode bridge and a filter capacitor (see Figure 10 on page 27). The transformer taps are set to produce approximately +60 Vdc under load. That supply is shared by the motor drive circuits and the fluoroscopic inverter. The microprocessor assures that only one of these circuits can be active at one time.

The power supply printed circuit card (Figure 5) contains two small transformers and the rectifiers and filters to produce +17, +9 and -17 Vdc. These voltages feed the on-board regulators of each of the individual card circuits via common bus lines of the card cage assembly.



T1: DIGI-KEY T125ND
 T2: DIGI-KEY T122ND

FIG. 5
 POWER SUPPLY PRINTED CIRCUIT BOARD

D. MOTOR GENERATOR POWER CIRCUITS

PURPOSE

This system provides the power and control signals needed to run the Bendix alternator as a motor. The shaft position of the flywheel-alternator assembly is sensed by the three optical sensors, and power signals are generated that cause the alternator to run in the motor mode.

POWER CONTROL

Figure 6 shows the power control circuit. The brake relay is energized whenever power is applied to the assembly. When power is on, the alternator stator is connected to the motor driver through the motor relay. When power is off, the brake relay connects the alternator stator to three load resistors and the permanent magnet exciter-generator output is rectified and fed through the 10 ohm resistor to the exciter winding. The effect is to cause the alternator to function as a self-excited generator feeding a heavy load whenever disconnected from the main power. This will cause the spinning flywheel-alternator assembly to decelerate rapidly. The exposure contactor and the motor relay are controlled by the microprocessor via the exciter board. The circuit logic of the exciter board inhibits operation of the motor relay if any current is flowing in the exciter winding.

OPERATION

The flywheel is painted with a ring of six alternating black and white sectors (see Figure 7). Each sector spans a 60° arc. Three optical reflection sensors are focused on this ring, each are spaced 40° apart. The outputs of the optical sensors feed into the three Position Detection Comparators, which toggle high when a black sector is under a corresponding

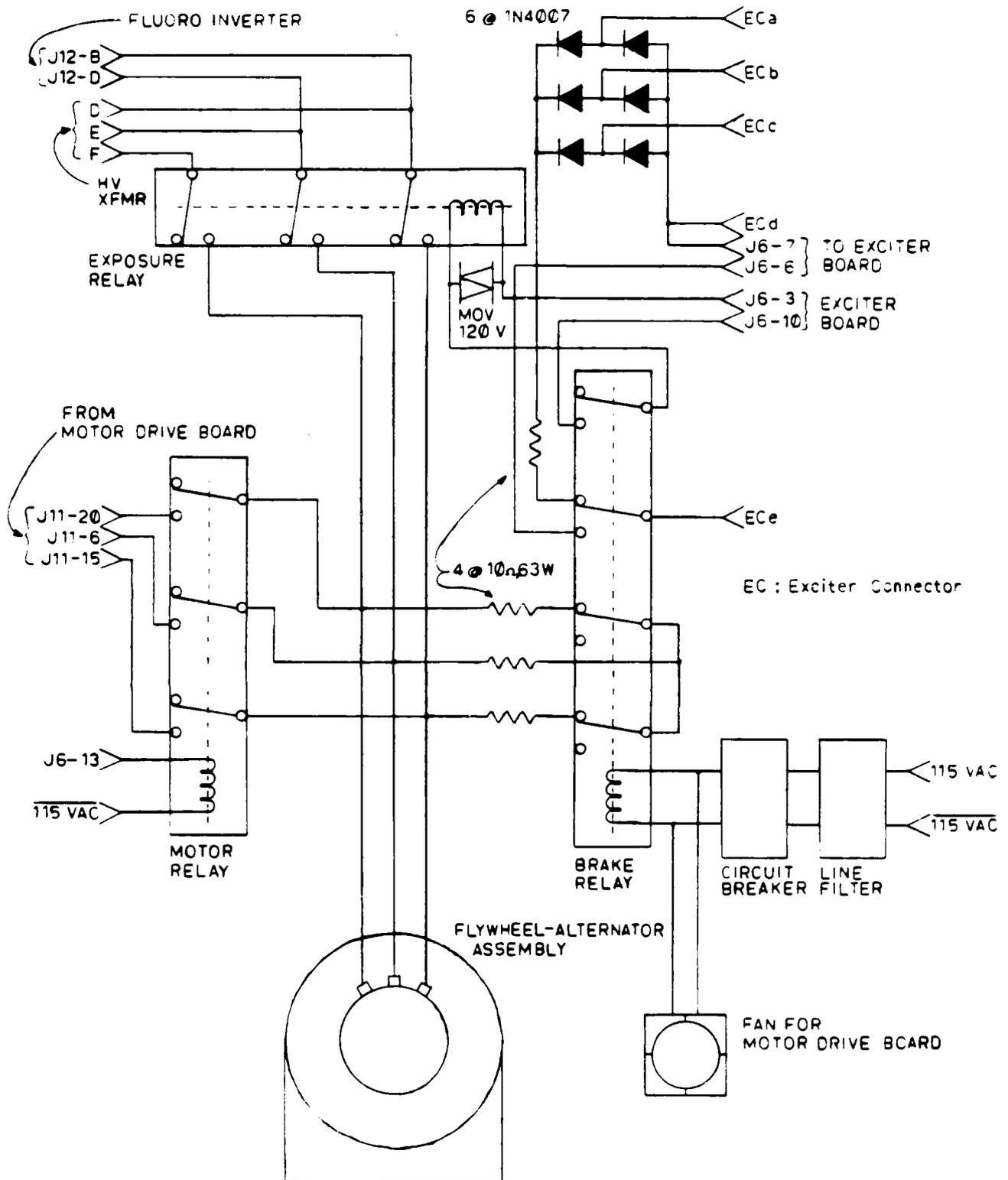
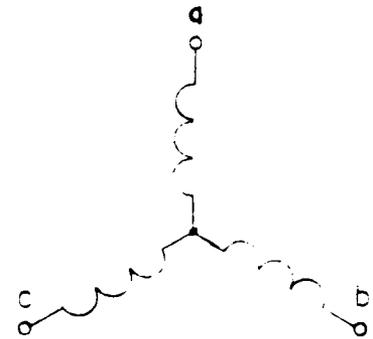
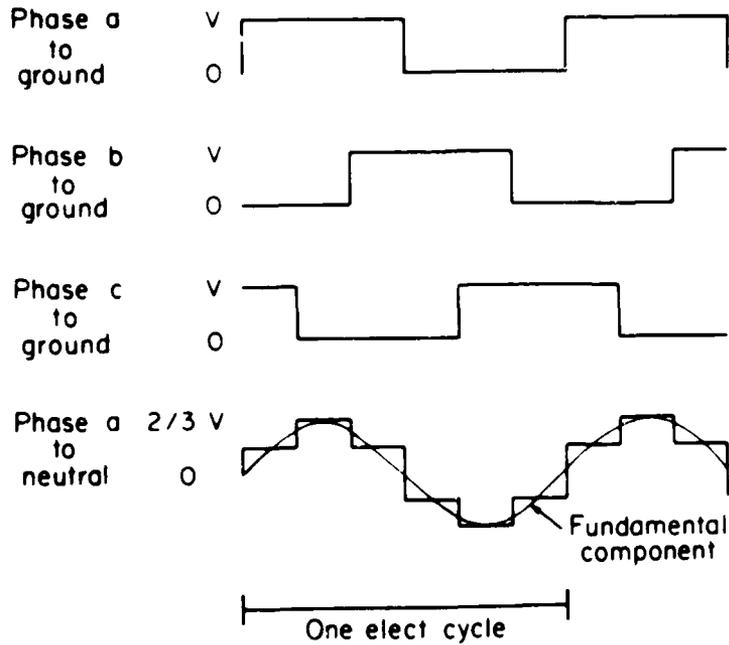


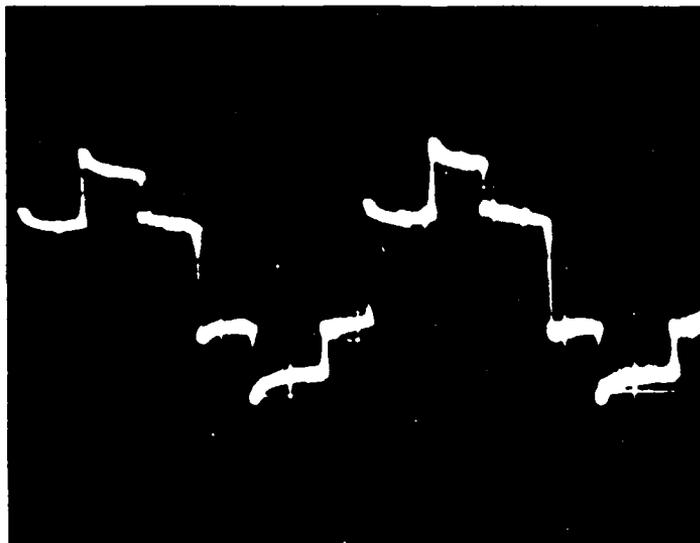
FIG. 6
MOTOR GENERATOR POWER CONTROL CIRCUIT

optical sensor. Each comparator remains in either the high or low state for a period of 60° of rotation. The 40° staggering of the optical sensors causes one of the Position Detection Comparators to toggle with each 20° rotation of the flywheel. These three position detection signals, and permutations of them, provide the gate signals to the Motor Drive Board, where the six step drive waveforms are produced (see Figure 8). The permuted Position Detection Signals provide phase shifted drive signals. Phase shifting is required so that the drive waveforms angularly lead the rotor poles causing the rotor to accelerate. When a Phase Shifting Comparator toggles high, the PROM outputs a particular permutation of the Position Detection Signals. These permuted output signals correspond to a 60° phase advance of the drive signals. An analog tachometer circuit provides a voltage proportional to the rotational speed of the flywheel. The signal is used to control the Phase Shifting Comparators and the motor start-up sequence. The Motor Drive Stages switch power between the three field windings of the alternator. Power switching is accomplished by power FET's. The Motor Start-Up Control provides power to the Drive Stages. As the speed increases, there is more back EMF to the Drive Stages. To maintain the current into the field windings, the drive voltage must be increased. This is accomplished by short circuiting power resistors that are in series with the voltage supplied to the Drive Stages.

SIX STEP DRIVE SEQUENCE



Relative switching of the phases used in the motor drive and the resulting voltage waveform, phase a to neutral on a Y-connected alternator. The harmonic fundamental component is superimposed on the resulting drive waveforms.



Photograph of six-step drive waveform, measured from one phase to neutral on the Y-connected alternator winding. Alternator speed: 8000 RPM. Scope setting: 20 V/div, 0.5 msec/div.

Figure 8. Six-Step Drive Waveforms.

THREE PHASE MOTOR LOGIC

FLYWHEEL POSITION AND PHASE SHIFT (see Figure 9)

The relative position of the alternator pole pairs to the field windings is measured by three optical reflection sensors mounted in the flywheel housing. The voltages from the sensors are fed into three comparators. The comparator switching points can be set to allow the duty cycle of each channel to be exactly 50%. Small changes in the duty cycle greatly affect the efficiency of the motor drive. The outputs of these three comparators (signals a, b, c) are fed directly to a 74S188 PROM. Two additional inputs to the PROM are provided by two Phase Shift Comparators, each adjusted to toggle when the alternator speed reaches a point where a phase shift should occur. The three output signals (ϕ_1 , ϕ_2 , ϕ_3) of the PROM supply the motor drive circuitry. For motor start up, the three PROM output signals (ϕ_1 , ϕ_2 , ϕ_3) directly correspond to the three position signals (a, b, c). At approximately 300 RPM the first phase shift occurs resulting in the output signals (ϕ_1 , ϕ_2 , ϕ_3) respectively corresponding to position signals (\bar{b} , \bar{c} , \bar{a}). The second phase shift occurs at approximately 3300 RPM with resultant PROM output signals (ϕ_1 , ϕ_2 , ϕ_3) respectively corresponding to position signals (c, a, b). Each phase shift advances the lead angle by 60° .

ANALOG TACHOMETER

Three signals from the Position Detection Comparators (a, b, c) provide the inputs for the Analog Tachometer. Three high-pass filters and diode combinations give a positive-going spike to a transistor inverter for each

positive-going edge of a, b, or c. The transistor inverter supplies negative-going spikes to a 555 timer IC configured as a one-shot. The result is that each positive-going edge on the outputs of the Position Detection Comparators produce a pulse of fixed duration from the 555 timer. These pulses are then fed to a unity-gain Inverting Integrator, consisting of one-half of an LM1458 dual operational amplifier, two resistors, a capacitor and a diode. The output of this operational amplifier is a voltage that increases negatively as the frequency of the incoming pulses increase. This negatively increasing voltage is fed through a voltage divider to provide the input voltage for the two Phase Shift Comparators. The output of the Inverting Integrator is also fed to an Inverting Amplifier of variable gain, with a small capacitor connected to provide ripple suppression. The gain of this stage is adjusted to provide an output sensitivity of one-half volt for each thousand RPM of the alternator.

START-UP AND OVERSPEED CONTROL

Running the alternator as a motor requires about 60 volts to maintain the speed at around 8500 RPM. However, this voltage at low speeds would draw current from the supply in excess of 30 amps--more than the power FET's in the Motor Drive Stage can handle. To limit the start-up current, power resistors are placed in series with the DC Power Supply (see Figure 10). As the alternator speeds up a back EMF is produced which reduces the current drawn by the alternator. To bring the alternator to full speed requires the short circuiting of portions of the power resistors, thus increasing the current available to the Motor Drive Stage. The maximum current is limited to 17 amps. One-fourth of U6, an LM324 quad operational amplifier, is

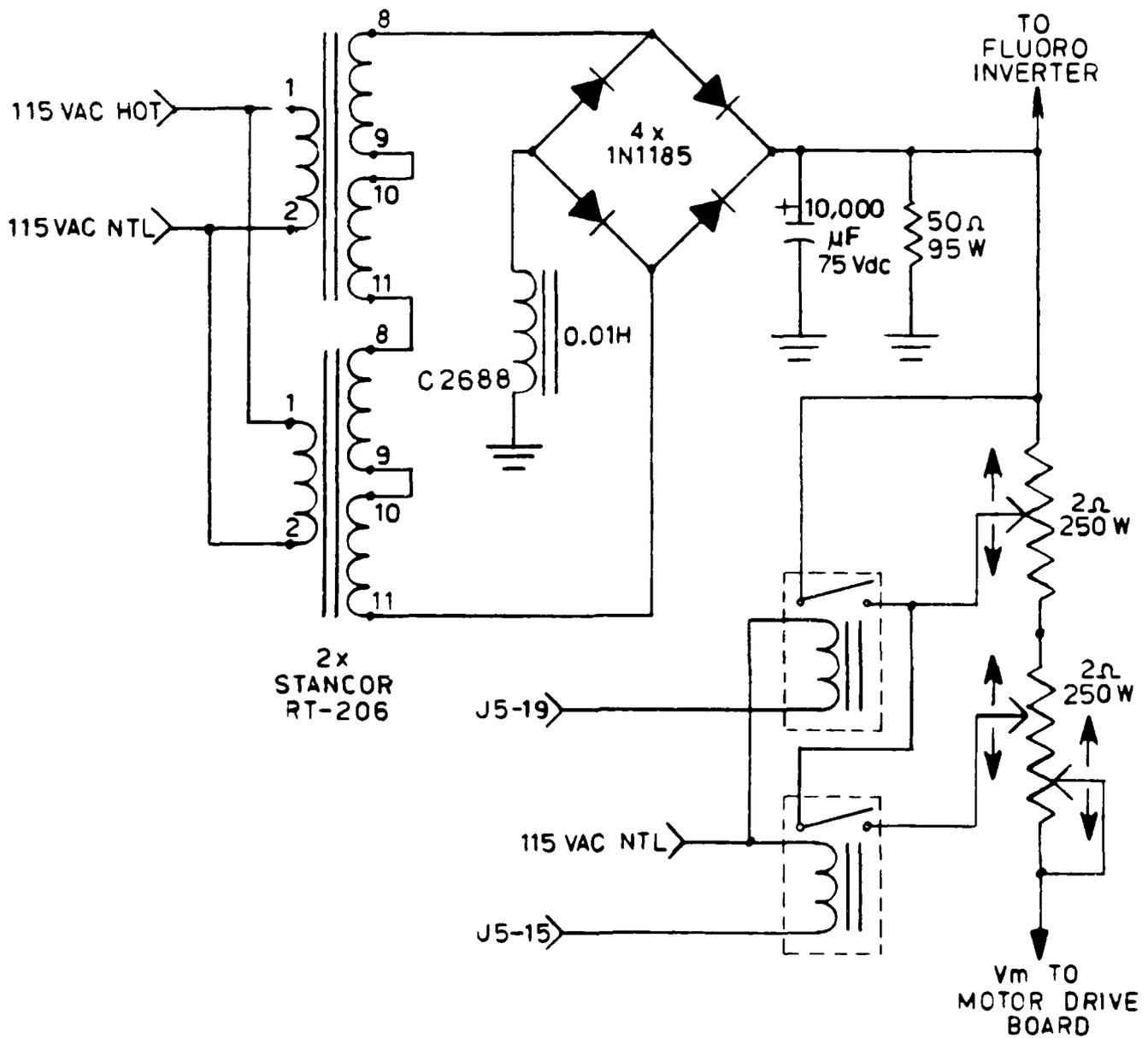


FIG. 10
DC POWER SUPPLY

adjusted to toggle low when the Analog Tachometer output voltage corresponds to approximately 2000 RPM. This low voltage then turns on a MOC3011 triac driver which causes one of the relays to close and short circuit part of the series resistance. One-half of U5, an LM358 dual operational amplifier, is adjusted to toggle low at approximately 6000 RPM, resulting in approximately 0.6Ω being short-circuited out.

To prevent an overspeed condition, the other half of U5 is adjusted to toggle low when the Analog Tachometer voltage corresponds to approximately 8500 RPM. This low output causes the voltage on the negative input of the Second Short Circuiting Relay Comparator to drop to about 1.2 volts (the voltage drop across the two diodes connecting the two U5 op amps). This lowered input voltage on the second Short Circuiting Relay Comparator results in the comparator output toggling high, the MOC3011 turning off, the relay contact opening up, the 0.6Ω resistance being placed back in the circuit, and the alternator slowing down. The amount the alternator slows down is determined by the hysteresis of the Overspeed Comparator. The $100k\Omega$ resistor between the input and the output terminals of the Overspeed Comparator provides the hysteresis which will drop the speed from 8500 RPM to 8000 RPM before the comparator toggles and the 0.6Ω resistance is short circuited again.

CURRENT SURGE PROTECTION

During the switching process between motor mode and alternator mode, current surges may be produced which could possibly damage the power FET's. To prevent such current surges the Second Short Circuit Relay Comparator has a $4.7\mu\text{F}$ capacitor connected to its negative input. In the alternator mode

this capacitor and the negative input terminal are short-circuited to ground by the Motor Relay contacts. With the negative input terminal at a voltage less than the positive input terminal, the Second Short Circuiting Comparator will cause the corresponding relay to open. When the motor relay switches back to the motor mode the time delay provided by the $100k\Omega$, $4.7\mu F$ time constant prevents the short circuiting relay from closing immediately. This time delay (approximately 2 seconds) keeps the 0.6Ω resistance in the circuit during the switching process to prevent current surges.

MOTOR DRIVER OPTICAL COUPLING BOARD

The Motor Driver Opto-Coupling Board (see Figure 11) takes the three incoming signals ($\phi 1$, $\phi 2$, $\phi 3$) from the PROM of the 3 ϕ Logic Board and produces inverses of each. These six signals are then coupled to the Motor Driver Board to provide the gate signals for the power FET's. Each incoming signal from the PROM controls one 4N36 phototransistor and one 2N3904 NPN transistor. If the incoming signal is high, the phototransistor will turn ON, causing a 10 volt potential across the $1k\Omega$ resistor connected to it. The high incoming signal causes the 2N3904 NPN transistor to saturate and provide a low output signal to the Motor Driver Board. When the incoming signal from the 3 ϕ Logic Board is low the phototransistor will be off and its output will be pulled low, the 2N3904 transistor will also be off but its output is pulled up to the 10 volt supply voltage. The output signals produced by the switching of the 4N36 phototransistors and the 2N3904 NPN transistors provide the gate signals for the switching of the power FET's on the Motor Driver Board.

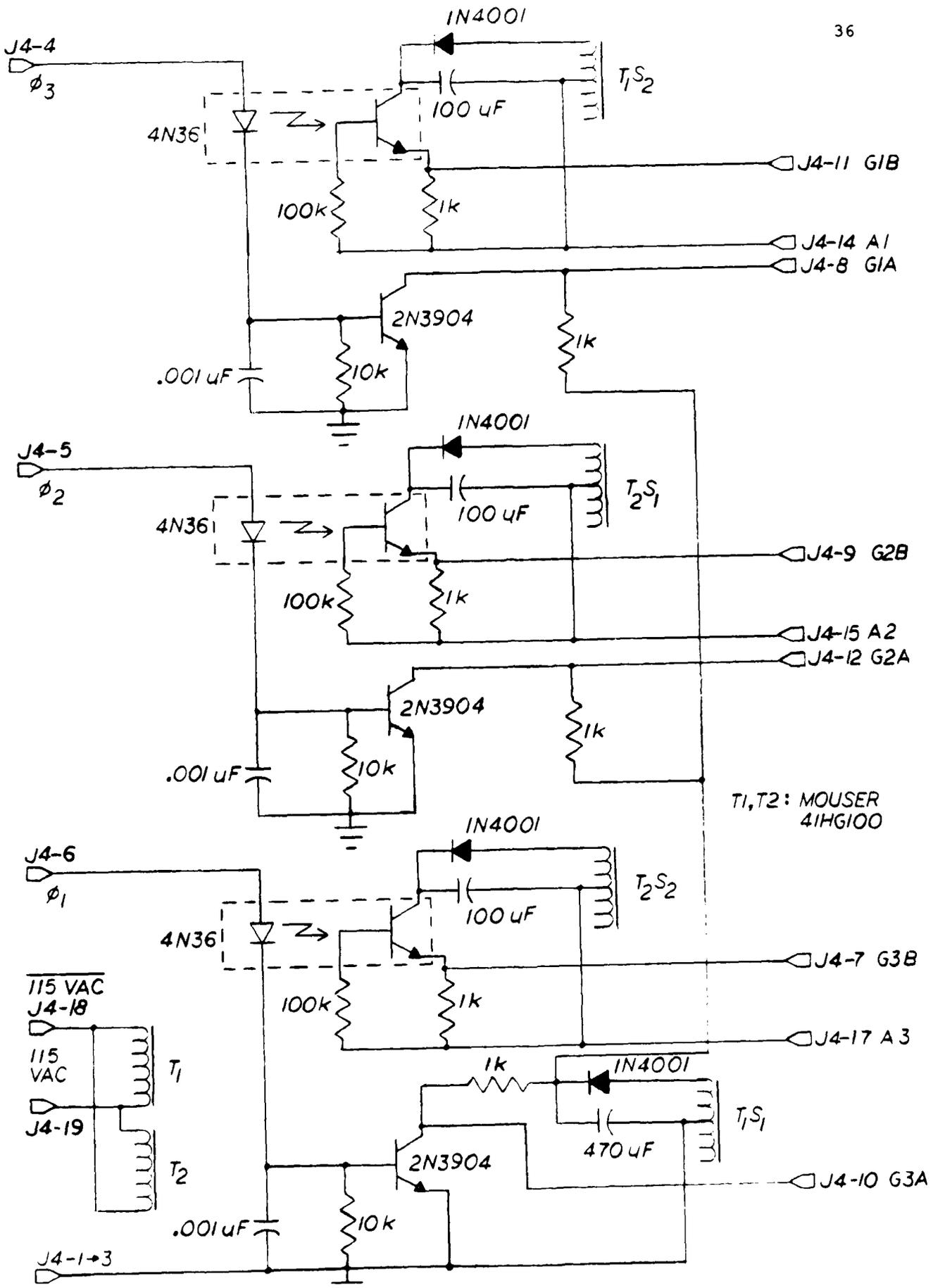


FIG. 11
MOTOR DRIVER OPTO-COUPLING BOARD

T1, T2: MOUSER
41HG100

MOTOR DRIVER BOARD

The Motor Driver Board (see Figure 12) consists of three pairs of IRF152 power FET's. Each pair is connected in series between the 60 DC volt supply and ground. Each of the three alternator field windings are controlled by one of the FET pairs. The row of FET's which are connected to ground are each controlled by one of the 2N3904 transistors on the Motor Driver Opto-Coupling Board. The upper row of FET's which are connected to V_m are controlled by the three 4N36 phototransistors on the Motor Driver Optical Coupling Board.

The phototransistors use isolated voltage supplies which float the gate signals above the source lead voltages of the upper FET's. When an upper FET is on, the lower FET in series with it will be off, which results in the corresponding field winding being pulled up to the supply voltage (V_m). When a lower FET is on, the upper FET will be off, and the field winding voltage will be pulled to ground. The zener diodes connected from gate to source of the FET's prevent voltage spikes from damaging the FET's. The 470 Ω gate resistors prevent parasitic oscillations from mistriggering the FET's. The .047 μ F capacitors and 390 Ω resistors form RC networks which are used to slow down the turn-on time of each FET. The 1N914 diodes are used to speed up the turn-off time of each FET. Precise timing of the switching is critical to prevent two series connected FET's from being turned on at the same time, which results in a short circuit between the power supply and ground.

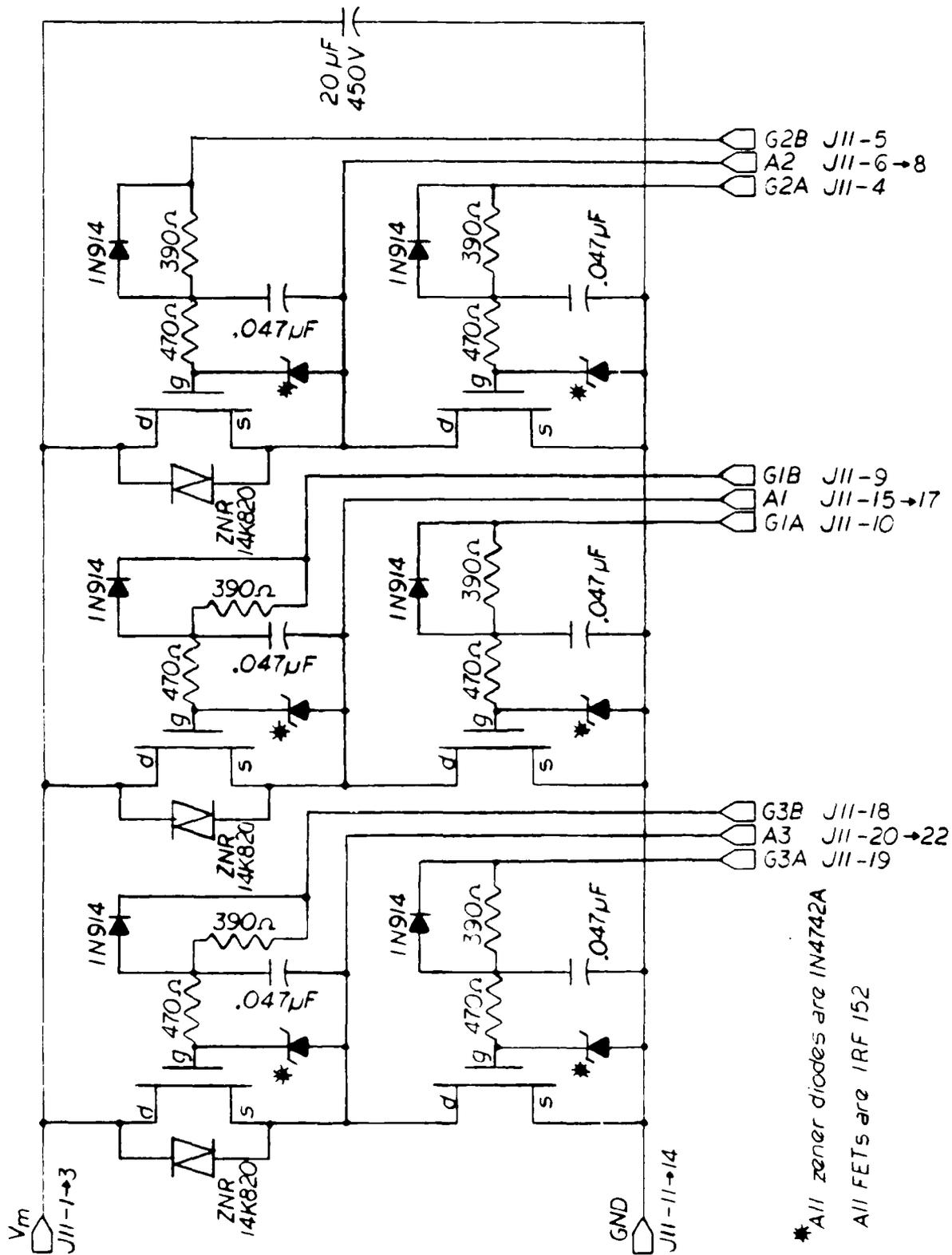


FIG. 12
MOTOR DRIVER BOARD

* All zener diodes are IN4742A
All FETs are IRF 152

EXCITER CONTROL CIRCUIT (See Figure 13)

Making an exposure requires precise control of the voltage supplied to the high voltage transformer. In addition, the motor drive circuitry must be momentarily disconnected from the alternator while the exposure relay connects the alternator to the HV transformer.

Two separate mechanical relays are used to connect the motor drive circuitry and the HV transformer to the alternator. It is crucial that only one relay be closed at a time. If the alternator were in the generator mode (i.e. if an exposure was being made) and the motor relay accidentally closed, the motor drive circuitry would be destroyed.

CIRCUIT DESCRIPTION

V_{ie} is an input signal provided to the exciter board from a DAC08 8-bit D/A converter which resides on the microprocessor board. V_{ie} may range from 0 to 10 volts DC and is used to control exciter current as well as the closure and opening of the motor relay. Since exciter current is directly proportional to the magnitude of V_{ie} , and since alternator output voltage is in turn directly proportional to exciter current, V_{ie} forms the x-ray tube voltage control signal.

The only other input signal to the exciter board is REG (Rad Exposure Gate) which controls the opening and closing of the exposure relay. If REG is high (+ 5V), the exposure relay is closed. This connects the alternator

(now operating in generator mode) to the HV transformer. If REG is high, the motor relay cannot be closed, regardless of the value of V_{ie} .

CIRCUIT OPERATION

V_{ie} is input to the noninverting terminal of op-amp U1A, which supplies base current to the TIP111 Darlington pair. The TIP 111 emitter is connected to the inverting terminal of U1A, thus forming a feedback loop which will tend to stabilize the emitter current (I_e).

I_e flows through a 1 ohm, 10 Watt resistor. As I_e increases, the voltage input to the inverting terminal of U1B must increase, so the output of U1B will be driven to about 0 volts. The output of U1B is input to the noninverting terminal of U1C; if this input voltage is at zero volts, the output of U1C will be about zero volts. U1C drives an optically coupled triac driver (MOC 3011). When active, this triac driver supplies the gate signal to a TIC 226 power triac which provides current to the motor relay coil.

The output of U1C goes to zero when V_{ie} is raised from zero volts to V_{ies} , a starting value defined in the microprocessor control system text. Thus when V_{ie} is raised in anticipation of an exposure, the motor relay will be de-energized since the MOC 3011 diode will not be active.

The diode-RC combination at the output of U1B provides fast turn-off and slow turn-on times for the motor relay. If V_{ie} is raised prior to an exposure, the output of U1B will swing to zero volts very quickly as the

capacitor's charge is bled off via the diode. After an exposure is complete, the output of U1B will rise towards a positive voltage, but a delay time will result from the recharging of the RC circuit. This fast turn-off/slow turn-on combination provides additional assurance that the motor and exposure relays will not be closed at the same time.

REG is input to the noninverting terminal of U1D. If this signal is low (0 volts), U1D will have an output of about 0 volts. The output of U1D is connected to the inverting terminal of U1C via a voltage divider. This ensures that if REG is low, the motor relay will be closed, whereas if REG is high, the motor relay is open; thus this circuit provides redundant control of the state of the motor relay.

The output of U1D is also connected to the gate of an IRF 740 FET which acts as a switch controlling current flow in the 24 V DC exposure relay coil.

Normally REG is raised high (+5 V) 100ms after V_{ie} has been raised to the starting voltage V_{ies} . With the output of U1D therefore positive, the FET will allow current to flow in the 24 V DC exposure relay coil. The alternator output is thereby connected to the HV transformer. After a 25ms delay, V_{ie} will be raised to a "boost" level V_{ieb} . The exposure time elapses, REG and V_{ie} both drop to 0 volts, and through the operations described above, the exposure relay opens, followed by the closure of the motor relay.

E. HIGH TENSION TRANSFORMER ASSEMBLY (See Figure 14)

The high tension transformer is assembled in an oil-filled steel can and contains the high voltage transformer, the rectifier diodes, the filament transformer and transfer relay, the tube sockets and various other connectors and parts.

HIGH VOLTAGE TRANSFORMER

The core is assembled from standard grain-oriented 6 mil 30-EI-1.8 laminations which are cut to 5.5" and assembled in a square section of 1.8 x 1.8". The delta primary feeds a wye-wye secondary. Three primary and six secondary coils are used. The primary coils were designed for 210 Vrms at 300 Hz; a single layer of 60 turns of bifilar 16 ga wire was used for each coil. The secondary design was based on 28 kVrms. Each high voltage coil was wound with 30 layers of 275 turns/layer and insulated with 12 mil kraft paper. When rectified, the complete circuit should yield 118 kVp for 210 Vrms input, no load. The voltage drop should be about 4 kVp/100 mA.

RECTIFIER BRIDGE

The rectifier assembly is a 12 leg circuit arranged as two three phase full wave rectifiers. Each leg uses 13 Varo H463 avalanche diodes rated at 9 kVpiv and 1 amp (2 sec pulse). Each leg is actually one half of a 26 diode stick. The anode rectifier assembly is returned to ground and the cathode assembly return is brought out to the main connector to read tube current.

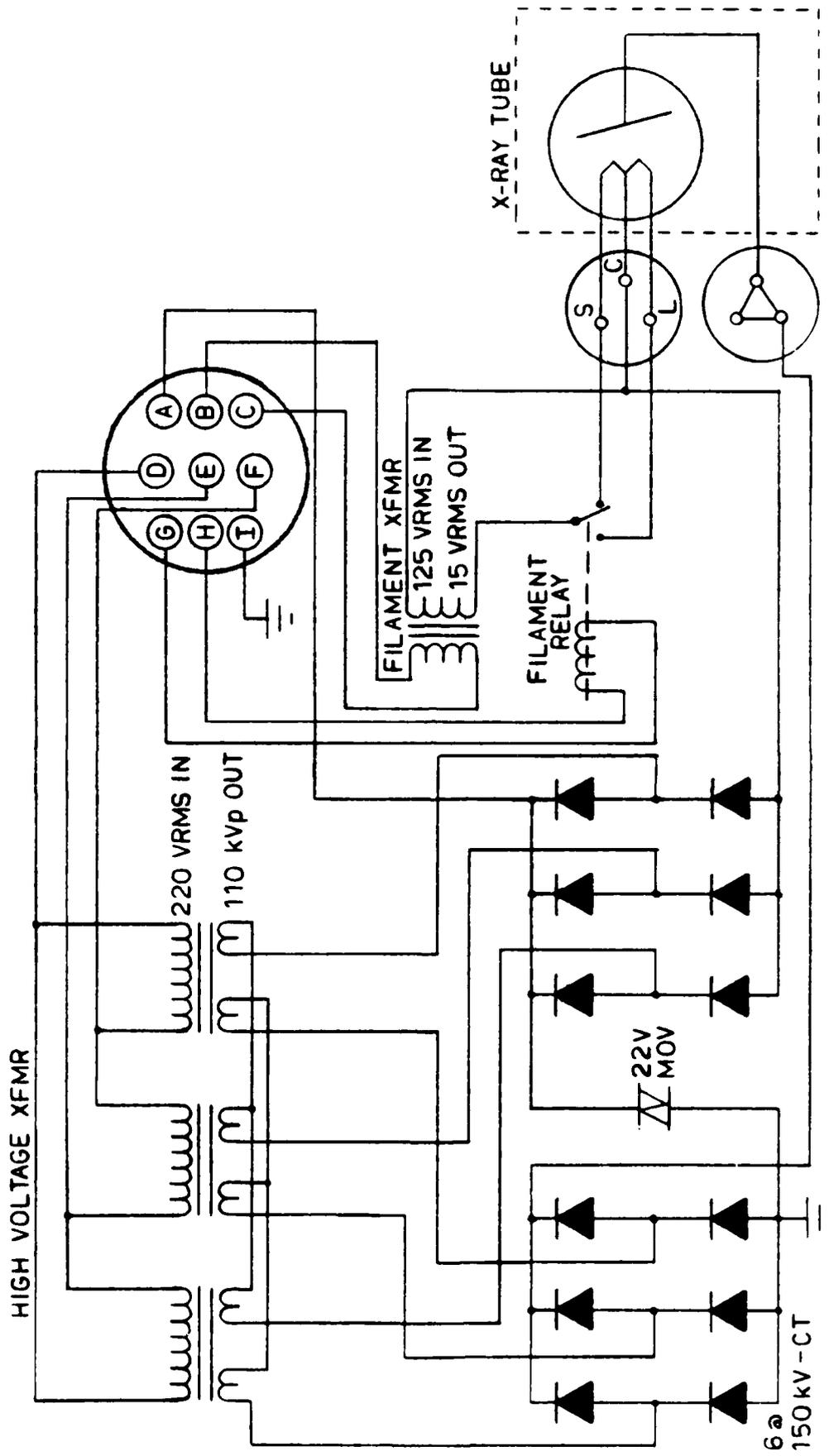


FIG. 14
HIGH TENSION TRANSFORMER ASSEMBLY

In the event of an open circuit in that return lead, a low-voltage varistor is connected to ground to complete the circuit.

FILAMENT CIRCUIT

The filament transformer was wound for 120 vrms 60 hZ input and 14 vrms output. The secondary was wound on the outside of a 2.5 inch long Delrin tube over the primary winding. The thickness of the tube was 0.25 inches and the secondary winding was confined to the center 1 inch section. The filament control circuit uses a triac to vary the conduction phase angle to set the tube filament temperature.

The transfer relay uses an ac solenoid to pull an insulated arm against a microswitch. The microswitch connects the filament transformer to the S or L filament terminals of the tube socket, the other side of the winding is connected to the C terminal. The S terminal is the de-energized position. The solenoid is energized by an external relay controlled by the microprocessor.

MECHANICAL ASSEMBLY

The assembly is built into a steel box of 12.5 L x 16.5 W x 12.5 H inches. The shape was designed to fit in the space just below the flywheel assembly at the lowest point of the system cabinet. The tube cable sockets and the main connector are mounted in the top plate. A transparent plastic plate is gasket mounted to the top to observe any arcing. The box is filled with Shell Diala oil. The assembly weighs 112 lbs.

F. TUBE ROTOR CONTROL

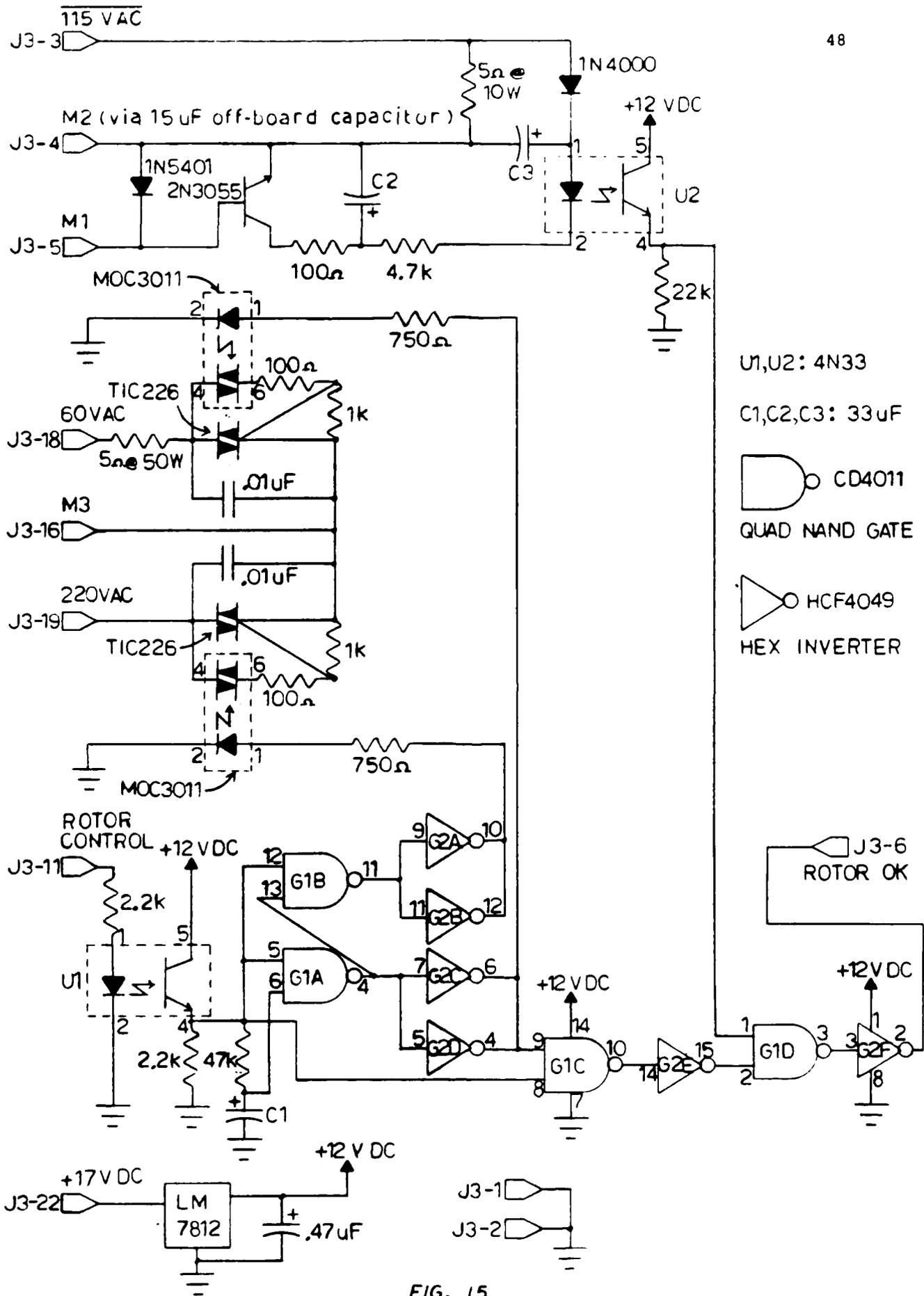
The split-phase rotor motor is started at 220 volts AC to achieve fast acceleration. Timing is provided to automatically switch to 60 volts AC operation after a short delay to prevent overheating. The circuit also prevents an exposure from being made if current is not flowing in the rotor motor windings or if the rotor is not up to speed.

CIRCUIT TIMING OPERATION (See Figure 15)

ON/OFF control of the tube rotor is provided by the ROTOR CONTROL signal generated by the 8748 microprocessor. Simple logic and an RC circuit provide automatic switching from the start-up power level to the operational level after 1.5 seconds.

When ROTOR CONTROL is high (+5V), opto-isolator U1 is on and supplies current to C1. Initially, the output of NAND gate G1A is at positive logic (+12V) so the output of G1B is at negative logic (0V). The output of G1B is inverted by G2A and G2B, which then turn on an optically isolated triac driver (MOC3011). This triac driver in turn energizes a triac (TIC 226) which allows current to flow into the motor windings from the 220 VAC supply. The motor accelerates rapidly.

After about 1.5 seconds C1 has charged up to a positive logic level. The output of G1A is then negative logic, the output of G1B goes positive, and the triac supplying current from the 220 VAC supply is turned off.



- U1,U2: 4N33
- C1,C2,C3: 33uF
- CD4011
QUAD NAND GATE
- HCF4049
HEX INVERTER

FIG. 15
TUBE ROTOR CONTROL BOARD

The output of G1A is inverted by G2C and G2D and with circuitry like that described previously, an optically coupled triac driver turns on another TIC 226 which supplies current to the motor from the 60 VAC supply. Thus, the two power supply voltages are automatically switched in proper sequence by the application of the ROTOR CONTROL signal. A 50 W resistor is placed in series with the 60 V supply to limit the current drawn by the motor.

EXPOSURE INTERLOCK OPERATION

A 15 μ F phase shift capacitor is in series with M2. Current is fed to the rotor via M3 and returned by M1 and M2. If current is flowing in M1 the 2N3055 transistor will be active and C2 will thus be kept discharged. If current is flowing in M2 there will be a voltage drop across the 5 Ω , 10W resistor and C3 will charge up. Only with C3 charged and C2 discharged can the U2 opto-isolator be turned on and a high level signal applied to NAND gate G1D.

When the previously described transition from 220 V operation to 60 V operation takes place, NAND gate G1A's output is negative logic, and is inverted.

The output of G1C goes from high to a low logic level, is inverted, and input to G1D. Thus, G1D receives two inputs; one signifies that the motor is at operating speed, and the other indicates current is flowing properly in both the motor windings. When these inputs are high (true), the output of G1D is low, passes through an inverter, and the ROTOR OK signal is thus high, indicating proper tube rotor operation.

G. TUBE FILAMENT CONTROL CIRCUIT

The temperature of the tube filament determines the anode current. There is a minor effect due to the anode voltage: increasing anode voltage will cause an increase of anode current. The circuit permits the selection of eight preset values of filament current and compensates for anode voltage effects. As originally designed, it was possible to select five radiographic values corresponding to 300, 200, 100, 50 and 25 mA and three fluoroscopic values of 4, 2 and 1 mA.

CIRCUIT OPERATION (See Figure 16)

The filament current is controlled by a series triac which turns on for varying parts of each half-cycle of the power line. A current transformer feeds the input of an AD536 integrated circuit. The output of that chip is a dc voltage proportional to the true rms current of the filament transformer primary. A line voltage crossover detector synchronizes a sawtooth generator to the power line. A current proportional to the selected filament current, a current proportional to the true rms filament current and the sawtooth are mixed and amplified to generate the control signal for the series triac. The control signal sets the duty cycle of the triac to regulate the true rms current.

The selection circuit uses two 4051 MOS gate devices. The first is used to select the preset voltage of eight potentiometers. Each potentiometer is set to produce a particular filament current and the selection is a BCD signal from the microprocessor. The second 4051 selects a signal from a simple voltage divider and is used to add a small signal in inverse proportion to the selected kVp. The kVp signal is also provided as a BCD signal from the microprocessor. Filament boost is provided by microprocessor

control by selecting a low filament current and then switching to a higher value. An on-board regulator, LM326, provides +/- 12 vdc.

CALIBRATION

The filament currents may be calibrated by use of the microprocessor or by use of the dummy control board. To calibrate, the system should be operated at 80 kVp and the 200 mA current and 80 kVp voltage selected signals sent to the filament board. Each of the filament potentiometers is set to the lowest value before calibration. As the system is operated using short exposure times, the actual exposure time is observed using a voltage divider and the tube current is measured using an mAs meter. Set the filament to yield the mAs value appropriate to 200 mA. Repeat for the other radiographic values.

To set the fluoroscopic values, operate in the fluoro mode and set each of the fluoroscopic potentiometers. Note that in the first demonstration unit, the 300 mA and the 4 mA values are not used. For test purposes, these should be set to 200 mA and 2 mA.

Because there are two filaments in the tube, verify that filament selection has taken place for the selection lines and in the high voltage transformer. If possible, measure the actual focal spot sizes at low current levels to be certain that the correct filament has been selected to avoid damage to the focal spot.

H. FLUOROSCOPIC CIRCUITS

PURPOSE

These circuits provide power to the high voltage transformer during fluoroscopic operation. The main circuits are the fluoroscopic power inverter and the brightness stabilizer. The fluoroscopic system permits the operator to use the system in either the manual or brightness stabilized modes with selection of three values of tube current.

FLUOROSCOPIC INVERTER

The secondary distributed capacitance of the high voltage transformer appears at the primary multiplied by the square of the transformer turns ratio. Consideration of the characteristics of such transformers reveals that the equivalent capacitance at the primary is of the order of 5.0 μ F. The loading of that capacitance is not significant for radiographic operation but presents a problem for conventional switching inverters. Most x-ray system companies have abandoned those circuits because the switching device must charge and discharge that capacitance during each half-cycle of operation. Various types of resonant inverters which use the primary capacitance as part of the tuned circuit are coming into common use.

During the early part of this research effort, a switching inverter was constructed for use with a series filter to compensate for the load. After several trials, that circuit was discarded and various types of resonant circuits were tried. Transient effects of arcing and other breakdown phenomena coupled through the filter and destroyed the output transistors on several occasions. It became clear that only circuits inherently resistant to these effects should be used.

Inductive input sine-wave inverters were tried and appeared to work very well but were load dependent. That particular problem was solved by adding a switching regulator in series with the inverter to regulate the output. The next improvement combined the two circuits so that the inductor of the switching regulator and the inductor of the sine-wave inverter were combined and the switching rates of the regulator and the commutation rate of the inverter are synchronized.

CIRCUIT DESIGN

The circuit is shown in the schematic diagram (Figure 17). The 3524 chip comprises an RC oscillator, comparator, and driver for control of switching regulators. The operating frequency is set for twice the sine-wave frequency and the oscillator output is fed via a VN10KN FET as phase inverter to the 4013 divider which drives the inverter power FET's. The drains of these FET's feed the output transformer. The center tap of the primary of that transformer receives current through the charging reactor. The 20.0 μ F capacitor across the primary circuit is tuned with the reactor to a frequency above two times the output frequency. This capacitor is charged twice during each output cycle via the 2:1 step-up action of the transformer. The near-resonant charging of the reactor could charge the capacitor to four times the supply voltage if permitted by the series power FET's. The actual charging voltage is coupled by the two 1N4007 diodes to the RC filter of 10K and 0.01 μ F and then to the resistive network feeding the control operational amplifier of the 3524 circuit. The current from the RC is added to the input current from the external control via E1-2 and compared to the 2.5 vdc reference to develop the control signal for the switching regulator.

The switching regulator comprises the double pair of MGP20N50 power

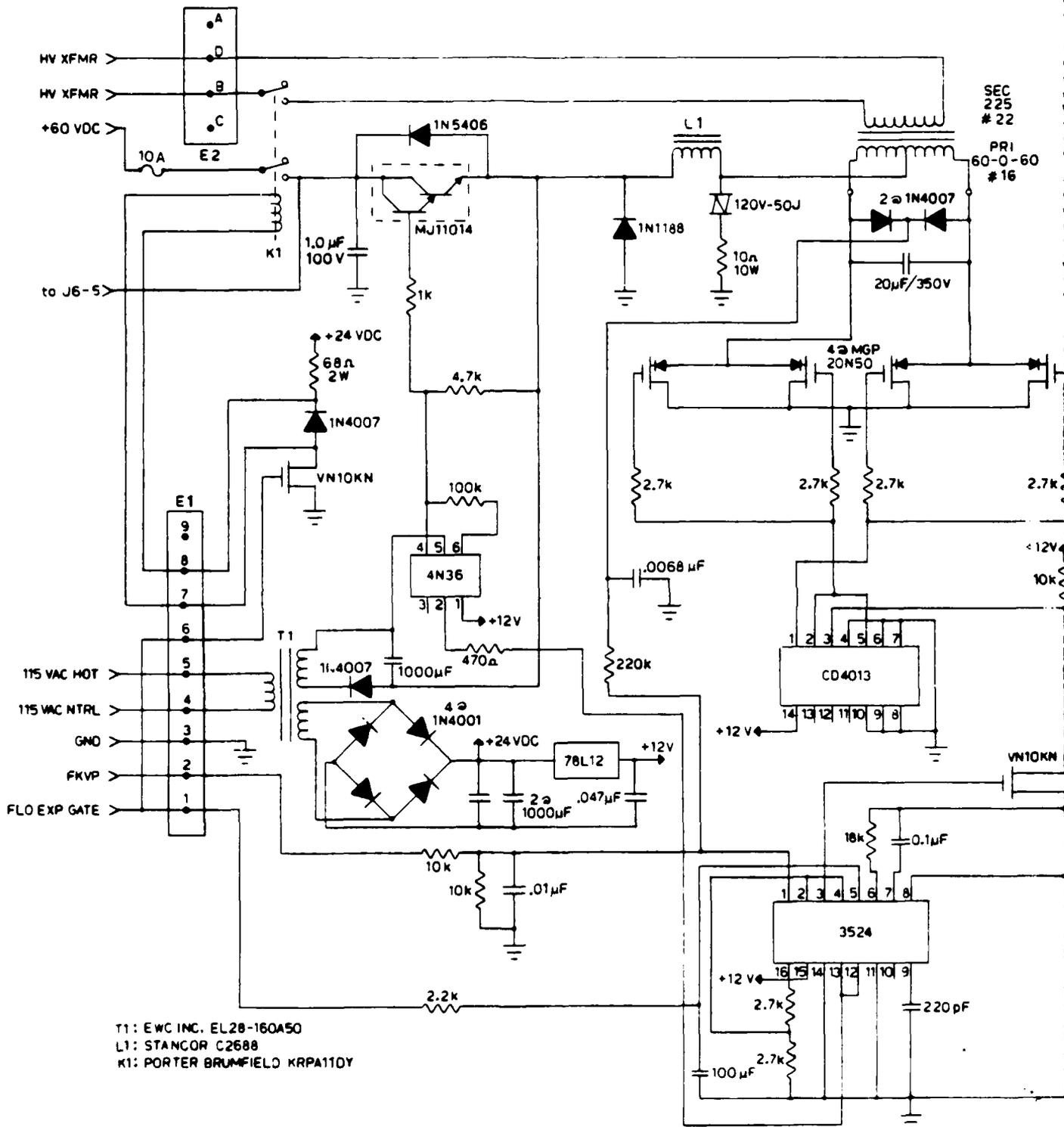


FIG. 17
FLUOROSCOPIC INVERTER CIRCUIT

FET's. Their duty cycle is determined by the 3524 control, through the 4N36 optical coupler. Their action is that of a conventional switching regulator so that, when turned off, current continues to flow through the 1N1188 power diode. The MGP20N50 includes a body diode which serves to clamp the input voltage of the reactor to below that of the input power supply.

The entire circuit functions as a sine wave inverter fed by a switching regulator with the duty cycle of the regulator controlled to maintain a constant sine-wave output. The switching regulator conducts once during each half cycle and is synchronized to the output.

The control circuit consists of a VN10KN FET controlling the relay. The relay switches the input current and connects the output power directly to the system high voltage transformer and to the x-ray tube. The 3524 shut-down circuit line, E1-1, is connected to the input of the VN10KN, E1-6, and then to the external control to turn on the inverter. Other components include the low voltage power supply and regulator.

I. FLUOROSCOPIC CONTROL

This circuit provides high voltage to the photomultiplier tube (PMT) located in the image intensifier assembly and accepts the output of the PMT to maintain constant image brightness. The circuit delays operation to allow the other components to come to equilibrium each time the foot switch is depressed. The output of the circuit feeds the microprocessor to change fluoroscopic kVp. Test inputs are also provided.

AUTOMATIC BRIGHTNESS STABILIZER (See Figure 18)

The output current of the PMT is proportional to scene brightness at the output screen of the image intensifier. The gain of the PMT is set by adjustment of its high voltage supply. The PMT anode is connected to the input of the first operational amplifier where the current is compared to 80 μ A bias current of the 150k Ω resistor. The amplifier is limited to low frequency operation by a 0.47 μ F feedback capacitor. The gain of the amplifier is set by the 4.7 M Ω feedback resistor. This resistor may be changed to a lower value to improve stability but reduce gain of the stabilizer. The output of the amplifier is compared to two preset values by the next two amplifiers. The top amplifier is biased at 3 volts and the bottom amplifier at 6 volts. These comparators are arranged so that both amplifiers are OFF (output high) if the output of the first amplifier is between 3 and 6 volts. The top amplifier will be ON if the output is below 3 volts and the bottom amplifier will be ON if the output is above 6 volts. The outputs of the comparators feed the circuit of six NAND gates which is also arranged so that the circuit may be disabled by the common input of the first two NAND gates and driven directly by a test input circuit. The output

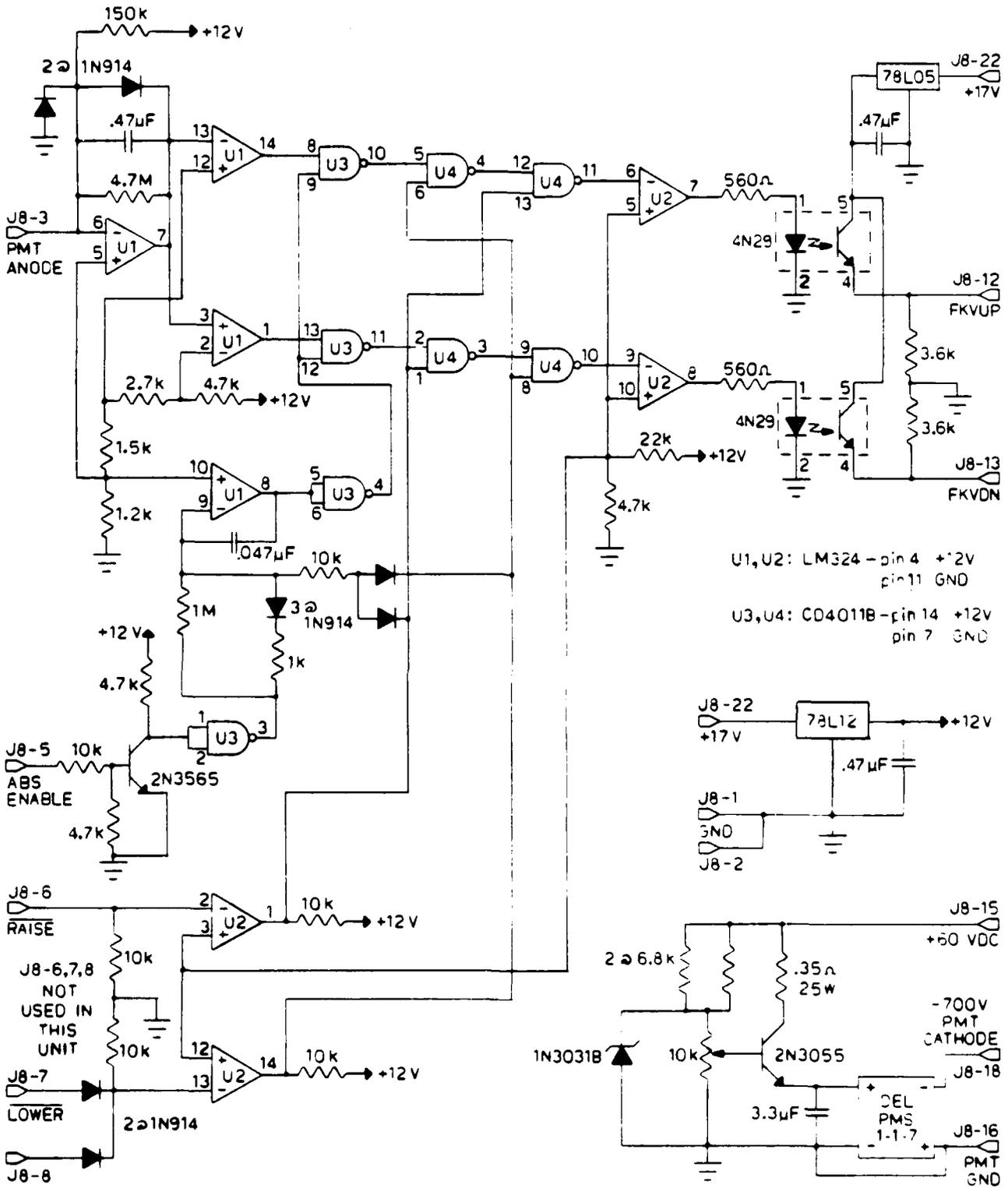


FIG. 18
AUTOMATIC BRIGHTNESS STABILIZER BOARD

of the NAND gates is buffered and fed to two optical couplers and then to the microprocessor. The circuit will cause the microprocessor to increase fluoro kVp if the brightness is low or decrease kVp if the brightness is high.

The ABS enable circuit is energized by the microprocessor only if: 1) the system is in the fluoro mode, 2) the footswitch is depressed, and 3) the brightness stabilizer has been turned on at the control panel. The input is converted from the microprocessor TTL logic level by the input transistor, fed to a NAND gate and operational integrator to provide a 0.5 sec delay of the operation of the six NAND gate logic circuit. Test inputs can override the PMT and comparators inputs and the delay of the NAND gate circuit and may also be used as system remote control of kVp (from the fluoroscopic optical system) in place of the front panel buttons.

PMT POWER SUPPLY

A Del 1-7-7 inverter power supply is supplied by a 2N3055 emitter follower. A 25 v Zener diode regulates the voltage across the adjustment potentiometer which is used to set the input voltage to the Del power supply. Increasing the voltage to the PMT will increase its gain and will cause the image brightness to decrease. Two on-board regulators, a 78L12 and a 78L05, complete the circuit card.

J. MECHANICAL ASSEMBLY

The entire assembly has been packaged as a mobile x-ray system by using a commercial enclosure. The enclosure of a Fischer Imaging M325 mobile x-ray system was purchased and modified for this application. The enclosure comprised the equipment cabinet, tubestand column, pantographic arm assembly, wheels and brakes. The tube and collimator are mounted to the arm. The flywheel assembly and high voltage transformer are mounted at the bottom of the equipment cabinet. The weight of the transformer serves as a counterbalance to the tube head assembly. The flywheel-alternator is mounted on rubber isolators to reduce operating noise.

EQUIPMENT CABINET

The microcomputer, controls and displays are assembled on the front panel. The connection to the rest of the system is via a 40 pin dip connector and an interface board in the card cage. The control panel is hinged on its lower edge so that it can be tilted forward for access to the card cage. Removal of the hinge screws permits the removal of the entire microprocessor-control panel assembly.

The card cage contains the individual circuit cards and their power supply. An extender board may be used as a convenience when taking data or for servicing. A test board may be used in place of the microprocessor for certain tests when it is not necessary to make x-ray exposures.

The component tray contains the power components and the fluoroscopic inverter. A fan mounted on the card cage cools the motor drive power FET's. The component tray slides in the space below the card cage. An aluminum plate is mounted at the rear of the cabinet which contains certain other parts: the rotor transformer, the filament transfer relay, the two power

transformers (for the main dc power supply) and the line power control circuit.

The flywheel assembly is mounted on three vibration isolators and may be removed and operated outside of the cabinet when required for service. During an exposure, the reactive forces on the flywheel are small; the assembly moves only slightly.

COLUMN AND TUBE ARM ASSEMBLY

The tube arm assembly is mounted on the vertical slide which moves in the column track. The suspension cable leads to a pulley at the top of the column and then to the counterweight. A safety brake causes the slide to jam if there is no tension on the cable. Counterweight plates may be removed to adjust the balance of the system.

The pantograph arms contain springs and tension adjusting screws. These are used to counterbalance the arm and the tube head. Friction locks are used to hold the system in its set position.

WHEELS AND BRAKES

Two large wheels at the sides are in contact with the brake shoes except when the brake release bar is used. Three smaller casters, one in front and two at the rear, bear the unbalanced weight of the cabinet. The precessional forces of the flywheel can be felt when subjecting the unit to rapid turns when the flywheel is spinning. However, the weight of the unit is such that these forces are not objectionable for normal positioning of the machine for radiography. For safety reasons, particularly in the event the machine tips while being transported, a spin-down circuit brakes the flywheel when power is off. Slow "residual" spinning of the flywheel produces almost no effect

and the unit may be safely moved to different locations. The reactive forces of the flywheel during x-ray exposures are lateral and small so that there is almost no motion of the machine when used on hard floors.

III. MICROPROCESSOR CONTROL SYSTEM

A. INTRODUCTION

Part of this project has been the development of a microprocessor system as a controller for the prototype unit. This chapter gives a description of this system in two parts. First, the requirements of the microprocessor system are presented by giving an overview of the needs of the x-ray unit. Next, the internal circuitry of the microcontroller is detailed.

B. X-RAY MACHINE SPECIFICATIONS

To understand what is needed in the microcontroller system, it is necessary to know the capabilities of the x-ray unit. The prototype was designed to function as follows:

- The machine has both radiographic ("rad" mode) and fluoroscopic ("fluoro" mode) capabilities.
- The tube voltage range is 60 to 120 kVp in rad mode; 60 to 120 kVp in fluoro mode.
- The tube current settings are 50, 100, 200, and 300 mA in rad mode; 1, 2, and 4 mA in fluoro mode.
- Rad mode exposures are between 10 and 5000 ms.
- In fluoro mode, a timer keeps track of total exposure time. Exposures of over five minutes cause an alarm to sound.
- Automatic Exposure Control (AEC) capabilities are provided in rad mode; Automatic Brightness Stabilizer (ABS) circuits are provided in fluoro mode.
- A switchable 115 VAC accessory outlet is provided.

C. MICROCONTROLLER TASKS

The major tasks of the microprocessor system are responding to commands from the operator, displaying the status of the machine to the operator, and coordinating control and status signals between the various circuits in the x-ray unit.

OPERATOR'S COMMANDS

The operator controls the x-ray unit by means of four input devices. First, the position of the film cassette will determine whether the unit is in rad or fluoro mode. If the cassette is positioned beneath the x-ray tube the unit operates in rad mode.

The operator also has control through the two handset switches. The first switch ("C1") causes the tube anode to rotate and the filament to heat up. The second switch ("C2") triggers the rad exposure. Both handset switches are ignored in fluoro mode.

Next, the operator can step on the footswitch ("C3") when fluoroscopic imaging is required. If the film cassette is positioned for rad exposures, the footswitch is ignored.

Finally, the various exposure parameters can be set through the push button switches on the x-ray unit's front panel (see Figure 19). The ON and OFF buttons control the main power to the x-ray unit and are not monitored by the microcontroller.

Four of the system parameters (rad and fluoro kVp, rad exposure time and rad mA) are controlled by a pair of up/down buttons. Pressing one of these causes the appropriate quantity to step to its next higher or lower value. If the button is held down, the value will repeatedly step up or down until the button is released, or until the upper or lower limit for that quantity

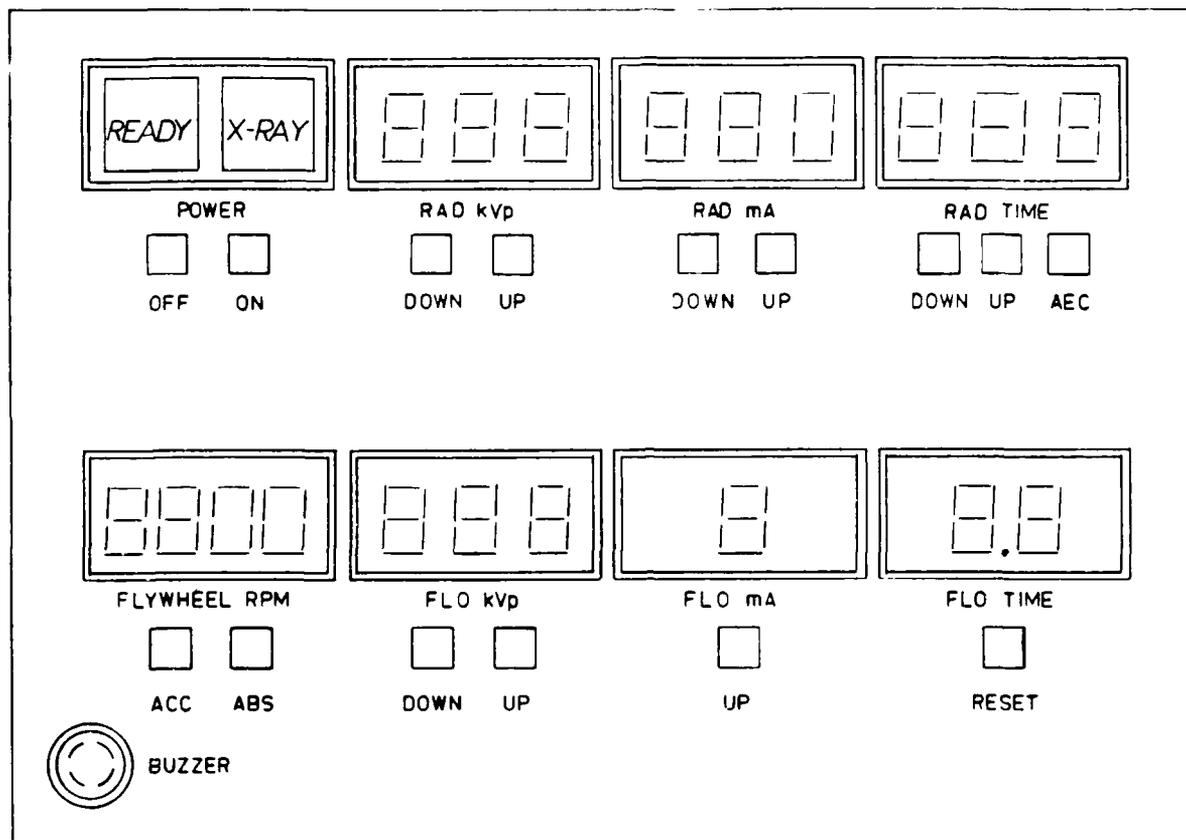


Figure 19. Front Panel of X-ray Unit

is reached. Attempts to raise or lower a value beyond its limits are ignored.

The fluoro mA UP button causes that value to step through its three possible settings; 1, 2, 4, 1, 2, 4, 1... etc.

The buttons for Automatic Exposure Control, Automatic Brightness Stabilizer, and Accessory outlet (labeled AEC, ABS, and ACC) are push-on, push-off action. Pressing one of these causes its associated circuitry to toggle between active and inactive states.

The Reset button for the fluoro time causes the exposure timer to reset to zero, and deactivates the alarm if the five minute limit was exceeded.

All of the push buttons can be pressed at any time except during rad exposures.

FRONT PANEL DISPLAYS

Figure 19 also shows the LED display and pilot lights present on the front panel. The push buttons described in the previous section also contain pilot lights. The ON and OFF buttons are lighted whenever the main power is on. The AEC, ABS, and ACC buttons are lighted when their associated function is active. The remaining buttons are associated with either rad or fluoro mode parameters. Either the rad group or the fluoro group of buttons will be lighted, indicating which mode the machine is in.

There are seven LED banks in the front panel which indicate numeric data. There are also two pilot lights marked READY and X-RAY. In rad mode, after the operator presses C1, READY will light when the machine has completed preparations for an exposure. READY is always lighted in fluoro mode. X-RAY indicates an exposure is occurring in both modes.

STATUS SIGNALS

The microcontroller has several input lines from the unit to indicate what the status of various circuits are. These input signals are listed below.

C1 IN: This line is connected to the handset switches. Closing the switch causes a logic "high" (+5 V) to appear on the line, indicating the pre-exposure sequence should be initiated.

C2 IN: Also from the handset, a logic high triggers a rad exposure. This line must return low before a second exposure can be made.

C3 IN: The signal from the footswitch, causing an exposure in fluoro mode.

ROT OK: The tube anode rotor control circuit provides a logic high on this line when the anode speed is sufficient for a rad exposure.

AEC IN: An external phototiming device is connected to this line and raises it high to indicate the rad exposure should be terminated.

RAD/FLO: A microswitch on the film loader senses the position of the film cassette and causes a logic high signal when the film cassette is in place, indicating the x-ray machine should operate in rad mode.

FKV UP, FKV DN: Two lines are provided by the Automatic Brightness Stabilizer, which indicate when the fluoro kVp should be raised or lowered. If both lines are high simultaneously, they are ignored.

ATACH: An analog signal provided by the alternator control circuitry indicating the speed of the flywheel. The speed is given by:
$$\text{RPM} = \text{ATACH (volts)} \times 2000.$$

CONTROL SIGNALS

The final task of the microcontroller is providing command signals to the x-ray unit. These outputs are listed below.

RAD EXP GATE: This controls the rad exposure relay. The relay is closed when this signal is high. The signal will go high if the READY conditions are met and C2 is pressed. Once C2 is pressed, the exposure will continue until it times out, or an interrupt is received from the phototimer (if the AEC circuit is active).

FLO EXP GATE: This line controls the fluoro inverter. The signal goes high in response to pressing the footswitch.

V_{ie}: An analog voltage produced by a digital-to-analog converter. The

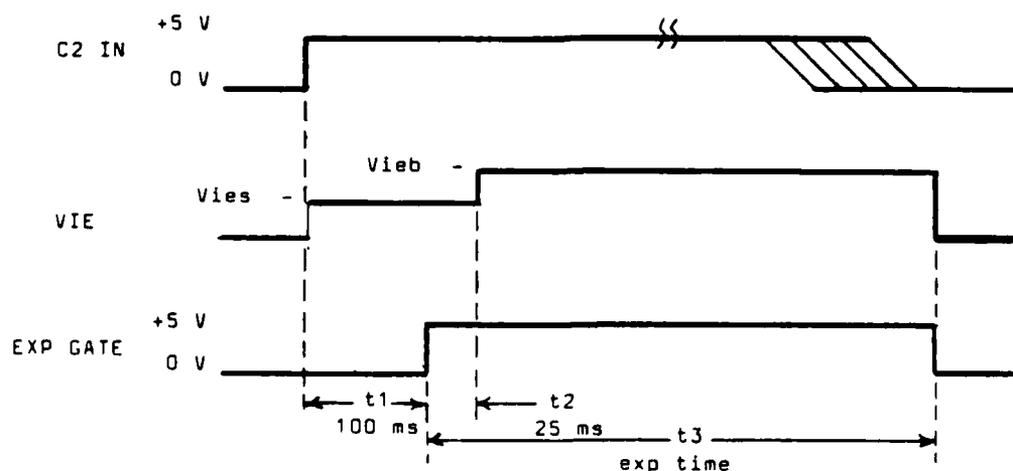


Figure 20. Rad Exposure Timing Diagram

alternator exciter current is proportional to this voltage. The timing of this signal is shown in Figure 20.

The exposure is initiated by closure of handset switch C2. Pressing C2 causes the alternator to leave the motor mode and enter the generator mode. Also, the exciter command voltage V_{ie} is raised to its starting value V_{ies} . This causes the alternator output to rise to the desired voltage. The 100 ms delay (t_1) allows for the slow response of the alternator. Next the rad exposure gate REG is raised, closing a contactor and applying the high voltage transformer to the output of the alternator. After another delay of 25 ms (t_2) the exciter current is boosted to a larger value, V_{ieb} . This compensates for the drop that would occur in the alternator output voltage due to the increased load. After the exposure time (t_3) is reached, the REG and V_{ie} voltages drop back to zero. The C2 switch must be released and depressed again to start the next exposure. Also, a delay of at least 500 ms occurs between exposures.

mA1, 2, & 3: The microcontroller provides three digital signals to the tube filament control circuit. These determine the tube current during rad and fluoro exposures. Table 1 gives the signal encoding.

Table 1. Encoding of Tube Current Command Signals

mA3	mA2	mA1	Tube Current	
0	0	0	IDLE	
0	0	1	1 mA	
0	1	0	2 mA	fluoro mA settings
0	1	1	4 mA	
1	0	0	50 mA	
1	0	1	100 mA	Rad mA settings
1	1	0	200 mA	
1	1	1	300 mA	

The IDLE current flows in the filament to keep it warm when no exposure is occurring. In rad mode, the filament current signals corresponding to the displayed tube mA is sent when C1 is pressed. In fluoro mode, the filament is boosted whenever the footswitch is depressed.

KVCOMP1, 2, & 3: Three other signals that are provided to the tube filament control circuit, indicating the tube voltage for the impending exposure. See Table 2.

Table 2. Voltage Compensation Encoding

kV Range	KVCOMP3, 2, 1
60 - 69	1 1 0
70 - 79	1 0 1
80 - 89	1 0 0
90 - 99	0 1 1
100 - 109	0 1 0
110 - 119	0 0 1
120	0 0 0

The filament circuit uses this data to compensate for the space-charge effect when determining the filament current necessary for the desired tube mA. The three lines indicate the range of either the rad or the fluoro kVp setting, depending upon which mode the machine is in. The signals are always present.

ROTOR CONTROL: This line controls the tube anode rotor. In rad mode, the signal is high whenever C1 is depressed. In fluoro mode, the signal raises high on the first press on the footswitch, and remains high for one minute after it is released. If no exposure is started in this time, the line returns low. This turn-off delay prevents the rotor control circuit from repeating its start-up sequence unnecessarily during a series of fluoro exposures.

ABS ENABLE: This output line activates the Automatic Brightness Stabilizer circuits of the fluoro inverter. The line is high during a fluoro exposure if the ABS button is lighted. The turn-on of the enable line is delayed 2 seconds from the start of the exposure allowing the x-ray tube output to settle before attempting to monitor the brightness. The microprocessor remembers the kV setting between exposures.

RAD/FLO OUT: Indicates which mode the unit is to operate in: high means fluoro mode, low means rad. This is essentially the logical inverse of the RAD/FLO IN signal.

ACC OUT: When this signal is high, the accessory outlet is powered.

FKVP OUT: This is an analog output produced by a second digital-to-analog converter, which determines the fluoro mode tube voltage. At FKVP OUT = 5 V,

the tube voltage is 60 kVp; at FKVP OUT = 0 V, the output voltage is 120 kVp.

The relationship is given by:

$$\text{kVp} = 120 - (12 \cdot \text{FKVP OUT})$$

D. MICROCONTROLLER SYSTEM BLOCK DIAGRAM

Figure 21 breaks down the microcontroller into its major sub-systems. The heart of the system consists of the Microprocessor and Memory components. The program that implements the system tasks is stored and executed here. By monitoring the status signals, the microprocessor can decide what response to send to the control lines. The status and control lines are connected to the rest of the system via a 40 pin dip connector and the Interface Board (see Figure 22) in the card cage.

The digital logic of the microprocessor can not directly handle analog signals like V_{ie} , FKVP OUT, or ATACH. The two sub-systems providing the necessary interface for these signals are the Digital-to-Analog Converters (DACs) and the Analog-to-Digital Converter (ADC). These converters allow data exchange between the microcontroller and the analog circuits of the x-ray unit.

The microprocessor alone does not have enough input/output (I/O) lines to accommodate all of the control and status signals. To remedy this, a bank of I/O Expanders are included. Through these the microprocessor communicates with the front panel interface and the x-ray unit status and control signals.

The interface to the front panel consists of three sub-systems. The LED Display Drivers maintain the sixteen 7-segment LED digits that provide numeric data. The Keypad Decoder monitors the push-buttons and informs the microprocessor which button was pressed. Lastly, a bank of transistors make up the Pilot Light Drivers, which switch the push-button, READY, and X-RAY lights.

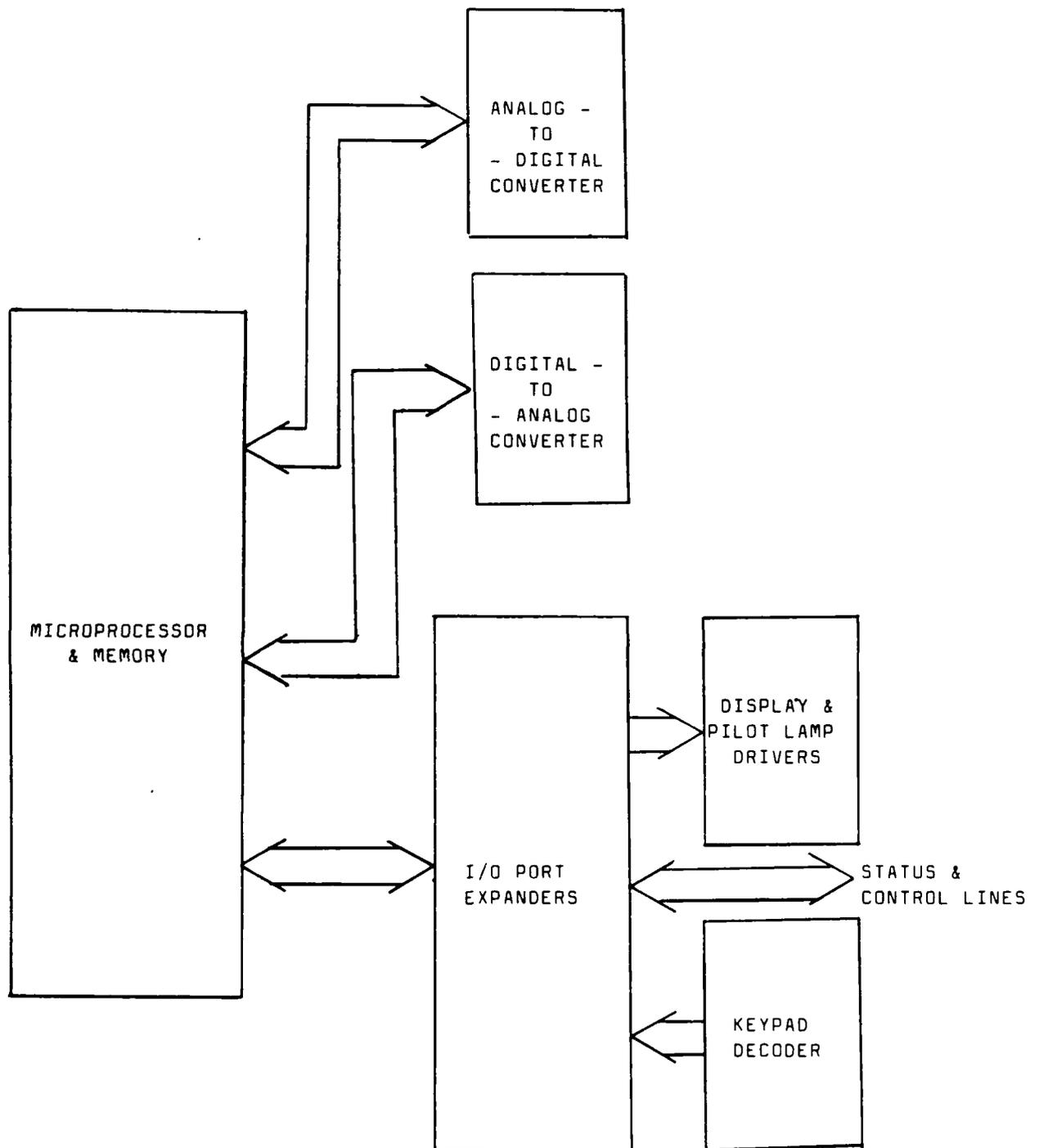


FIG. 21
MICROCONTROLLER SYSTEM BLOCK DIAGRAM

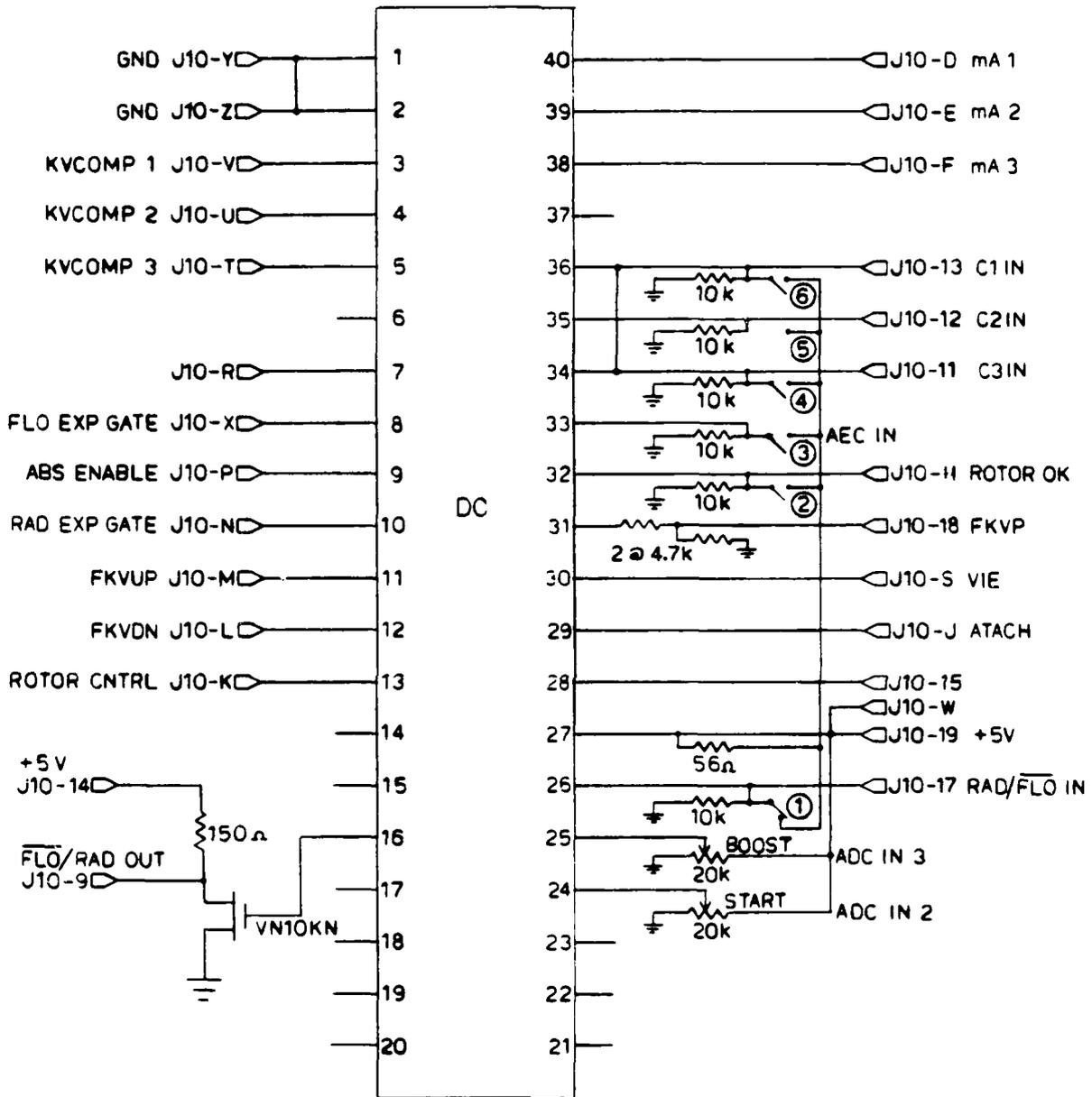


FIG. 22
INTERFACE BOARD

E. MICROPROCESSOR AND MEMORY COMPONENTS

The Microprocessor System Schematic diagram (Figure 23) should be referred to when reading the following descriptions.

INTEL 8748 SINGLE COMPONENT 8-BIT MICROPROCESSOR

The microprocessor chosen is an Intel 8748. This single 40-pin chip is a complete microcomputer containing an 8-bit CPU (central processing unit), a 1 kbyte EPROM (erasable/programmable read-only memory) for program storage, a 64 byte RAM (random-access memory) for data storage, 27 I/O lines, and an 8 bit timer/counter.

The 8748 provides an EA (External Access) control line. This input allows switching between the on-chip ROM and external ROM. If the EA pin is high, the CPU will fetch instructions from the 2716 EPROM, which contains the program for controlling the x-ray unit. Switching the EA pin low causes the program residing in internal ROM to be run, which is intended to be used in this system as a diagnostic program to test the microcontroller.

The 8748 also provides two test inputs, T0 and T1. In this system, T0 is connected to the EOC (End of Conversion) output of the ADC0809. This allows the software to test for the completion of a requested A/D conversion.

The $\overline{\text{INT}}$ input of the 8748 is the external interrupt line. Pulling this low causes the CPU to temporarily suspend execution of the current program and run a special interrupt service routine. For this system, the $\overline{\text{INT}}$ pin is tied to the $\overline{\text{TIMER OUT}}$ of the 8156. During rad exposures, the 8156 is programmed to provide 1 ms interrupts to the 8748, which are used to time the exposure length.

All other pins of the 8748 are connected according to guidelines in the Intel MCS-48 User's Manual. For this and other chips, only connections that

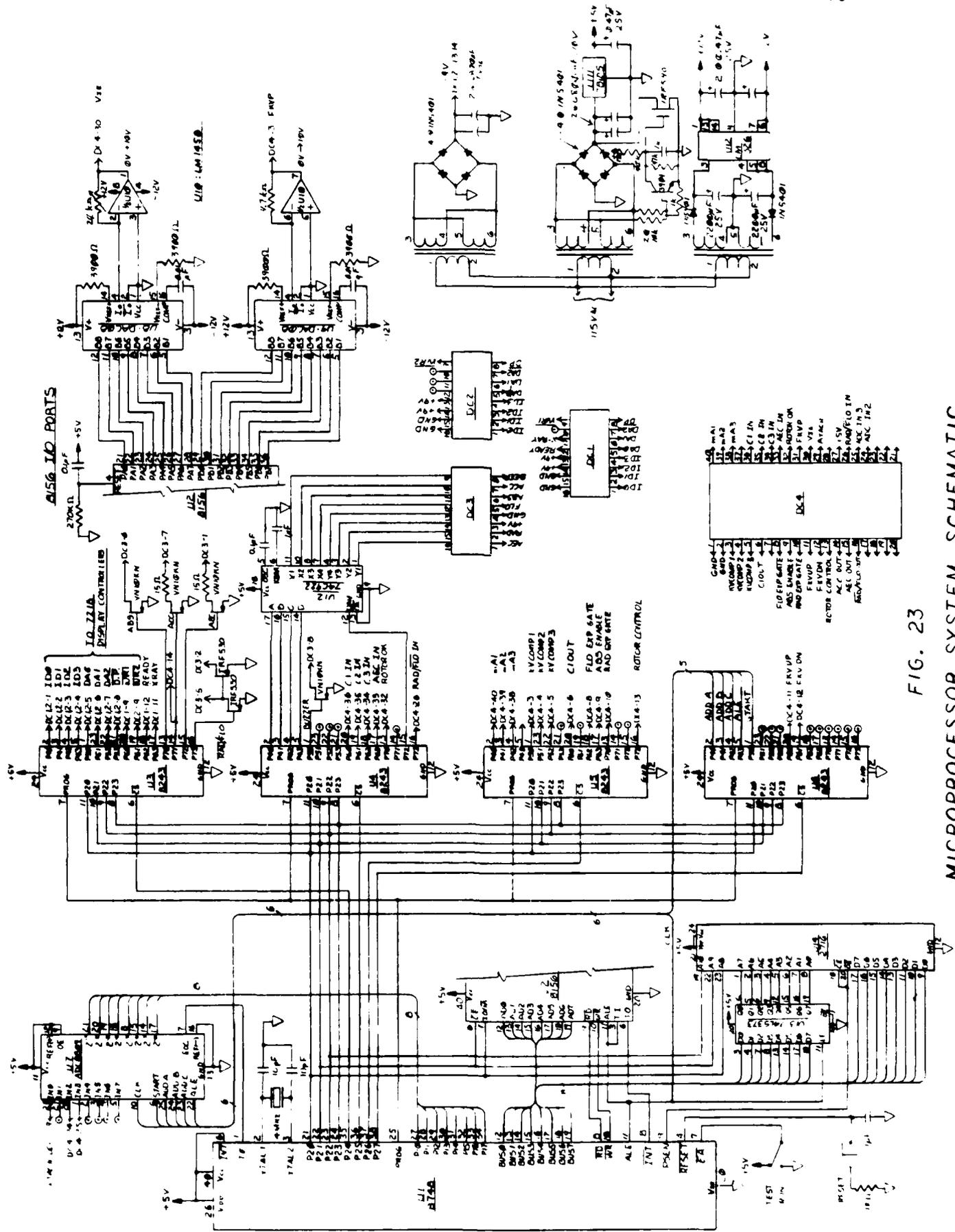


FIG. 23

MICROPROCESSOR SYSTEM SCHEMATIC

are unique to this system will be explained here: readers can consult the individual component's data sheets for further information.

The selection of this microprocessor was affected by several things. At the time the system was being considered, the price of an 8748 was comparable to other similar single chip micro's (although this is, at last report, no longer true). It was felt by the people involved with system design that this chip was adequate to meet the requirements at the time. Also, the designers had past experience with using the 8748, and had access to a development system for it.

INTEL 8156 RAM WITH I/O PORTS AND TIMER

The inclusion of this chip in the system was due mainly to the fact that the x-ray unit design was being done concurrently with the microcontroller design. This meant that the complete requirements on the microcontroller were not fully known at design time, and what was known could easily change. By adding this component, it was felt the system would have enough flexibility to handle the uncertainties.

The Intel 8156 contains 256 bytes of RAM, two 8-bit and one 6-bit I/O ports, and a 14-bit timer. Control lines allow direct connection to any standard Intel data/address bus.

Two signals not provided by the 8748 bus are the CE (chip enable) and the $\overline{IO/\overline{M}}$ (port vs. memory access control). Port 2 of the 8748 is used to create these signals. To access the 8156 I/O ports, port 2 of the 8748 must contain 1's in the two least significant bits ("xxxx xx11", where "x" denotes bits that can be either 1 or 0). To access the 8156 RAM, 8748 port 2 must contain "xxxx xx10".

The 14-bit timer provides a low going signal on the $\overline{TIMER\ OUT}$ pin

whenever it reaches zero. This is connected to the interrupt input of the 8748 for timing rad exposures. The exposures are timed by running the timer in a continuous square wave mode with a 2 ms period. The Timer Out line is high for 1 ms and then drops low. This low signal causes an interrupt in the 8748. The interrupt service routine of the 8748 restarts the timer, so the net effect is a series of pulses 1 ms apart. The interrupt routine essentially counts these pulses to provide the rad exposure timing. This scheme of restarting a square wave to provide pulses was necessary since the continuous pulse mode of the 8156 timer does not hold the Timer Out line low long enough to insure the 8748 would detect an interrupt.

Two output ports PA and PB are connected to the data lines of the DAC08's. To send data to a DAC, the 8156 I/O is selected as described above, and the data is written to PA or PB.

Further information on this chip can be found in the Intel Microprocessor and Peripheral Handbook.

2716 2-KBYTE EPROM

This is a standard memory chip. It contains 16 kbits (2k x 8 bit) of memory that is erasable by ultraviolet light, and can be electrically programmed.

To connect this to the Intel multiplexed data/address bus, an external address latch must be provided. This is accomplished by the 74LS373, a TTL octal latch. The gate for this latch is connected to the Address Latch Enable (ALE) of the 8748. This gives the 2716 the lower 8 bits of the address on the falling edge of ALE for external ROM accesses.

The Output Enable and Chip Enable (OE and CE) of the 2716 are connected

to the 8748 Program Store Enable (PSEN). When PSEN is low, the data from the EPROM will appear on the 8748 BUS lines.

F. ANALOG SIGNAL PROCESSING

NATIONAL DAC08 8-BIT DIGITAL-TO-ANALOG CONVERTER

The DAC08 is a high speed current output digital-to-analog converter with a typical settling time of 100 ns. It is used to provide the analog control voltages V_{ie} and FKVP OUT. It is described in detail in the National Data Acquisition Handbook.

The current output of each DAC08 is fed to an LM1458 op amp configured as a current-to-voltage converter. The 20k Ω feedback potentiometer for each op amp is adjusted to provide 10 V out with all data lines of the DAC08 high. If all data lines are low, the output is 0 V. If "B" represents the digital data of the inputs of the DAC08, the output voltage at the output of the op amp is given by:

$$V_0 = \frac{B}{25.5 \text{ volts}}$$

To output data to a DAC08, the appropriate 8156 I/O port must be selected and written to as described above.

NATIONAL ADC0809 SINGLE CHIP DATA ACQUISITION SYSTEM

The ADC0809 is an 8-bit, 8-channel, successive approximation analog-to-digital converter. In this system, it is connected to read one of eight 0 V-to-5 V signals and produce an 8-bit output DB7..DB0 according to:

$$DB = 51 \cdot V_{in}$$

The accuracy of the data is +/- 19.6 mV.

The control signals for running the ADC0809 are connected to 8243 I/O Port Expander U6. To perform a conversion, the 8-bit channel address must be placed on P42..P41 of the 8243. Next, the Address Latch Enable (ALE) of the ADC0809 must be pulsed by raising 8243 P43 high. Then the START input is pulsed by raising P50. Strobing the START line will initiate the conversion. Both the ALE and START lines can then be returned low.

The End-Of-Conversion (EOC) output signal is tied to the TO Test input of the 8748. Shortly after the start of conversion, EOC will drop low. When the conversion is completed, EOC will raise high. By testing the TO test input, the 8748 software can determine when the data is ready. The ADC0809 data lines are connected to Port 1 of the 8748. The data can then be read by inputting P1.

The ADC0809 requires a clock (CLK) input for timing in the successive approximation circuitry. The ALE output of the 8748 is used for this, which provides a 267 kHz clock.

Detailed specifications can be found in the National Data Acquisition Handbook.

G. INTEL 8243 INPUT/OUTPUT EXPANDER

The Intel 8243 is a 24-pin chip consisting of four 4-bit bidirectional static ports and one 4-bit port that serves as an interface to any Intel MCS-48 series microcomputers. Each of the four expansion ports (P4 - P7) can be used as either input or output lines. The Intel MCS-48 User's Manual has complete component specifications.

The architecture of the 8748 contains special instructions that directly support this chip. Data can be read from or written to each of the four ports. Also, two instructions allow setting or resetting individual bits in the ports by logical "ANDing" and "ORing" the port with a bit mask. This capability makes this chip attractive in a system such as this, where several output lines must be controlled individually. Also attractive is the ability to reassign ports as either input or output by software, providing easy modification and expansion of I/O lines.

The chip selects (\overline{CS}) of the four 8243's are connected to the upper four bits of P2 of the 8748. To select one of the 8243's, the proper bit in P2 must be set to zero. Care must be taken not to have more than one of these select lines low. If this occurs followed by a port read, the selected chips will be sourcing the same lines, possibly damaging the 8243's. Outputting to the ports with more than one selected will cause the corresponding lines of each selected port to change.

All of the digital control and status signals between the microcontroller and the x-ray unit are connected to port lines on one of the 8243's. Interconnections are made by DIP connectors and ribbon cable.

H. FRONT PANEL INTERFACE

NATIONAL 74C922 16 KEY ENCODER

This CMOS chip provides all the necessary logic to fully encode an array of 16 SPST switches. The array scan rate is determined by a single capacitor connected to the OSC pin. Key debounce is provided using a second capacitor at the KBM pin. The 4 bit output is compatible with standard microprocessor busses. The array lines to the switches (X1 through X4, Y1 through Y4) are connected to a DIP connector which feeds a ribbon harness to the push buttons on the x-ray unit's front panel (see the Front Panel Push Button and Pilot Lights Schematic, Figure 24). For further information, consult the National MOS/LSI Handbook.

The four data lines (D3 through D0) of the 74C922 are connected to an 8243 port (port 4 of chip U4). Table 3 gives the data output corresponding to the front panel keys. When the encoder detects a key closure, it raises its DAV line, signaling that the encoded data is available. DAV will remain high as long as the key is held down. The encoder will not recognize a second key closure until the first is released. The DAV signal is scanned by the 8748 software by inputting port 7 of 8243 U4.

If a key is held down, the 8748 will respond in the following fashion. Upon scanning, if the 8748 sees DAV is high, it responds immediately to the key. Upon further scanning, if the DAV is still high and the same key is being outputted by the 74C922, there will be a half second wait before another response to that key is made. The 8748 will then respond about 6 times a second as long as DAV remains high and the same key is being encoded. This allows the operator to hold down a key and repeatedly step a value through its possible settings.

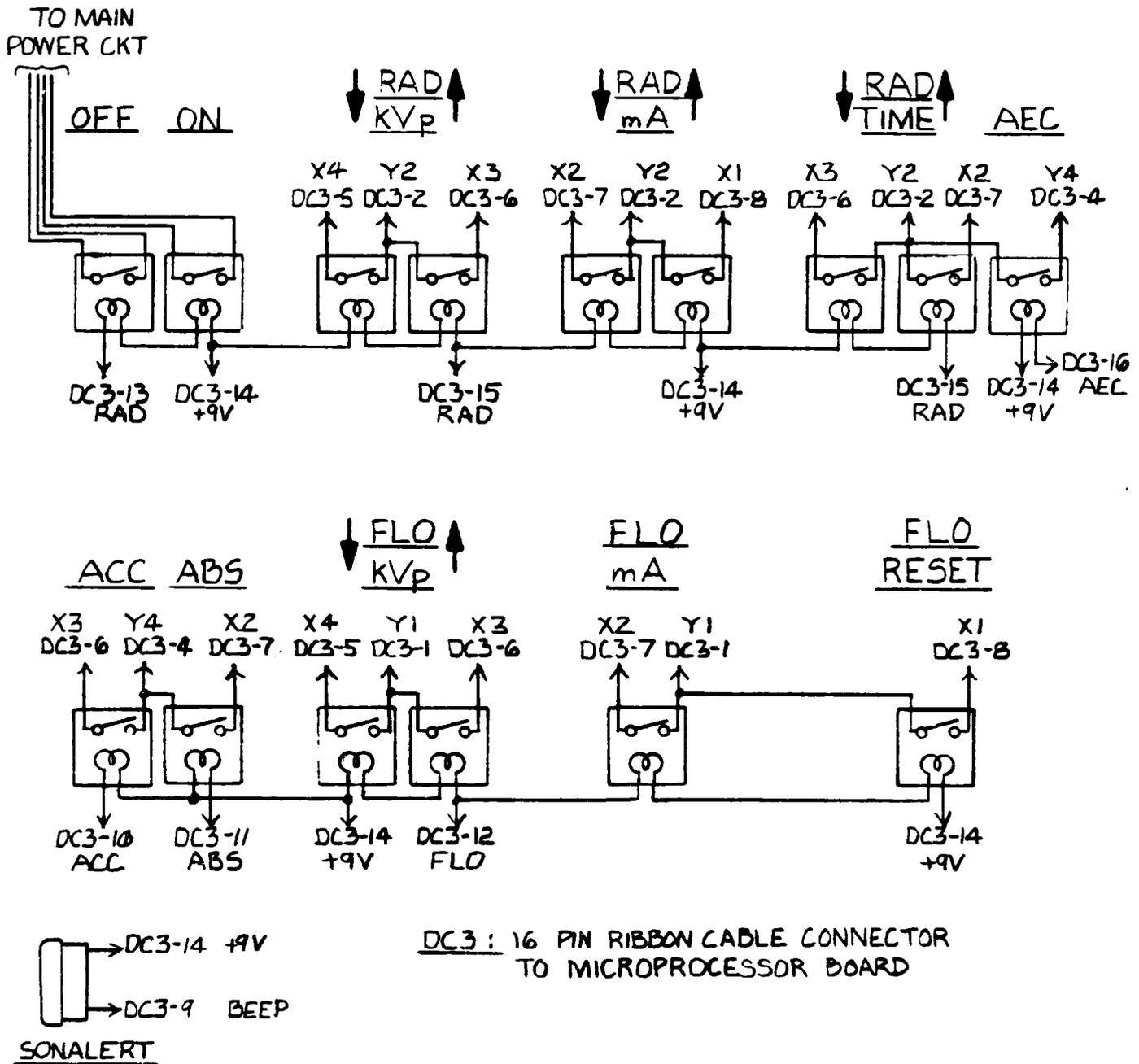


FIG. 24
FRONT PANEL PUSH BUTTON AND PILOT LIGHTS

Table 3. 74C922 Data Out vs. Front Panel Push Buttons

D C B A	DEFINITION
0 0 0 0	Reset fluoro Time
0 0 0 1	Raise fluoro mA
0 0 1 0	Raise fluoro kVp
0 0 1 1	Lower fluoro kVp
0 1 0 0	Raise Rad mA
0 1 0 1	Lower Rad mA
0 1 1 0	Raise Rad kVp
0 1 1 1	Lower Rad kVp
1 0 0 0	not used
1 0 0 1	Raise Rad Time
1 0 1 0	Lower Rad Time
1 0 1 1	not used
1 1 0 0	AEC
1 1 0 1	ABS
1 1 1 0	ACC
1 1 1 1	not used

INTERSIL 7218C EIGHT DIGIT LED DRIVER SYSTEM

The Intersil 7218C is a CMOS package that interfaces 8 common anode 7-segment LED digits to a microprocessor bus. It contains an 8x8 static display memory, 7 segment decoders, multiplex scan signals, and high power drivers for the LED anodes and segments. The LEDs are driven directly from the chip's outputs: no series resistors are required. Refer to the Rad Display and Fluoro Display Schematics (Figures 25 and 26) when reading the following descriptions.

Sixteen of the digits on the front panel are driven by a pair of Intersil 7218C's. The remainder of the digits are connected to always show zero. On Figure 19, any digit that shows a zero is one of these. The Fluoro Display Schematic shows two of the RPM digits are driven by a CMOS 4049 timer through two 2N2219 transistors. This timer drives the two digits alternately with a 50% duty cycle signal. This was made necessary by the physical proximity of the two LED's: there was not room to run lines from separate resistor packs on the PC board layout. Using the CMOS timer allows the digits to share one resistor pack.

The 7218C is configured to provide its "code B" character set. This is accomplished by floating (not connecting) pin XXX. This character set consists of the following: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, H, P, L, E, -, and blank. The code for these characters is listed in the assembly listing attached to the end of this report.

To send a digit to the LED display, a 4 bit character code must be placed on data inputs ID3 through ID0 of the 7218C. Also, a 3 bit address must be placed on the digit address lines DA2 to DA0. The decimal point input \overline{DP} must be set to logic 0 if the decimal point for this digit is to be

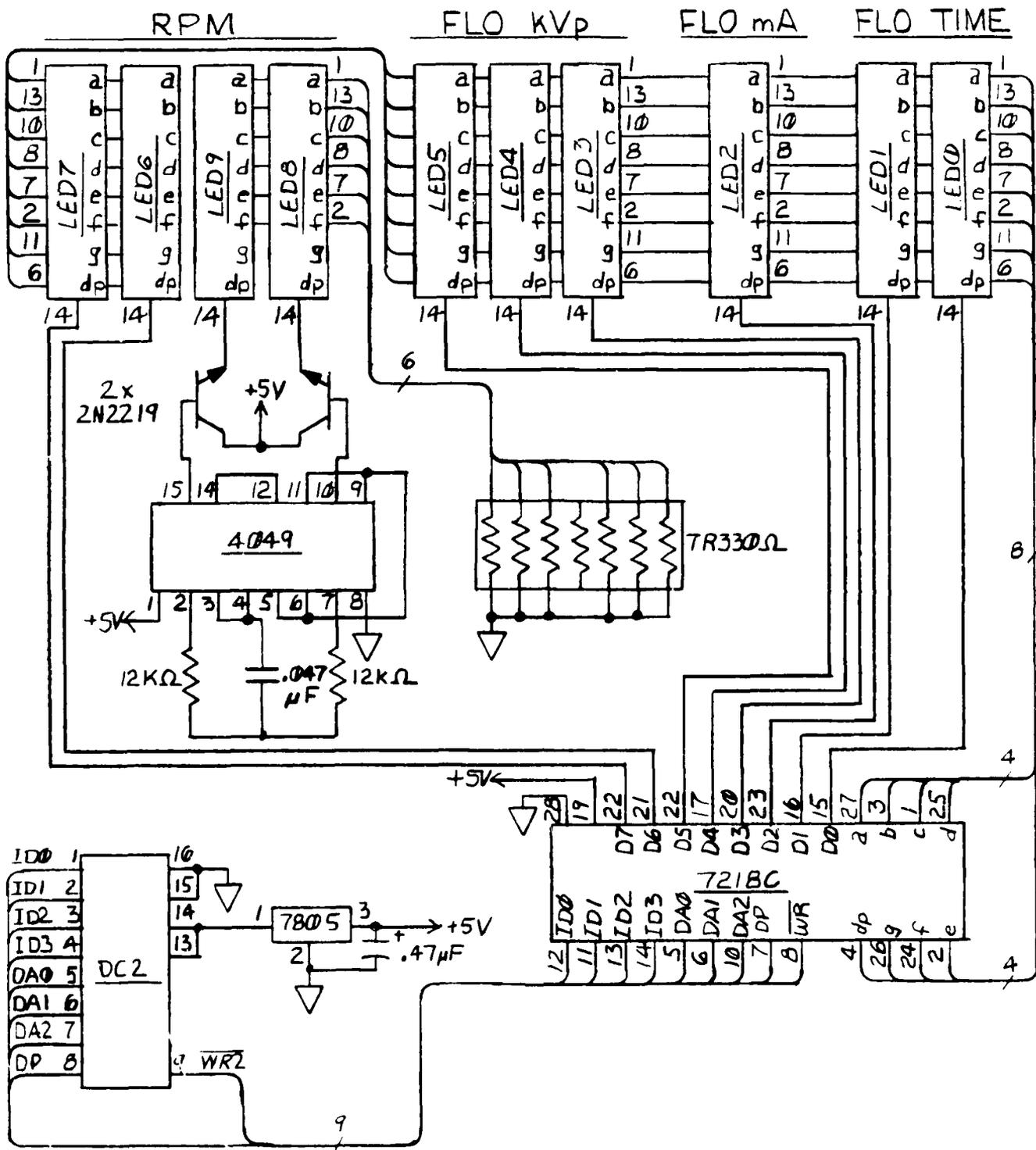


FIG. 26
FLUORO DISPLAY SCHEMATIC

lighted. The 7218C will output the desired digit when the write enable \overline{WR} is pulsed low.

In this system, both 7218C's share the DA, ID, and \overline{DP} lines. Which of the two 7218C's is to respond is determined by which write enable is strobed. The microprocessor schematic diagram shows the connections of the 7218C's to ports P4, P5, and P6 on 8243 U3 through dip connectors DC1 and DC2.

PILOT LIGHT DRIVERS

The pilot lights for the front panel are connected to an unregulated 9 volt power supply. The ground connection to the lights is switched by FET transistors, turning the lamps on and off. The FET's used are IRF530's for multiple lamp circuits, and VN10KN's for single lamps.

Both FET's turn on by raising the gate to 5 volts above the source, which is connected to ground. This allows the FET's to be directly driven by output lines from the 8243 port lines. Setting one of these lines causes its corresponding lamp to light. The connections for the lamps are shown on the Microprocessor Board Schematic, and the Rad Display and Front Panel schematics.

I. SOFTWARE OVERVIEW

The assembled machine language program that runs the system is given in the Appendix. The comments included in this listing provide detailed descriptions of how the program functions. The major sections of the program are summarized in the following paragraphs.

SECTION #1 SYMBOL DEFINITION AND MACROS

The first section of the assembly listing contains definitions for symbols that the assembler recognizes as constants. When these symbols occur in the program, the assembler will use the defined value.

This section of the program also defines macros. Macros are symbols that define a block of text. When the macro name is found in the program, the assembler will insert the block of text associated with that name in place of the name. In the macro definitions, a backslash (\) followed by a digit (e.g. "\1") directs the assembler to look for an argument in the macro calls. Arguments are any symbols that occur after the macro name in the program body. The assembler replaces a "\n" with the "nth" argument in the macro call.

SECTION #2: INTERRUPTS AND INITIALIZATION

This section contains the Timer Interrupt Service routine. This is a subroutine that is executed whenever the 8748's internal timer counts down to zero, causing a "timer interrupt". The timer is programmed to interrupt at a 60 Hz rate. This is used to time all functions of the system except rad exposures.

Also in this section is the External Interrupt Service routine. The 8748's external interrupt is connected to the Timer Out pin of the 8156 as

described earlier. When this interrupt is enabled, the routine is executed every millisecond.

Section #2 also contains routines that are used to initialize the 8748 and the 8156.

SECTION #3: PUSH BUTTON AND LED DISPLAY ROUTINES

The main program loop begins here. At the beginning of each main loop pass, the 8748 scans the push buttons for any new key entries. If a button is pressed, it is processed at this time. The main loop then updates any LED displays or pilot lights that need to be changed due to key presses or due to a change in status input lines.

The end of this section determines if the machine is rad or fluoro mode. The program jumps from here to either Section #4 or #5 depending which mode is active.

SECTION #4: RAD MODE ROUTINE

This section is executed only when the machine is in rad mode. The routine first checks to see if C1 is depressed. If so, a series of conditions are checked to determine if the machine is ready to make an exposure. The conditions checked are: C2 must have been released after the last exposure, 1/2 second must have elapsed since the last exposure, and the ROTOR OK signal must be high. If these are met, the READY lamp is lighted, and C2 is checked. If C2 is pressed, the exposure sequence is initiated. The end of this section jumps back to the start of the main program loop.

SECTION #5: FLUORO MODE ROUTINE

If the main program loop determines that the machine is in fluoro mode,

then this branch of the loop is taken. This routine checks the footswitch input C3. If high, the fluoro exposure is started (or continued, if already active). The timing for the ABS signals, the filament control lines, and the fluoro exposure gate occur here. The end of this section jumps back to the beginning of the main program loop also.

SECTION #6: LED DISPLAY ROUTINES

This section contains the subroutines that maintain the front panel LED displays. The first routine, "Sendigit", is called to write a particular character to one of the LED digits. The remaining routines are called to convert and send data to an entire LED field on the front panel.

SECTION #7: SIGNAL INPUTTING ROUTINES

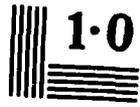
The various status signals are read in by the routines in this section. The routines read the Rad/Flo, Rotor OK, AEC In, C1, C2, C3, and the analog inputs of the ADC0809.

SECTION #8: SIGNAL OUTPUTTING ROUTINES

The routines handling the x-ray unit control lines make up this section. The voltage compensation outputs are determined here along with the mA lines. Other routines handle the DAC08's, and turn the control signals on and off.

SECTION #9: MATHEMATICS ROUTINES

These subroutines implement 16 bit multiplication and 16 bit division. The routines are modified versions of those appearing in the Intel MCS-48 User's Manual.



1.0

2.8

2.5



1.1

3.15

2.2

3.5

2.0

4.0

1.8



1.25



1.4



1.6

5.0
5.6
6.3
7.1
8.0
9.0
10.0

J. CONCLUDING REMARKS

After working with this system for one year, several lessons have been learned. First, having the development system for the microprocessor located outside of the normal working area is not time efficient, especially when the two locations are in separate buildings three blocks apart. Much time is lost shuttling back and forth with EPROMs and printout. Also, it would be worthwhile to design the system to run programs downloaded directly from the development system into RAM, instead of reprogramming EPROMs with each new program modification.

The choice of microprocessor turned out to be another cause of lost time. The 8748 is intended to be used in large-volume, small system applications, and therefore has a primitive instruction set. In a project of this nature, where only one unit is to be built, programming time could be saved by using a more advanced microprocessor.

The added expense of additional RAM for downloading programs and for using a better microprocessor would be recovered quickly in programming man-hours.

In spite of the above mentioned time loss, the system has met all of the requirements, and at no time was there a danger of running up against constraints of the microcontroller. The speed of the system was never a problem, and there was adequate methods available to perform the necessary timing for the x-ray unit. The addition of the 8156 RAM/Timer chip turned out to be unnecessary, but its presence helped simplify the timing of rad exposures and sending data to the DAC's. The main reason for including this chip was fear of running out of RAM in the 8748; however this never became a concern.

It was known from the beginning that noise from the x-ray unit could be

a problem, causing the controller to act incorrectly. The original research in flywheel systems was plagued by transients occurring in the system power supplies, caused largely from the motor drive circuitry of the alternator. The step taken to remedy this was to give each board in the system its own voltage regulators. This seems to have been satisfactory, since the controller and the rest of the unit have been free from any such transient problems.

Work remains to be done on the controller. The listing given here does not reflect changes made to accommodate the latest method of controlling the fluoro inverter. (These revisions have been worked out).

Also and more importantly, the final routines that control the alternator output during a rad exposure must be written. This will be done when the x-ray unit is able to make such exposures. (So far only dummy load data has been taken). These routines must determine the exciter current command voltage V_{ie} from the rad kVp and mA settings, and from the flywheel speed. The mathematics for the necessary computations already exist. Routines must be written to implement the curves found from collected data. By adding variable resistors to the unused inputs of the ADC0809, code can be written to read and display values from these resistors during test mode operation. These values can then be used as constants in the V_{ie} equations. This arrangement would allow adjustment of the alternator output as the x-ray unit ages.

IV. PERFORMANCE MEASUREMENTS

Photographs were made of certain internal and load waveforms during this study. Radiographic exposures were made using several resistive dummy loads as substitutes for the high voltage transformer and x-ray tube. Actual radiographic x-ray exposures were made using the original experimental transformer but were not made with the final version of the transformer used in the model. The final transformer exhibited some arcing and insulation breakdown at about 120 kVp and it was feared that a minor failure of the radiographic control circuit would destroy the insulation or rectifiers of that transformer. It was, however, used for testing the fluoroscopic circuits.

A. DUMMY LOAD TESTS

The shape and amplitude of the envelope of the alternator output are determined by the exciter signal. The reactance of the exciter winding determines the dynamic characteristics. The exciter current command voltage will have two components: a static signal and a boost signal which occurs 25 ms into the exposure time. The levels of both are influenced by the value of rotor rpm. As described elsewhere in this report, software routines must be provided to generate these signals from the panel settings of kVp and mA and from the tachometer signal, i.e., rotor rpm. For test purposes, the V_{ies} and V_{ieb} values are obtained from two potentiometers located on the Interface Board. A digital readout of these settings is provided when the C1 switch is closed. Then, the digital value, D_{ies} , of V_{ies} is displayed on the Rad kVp LED's and the digital value, D_{ieb} , of V_{ieb} is displayed on the Fluoro kVp LED's. Figure 27 shows the x-ray tube anode waveform when V_{ies} is set too

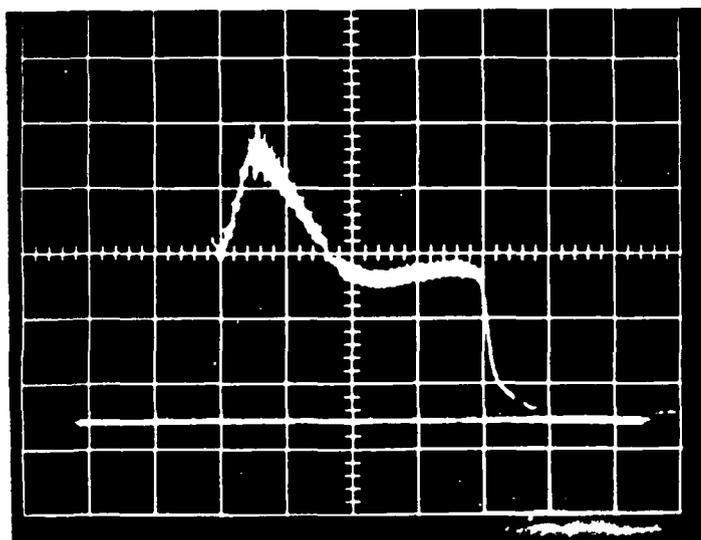


Figure 27. Anode waveform from improper adjustments. The V_{ies} setting is too high and the V_{ieb} setting is too low to produce a 30kVp waveform. Scope settings: Vertical 10 kV/cm, Horizontal 20 msec/cm.

high and V_{ieb} is too low. Figure 28 shows the result when the values are set correctly.

When using a single resistor as the dummy load, the output of the alternator is rectified using a three phase full wave bridge. The dc output is applied to the load resistor, usually several paralleled heating elements of 2.2 ohms capable of accomodating a 50 kWp pulse for several seconds. Figure 29 shows a 40 kWp output pulse.

Other dummy load exposures illustrate the capability of the circuit to maintain constant voltage pulses under various conditions of load, rpm and exposure time. Figure 30 is 0.10 sec at 5.3 kWp at 8200 RPM. Figure 31 is

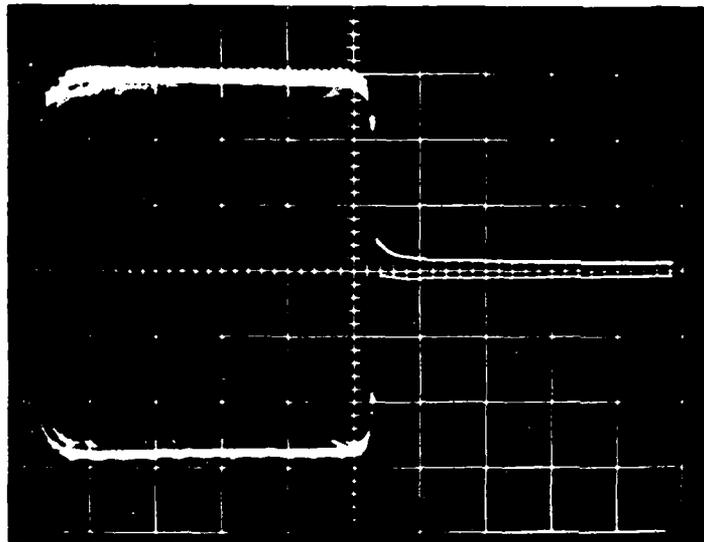


Figure 28. Anode to cathode waveform showing proper adjustments. The V_{ies} and V_{ieb} settings produce a steady 60kVp tube voltage. Scope settings: Vertical 10 kV/cm, Horizontal 20 msec/cm.

0.15 sec at 8.3 kWp at 7200 RPM. Figure 32 is 0.22 sec at 10 kWp at 8700 RPM. Stability for long exposures is shown in Figure 33 for 0.75 sec at 10 kWp at 8700 RPM.

A plot, Figure 34, of the dummy load output vs the settings of V_{ies} and V_{ieb} at a particular rpm shows that V_{ies} is a linear function and V_{ieb} can be approximated by a 2nd degree polynomial. The slopes of these curves are dependent on the load characteristics. It is necessary that measurements are made with an actual x-ray tube in order to make the program settings required for system calibration.

The data from the curves of Figure 34 were collected using a 1.0 ohm

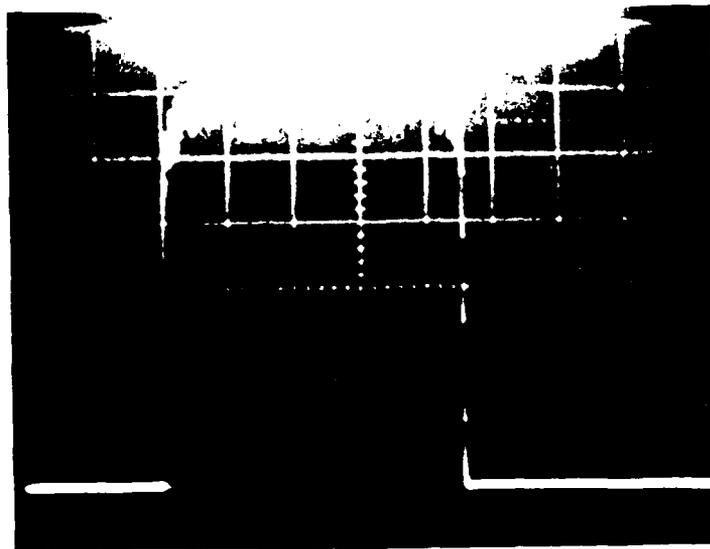


Figure 29. Rectified alternator output across a 2.2Ω dummy load. The 300 volt level produces a 40kWp output. Scope settings: Vertical 50 V/div, Horizontal 10 msec/div.

dummy load at 8000 RPM. The output of the alternator, V_{op} , can be obtained from:

$$V_{op} = 12.4 (D_{ies}) - 31$$

The output as a function of D_{ieb} can be approximated by:

$$V_{op} = -0.00303 (D_{ieb})^2 + 4.08 (D_{ieb}) - 10$$

Many tests of performance were made using dummy loads to determine the overall limit of output as a function of time, rpm and load. It was observed

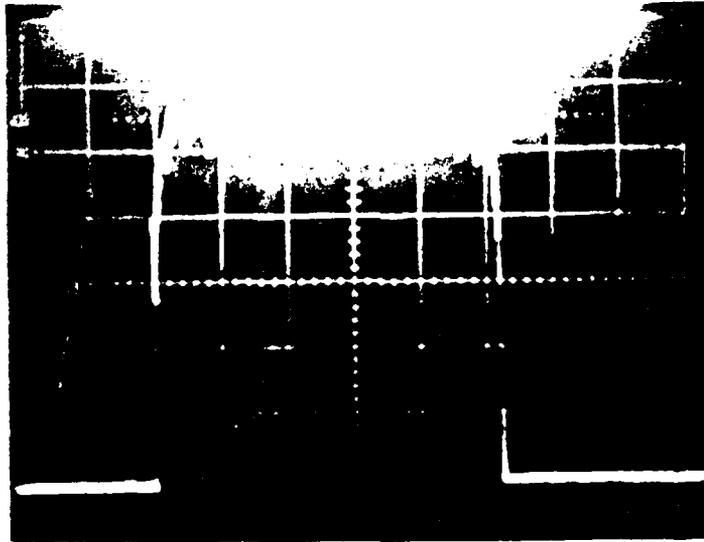


Figure 30. Typical 100msec exposure at 8200 RPM. V_{ie} signal is approximately one-fourth of maximum. 5.3kWp output. Scope settings: Vertical 20 V/div, Horizontal 20 msec/div.

that output pulse levels greater than 50 kWp could be obtained at 8000 RPM or more but that there was some loss of control, i.e., it was not possible to control the exciter to produce a constant output during the pulse. A practical limit of regulated output power appears to be just below 50 kWp for the two alternators tested.

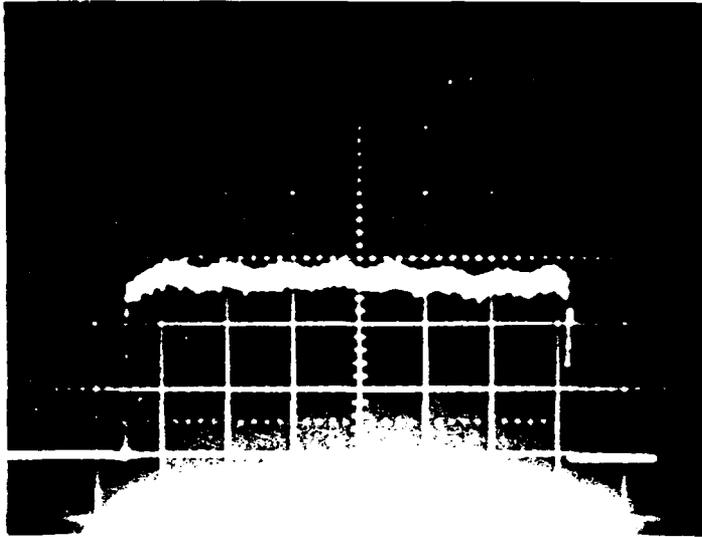


Figure 31. Example of significant output capability even at relatively low flywheel speed of 7200 RPM. Exposure is 150msec long with no droop. V_{ie} signal is approximately one-fourth of maximum. 8.3kWp output. Scope settings: Vertical 50 V/div, Horizontal 20 msec/div.

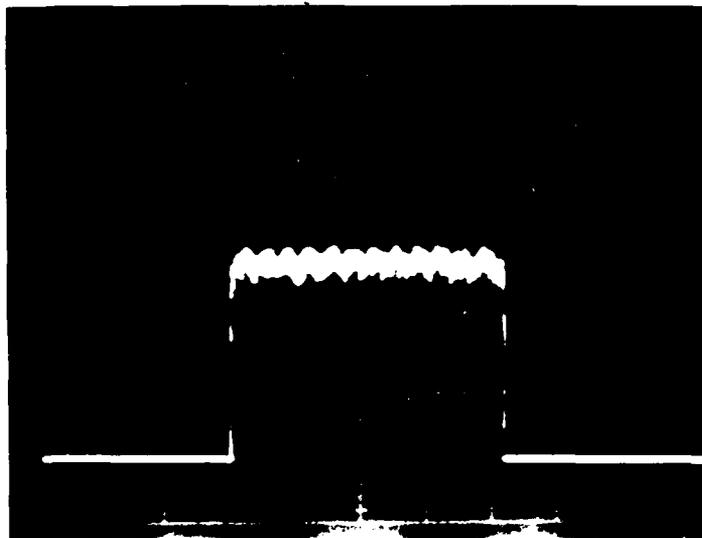


Figure 32. Typical 220msec exposure at 8700 RPM. V_{ie} signal is approximately one-fourth of maximum. 10kWp output. Scope settings: Vertical 50 V/div, Horizontal 50 msec/div.

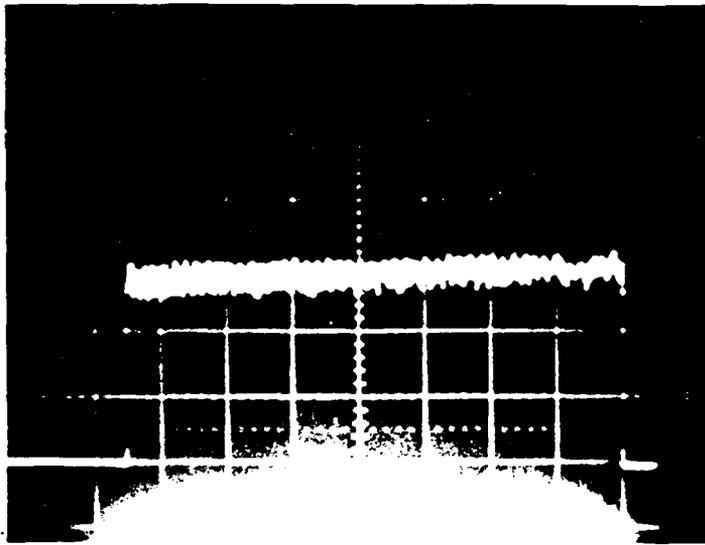


Figure 33. Example of no droop output even during relatively long exposure time of 750msec. Notice also precise timing of exposure duration. Flywheel speed is 8700 RPM. V_{ie} signal is approximately one-fourth maximum. Scope settings: Vertical 50 V/div, Horizontal 0.1 sec/div.

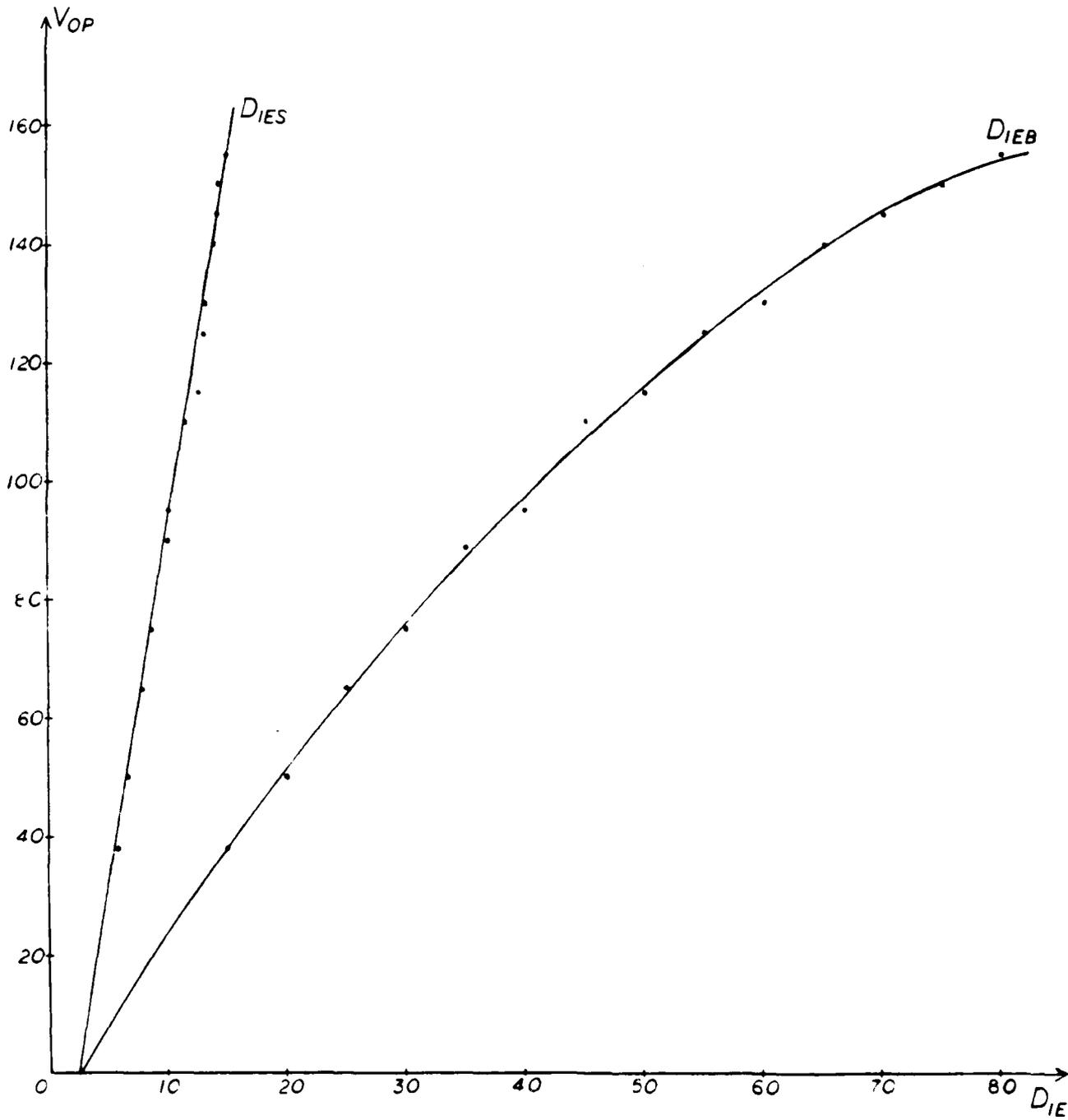


Figure 34. Plot of Dies and Dieb settings vs. V_{OP} using a dummy load.

B. FLUOROSCOPIC TESTS

The fluoroscopic inverter circuit feeds one phase of the three phase transformer. The distributed capacity of the secondary circuit of the transformer is reflected as a very large capacitance at the primary. For efficient energy transfer, required to keep the overall system power demand under 0.5 kW, the inverter must be capable of feeding this capacitance. A simple switching or square-wave inverter cannot be used as the charge/discharge currents would be too high. A resonant or inductor-fed inverter is used. The waveform of Figure 35 shows the symmetric charge, almost triangular, waveforms across the transformer primary. The waveform is almost the same when a dummy load of two 100 W series-connected light bulbs is used. Figure 36 shows the drain and transformer center tap waveforms of the fluoro inverter. The power devices are "Gemfets", MOS power devices incorporating series diodes in the drain connections. The resonant charging effect is seen as each drain is permitted to swing below ground and the center tap resonant charging waveform occurs twice each cycle.

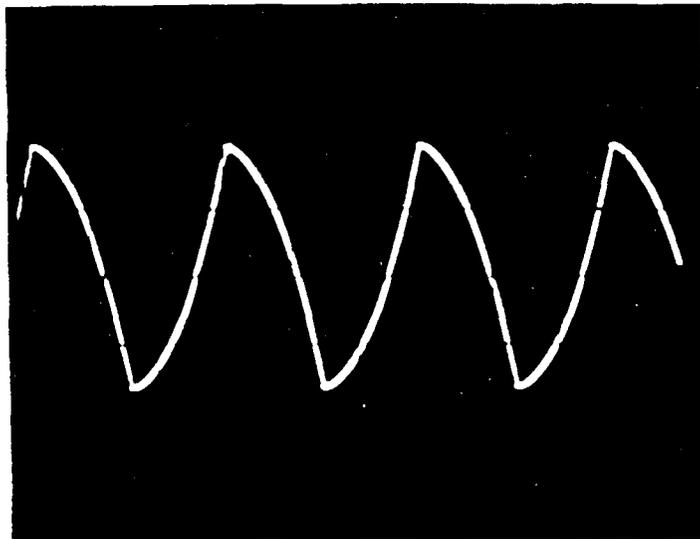


Figure 35. Output of fluoroscopic inverter circuit across two 100W light bulbs. Waveform has the same shape when viewed across the single phase of the high voltage transformer. Scope settings: Vertical 200 V/div, Horizontal 1msec/div.

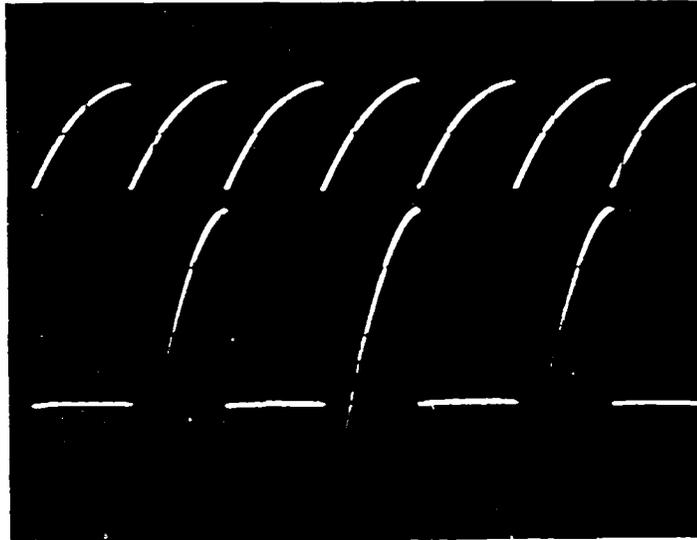


Figure 36. Inverter waveforms. Top waveform is center tap of output transformer showing resonant charging. Bottom waveform is drain voltage of switching inverter power FET. Scope settings: Vertical 50 V/div, Horizontal 1msec/div.

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