

Imatron Inc.
Medical Imaging Technology

389 Oyster Point Boulevard
South San Francisco, CA 94080



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DESIGN AND DEVELOPMENT OF AN ENGINEERING PROTOTYPE

COMPACT X-RAY SCANNER (FMS 5000)

Final Report

31 March 1989

Douglas P. Boyd, Ph.D.

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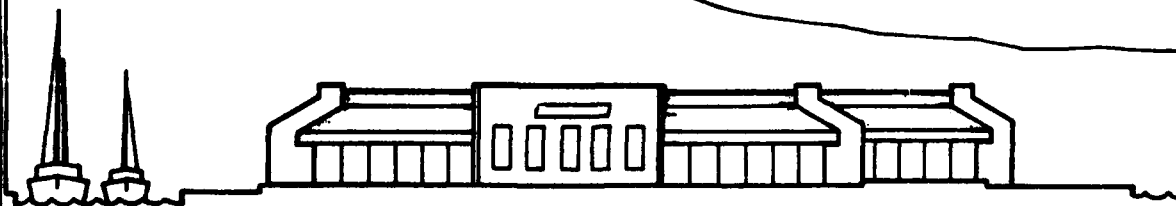
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1 INTRODUCTION

1.1 The Army's Need

DEPMEDS (Deployable Medical Systems) are the field-mobile medical facilities utilized by the tri-services for the "austere but adequate" health care of trauma patients. They include an array of facilities, from Echelon 1 aid stations near the forward line of battle to Echelon 4 general hospitals serving the communications zone. Because DEPMEDS facilities are mobile and must survive and function in "inhospitable" environments, equipments intended for these facilities must meet rigorous standards for ruggedization and logistical support which comparable commercial equipments serving conventional medical centers need never address. Although DEPMEDS policies recognize that "CT Scan equipment meeting appropriate RAM [Reliability, Availability, Maintainability] characteristics for the combat zone should be vigorously pursued," at the present time no equipment satisfying this requirement exists (i.e., there are no CT scanners among the "Approved DEPMEDS Materiel Sets"). Thus, military trauma surgeons, unlike their civilian counterparts, are forced to operate without the benefit of the clear and unambiguous diagnoses that CT systems can provide.

The difficulties posed by the absence of CT scanners in SEA were very evident to the surgeons operating in that theatre, and at present a consensus exists among U.S. military surgeons that CT scanning should be required for the treatment of craniocerebral, orbital, and abdominal trauma. During the Israeli incursion into Lebanon, casualties were evacuated by air directly to the emergency room of a permanent-site general hospital with waiting CT scanners. A. Rosenberger *et al.* (1), reporting on the Israeli experience, noted the value of CT for craniocerebral, orbital, and abdominal injuries (so that "unnecessary exploratory laparatomies can be avoided"), as well as for finding foreign bodies in the chest and establishing the extent of spinal injuries. Twelve percent of all incoming casualties were CT

scanned directly from the triage area, "establishing surgical priorities through improved classification of the wounded."

U.S. experience with CT scanners in mass casualty situations is limited. However, CT scanners are routinely used in the treatment of trauma. Writing of his experience with emergency CT of abdominal trauma at the San Francisco General Hospital over an 18-month period, M. Federle (2) stated:

The number of laporotomies that have been avoided as a result of CT is difficult to calculate but we are certain that it is substantial. All but a few patients with negative CT scans were discharged after a short period of observation. The savings in hospital costs alone are a strong argument in favor of CT in trauma.

While the clinical importance of CT to the DEPMEDS system is well-established, this is only half the story. For a CT scanner to gain acceptance within the military, it must be, and remain, reliable. It must withstand extended storage at environmental extremes; it must be transportable by air, sea, and land (by truck over unimproved roads and by rail); and it must operate with minimal set-up time and without benefit of such niceties as clean air or heat. It must also not pose an unacceptable logistical burden in terms of weight, size, or power requirements. Most importantly, however, it must be capable of quickly handling a mass casualty situation without itself becoming the bottleneck in the treatment process. Finally, the CT system capable of handling these difficult and diverse requirements must be comparable in cost to commercial CT scanners designed for handling a modest and carefully scheduled case load under the most benign of environmental conditions.

1.2 The Army's Approach to the Problem

The responsibility for the development of diagnostic instrumentation suitable for utilization in DEPMEDS resides with the U.S. Army Medical Research and Development Command (MRDC) at Fort Detrick. In June of 1987, MRDC awarded a 25-month cost-plus-fixed-fee (CPFF) contract (DAMD17-87-C-7108) to Imatron, Inc. for the design and development of an engineering prototype Compact X-Ray Scanner. It was MRDC's intent that this scanner would demonstrate the feasibility of successfully addressing the mobile Army's requirements for a compact, lightweight, low-power, and high-throughput device capable of acquiring cross-sectional and projection images of diagnostic quality.

During the course of the contractual effort, at the request of MRDC, Imatron introduced ruggedization considerations into the design of the scanner, and accelerated the pace of development. In December, 1988, Imatron produced the first images with the Compact Scanner (termed the FMS 5000) and introduced the scanner at the annual Radiological Society of North America (RSNA) meeting. This scanner met the Army's stringent requirements for size, weight, and peak power consumption, and the images it produced were of diagnostic quality.

The following is the Final Report covering the design and development of the FMS 5000 under the terms of the MRDC contract. At the present time, the FMS 5000 exists as an engineering prototype at Imatron's laboratories in South San Francisco. This prototype system demonstrates the feasibility of producing projection and cross-sectional images of diagnostic quality with a compact and lightweight system requiring low peak power. As an engineering prototype, however, further development will be required in order for this system to be mounted in an Army ISO shelter and clinically tested under field conditions.

2 DISCUSSION OF WORK PERFORMED

2.1 Imaging with X-rays

2.1.1 Density Resolution is Photon-Limited

In order to understand the underlying ideas of the FMS CT design the following paragraphs will prove useful.

The goal in medical imaging with x-rays is to see object-related details in the radiograph. It is easiest for the purpose of this introduction to consider the two extreme imaging tasks separately: 1) imaging of small contrast differences in the object, and 2) imaging of small details with larger contrast. Whereas task 1 is in general limited by image "noise", task 2 is limited by the size of the data arrays, and/or by how fine a sampling the equipment is designed to perform.

Ideally, the design of medical x-ray based imaging equipment (such as Image Intensifier/TV chain, CT Scanner, even directly x-ray recording media such as film-screen combination), should be such that the information in the their images is limited by x-ray photon noise, and that the level of this noise is as close to the theoretical limit as possible.

X-ray photon flux is statistical in nature (somewhat like the droplets in a spray of paint) causing noise in x-ray images, mostly random. Object features are obscured by such noise, thus increasing false positive and false negative results. The statement above demands that the limitation should be due to photon noise and not be due to other avoidable noise sources (e.g. granularity in silver-gelatin film, flaws on films and screens, defective processing, electronic noise, and microphonic interference).

When measuring a photon sample (with assumed ideal equipment) the precision of that measurement will increase with the number of photons contributing to the

measurement: the signal-to-noise ratio is equal to the square root of the number of photons.

As an example: in CT it is necessary to perform up to a million precision measurements per scan. One measurement may involve as few photons as 50 or as many as four million. The signal-to-noise ratio of the low signal would be about 7, for the high signal it would be about 2,000.

In order to increase the information in the image, more photons have to be applied when generating the image detector response. In x-ray imaging with a given piece of equipment this is generally achieved by increasing the product of exposure time (or scan time) and x-ray generator current. Increasing this product, usually measured in milliamp-seconds (mAs), has at least two definite disadvantages:

- 1) The patient dose (sometimes a matter of concern) increases proportionally.
- 2) More x-ray power has to be provided (resulting in a bigger power supply and/or longer exposure time, higher installed electrical power, bigger x-ray tube, and/or shorter tube life, and/or lower throughput).

One other important point: More photons only "help" when they are being recorded by the detection system in the sense that each is giving the same contribution to the signal. In a given x-ray detection system this is often not the case. The fluorescent radiation losses in xenon gas-based CT detector arrays, for example, are in effect degrading the photon detection statistic of such detector. The parameter which quantifies the statistical performance of a detector system (and its components) is called the Detective Quantum Efficiency, or DQE. The DQE can be calculated when the underlying physics parameters are well known, K Peschmann (3), and it can be measured, most easily by comparison with a well-known standard x-ray detector. (See this report, Section 2.4.5.9 Detector Performance.)

Example: Two CT systems (alike otherwise) will deliver the same image quality if and only if their respective product of DQE and amount of x-ray flux is the same. Or:

to compensate for a factor of two lower DQE, the x-ray power (as well as patient radiation dose) has to be increased by two.

Although not as significant a factor as in conventional film radiography, scattered radiation does contribute to image noise for fan-beam CT systems. CT systems based on the "fourth generation" (stationary detector ring) sampling scheme suffer more from such scattered radiation effects than do first-, second-, or third-generation systems: The individual detector channels are taking measurements from many angles and therefore cannot be collimated to exclude scattered radiation.

2.1.2 Spatial Resolution

In the "early days" of CT the new modality had to overcome the general preconception that an imaging device had to have the relatively high spatial resolution values of screen film radiography (approx. 60 line pairs per centimeter), or at least of the Image Intensifier - TV chain (approx. 25 lp/cm), to be successful. Quickly it became apparent that the 3-D nature of CT combined with the detectivity for low contrast objects was more useful than the high spatial resolution of traditional imaging.

In CT, high spatial resolution comes at the expense of at least two of the following: higher mechanical precision/ more computer power/ larger data acquisition system (or smaller scanfield)/ longer scantime. And it certainly costs more.

In third-generation rotate/rotate scanners like the FMS, it is the number of detector and data acquisition channels which determines the limits of spatial resolution. The FMS with 672 channels has been designed for high spatial resolution as well as the largest scanfield of all scanners.

2.2 FMS Design Approach, Unique Features

The design philosophy behind the FMS 5000 is to reduce the x-ray power-demand per scan and thereby increase the number of scans which can be performed per minute or per hour or per day.

The x-ray power required has been reduced by two factors:

- 1) The x-ray tube is moved close to the patient, which increases that fraction of the total generated x-ray photons which go through the CT-slice to be imaged ("x-ray utilization"). The low x-ray power demand enables the designer to use a small focal spot, which makes the concept of moving the x-ray tube close to the patient possible, without degradation of spatial resolution.
- 2) A solid-state x-ray detector array has been developed which has a very high detective quantum efficiency (DQE). High DQE is further preserved by a scatter-rejection collimator. It is possible to use such a collimator in the rotate/rotate geometry of the FMS.

An important side benefit of the high DQE and of scatter reduction is the high dose efficiency or (genuinely) low-dose scanning of the FMS 5000.

The low peak-demand of x-ray power enables us to use a very compact and lightweight high-voltage power supply, and to mount it directly on the rotating gantry itself. This not only helps to reduce the scanner's installation space to a minimum, but putting the high voltage supply on the gantry also enabled us to employ a reliable low voltage slip-ring system. Through this slip ring--one of the many components developed especially for the FMS 5000--the equipment on the rotating gantry is powered-up, and the (digitized) CT-data get sent to the reconstruction computer.

Slip-ring connection instead of cable wrapping/unwrapping implies the following benefits:

- 1) Constant and continuous rotation instead of acceleration/deceleration; therefore

comparatively little motor drive power, "peak torque", and motor mass are required, resulting in practically noise- and vibration-free operation, easy installation, and high portability.

- 2) Slip-rings require less space than a cable mechanism, resulting in a smaller package.

Low-voltage slip rings are many times more reliable than high-voltage slip rings and even more reliable than the mechanically stressed high-voltage cables in conventional CT scanners.

Finally, low x-ray power demand per scan results in the highest patient throughput with any given x-ray tube system.

2.3 System Overview

Compared to other CT scanners, the FMS consists of a minimal number of separate units:

- 1) Scanner gantry
- 2) Patient table
- 3) Rear table support
- 4) Operator console (including computer systems)
- 5) (Optional) Operator radiation shield panel.

The purpose of the radiation shield is to be able to have scanner (plus patient) and scanner operator in the same room. In operation, the two patient table units are rigidly connected to the gantry.

Figure 1 is a photograph of the FMS engineering prototype; it does not yet show the operator console

Figure 2 is a sketch of a FMS installation in a rigid ISOshelter with less than 8 ft. by 20 ft. of floor space. It shows the five components mentioned.

Figure 3 is a block diagram showing some of the main subcomponents in the gantry, the console, and the patient table.

2.3.1 Gantry Components

Figure 4a shows the gantry subcomponents. These are:

- o X-ray tube/ anode rotation starter module/ tube-heat exchanger/ tube-shutter/ fan beam collimator (slice thickness)/ high voltage power supply
- o X-ray detector array/ data acquisition system
- o Electronic control modules (five major ones)
- o Gantry rotation and positioning system

Figure 4b shows the components of the gantry rotation system (4) in some more detail.

2.3.2 Patient Table Components

The main table subcomponents are:

- o Pallet
- o Horizontal motion control
- o Up-and-down motion control (optional) for patient loading
- o Pedestal

2.3.3 Console and Computer

As far as computer system and operator console are concerned the current FMS prototype differs from the CEP prototype (which will be the result of the next phase of the program). The present system uses a developmental computer and software. This system, shown in Figure 5, consists of a SUN 160/G workstation, the data acquisition computer (FORCE), array processors (Mercury), and backprojector system (Imatron). For the CEP this system will be replaced by a similar one with additional hardware and a new display computer, with the goal of supporting the tremendous patient throughput capability of the scanner hardware. The console (keyboard and monitor) will be integrated into one rack which also will contain the reconstruction computer hardware, disc drives, display computer, as well as an air conditioning system for operation in an extended temperature range.

2.3.4 Software

The central part of a Computerized Tomography System is a computer which is programmed to reconstruct two-dimensional images from many one-dimensional projection measurements. In addition to this very central task, computer and software also perform the following tasks:

- 1) Complete system control:
 - main power control
 - secondary power control (e.g. x-ray control)
 - gantry motion

- table motion
 - gantry and table position
 - x-ray shutter and collimator
 - data acquisition loop - control
 - scanner calibration
- 2) Safety and interlock functions
 - 3) Display system functions and control
 - 4) Image processing
 - 5) User interfacing function
 - 6) Archiving and network functions

A substantial amount of software to perform these tasks has been created. Much of the software written has been essential for speedy development work, such as checking the proper function of some of the newly developed hardware. Fairly complete software for scanner control has been written, as well as the reconstruction software and some user software for patient handling (table control), scan projection mode, CT mode, and display software. For the CEP, additional software will be generated.

2.4 Component Development, Hardware

2.4.1 Electrical System

2.4.1.1 Overview

The gantry electrical system provides power and control functions for the various components of the FMS 5000. The major portions of a CT scanner gantry consist of the x-ray radiation components, the detector and data acquisition system, the gantry rotational components, and the patient table. The electrical power system provides the motors, electronics and power supplies with the raw power needed for operation. The electronic control system coordinates all the activities of the various subsystems. The block diagram of Figure 6 shows the way the various components are connected electrically.

The electronic control system of the FMS is composed of two main modules that control the operation of the components on either the stationary or the rotating part of the gantry. The control module stationary (CMS) is responsible for the patient table and ac power distribution. The control module rotating (CMR) controls all the components on the gantry such as the radiation system, the rotation system, and the detection system. A large slip-ring electrically connects the stationary and rotating parts of the gantry assembly. The slip ring allows electrical power to be transmitted to the rotating components. A digital data interface on the slip ring allows the control system to accept commands from the computer and to send data back to the computer. A precision bearing allows a balanced mounting plate to be accurately rotated around the patient.

The ac main power coming from the primary power hook-up goes to the ac distribution panel of the gantry where it is fused, and controlled by large relays or contactors before it goes to the patient table and the power part of the slip-ring assembly. The scanner uses three-phase 208 V ac for the high voltage power supply and 120 V ac for all the accessories including the computer console.

The radiation components are the x-ray tube, heat exchanger, anode starter, and high voltage power supply.

Also associated with the radiation system is the shutter and collimator assembly. The high voltage power supply produces x-rays in the vacuum tube. The voltage and power level of the supply are controlled by the HVIC interface to the computer system. The rotating power control module (PCMR) distributes power to the heat-exchanger, the anode starter, and to the shutter and collimator assembly. The heat exchanger circulates oil through the tube housing which is used to cool the x-ray tube. The anode rotor starter rotates the anode of the x-ray tube at high speed to enable it to take the electron-beam power dissipation. The shutter and collimator control the x-ray fan beam used for imaging. All these components are computer controlled through the electronic control system.

The rotation motive system consists of a motor which is rotated on the gantry and uses a friction wheel against a stationary track to spin the rotate plate around the patient. The position of the gantry is determined by an encoder capable of resolving the angular position to a fraction of an arc-second. This precision is necessary to obtain good images. The encoder forms the input to a servo loop that is controlled by a digital motion control processor in the CMR module. The motor is driven by a servo amplifier which is powered by the PCMS module. This allows precise speed control and positioning of the gantry. The motor system is optically coupled to the computer control system in order to prevent electrical interference.

The detection system consists of the large x-ray scintillator detector array, the preamplifiers, the data acquisition system, and the interface to the computer. This system is responsible for collecting the data that are used to compose the image. The detectors use scintillating crystals, photodiodes, and low-noise preamps to convert the x-ray photons to an electrical signal. These analog electrical signals are converted to a digital format by the data acquisition system. The data acquisition system is capable of 16-bit precision over a six-magnitude dynamic range. The detector array is sampled every few milliseconds and the "view" is sent immediately through the slip ring to the computer for processing into an image.

The patient table is powered from the main ac distribution panel, and switched by the power control

section of the stationary control module (PCMS). The position of the axial drive is determined by an encoder. The index and limit switches are optical for high reliability. The motors are driven by servo amplifiers and controlled by digital motion processors. This state-of-the-art design allows the table to be accurately positioned rapidly. Powerful motors and ball-screw actuators provide reliable motion. The patient table can be controlled also manually from the gantry display panel (GDP), which displays the axial position and gantry tilt angle.

2.4.1.2 Scanner Control System Components

The electronic control system of the FMS 5000 scanner allows the computer system to control and monitor all the various operations of the scanner gantry and the patient table. The control system is an integrated, distributed, modular system that provides a high-speed data pathway through the scanner. It provides control of the x-ray system, the motion drive systems, and the data acquisition system. It responds to computer commands and controls devices that are located in different parts of the scanner. It allows high-speed image data communications over the slip-ring assembly and the main scanner control cable. It contains interlocks that ensure safety in the event of a computer or control system malfunction.

The control system consists of five major modules; the S-Bus Driver (SBD), the Control Module Stationary (CMS), the Control Module Rotating (CMR), the Power Control Module Rotating (PCMR), and the High Voltage Interface Card (HVIC). The block diagram of Figure 6 illustrates the connectivity of the various modules. The computer directly communicates via a parallel I/O channel with the SBD. The computer is optically isolated from the control system for electrical noise immunity. The SBD translates the parallel channel into the Scanner Bus (S-Bus) data protocol and signal levels. Cable drivers and receivers on the SBD allow error-free data transmission through the main scanner control cable. The SBD also interfaces console control panel functions to the computer and scanner.

The CMS, shown in Figure 7, is responsible for all control functions on the stationary part of the gantry,

including the patient table. Its primary function is data communication between the computer via SBD and the rotating components via CMR. The data path to the rotating part of the gantry is through the slip-ring assembly; therefore this data link is named the Slip-Ring Bus (SR-Bus). The CMS contains line drivers and receivers that communicate data over the SR-Bus. It forms a "T" type network, connecting the S-Bus to the SR-Bus, and tapping off a parallel channel to use for its own control functions. The CMS contains an interface to the left and right Gantry Display Panels (GDP) that are used to input keypad data for control of the patient table and gantry tilt and also display the table position and tilt angle.

The CMS controls all main ac functions through a submodule called the Power Control Module Stationary (PCMS), shown in Figure 8. Through CMS and PCMS, the computer can control the main gantry power that goes to the slip ring, the main ac power to the patient table motors, and the auxiliary devices such as warning lamps and laser alignment lights. The switching of ac power loads is accomplished by contactors for large loads and solid-state relays for the smaller loads. The emergency stop circuit overrides all computer commands and shuts off power to the rotating scan platform and the patient table. This safely brings everything to an immediate halt.

The patient table and tilt motor functions are controlled through the PCMS. The power circuits are optically isolated from the communications functions. The positioning motor system and the tilt motor system are digitally controlled servo loops that provide precise positioning and speed control. The position feedback devices (such as encoders and optical limit switches) are connected directly to the CMS, which contains the digital motion control processors. The motion control chips control the motors through digital-to-analog converters and servo amplifiers. An independant overtravel circuit shuts down main ac power if any of the motor drives should travel past the normal operating range. Additionally, the motion control processors can detect a drive that is stalled by some mechanical interference, and shut down the motor. These features enhance the safety of motion control systems capable of moving hundreds of pounds.

The rotating scan platform of the gantry is the central part of the scanner. This is where the x-ray power is generated, and where the fluence of the x-rays is detected, converted to a digital signal, and transmitted to the computer system. The CMR module is the main electronics control for the generation of x-rays and the acquisition of image data. Additionally, it controls the gantry rotation through a digital servo loop. The CMR block diagram is shown in Figure 9.

The main function of the CMR is the control of scanner view acquisition. The CT image is formed from x-ray attenuation data that are taken at a large number of different angles around the patient. These angles must be precisely determined by an angular encoder, and the DAS must be triggered at precisely the right moment in order to ensure a good image. There are several different modes of triggering the DAS for various calibrations and types of scans. The view data from the DAS are buffered locally in the CMR, and promptly transmitted back to the computer via the SR-bus and S-bus.

The CMR sends and receives data from the computer through the slip ring and CMS. CMR relays certain commands and data to the HVIC to control the High Voltage Power Supply (HVPS) for the generation of x-rays. CMR contains a special interface to the Data Acquisition System (DAS). CMR controls ac power functions and the gantry rotation motor through the PCMR module.

The PCMR of Figure 10 controls functions of various subsystems on the rotating gantry. The x-ray system requires control of the heat exchanger and anode rotation starter. The shutter and collimator require motion control circuitry. The gantry rotation drive system requires control of the power and the motor torque. Additionally, the PCMR is the electrical junction box for all the ac components on the gantry. It contains fuses, and interlocks for the electrical safety of the various components.

The High Voltage Interface Card (HVIC) contains circuitry that allows computer control of the HVPS. This module allows the computer to set the kilovoltage and the emission current, turn the high voltage on and off, and monitor the operation of the HVPS. The HVIC

is optically isolated from the CMR to provide EMI immunity. The HVIC is housed in the HVPS control chassis.

The HVIC is the data communication link between the control system of the scanner and the HVPS. The HVIC block diagram is shown in Figure 11. The HVIC contains three digital-to-analog converters (DACs), an eight-input analog-to-digital converter (ADC), and a control and status port. The DACs and ADC are all 12-bit devices, capable of resolving one level out of 4096.

The three DACs are used to select the desired voltage, tube beam current, and the filament idle current. The ADC is used to monitor these three DAC reference voltages, and to monitor outputs from the HVPS which indicate the actual values being generated by the HVPS. The control port is used to reset and enable high-voltage generation. The status port is used to monitor various fault conditions in the supply.

The accuracy of the HVIC and HVPS is checked by calibrating the HVIC to provide precise reference voltages for a given programmed control word. The ADC is calibrated so that this analog value, when converted back to digital format, yields the same number within two counts. The HVPS is calibrated at the factory using precision high-voltage measurement test equipment. This ensures accuracy in the generation of the x-ray beam.

2.4.1.3 Data Acquisition Modules

The data acquisition system (DAS) is a major subsystem of a CT scanner. It samples each of the multiple detector channels and converts the x-ray intensity signal from the detector preamplifiers into a digital word for transmission to the computer. The block diagram of Figure 12 shows the modules that form the DAS. The front end of the DAS consists of the left and right analog chassis assemblies. The control chassis samples each of the detector channels and converts the analog signal levels into a digital word. The computer system reads these data through the control electronics to reconstruct the image.

The two analog chassis contain many sixteen-channel input amplifier and filter cards that low-pass filter

the detector signals and multiplex the signals to the analog busses. The low pass filtering is necessary to properly pre-process the input signals for conversion to an image. The analog backplanes in the chassis allow the 672 detector channels to be efficiently routed to the analog-to-digital converters in the control chassis. The multiplexing converts the 16 input channels into 4 analog busses, which connect to the analog chassis via a differential cable.

The control chassis contains four analog-to-digital converter cards. These complex circuit boards contain a floating point amplifier (FPA), a sample and hold (S/H), and a 16-bit analog-to-digital (A/D) converter module. The DAS can convert signals over a large dynamic range, measuring from 10 microvolts to 10 volts. This requires the analog signal to be scaled by the floating point amplifier. The FPA will amplify a signal by 1 or 8 or 64, depending on the magnitude of the input signal. This allows the A/D converter to handle a smaller dynamic signal range. The sample-and-hold circuit holds the analog input voltage value constant during the conversion process.

The control chassis contains all the timing and clock circuitry that allows the DAS to coordinate the sampling of the input channels and the transmission of data to the computer. The DAS waits for a trigger signal from the gantry control electronics before beginning to sample the analog input channels. The input channels are then sampled in consecutive order through input channels 0 to 671. As each input channel is converted to digital format, the digital word is sent to the CMR module for transmission over the slip ring.

2.4.2 Gantry and Rotational System

By its design, the FMS 5000 gantry addresses the desired properties of field mobility, high patient throughput, and simplicity of operation. In order to achieve the mobility, the gantry has to be lightweight; aluminum alloy is used as the primary structural material. The only steel structure is the base support frame (J frame) because it supports ninety percent of the scanner weight. A large-diameter aluminum cone is used as the cantilevered beam to support the rotary plate. The cone shape is ideal as a light-weight structure for

cantilever support. Supported by the small-diameter (26.4 inches) end of the cone is the stationary inner part of a ball bearing. This bearing has a very large dynamic capacity and a predicted service life of more than a million rotations. The outer part of the bearing allows rotation of an annular circular plate of substantial rigidity. The purpose of this arrangement is to generate an aperture as large as practically possible, through which the patient can be moved during scanning.

The rotating plate carries all of the major components, such as the high-voltage power supply (HVPS), x-ray tube, shutter and collimator, detector, and data acquisition system (DAS). For ruggedization and ease of installation, a solid rotary plate is chosen as the component-support base. The structure is simple, rigid, and provides for accurate mounting of the system components. See Figure 4a.

To permit the system to scan continuously, the power input and the signal output have to be continuous. To do so, a slip ring has been designed and installed on the stationary support cone adjacent to the bearing. Its purpose is to deliver power and data signal in and out of the gantry continuously.

With the outstanding engineering design and the excellent vendor cooperation, the gantry is both simple and practical. It weighs about 1200 lb. (1400 lb. w/gantry tilt) and stands in a space of 65(H) x 62(W) x 31(D) inches. And since the gantry can be delivered as one unit, field installation is very simple.

2.4.3 Patient Table

The purpose and function of the patient table is to move the patient in a precise manner through the opening in the scanner gantry. Its motion is controlled by the operator either via the table control panels mounted on both sides of the gantry, or via the keyboard terminal and software protocols. The table is an important interface between patient and scanner system and has been constructed observing ergonomic factors. (The industrial designer observed many hours of CT scanner operation in clinical setting. He also interviewed the patient care personnel to get their input.)

Technically interesting is the patient support pallet, designed for the FMS. The pallet is scanned, together with the patient, in CT mode as well as in SPR (scan projection radiography mode). In order to keep its contribution to the image as small as possible it has been constructed from a carbon fibre reinforced shell, filled with polyurethane foam. Its cross-sectional shape is optimized to cause minimal impact on the scan data and to support the heaviest patients.

The trauma application and the high throughput requirement have caused us to design the table in a way that the scanner operator does not have to make a decision on which half of the patient he or she will have to scan. The travel of the table (and the length of the pallet) are sufficient to position any part of the body at the scan plane, once the patient is on the table.

The table consists of at least four main components (Figure 13):

- 1) Upper frame with horizontal pallet motion
- 2) Lower frame with up and down motion
- 3) "Pedestal" for pallet support and patient handling in flow-through operation
- 4) Motion control system

The patient table has been designed to fully address the need for field mobility, simplicity of operation, and high patient throughput. In the development of the table we have solved the conflicting goals of ruggedness and less weight. To accomplish the two contrary requirements, the frame structure is based on lightweight, but structurally strong aluminum alloy material in such shapes as angle, channel, and tubing. Two large channels placed parallel with rectangular tubings welded in between form the rigid upper frame of the table on which the horizontal driving system and pallet support system is mounted. Similarly, the lower frame is also constructed of aluminum tubings and angles. The whole table (including all mechanical and electrical components) weighs about 200 lbs. In operation, the table and pedestal are connected to the gantry. This connection is quick to make or break and supports the portability of the system. Figure 14 shows the dimensions of the table and gantry assembly.

The drive mechanism supports any pallet speed up to 7 inches per second and will hold positional repeatability to 1/16 of an inch.

The upper frame is supported by two parallel swingable frames. A linear electrical actuator drives the frames up or down and thus moves the upper frame up or down. The 18-in. down allows the patients to be positioned effortlessly on the table.

The pallet travel is a full six feet, allowing complete trauma scanning from head to knees without repositioning the patient. To avoid the excessive deflection of the 6-foot-cantilevered pallet, a pedestal is mounted on the rear side of the gantry. Its function is to provide additional support for the pallet and guide the pallet's linear motion. The pedestal is also an aluminum structure and weighs about 50 lb.

2.4.4 Shrouds (Covers)

Shrouds (or skins) have been designed for the scanner gantry and for the upper and lower parts of the patient table.

These covers have various important functions and properties:

- 1) Protect the inner components from environmental influences, such as spills, dirt, dust, and impact
- 2) Protect patient and personnel from moving parts, edges, electrical shock, and hot surfaces
- 3) Have a pleasing appearance for patients and personnel
- 4) Prevent RF interference (both directions)
- 5) In the case of the table shroud especially: provide good ergonomics for patient handling and operation of the equipment
- 6) Support the goal of low total system weight
- 7) Support easy maintenance of the components enclosed

Because there are so many constraints, the construction of the shrouds is a complex matter. We deviated from the customary shroud design by using rib-reinforced

aluminum sheet, (instead of glass-fiber-reinforced plastic). The 60-mil-thick aluminum has been roll-formed and its outside has been painted with polyurethane paint.

For the CEP test it will be necessary to add insulation layers and to seal the joints.

The gantry shroud parts are mounted on an aluminum shroud frame. The frame is supported by the gantry support frame. The gantry is enclosed by five shroud panels: a front panel, a rear panel, a top panel, and two side panels. Each panel, except the top one, is mounted on retractable hinges and can be opened independently and easily. (Opening the back panel requires the pedestal to be disconnected.) This makes the entire gantry very accessible and servicable.

Easy-to-interpret "pictogram" controls for the patient table are mounted on both sides of the front gantry shroud. The digital readouts are easy to read. One particular aspect of the upper patient table shroud is that it provides ergonomic support for patient handling. The patient table moves up and down in a curved path, instead of just vertically. This moves the patient up and at the same time into the gantry opening. Thus a simple bellows or a telescoping shroud would not work. Through a series of calculations and modeling, a laterally telescoping table shroud was developed.

2.4.5 Detector system

2.4.5.1 Purpose

The function of the detection system is to measure x-ray beams, attenuated and spatially modulated by the object located between the x-ray focus and the detector. Those measurements then form the database for the CT reconstruction algorithm. A complete CT detection system consists of

- 1) X-ray sensors
- 2) Preamplifiers and powersupply
- 3) Housing (packaging)
- 4) Cable connections
- 5) Multiplexed analog-to-digital convertor, often called the Data Acquisition System, or DAS.

2.4.5.2 Number of Detectors

In order to reconstruct a cross section of the size of a human body with submillimeter resolution, about half a million measurements are required. CT scanners have been and are being built with between one and thousands of detector channels. Short scan times on the order of seconds are being achieved with systems employing hundreds of detector channels. The FMS has 672 detector channels.

2.4.5.3 Design

At the beginning of the program we had to decide on the x-ray sensor principle to be used. Imatron's engineers have many years of experience with the two detection principles used in rotate/rotate CT scanners: Xenon gas ionization chamber arrays (3) and solid-state detector arrays (4).

For the FMS, a 672-channel detector array has been designed. Each channel is composed of a scintillator crystal mounted on the light-sensitive surface of a large-area silicon photodiode.

The reasons for this choice are:

- 1) The Detective Quantum Efficiency (DQE). The DQE of solid-state detectors is superior to xenon-based detectors. About a factor of three less x-ray power is required for the same contrast/detail performance, supporting the overall goal of continuous triage operation.
- 2) Shelf life. The shelf life of a solid-state device is superior to that of a gas-based device wherein one relies on an O-ring rubber gasket sealing a pressurized (10-20 atmospheres) container over an extended period of time and range of temperature.

It should be mentioned that recently the manufacturer of the majority of the xenon-gas-detector-based CT systems introduced an optional solid-state detector array, called "highlight". Clinical studies have now verified that this new solid-state detector requires a factor of

two to three less radiation for the same resulting image information.

Currently the FMS detector uses Cadmium Tungstate (CdWO_4) single crystals as the material to perform the x-ray-to-light conversion. Future progress can also be expected to result in better light-to-photocurrent conversion efficiency, which then would allow us to reduce the currently very tight and costly specifications of the silicon photodiodes.

The detection system of a CT scanner is a device with very high precision:

- 1) In CT the precision of a digital computer is applied to mathematically reconstruct images with high level of information content and accuracy. The data acted upon by the computer are supplied by the detection system which therefore has to match this precision.
- 2) Diagnostic x-rays are strongly attenuated when passing through tissue. The ratio of the highest x-ray signal (the "air signal") and the smallest signal in the FMS 5000 (the dynamic range) is 500,000. The detection system has to precisely measure signals of such different magnitude.
- 3) Naturally the mechanical precision has to match the spatial resolving power of the imaging device. The FMS 5000 has a standard resolution of 8 linepairs per centimeter, corresponding to about 0.025 inch. In order to preserve this resolution, the mechanical precision in the detector and in many structural scanner components has to be about ten times better than that, or 0.0025 inch.

The steps of the design were as follows:

- 1) Choose the appropriate sensor principle.
- 2) Choose the scintillator material.
- 3) Choose the number of channels in the array.
- 4) Choose the aperture height.
- 5) Choose the scintillator thickness.
- 6) Choose the light collection parameters of the scintillator.

- 7) Choose the photodiode parameters (deadspace between channels, diffusion parameters, electrical impedance-dc/ac (over temperature), substrate material.
- 8) Choose detector-collimation principle, collimation ratio.
- 9) Design collimator and its production jig.
- 10) Design pre-amplifier circuit and signal conditioning (dc/ac properties, like: stability, bandwidth, noise, 1/f-noise, crosstalk).
- 11) Choose operational amplifier and passive components.
- 12) Design amplifier/signal conditioner printed circuit board lay-out.
- 13) Design interconnects, grounding scheme.
- 14) Design packaging (housing), mounting and adjustment means.
- 15) Design environmental detector control.
- 16) Design scintillator assembly fixture.
- 17) Design sensor and sensor/amplifier test fixtures.

The design of a CT detector system is a creative process with input from vendors, and involving multiple steps of testing, prototyping, and mathematical modelling. Such a detector incorporates mostly custom-made components.

2.4.5.4 Scintillator Crystals

The scintillator material of the FMS 5000 detector is being used widely in CT scanner systems with stationary detector rings, for example the Picker-Imatron C-100 Fastrac). The single-crystal cadmium tungstate material is shaped into elongated rectangular prisms, one long side of which is glued with an optically transparent epoxy to the light-sensitive surface of the silicon diode. All other surfaces are painted with reflective paint. The x-radiation hitting the surface of the crystal, which is directed to the x-ray tube, penetrates into the material and causes the radiation-induced luminescence. About 5 percent of the x-radiation energy is converted into light energy, which is propagated in the essentially clear crystal material. The light "leak" out of this high-refractive-index cavity is mainly directed into the photodiode. The number of 5% energy conversion efficiency means that on the average one

x-ray photon generates 1200 light photons, of which about 300 contribute to the electrical photodiode signal. The efficiency of the light-photon-to-photocurrent conversion is very high (approx. 75%). These numbers mean that the x-ray photon statistics, which ideally should limit the density resolution in the CT image, are not spoiled by the statistics of the x-ray-photon-to-light-photon conversion.

2.4.5.5 Photodiodes

The FMS uses custom-designed silicon photodiodes to "read" the crystal luminescence and convert it into a "photocurrent." The photodiodes are optically coupled through a transparent epoxy to the light-emitting crystal. The surface of the silicon devices is passivated to prevent impurities from diffusing into the high-purity silicon material. The FMS photodiodes have an additional non-standard diffusion, which we believe will render the device insensitive to contamination during operation under extreme environmental conditions.

2.4.5.6 Detector Collimator

A radiation collimator with 672 precision channels has been designed for the FMS; it is mounted onto the front of the detector array. The main purpose of this collimator is to reduce the receptivity of the detector to multiple scattered radiation, mainly from the edges of the scanned object. This collimator increases the precision of the FMS 5000 as a quantitative tool for the exact measurement of x-ray densities. In particular, it causes a uniform phantom to be displayed ideally flat without the necessity of any software correction.

2.4.5.7 Preamplifiers

Some 672 electronic preamplifiers are required to convert the rather faint photocurrent of the silicon light-detection devices into a signal (voltage). The simplest circuit (and the circuit with the best performance) we have found, is the so-called transimpedance configuration. It essentially involves one operational amplifier and one resistor with value R .

The voltage signal U generated by the diode photocurrent i is, with great precision, $U=R*i$.

The art is to pick the best-suited operational amplifier, the best resistor and capacitor, and the best lay-out and printed circuit board technology. The possible number of pitfalls is, considering the simplicity of the circuit, amazing. The goal of the development was to achieve (followed by realized values):

- 1) High sensitivity (input signal current: min. 0.5 pico ampere, max. 0.1 micro ampere)
- 2) High offset stability (± 10 microvolts)
- 3) Low "one-over-f noise" (see next paragraph)
- 4) Low noise floor (20 microvolt rms)
- 5) High signal resolution (one in 500,000)
- 6) High linearity
- 7) Low temperature drift
- 8) Low power consumption/self heating
- 9) "Affordable" components (the cost multiplier is 672!)
- 10) Low sensitivity to electromagnetic interference (hum component lower than 10 microvolt peak to peak)
- 11) Low electronic crosstalk (-90 dB for neighbors)

Extensive testing was performed on a variety of operational amplifiers with different operational principles, like "chopper" amplifiers, as well as normal biased op-amps, amplifiers with junction FET-input, discrete FET input, as well as bi-polar input were also tested. One of the surprises of this activity was that, at least in regard to $1/f$ noise and offset stability, catalog information turned out to be misleading.

The $1/f$ noise is a phenomenon pervading almost every area of high-gain analog electronics. The letter "f" stands for frequency and $1/f$ expresses the fact that this noise approaches a singularity at very low frequencies. It therefore is related to offset stability.

The $1/f$ noise is often attributed to surface contamination of silicon devices. Resistors as well can show $1/f$ noise many times higher than they should have.

Unfortunately, $1/f$ noise is not quoted in the specification books of the manufacturer.

We have found that the presence of $1/f$ noise in the sensor train of a CT scanner can be detrimental to image quality. $1/f$ noise falsifies the highly attenuated ray measurements and therefore, in general, leads to image artifacts or at least increased noise, or both.

2.4.5.8 Packaging, Maintenance

The photodiode array of 672 channels and the associated preamplifier array are composed of modules. One module contains 16 channels. The number of modules for each modularized component is 42. The circular detector arc is approximated by a 42-sided polygon. The detector housing is a curved aluminum box with the sensor arrays precisely mounted within it. The housing has to be totally light-tight since the photodiode sensors are essentially low-level light detectors, and the x-ray measurements would be rendered false by an added external light signal.

The detector is designed to be maintenance-free. With 672 channels with a specified precision and stability of 1 in 500,000, however, and about 5000 individual components, failures can occur. The FMS detector is designed for instant exchange with a spare part. Its modular design allows repair by a field service engineer.

The scanner is designed to degrade gracefully with detector channel failure. Software automatically recognizes a defective channel. The operator then activates a correction routine which will discard that detector's measurements and will replace them with automatically derived best estimates.

2.4.5.9 Detector Performance

Ultimately, the performance of a CT detector system can best be measured after full integration in the scanner system. "The truth is in the image." In other words, a CT imaging system is the best test fixture for a CT detector. And only the final product, the image, will tell whether the detector system does its job. Hence the

whole customized system has to come together in order to be able to "release" or "sign-off on" a detector design.

During the bench test (Phase I) of this CT development program we had the chance to test the complete detection system design before it was integrated with a rotating gantry. In the bench test the rotation of the x-ray tube plus detector around the object to be scanned was simplified and simulated by reversing roles: rotating the object within the stationary assembly of detector and x-ray tube.

Measured detector performance:

1)	Offset stability	+/- 15 microvolt
2)	Noise floor	20 microvolt rms, typical
3)	Dynamic range (signal/noise)	500,000
4)	Collimation ratio	1:10
5)	Sensitivity	20,000 V/mA photo current
6)	Total cross talk	< 1%
7)	Overall DQE	0.67
8)	X-ray response	167 mV/mA tube current

The DQE (detective quantum efficiency) is possibly the single most important parameter of any medical x-ray imaging device. This has been discussed in some more detail in the previous section "Design approach statement."

Sir Geoffrey Hounsfield, inventor of CT scanning, has questioned whether the detector principle (small scintillator crystals optically mounted on large area silicon photodiodes and coupled to electronic amplifiers) makes a viable CT detector with high detective quantum efficiency. He suggested that we measure the basic photon detection capability of our cadmium-tungstate on silicon photodiode detectors. He was concerned about degradation of the x-ray photon statistics through effects such as

- 1) weighting of light photons (generated by the x-ray photon) caused by different trajectories, involving reflection on the various crystal/paint surfaces;

- 2) direct interaction of x-ray photons with the silicon photodiodes;
- 3) poor matching of the photosensitivity of the photodiodes to the spectral output of the scintillators.

Dr. Hounsfield said that a comparison of the signal-to-noise ratio at a given photon flux and at rather low detection bandwidth would satisfy his curiosity, as long as the detector was compared to a sodium-iodide crystal mounted on a photomultiplier. We obtained such a system from Harshaw (a 1.5-in.-long by 1.5-in.-diam. Tl-doped sodium iodide crystal mounted on a PMT) and we used a dc x-ray source. We carefully shielded the two detectors and outfitted both with a collimator.

The electronic was bandlimited in both cases with matching filter. The results are given for three bandwidths, 1 kHz, 0.3 kHz, 0.1 kHz, where the 1-kHz values are thought to be slightly affected by differences in the roll-off function. Peak-to-peak values were measured using a sensitive plug-in to an oscilloscope.

Table 1 gives the results corrected for noise-floor offset, distances (signal correction factor of 1.11) and beam attenuation (signal correction factor 1.15). The radiation was 61 kV dc, 0.7 mA, 0.4 mm steel filter, 28-ft distance. The PMT load resistor was 100K, and the photodiode amplifier feedback resistor was 10 Mohm.

It was concluded that within the precision of the comparison (10%, probably 5%) the cadmium tungstate-photodiode and PMT detectors showed very similar signal-to-noise ratios at bandwidth and radiation levels of CT systems. This result qualifies the cadmium tungstate-photodiode-amplifier detector system for the FMS.

TABLE 1 Results Corrected for Noise-Floor Offset

NaI(Tl)-PMT Signal 2.4 V					
Measured Noise p-p (mV)	rms (mV)	Bandwidth	S/N	Measured Ratio	Ideal Ratio
368	61.4	1 k	39	> 1.79	1.83
206	34.4	0.3 k	<u>70</u>	> 1.74	1.73
117	19.7	0.1 k	<u>122</u>		
CdWO ₄ -Photodiode Channel Signal 5.3 mV					
Measured Noise p-p (uV)	rms (uV)	Bandwidth	S/N	Measured Ratio	Ideal Ratio
837	140	1 k	38	> 1.9	1.83
434	72.3	0.3 k	<u>73</u>	> 1.78	1.73
245	40.8	0.1 k	<u>130</u>		

2.4.6 X-ray System

2.4.6.1 X-ray Tube

The x-ray tube is an important factor when addressing the throughput issue: Per design, the FMS 5000 has the highest x-ray power utilization/ throughput, and the largest reconstruction circle diameter. The tube had therefore to be of a custom design: it allows us to use a very large fan angle, 61 deg, position the tube close to the patient, and still cover the largest reconstruction circle in the industry (53cm). In order to preserve spatial resolution at the edges of the fan, the focus had to be designed to be very "short." The focus of the FMS x-ray tube, in fact, is shorter than wide (effective size 0.9 mm wide, 0.7 mm high.

Although such a short focus tends to increase the track temperature of a rotating anode tube, the FMS tube can run with much smaller peak power, just because the tube has been placed close to the patient and a larger fraction of the tubes output is being used for imaging. As a result, the track temperature is not higher than usual. The FMS x-ray tube has a high heatload capacity target (1.5 million to 2 million heat units) in order to benefit from the associated high average tube heat dissipation. It is high average dissipation which is required when scanning continuously as specified for the FMS. Figure 15 shows the rating curve for the 1.5-kHU tube.

2.4.6.2 X-ray Shutter

The shutter developed for the FMS 5000 is a solenoid-driven device that is being used to control the delivery of x-rays to the scan area independently from the x-ray tube and HVPS status. The shutter is controlled through the PCMR (power control module, rotating). The command sent from the computer to open the shutter is received from PCMR; then a relay is actuated to apply power to the solenoid. As a safety measure, there is independent feedback to the computer (by an optical position sensor) as to the status of the shutter. This feedback signal is used as an interlock for "high voltage on." The "at rest" position of the shutter is the closed position. Power must be applied to open the shutter.

2.4.6.3 Slice-Thickness Collimator

The slice thickness collimator of the FMS 5000 has been designed as a high-precision device, utilizing a "Geneva" drive system. The collimation itself is performed by three high-precision pairs of tungsten rulers which have been machined by "wire-EDM" (electro discharge machining). Three different slice thicknesses can be selected from the scan menu. The set of slice thicknesses as it is adjusted now is 2.5/5/10 millimeters (measured at the center of the scan circle). The setting of the collimator is controlled by PCMR. The computer sets appropriate control signals to rotate the collimator in the correct direction to the desired slice width. Mechanical switches actuated by cams provide the needed positional feedback.

2.4.7 Electrical Power System

2.4.7.1 Power Input Requirements

The FMS 5000 scanner system is designed to be operated from a common five-wire 208 V ac three-phase power circuit. This type of circuit is used whenever more than ten kilowatts of power are needed by a machine. For example, lathes and milling machines in a machine shop usually use this type of input power. A three-phase circuit delivers power more efficiently than a single-phase circuit because three conductors share the current load rather than two. The three phases have 208 V ac between them at a phase angle of 120 degrees. A fourth conductor (called neutral) is ground referenced and the potential between the three-phase windings and the neutral is 120 V ac. The fifth conductor, equipment ground, is connected to the frame of the scanner and a good electrical grounding point. This is the safety ground that ensures that all scanner electrical equipment is securely grounded through a copper conductor. Neutral and equipment ground are generally connected together at the power source. The difference is that neutral carries normal load current. The ground carries only fault current. Therefore, the five-wire three-phase system provides flexible input power for both 208 V ac three-phase circuits and 120 V ac single-phase circuits.

The main power consumer in this scanner system is the high voltage power supply that provides the power to generate x-rays. This power input is three-phase current only. The peak power input for this purpose is 9.6 kW. The average power used for most scanning is about 4.8 kW. This represents a current in the three phase conductors of 45 amperes and 23 amperes respectively. The maximum duty cycle is 4/5. This current level is very moderate, requiring inexpensive cables and generators.

The rest of the gantry has low power requirements and is powered from the 120 V ac circuits of the ac power input circuit. The sum total electrical requirement of the other equipment on the gantry is about 2 kW or a current of about 20 amperes. This power is evenly distributed among the three phases to balance the current being carried in the conductors. An additional peak current requirement of 10 amperes is required when lifting a

heavy load with the patient table, but this is done only when the high voltage power is off. Therefore the peak power requirements of the scanner assembly are 10 kW maximum and 6 kW average, not counting the computer console.

The computer console requires 120 V ac to run the electronic systems, disc drives, and cooling fans. This power is under 2 kW average. This represents about 20 amperes of load current. The electrical loads will be balanced among the three phases.

Adding it all up, we arrive at a scanner power dissipation of 2.5 kW in standby mode, of 8 kW during normal scanning, and a peak power requirement of 12 kW. Air conditioning, if required, will add to this total.

2.4.7.2 High Voltage Power Supply

One of the major components of a CT system is the high voltage power supply (HVPS) driving the x-ray tube.

In the last few years, the silicon device technology for high power applications has reached the point that the traditional, vacuum tube-equipped power supplies for x-ray imaging equipment can now be based entirely on solid-state devices. The efficiency of these silicon power components is very high even at comparatively high frequencies (up to 100 kHz). This allows the step-up transformers to be made much smaller and lighter because they are run at a much higher frequency. This, combined with the diode multiplier circuit, has resulted in the recent development of the fairly compact and light "switching" high voltage power supplies.

In the FMS 5000 the entire HVPS for the x-ray tube has been placed on the rotating gantry. This, in turn, made it possible to avoid the major complication of having to transmit high voltage through a large-diameter slip-ring assembly or using bulky, failure-prone, and time-consuming cable wrap mechanisms.

The switching HVPS technology is fairly new and so it was not easy to find vendors who could promise to deliver a working prototype on schedule and within a reasonable budget. The first very promising vendor-relation unfortunately had to be given up because

of prior commitments made by that vendor to another CT company.

The most relevant specifications of this power supply are the output rating and the manner of beam current regulation. x-ray tubes require a constant potential at a constant beam current to produce a constant x-ray beam. This is achieved by using a feedback method called emission current regulation (ECR), in conjunction with a constant voltage source. The power supply monitors the beam current and adjusts the cathode filament heater in order to regulate the current. If the beam current is too low, the regulator boosts the cathode filament power, thereby increasing the cathode emission current. The output voltage is monitored and kept constant through a separate voltage regulator. This power supply will output 50 kV to 140 kV at beam currents of 0 to 60 mA. The filament supply will deliver 60 watts to the cathode heater. The output is balanced around ground potential, with the positive multiplier capable of +70 kV and the negative multiplier supplying 70 kV maximum.

The block diagram of the high voltage power supply is shown in Figure 16. The power supply consists of four functional modules, the control chassis, the driver chassis, the positive multiplier, and the negative multiplier/filament supply. Main ac power (208 V ac three-phase) is supplied to the control chassis, where it is converted to the primary low voltage dc drive voltage required by the switching regulator. The control chassis contains the high voltage interface card (HVIC) which allows the computer to set the power supply output, turn the high voltage on and off, and monitor the output and fault conditions. The control chassis contains the high voltage feedback monitor circuits which adjust the pulse width of the switching regulators, thereby regulating output. Additionally, the control chassis monitors fault conditions in the power supply, and shuts off output when necessary.

The driver chassis contains the high frequency switching bridge circuits, high current drivers, and the high voltage transformers. The primary dc current is pulse-width modulated by the switching current drivers into the primary of the transformers where it is stepped up by a factor of roughly 20. The secondary windings of the high voltage transformers are connected via high

voltage cables to the positive and negative multipliers where the voltage is multiplied by a factor of 10. The driver dissipates most of the excess heat so that the chassis is fan cooled.

The positive multiplier delivers 0 to 70 kV to the anode of the xray tube. It is a sealed design utilizing state-of-the-art insulating compounds. The negative multiplier is similar but contains an additional transformer that is used to supply the cathode filament heater with up to 10 amps of low voltage dc current.

The testing of the prototype high voltage supply was performed at the vendor using special equipment designed for high voltage measurements. The control interface was tested by commanding the supply to provide several different voltages and currents and the output was calibrated to provide about one percent accuracy on the setting and monitoring of the high voltage output. The output of the supply was connected to an x-ray tube to test the emission current regulation. The output of the supply was connected to a large resistor array to test the peak output capability. The supply was burned in for 48 hour at 140 kV and 25 mA. The outputs were continuously monitored for this period and there were no variations. The fault and arc protection of the supply was tested by repeatedly arcing the output to ground and observing recovery.

2.4.7.3 Slip Ring System

The slip ring is one other component which has been custom designed and built for the FMS 5000. It enables us to:

- 1) Rotate the gantry continuously (only interrupted for scan projection data acquisition) and avoid the interscan delay imposed by the otherwise required reversal of the gantry rotation between scans.
- 2) Ensure portability of the system because with the continuous rotation, the gantry does not have to be secured to a massive floor construction, which would otherwise be necessary to dampen shock and vibration during acceleration.

- 3) Use a low-power, low-weight version of the gantry rotational drive because high acceleration is not required.
- 4) Eliminate the mechanically stressed, wind-up high voltage cables of CT scanners that are known to be an important reliability issue.

The reliability of slip rings has been proven in a multitude of military equipment and installations (i.e. tanks, radar antennas, and gun turrets).

The slip ring assembly consists of the slip ring subassembly and the brush block subassembly. The slip ring consists of many electrically conductive rings, most of which carry digital information. Wider rings carry power to the rotating components. The slip ring is mounted to the stationary mounting cone of the gantry assembly. The brush block subassembly consists of a power brush set and a digital signal brush set. They are mounted together on the rotating assembly and provide all the electrical connections between the rotating part and stationary part of the gantry assembly.

The main power to the gantry consists of a five-wire 208 V ac three-phase circuit. Three of the main conductors are used to provide the three-phase circuit which can carry up to 50 amperes on each conductor with 208 V ac between any two of the three wires. The high voltage power supply and the x-ray tube anode rotor controller use three-phase power. A fourth main conductor carries the main power neutral line which provides 120 V ac between it and any of the three-phase wires. This is used to power all the 120 V ac devices on the gantry. A fifth safety ground conductor is used to connect the frames of all the electrical equipment on the gantry together and to an external safety ground, such as a water pipe. This conductor carries only fault current which can result from a short to the frame or from an x-ray tube arc. This frame ground also serves as the tie point for all electrical shielding used in the system.

Digital information can be passed both ways over the slip ring assembly. For this purpose, a proprietary digital interface called the Slip Ring Bus (SRBUS) controls the flow of information from the computer system to the gantry control modules. A special digital

signal standard is used to ensure accurate information transfer in the presence of electrical noise. The transmission-line characteristics of the slip ring assembly were carefully analyzed and tailored to provide a data rate capability of over 1 million data transfers per second. Special shielded cable assemblies and terminations are used to connect the slip ring assembly to the control module circuit boards.

The slip ring performs well in the prototype scanner. The power losses are nearly zero, because the power rings and brushes are overdesigned. The digital data transfer exceeds all expectations. The signal quality is better than if the data had been transmitted through 20 feet of cable. The time distortion due to the rotation changing path lengths is not measurable. No electrical interference problems were noted.

2.4.8 Developmental Computer System

During the development of the FMS 5000 product, a computer system architecture was used that differs significantly from the final configuration to be shipped with the scanner. The needs of hardware and software debugging require that the reconstruction be performed on a higher level workstation-type computer system. The programming is also developed on this workstation. When everything works well on the workstation, the software and processing hardware are ported to the reconstruction computer, where it runs much faster. The block diagram of Figure 5 shows the development computer architecture.

The fundamental difference between the development system and the computer system for the CEP is that reconstruction is performed on the UNIX Sun 3/160G workstation. As a result, the array processor and backprojector hardware are connected to the Sun 3 computer system. The reconstruction computer only controls the scanner and acquires the raw data. The Sun 3/160G is a grayscale graphics display system capable of displaying full-resolution images.

The user interface for operating the scanner is incorporated into the Sun 3 window environment. The operator chooses from a menu the various options such as the x-ray power level, the slice thickness, and type of

scan. The Sun 3 passes this command over a serial data link to the target data acquisition computer. The target computer performs the requested scans, acquires the data, and stores the scan data to its local disc. The data acquisition takes four seconds and three seconds are required to store it on disc.

The raw scan data are uploaded to the Sun 3 from the target computer over a high-speed parallel data link. This takes about seven seconds. The raw data are converted to integer format, and pre-processed using the calibration data. The processed view data are then backprojected in the dedicated hardware backprojector. A low-resolution image takes only eight seconds to reconstruct. The high-resolution image takes about 30 seconds using this hardware setup. When the reconstruction is performed on the real-time system instead of the Sun 3, a speed improvement of eight times is expected.

The image data are stored on the Sun 3 local disk. To display the data, the image is read from disc, scaled for the display, and written to the display memory area. This process is assisted by an array processor with DMA, so that initial read and display takes about two seconds and re-scaling takes about half a second. In the actual product, these functions would be performed by a dedicated graphics processor.

The image data are displayed on a 19-in. diagonal size grayscale monitor. The operator has a keyboard and mouse to control the computer programs. The Sun window environment is used to provide a user friendly graphics interface. The image scaling, window and level, is performed in hardware to provide 128 (will be 256 in the final system) gray levels in hardware. The full range of 4096 Hounsfield units is accommodated by re-scaling the data using the array processor to perform the function in a half second.

The Sun 3 computer has an auxiliary terminal, which allows two people to develop software at the same time. One can test the programs while the other debugs the code. The development computer system is connected to the Imatron software development system via an Ethernet network. This allows the main file servers to be used to compile and store the software programs, so that orderly tracking of the revisions can occur.

2.4.9 Computer System (CEP)

The computer console for the FMS 5000 scanner is an integrated system that performs scanner control and data acquisition, image reconstruction, image display and manipulation, and data storage and communication functions. All electronic hardware is packaged in one rack, with the display monitor and keyboard in the top section, and data processors and disc drives contained in the bottom section. The packaging is designed for easy transportation and installation. Additionally, the unit will be ruggedized for field use by shock mounting critical components such as power supplies and disc drives and by the use of air conditioning to accommodate high ambient temperatures.

The FMS 5000 scanner is designed to perform scanning, image reconstruction, and image display functions simultaneously. Additionally, the processing hardware must keep up with the throughput rate of this advanced scanner. Acquiring the scan data, processing the raw data into an image, saving the image to disc, and viewing the image on the display all occur in a "pipelined" manner within the single scan cycle time of the system. For example, lets look at the processing sequence for a scan cycle time of five seconds: which consists of four seconds of scanning with one second to move the patient table.

Processing of the scan data can begin with the acquisition of the first view, immediately after the scan has started. The time needed to reconstruct the first scan using the reconstruction computer is approximately five seconds. Therefore the image will be ready to transmit to the imaging workstation about two seconds or so after the first scan is complete. If the workstation requires three seconds to read the image data, store it on disk and display it on the monitor, the first scan should be ready to view about five seconds after it is performed. Note that while the reconstruction and display of the first image is happening the scanner is acquiring a second scan. This image is displayed on the monitor at the beginning of the third five-second period. Therefore, all of the major processing tasks, data acquisition, image reconstruction, and image storage and display can take at most two scan-cycle times with each task running concurrently. The processing tasks keep up with the

scan cycle time with each image displayed five seconds after the scan is completed. Patient scanning will never need to be interrupted to allow the rest of the data processing to catch up.

The goal of performing all these tasks concurrently is best achieved by a parallel processor, multitasking, real-time system with dedicated computer hardware to perform the computationally intensive tasks. The dual computer approach of Figure 17 has been chosen because the tasks differ considerably in the manner in which the computer system must respond to real-world events. Scanner control, data acquisition, and image reconstruction require a computer system that can respond to conditions in real time. These tasks are performed by the reconstruction computer. This computer system has the necessary hardware and software to allow efficient scheduling of tasks so that all requests are promptly answered. Additionally, this system is provided with array processors and backprojectors to speed up the reconstruction task. The second half of the dual computer architecture consists of the imaging workstation. This computer has a sophisticated user interface that allows the radiological technician to perform the sequence of scans required and to review the images as they are reconstructed. It also allows the radiologist to review the images, compare images, and perform certain graphical and mathematical functions on that data to arrive at a diagnosis.

The reconstruction computer performs the functions of scanner control, data acquisition, and image reconstruction. It is the real-time computer that manages all tasks that requires prompt attention. The basic computer system is a VME bus-based microprocessor system. A fast 32-bit CPU with a large array of dynamic memory and fast instruction cache is used as the central processor. The scanner interface consists of an optically isolated parallel port that uses direct memory access (DMA) to acquire the raw data that are used to construct the image. The scanner receives its commands over the same interface. The system has its own large capacity disk for storage of calibration and raw data files. The communication pathway between the reconstruction computer and the imaging workstation is a high-speed parallel data link. The raw horsepower required for fast image reconstruction is provided by up to four array processors running in parallel. Each

array processor contains local memory and a DMA channel. They perform the calibration and convolution functions on the raw data. The process of backprojection is the computational algorithm used to form CT images from the convolved raw data. This occurs in a special hardware unit dedicated to this function called the backprojector. The backprojector is given the convolved data over a parallel data link, computes the image, and passes the finished image back to the computer. A real-time operating system is used for this computer system. The operating system sets up the filing system, launches the applications programs, and schedules tasks. This computer system is not flexible because the array processors, backprojector, and scanner interface all require custom hardware and software interfaces. This computer system is the hardware engine that drives the scanner and so it is optimized for that task.

The imaging workstation provides the user interface for the system. All interactions between the operators and the scanner occur through this computer system. This workstation can be one of several different types. There is flexibility in the choice of this computer system because it is fairly hardware- and software-independent. A lower performance workstation can be substituted for a cost savings. A high-performance color system could be used for fancy graphics or three-dimensional rendering. A network interface is provided to allow a number of other workstations access to the image data from the scanner. Thus the images would be available to the radiologist in his office, or the surgeon in the operating room. The images could be transported by magnetic or optical media, or transmitted by modem or optical network.

The imaging workstation chosen for the FMS 5000 is a ruggedized Sun series 3 product. This is one of the leading graphics workstations used today. The basic configuration consists of a set of standard sized (6U) VME cards that implements a graphics workstation similar to the Sun 3/160G model. The main processor card is a 20 MHz 68020-based computer with a 68881 floating point co-processor, 4MBytes of local memory, two serial ports, and a memory management processor that delivers 3 MIPS of integer performance. A second VME card contains an additional 4 MBytes of DRAM connected to the P2 expansion bus. Another card controls a SCSI hard disk of 320 MBytes, SCSI 1/4-in. tape drive, and an Ethernet

network interface. A third-party graphics subsystem consisting of two VME cards is used with 1024 by 1250 line resolution and 8 bits (256 levels) of gray-scale display. A local graphics processor allows scaling and other functions to be performed quickly without the assistance of the main CPU. An optional array processor can be installed to speed up graphics performance and to provide fast region of interest calculations. The data link to the reconstruction computer is implemented via a parallel data port.

The operating system for the imaging workstation is the Sun OS version of the Unix BSD operating system, with network and graphics enhancements. This operating system is the real reason for the popularity of the Sun workstation computers. It manages to integrate the highly popular Unix operating system with the Ethernet network to distribute system resources. Additionally, it provides a graphical windowing user environment for applications programs. This operating system promises to remain the mainstay of high-performance workstations.

The layout of the console operator panel is shown in Figure 18. The primary readout device is a single CRT screen that mixes multiple image display with menus for scanning, reconstruction, and viewing. The monitor chosen is a 19-in. high-resolution gray-scale type. The large size is to accommodate all the menus required to scan, reconstruct, and view the images on a single screen.

The input devices consist of a keyboard with function keys and numeric keypad, a graphical pointing device such as a mouse or trackball, and dedicated window and level controls. The keyboard is used to input patient data, scan parameters, and other alphanumeric data. A graphical pointing device is used to select menu options for execution, which allows the operator to point to an option and click a button to choose that option. The graphical pointing device is used to choose options, manage pull-down windows, and delineate regions of interest on the image. Two infinite turn knobs are used to provide dedicated level and window image contrast functions. The window and level controls allow the operator to adjust the image contrast easily and continuously. The input devices are housed in a folding drawer that is positioned for operator convenience and comfort.

Scanner power and x-ray generation are controlled by a separate primary control panel. This control panel and the window and level controls are the only custom user interfaces in the console. The primary control panel has the main power switch, a button enabling the generation of x-rays, an x-ray warning lamp, and an Emergency Stop button. These controls are vital to the safe operation of the equipment and are hard-wired to the scanner. The power switch controls main power to the console and the power indicators show the power status for both the gantry and the console. The Scan Enable and Abort buttons allow the operator to determine when x-rays are produced. The x-ray warning indicator is lit when the scanner is producing radiation. The Emergency Stop button cuts all power to the gantry and patient table.

2.5 Component Development, Software

All software is written in C language under Unix on Sun workstations. The software is divided into 3 main parts:

- Acquisition
- Reconstruction
- Display

2.5.1 Acquisition

The acquisition software controls the motors, the tube and all the hardware of the scanner. This program runs on a 68020 computer made by FORCE, under the PSOS operating system. The software is written and compiled on a Sun and then downloaded to the PSOS computer.

This program can run from a Sun shell window or from a 24-line terminal with no mouse. It is menu-driven with direct access from any menu to any other one. A Help menu is implemented with a brief description of all the menus available. At each menu the command "h" will give a full explanation of all the parameters the user can set. The command "h3" will print a description of the parameter number 3. In principle, the user can learn how to use the program by navigation through the help commands.

The acquisition software supports:

- 2 user modes: regular user or service engineer
- Multiple CT data acquisition
- SPR data acquisition (Scan Projection Radiography)
- Air data acquisition
- Beam hardening data acquisition
- Start or stop gantry rotation at any angle
- Offset data acquisition (for analysis)
- Test data acquisition (for testing leakage, shutter, x-rays)
- Save, read, default setup
- Memorize last setup
- Read-back technical values
- Automatic data check
- Emergency error
- Automatic file name creation

- Automatic offset acquisition before each scan
- Checks parameters before execution
- Debugging interface

2.5.1.1 User Modes

The acquisition software can be used under two modes: regular user or field service engineer.

Regular User: Technical factors are preset and cannot be freely changed.

Preset values for CT scan:

Only three modes are allowed

- 1) 750 views 135 Kev 30 mA 4s rotation
- 2) 1500 views 135 Kev 30 mA 4s rotation
- 3) 750 views 100 Kev 20 mA 4s rotation

With any of the following slice thickness:

2.5 mm
5.0 mm
10.0 mm

Preset values for SPR scan:

Only one mode is allowed

- 1) 135 Kev 15 mA 2.5 mm collimator

With two gantry positions: A/P or Lateral

Field Service Engineer: For safety, a password is required. Technical factors are free (but limited within the specifications).

Tube Voltage: between 50 Kev and 145 Kev

Tube Current: between 1 mA and 55 mA

Gantry rotation speed: between 2 and 10 s/rev

2.5.1.2 Multiple CT Scan Acquisition

The menu Setup Scan allows the user to acquire multiple CT scans. The first scan can start at any relative

position given by the user. Each subsequent scan is made after a table increment. The user will have to specify the number of scans and the increment table value. So far, only one increment can be given. This means that the multiple scans can only be equidistant. At execution time, files are written for each slice. The names of the created files are displayed on the menu. For example:

Last scans made: al03 - all0 (8 slices)

The acquisition starts where the gantry is. While the files are being saved, the multi-tasking implementation allows the program to move the table to the next position.

2.5.1.3 SPR Data Acquisition

The menu Setup Preview allows the user to acquire a SPR scan (called also Preview). The user can set the speed of the table movement to between 100 and 150 mm/s. The direction of the table (in or out) and the length of the SPR can also be set. The technical factors set by the user do not affect the technical factors set for a CT scan.

Before data are taken, the table will move to a specified position. At execution time, the gantry will first go to the specified position (Tube Orientation). The program will then ask if ready to go. The data acquisition is synchronized with the motion of the table. Hence if the speed of the table varies, the data sampling is not affected.

2.5.1.4 Air Calibration

To make an air calibration, we need to be able to take data without rotating the gantry; the menu Air Calibration allows this. At execution, the program asks if the table is not in the path of the x-rays. Then it will acquire 750 or 1500 views synchronized by a timer. The information file will be flagged as an air calibration file, so the reconstruction software will be aware of doing a calibration (as opposed to a reconstruction).

2.5.1.5 Test Data Acquisition

The menu Air Calibration can also be set for test purposes, if the user is in the field engineer mode. Under test mode, this Air Calibration menu will allow the user to leave the shutter closed and/or to leave the x-rays off. This is very useful for diagnostics and simulations. For instance, the user can create offset data (no x-rays), leakage data (x-rays on and shutter closed).

2.5.1.6 Gantry Rotation

The command "G," accessible from any menu, allows the user to stop the gantry at a specified position or to start rotating it at the specified speed. It is necessary to have the gantry rotating while acquiring CT images since data are triggered on the gantry itself.

2.5.2 Reconstruction

The reconstruction software is currently running on a Sun 3/160 with a Unix operating system. The user interface is written with the SunView primitives. It is a window mouse-driven interface. Since the reconstruction is view-independent, views are processed sequentially. The data of the view are first downloaded to an array processor (MC). Then the array processor performs all the following computations:

- o Real32 conversion from DAS format
- o Offset correction
- o Air normalization
- o Beam-hardening correction and linearization (simultaneously)
- o Bad detectors correction
- o Convolution
- o Interpolation
- o Intl6 conversion from real32

Then the view is sent to a back-projector. Without waiting for back projection to be done, the next view is downloaded to the array processor (MC).

So far the total running time for a 750-view image is 24 seconds. The convolution is made with different

selectable kernels.

The following (too many) reconstruction sizes are currently available:

530 mm
500 mm
400 mm
300 mm
200 mm
100 mm

The following image sizes are available:

512 * 512 pixels
256 * 256 pixels

The user can select to reconstruct a reduced image (one view out of three, or one view out of two) for fast viewing (6 to 9 secs). This is useful when doing multiple scans. The reduced reconstruction will create 256*256-pixel images and display them one after the other. The user can, then, select one to fully reconstruct. This saves time and disk space.

At the first reconstruction of an image, the current data base (air, offset, beam hardening, bad detectors) is attached to that file. At any other time, the user can make sure that if he reconstructs again the same data, he will get the same result, whatever happened to the data base (new bad detectors, different air, different beam hardening).

A large number of tools is also available for analysis and development purposes. For instance, data can be created after any of the following steps:

- o Reconstruction:
 - real32 conversion,
 - offset correction,
 - air normalization,
 - beam hardening,
 - bad detectors,
 - convolution,
 - interpolation
- o Adjustment of water attenuation
- o Switch off the intensity correction
- o Calibration of center

- o Batch processing
- o Standard Deviation, Average, Slope
- o Plot program for a given view
- o Plot of polygon for the beam hardening calibration value.

2.5.3 Display

The display software consists of two windows on the Sun monitor display. The first window is used to display the Preview and the reduced multiple images. The second window is used exclusively to display a fully reconstructed CT image.

Both windows have the following features:

- o Real-time selection of window and level
- o Automatic scaling
- o Manual scaling
- o Preset window and level values
- o Standard deviation and average on a rectangular or circular region
- o Read value at any point in Hounsfield unit
- o Display data of others formats (e.g., sinograms)
- o Scroll up and down for long Preview or multiple CT images
- o Plot vertical or horizontal line
- o Automatic display after the image is processed
- o Different choices of cursor

2.6 Special Issues Concerning Gantry Tilt and Vertical Table Position

The FMS 5000 prototype has gantry tilt and table vertical movement designed into the mechanical and electrical systems. At this time, the table up down function is complete, but the gantry tilt feature is only partially implemented mechanically. The electronic control features have yet to be designed and built.

2.6.1 Gantry Tilt

Gantry tilt is a key mechanical feature that must be incorporated into the design at its inception because the base of the gantry must be highly modified to support this feature. The bearings, gearbox, motor, and rack and pinion gear drive are built into the prototype and have been tested. The positioning sensors, servo amplifier, cabling, and software have to be designed to complete this feature. Most of the electronic control circuits have been designed and built into the control modules already.

Although not foreseen in the proposal, gantry tilt is believed to be necessary in the clinical setting because imaging of the head and spine are often performed at odd angles for diagnosis of certain conditions. However, gantry tilt can easily be eliminated. This may be desirable in order to improve the shock and vibration resistance of the gantry assembly. A nontilting gantry would be firmly mounted to the floor, would have full support from the base to the heavy components, could be sealed for environmental protection, and would be smaller, lighter and less expensive.

2.6.2 Patient Table Vertical Positioning: Up/Down Drive

The table up and down feature is fully implemented in hardware and software. It provides about a foot of vertical travel, facilitates patient handling. The table raises up and into the gantry in a smooth arc when the operator presses the appropriate front panel key.

Due to the compact nature of the FMS 5000, the gantry opening is unusually low (close to the floor), so that

lowering the table may not be necessary for the majority of patients. Certainly in the case of a nontilting gantry the patient table height would be lowered so far (down to about 28 inches) that the up and down motion of the patient table becomes superfluous.

3 CT SYSTEM TEST RESULTS

3.1 Image Quality Test Results

Image quality tests were performed according to the plan outlined in section 3.2.3.3 of the December 1984 proposal. A summary is provided in Table 2. Phantoms used included the American Association of Physicists in Medicine (AAPM) CT performance phantom, the Imatron Image Quality Phantom, and the Picker Low-Contrast Phantom. The AAPM phantom was used for high-contrast resolution, and uniformity measurements. The Imatron phantom was used for slice thickness measurements. Although the Imatron phantom also contains high- and low-contrast resolution tests, the FMS 5000 proved to perform at a superior level beyond the range of this phantom. The Picker Low-Contrast Phantom was used to determine low-contrast detectability.

For all tests, except as noted, the scanner was operated at 135 kVp, 30 mA, and used 4.0-second scans. The image matrix size for all tests was 512x512.

Spatial resolution: High-contrast spatial resolution of CT scanners can be measured in several ways: In one method a thin wire is imaged and the Fourier transform of the measured line-spread function gives the modulation-transfer-function. An alternative method is to image a hole pattern in which air-filled holes in lucite are spaced at various center-to-center distances. The AAPM phantom uses holes ranging from 3 mm down to 0.6 mm and spaced at twice the hole diameter. Limiting resolution can be estimated by the formula:

$$\text{Resolution (lp/cm)} = 1/(2 \times \text{hole diameter (cm)}).$$

Typically, limiting resolution was found to be approximately 0.8 mm. In the best case (15-cm diameter), the 0.6 mm holes were resolved. Thus limiting resolution is recorded at 8.3 lp/mm.

TABLE 2 Prototype Performance Tests, Summary
(X-ray tube specifications in Attachments)

Test Description	Test Goal (proposal, Dec 1984)	Test Result (February 1989)	Range: Commercial Scanners
3.2.3.1 Installation Time Test.	2 Hours	1 hours	24-600 hours
3.2.3.2 Power-Up Time Test	15-30 Minutes	15 minutes boot & powerup 15 minutes warmup (optional)	10-100 minutes
3.2.3.3 CT Image Quality Tests:			
1. Spatial Resolution	5 lp/mm	8 lp/mm	6-8 lp/mm
2. Density Resolution	.4% at 4 mm	.6 % at 3 mm	.4% at 4 mm
Std. Deviation of noise:	not specified	.56% for 10" phantom	.3-.8 %
Minimum detectability:	.4% at 4 mm	.53% at 3 mm	.4% at 4 mm
3. Slice Thickness	2.5, 5.0, 10 mm	2.5, 5.0, 10.0 mm	1.5-10 mm
4. Dose	6.6 R at 270 mAs (see page 3-12)	6.1 R at 120 mAs	2-8 R
5. Image Uniformity	0.20%	0.2% plastic, 0.4% water	.2-1%
3.2.3.4 SPR Image Quality	not specified	2.5-5.0 lp/cm	3-8 lp/cm
3.2.3.5 Patient Couch position accuracy.	0.25 mm	<.5 mm	.25-1 mm
3.2.3.6 Patient throughput SPR AP and lat., 20 level head and 20 level body.	15 minutes	5.6 minutes, reduced resol. * 14.3 minutes, high resolution*	15-30 minutes
3.2.3.7 CT Recon struction Time	29 seconds	22 seconds *	7-30 seconds
3.2.3.8 SPR Proces- sing Time	not specified	10 seconds *	10-30 seconds

*These results will be faster in the final system. A dedicated and much faster computer system will be part of the CT scanner.

This value is somewhat higher than the stated goal of 5 lp/cm. The improvement is due in part to the increase in matrix size and the number of detector elements.

Density Resolution: All density resolution measurements were made using the 10-mm slice thickness. Density resolution, also referred to as low-contrast resolution, fundamentally depends on the pixel noise in the image. Pixel noise is measured by scanning a uniform water-filled phantom and using a region-of-interest program to calculate the standard deviation of the pixel values. Standard scan parameters yielded a pixel noise standard deviation of 5.6 Hounsfield units (0.56%) for a 10-inch diameter water phantom and 16 Hounsfield units (1.6%) for a 14.5-inch diameter polyurethane phantom (density 1.08).

A low-contrast object can be seen if its density value differs from the background by about five times the noise value for that size object. In certain cases this noise value can be approximated by the pixel noise divided by the number of pixels raised to the $3/4$ power (w to the $3/2$ power law). One condition for this approximation is that the pixel size be equivalent or larger than the system resolution.

Low-contrast detectability was measured by using the Picker Low-Contrast Phantom. This phantom uses thin sheets of plastic to achieve low contrast and is relatively independent of x-ray energy. At a contrast of 0.53% contrast the minimum diameter holes that were detected was 3 mm.

The product of hole size and contrast is 1.6 %-mm, in good agreement with the value of 1.6 %-mm estimated in the original proposal. This value is also consistent with the measured image noise.

Slice Thickness: The slice thickness was measured by using a bead ramp in the Imatron phantom. This ramp is angulated so that each bead corresponds to 1 mm of thickness along the scanner axis. Slice thickness is measured by estimating the number of beads visible using the full-width-at-half-maximum to define the slice boundaries. The scanner is equipped with a variable collimator at the source that gives a nominal 2.5-, 5-, and 10-mm slice thickness. Using the bead ramp, the measured width of the 10 mm slice was found to be 10 mm.

Dose: The complete characterization of the dose profiles and distributions for a CT scanner is a complex and time-consuming process. However, the FMS 5000 uses a collimation system similar to that of many commercial third-generation CT scanners. Thus the dose distributions are expected to correspond closely to those of other scanners. Using this assumption, only a small number of dose measurements are needed to determine the normalization of dose to the x-ray current, voltage, and exposure time. Here we relied on thermoluminescent dosimeter measurements of the surface dose of a single slice as measured by Professor Siedbahn on Feb 26. Using the standard conditions mentioned above, the peak surface dose was measured to be 6.1 Rads at 120 mAs. In the original proposal we estimated 6.6 Rads at 270 mAs. The fact that the dose is higher at a given exposure mAs than was projected results from the lower degree of beam filtration actually used and the absence of a shaped (bow-tie) filter at the source as originally planned. Based on these results it is planned to consider a slight increase in beam filtration.

Image Uniformity: Image uniformity was evaluated by measuring the uniformity of density values along the diameter of a water-filled phantom. Deviations from uniformity are usually attributed to errors in the beam-hardening (linearity) correction, or to scattered radiation. Flatness is often recommended to be less than a noise standard deviation (which in our case is 0.56% - 1.6%). The proposal suggests a tighter goal of 0.2%. The actual measurement gave a value of 0.2 % using the polyurethane phantom and 0.4 % using a water-filled phantom. The difference is felt to be due to the use of plastic rather than water in calibrating beam hardening.

3.2 Scanned Projection Radiology (SPR) Mode

The SPR mode was evaluated using the following operating parameters: table speed, 10 cm/s; sampling interval, 0.8 mm; slice thickness, 2.5 mm; tube current, 15 mA; tube voltage, 135 kV.

Table Position Accuracy: The table position is used to define the slice position from the SPR image. The table was exercised several times to the extent of its travel and then asked to return to a predefined coordinate. The standard deviation of the error in positioning was found to be ± 0.5 mm. The proposed goal for this specification was ± 0.25 mm.

SPR Image Resolution: The spatial resolution of the SPR images is set in the axial direction by the slice-thickness collimation of 2.5 mm and in the transverse direction by the detector spacing, referred back to the object, of 0.7 mm. Thus resolution is low in the axial dimension. Two improvements have been suggested: A deconvolution sharpening operation that takes advantage of overlapping samples could be applied; a fourth slice collimator with a nominal 1-mm slice thickness could be added. With these improvements, a more isotropic resolution could be obtained in the 5-7 lp/cm range.

3.3 Installation Test

To demonstrate the light weight and portability of the FMS gantry and patient table, the support feet of both were lined with teflon pads. The gantry was then relocated by sliding along the plastic tile floor (two people required). The table is easily repositioned by one person. The time required to disconnect or reconnect the table and pedestal with the gantry is currently four minutes each. We have moved each component of the FMS over 100 meters, which took five minutes each (total 20 min). Placing and leveling the FMS took 15 minutes. The connection of the (only) two main power cables to the prepared outlets took five minutes; the one-cable connection from gantry to computer and the table to gantry cable connection (2) took five minutes each. Thus the total installation time is 60 minutes.

After installation, the scanner is ready to scan 30 minutes later after a 15-minute boot and power-up procedure, and allowing 15 minutes for warm-up.

In the case where the x-ray tube has been transported off the gantry in a separate (shock-proof) crate it will take another 30 minutes to install the premounted x-ray tube plus its heat-exchanger onto the gantry.

3.4 Throughput Simulation

A throughput simulation test was performed on February 28, 1989 as described in the bar graph (Figure 19). The brassboard computer system, not the x-ray system, is the limiting factor in this demonstration. The time scale on the right-hand side is valid for the CEP. The major slowdown is caused by the slow downloading of the scan data to the reconstruction computer and by the fact that data acquisition, image reconstruction, and image display are not being performed simultaneously.

Still, fast data acquisition and high scan rate have been demonstrated:

- 40 cm SPR (scan projection) in 10 seconds
- 20 consecutive CT scans acquired within 2.66 minutes. (This time to be reduced to 1.75 minutes in the final unit for CEP tests)

In the test described above, the time required for data transfer and display of the scan projection image was 10 seconds. A CT reconstruction took 7 seconds for the reduced data set reconstruction and 22 seconds for a full resolution image.

In the throughput test of the original proposal (paragraph 3.2.3.6) a somewhat longer procedure that included an extra 20-level body scan was suggested. For this test the goal was 15 minutes. Extrapolating from the above results, this expanded throughput test would be performed in 14.3 minutes, slightly under the goal.

3.5 Summary of Performance Tests

Table 2 above summarizes the results of the performance tests of the brassboard system. Column 1 gives the test description and refers to the descriptive paragraphs in the original proposal. Column 2 gives the proposed test goals. Column 3 is the actual measured brassboard performance. Column 4 gives the typical range for commercial CT scanners, and is intended to give a perspective regarding comparative results.

All test results are in the expected range and agree with typical commercial scanner performance except in the key categories of installation time, and patient throughput, where unique design goals have been achieved.

3.6 Design Characteristics

In addition to the performance tests mentioned above certain other key design goals have been achieved. These goals are characteristic of the size, weight, power consumption, etc. of the as-built system and are compared below to the design goal, and the range of typical commercial scanners.

Space Required: The footprint of the FMS is as compact as expected; the gantry width is 64 inches, depth 31 inches, and height 65 inches. It requires a space of only 90 to 160 sq. ft.

Weight of System: The weight of the components of the FMS brassboard, excluding console, is tabulated below:

Gantry, including pedestal	1400 lb
Patient table	280 lb

The total weight is 1680 pounds, excluding console, as compared to design goal of 1600 pounds (console included).

Peak Power Required: At the test operating conditions of 30 mA and 135 kV the scanner uses 8 kW of power. Of this power, approximately 5 kW are for high voltage and 3 kW for electronics and the computer. The quiescent power requirement used between patients is thus 3 kW. As discussed elsewhere in this report (section 2.4.7.1), the FMS has options for operating either at higher or lower power levels.

Other Key Design Characteristics: Other design characteristics have changed only slightly from the proposed values and are listed in the summary table (Table 3) below.

In summary the key requirements of space, weight, and power consumption have been achieved and represent a radical improvement over commercial CT systems.

TABLE 3 Design Characteristics, Summary

Design Description (Table 3-1)	Design Goal (Dec. 84 proposal)	Measured Result (February 1989)	Range, Commercial Scanner
Space Required	90 sq ft.	90-160 sq ft.	250-600 sq ft.
Weight of System	1600 lb	1600 lb	5000-14,000 lb
Peak power required	8.5 kw	8 kw	20-100 kw
Quiescent power	4 kw	3 kw	4-14.5 kw
Detectors	512 solid-state	672 solid-state	500-1000
Maximum reconstruction size	48 cm	53 cm	30-100 cm
Slice thickness	1.5, 5, 10 mm	2.5, 5, 10 mm	1.5-10 mm
Scanning speeds	4.5, 9.0 sec	4.0 sec	2-10 sec
Maximum number of scans at 9/min.	727	unlimited	9-1
X-ray power	140 kV, 50 mA	135 kV, 50 mA	120-140 kV 60-500 mA
Anode heat capacity	1000 kWh	1500 kWh	1000-2500 kWh
Image matrix size:			
CL	360x360	512x512	512x512
SPR	512x512	672x1000	512x512

4 RUGGEDIZATION CONSIDERATIONS

4.1 Mechanical Components

The mechanical ruggedization of these components will consist of shock mounting/ strong bracing and reinforcement/ various ways of securing fasteners. Elimination of the gantry tilt operation and the up-down motion of the patient table would contribute substantially to ruggedization (fewer components, more effective and simpler sealing of gantry and table shrouds) and further weight reduction.

4.2 X-ray System

The x-ray power system requires thermal management of the 3.5 kilowatts of heat it is generating at full scan load. The prototype FMS has been designed for efficient collection of waste heat. This is an important feature, especially when the system has to operate at elevated ambient temperature, such as 100 deg F. At the highest ambient temperatures the duty cycle of the x-ray system has to be reduced. Rotating x-ray tubes are difficult to ruggedize. The FMS avoids the problem by transporting the tube (as well as the spare tube(s)) in a shockproof container.

4.3 Extreme Temperatures, Gantry

The extremes of the operational temperature range can be dealt with by added heaters inside the gantry for the lowest temperature and cooling for the highest. This will be much more economical than to design all components for the full temperature range.

4.4 Computer System

The packaging of the computer systems is an important issue for a scanner that is to be field mobile. The

system must endure the shock and vibration encountered during transportation, the environmental hazards such as dust and moisture, and it must operate reliably over a wide ambient temperature range. The diagnosis of faults and field servicing must be accomplished quickly without special tools or personnel. Field service must be limited to module replacement. In addition, the system must function after a ten-year storage interval.

A wide variety of techniques may be employed to ruggedize electronic systems to meet the operational goals associated with field use. Printed circuit board stiffeners, locking card guides, and heavy duty enclosures are used to protect the electronic assemblies from vibration, shock, and environmental hazards. Shock mounting is used on disc drives, and power supplies. The large CRT monitor in this system is a special concern. This will be packaged by an outside vendor, using shock mounts and a special enclosure. The ten-year storage requirement can be met by substituting EPROMs with mask-programmed ROMs, and by using a non-volatile storage medium such as optical disk to store the operating programs. The thermal performance of the console can be improved by the use of fans, blowers, and heatsinks. The electronic assemblies used in the console can generally operate over the industrial temperature range of 10 to 50 degrees C. By using convective air cooling, this would be the approximate ambient temperature range that could be accommodated. However, the compact package and the extended ambient temperature range encountered in the field are factors that would mitigate for the use of an optional air-conditioning system for the console.

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- 4 K. R. Peschmann, J. L. Couch, D. L. Parker, New Development in Digital X-ray Detection, SPIE 34, 50-54, 1981.

6 ATTACHMENTS

- 1) Rosenberger, A et al. Diagnostic Radiology in Wartime, Israel J. Med Sci. 20:330-332, 1984.
- 2) Tube Specifications

DIAGNOSTIC RADIOLOGY IN WARTIME

A. ROSENBERGER, O. ADLER, Y. BRAUN, D. GOLDSCHER, A. ENGEL, J.K. KAFTORI, U. KLEINHAUS, M. PERY and L.Y. WEICH

Department of Diagnostic Radiology, Rambam Medical Center, and Faculty of Medicine, Technion-Israel Institute of Technology, Haifa, Israel

ABSTRACT. During the Lebanon War, 1982, over 80% of the wounded were sent from the triage area of the hospital directly to the radiology department. This article reports changes in the working pattern and organization of the department that were instituted for emergency treatment in wartime, and describes radiological examination methods for different organs. Computerized tomography is emerging as the most important diagnostic tool in addition to conventional radiological examinations.
Isr J Med Sci 20: 330-332, 1984

Key words: wounds and injuries, combat; tomography, computerized; diagnosis; radiology; military medicine

Diagnostic radiology plays an important role in assessing mass casualties and war injuries. This role of radiology has not been emphasized enough in the pertinent medical literature, in sharp contrast to the recognized importance afforded diagnostic radiology in everyday practice.

HISTORICAL NOTES

X-ray evaluation of foreign bodies and injuries in war casualties was performed only a few months after Roentgen described these new rays in November, 1895. By the spring of 1896, at the Naples military hospital, wounded Italian soldiers from the Ethiopian campaign were already being X-rayed. In all subsequent wars and conflicts at the end of the 19th century, such as the Greco-Turkish War in 1896, the Sudan War in 1898 and the Boer War in 1899-1902, radiology was used and its importance established (1). However, it was not until World War I that X-rays were extensively utilized by all armies involved, and X-ray machines became an essential part of military hospital equipment. The further development of radiology between the two World Wars was mirrored in the extensive use of radiology among the fighting armies in World War II, all of which used portable

fluoroscopic and radiographic equipment, which were standard equipment in the field hospitals (2). There is no detailed information available to us on the use of radiology in the Korean and Vietnam Wars.

Our experience in the October 1973 War regarding the importance of the radiology department has been reported in the radiological literature (3). The present paper discusses additional experience gained during the Lebanon War, 1982 with regard to the functioning of the department and the utilization of modern radiological technology (4).

ORGANIZATIONAL ASPECTS

The radiology department in our hospital is situated about 50 m from the emergency room (which serves as the triage area), on the same floor; thus, transportation and communication between these two departments present no problems. Five radiology rooms - three general and two fluoroscopy-radiography rooms - form the basic working area, and two computerized tomography (CT) units are situated next to the main radiographic area. Moreover, the corridors and waiting rooms, as well as the examination rooms of the department, are fairly large and are equipped for emergency medical care, so that wounded patients awaiting examination can continue receiving the same supportive treatment as in the triage area. When casualties are brought in, the five radiologists and the permanent staff of the department are reinforced by a large number of nurses who help in monitoring

Address for correspondence: Dr. A. Rosenberger, Department of Diagnostic Radiology, Rambam Medical Center, POB 9602, 31096 Haifa.

and treating the severely wounded. In addition, one or two physicians from the medical wards are always present in the department for the same purpose.

Flow of Patients

Positive identification of the wounded is established upon their arrival at the radiology department. The same identification number given to the patient in the triage area is retained in the radiology department, on the medical file containing the examinations and reports, and during the patient's entire hospital stay.

A senior radiographer is present when the patients are brought in, and carries out a second triage, directing each patient to the proper examination room. The radiographer is also responsible for verifying that patients are released only after completion of the radiological workup. The decision to send the patient to a CT examination is made by a senior radiologist.

Reporting

Teams of two radiologists are responsible for interpreting X-rays and writing reports; they also decide if additional examinations are necessary. The radiologists in the CT area work in an identical manner. The most effective procedure for reporting findings is to dictate them directly to a typist, so that the patient leaves the department with a medical file containing both the films and the written reports. The findings are discussed with the specialists caring for the wounded; this is especially important in cases of multisystem injuries. Based on the information furnished by the radiological examinations, the final decision on the destination of the wounded — operating theater or hospital ward — and on the plan of treatment is made. No patient is returned to the triage area.

DIAGNOSTIC PROBLEMS

Chest

The chest X-ray is still the simplest and quickest single radiological examination for diagnosing chest injuries. In the Lebanon War, as in the October 1973 War, virtually every injured patient had a chest X-ray. Patients with chest injuries were X-rayed in frontal and lateral projections. However, the often tedious and time-consuming procedure of locating foreign bodies, which used to require additional X-rays in several projections as well as fluoroscopy, was greatly simplified by emergency CT examinations. This was especially true in cases of foreign bodies in the mediastinum, near the diaphragm, and in oblique locations in the chest wall. CT is also much more sensitive in detecting slight pleural and mediastinal bleeding and slight pneumomediastinum and pneumothorax, which is especially important in patients destined for assisted respiration.

Skull

Plain X-rays of the skull were used for general orientation, and their number has been reduced to anterior-posterior and lateral views. Every patient with obvious head injury or neurological signs was sent for CT examination. CT of the skull gives exact information on the number and location of foreign bodies and on the brain damage caused by them, and the track of the missile can easily be visualized.

Orbits

The pinpointing of foreign bodies in the orbit and eyeball has been revolutionized by CT. This is especially true for retrobulbar foreign bodies, which are inaccessible to direct clinical examination, and for ocular foreign bodies when the eye media are clouded by blood. Associated soft-tissue damage can also be assessed by CT. CT is the procedure of choice when eye trauma is diagnosed clinically; conventional X-ray of the orbit and other radiographic methods for locating foreign bodies are no longer indicated.

Abdomen

The value of CT as used by us is best demonstrated in the diagnosis of abdominal injuries. The plain X-ray of the abdomen, albeit the first and basic radiological examination, is of a very low specific diagnostic yield in contrast to the chest X-ray. Therefore, in the past, additional examinations such as X-rays in different positions, contrast material administration, and angiography had to be performed. The latter was indicated to assess parenchymatous and vascular damage. These time-consuming and cumbersome procedures have been largely replaced by CT. The CT examination of the abdomen furnishes detailed information about the location of splinters and the presence and extent of accompanying organ injury. It demonstrates retroperitoneal and any significant amount of intraperitoneal blood, often obviating peritoneal lavage. It can detect much smaller amounts of extraintestinal air than can the plain X-ray. Since CT gives abundant information and is potentially easy to follow up, it can clarify the indications for laparotomy, and — more importantly — unnecessary exploratory laparotomies can be avoided. Thus, except in cases of acute life-threatening injuries, we perform a CT examination prior to any abdominal surgery.

Spine

CT examination is used as a complement to the plain X-ray for determining the extent of injury in the transverse plane, giving information not obtainable by any other diagnostic method. Vertebral alignment and penetration of foreign bodies and osseous fragments into the spinal canal can be assessed.

Blood Vessels

Direct injuries to the large blood vessels, causing profuse and severe hemorrhage, are treated by emergency surgery. Angiography is performed in some cases for studying late complications in the vascular tree, but is no longer a primary means of diagnosing organ injury when CT is available.

DISCUSSION

The relative importance of the radiology department in mass casualties and war injuries is best demonstrated by the fact that 80% or more of the injured are sent from the triage area for radiological examinations. Based on our recent experience in evaluating the usefulness of the different radiological techniques in mass trauma and war injuries, we conclude that the mainstays of the radiological workup are plain X-rays and CT. Other techniques, such as fluoroscopy, ultrasonography and angiography, are of minor value in the emergency evaluation of penetrating trauma.

The introduction of CT into radiological practice has dramatically changed the capability of diagnosing penetrating injuries and injuries caused by blunt objects. It was first used by us (5) for diagnosing penetrating war injuries in the chest. Fifteen percent of the injured who were sent for radiological examinations also had an emergency CT examination.

Additional CT examinations were done at a later stage, to evaluate complications or for follow-up. Although the primary means of diagnosing injuries to the extremities, skeleton and chest are still plain X-rays, CT is indispensable in craniocerebral trauma and in certain spinal injuries. Its cardinal role in orbital, abdominal and chest injuries is only now emerging. A major advantage of CT in diagnosing war injuries lies in its being an efficacious, fast and comfortable examination method, furnishing information hitherto unavailable by noninvasive means. Another impact of CT in a mass casualty situation, verified by our experience, is its role in establishing surgical priorities through the improved classification of the wounded.

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Attachment to IMATRON P.O. _____, 11/9/87, (EIMAC-VARIAN)

TUBE Specs

A. General:

1. The x-ray tubes will be used in computerized Tomography System prototypes and hence should have optimized performance for CT application. As an example, the focal spot movement - after moderate heat-up conditioning - should remain as small as possible and the amount of off focus radiation should be kept as small as possible.
2. Our ultimate goal is to obtain an x-ray tube/housing/heat exchanger combination which has a maximum dissipation of 3.5 or even 5 KW. Since the ideal tubemodels are still under development we intend to phase them in as they become available. This is the reason that we ordered one GS 1594 (with 60-90 days delivery) and one GS 2094 (90-120 days delivery). We would like to evaluate your 5 KW dissipation tube as soon as a prototype will be available.

B. Special features

1. Focal spot: The focal spot we require is a bit unusual in that the effective length dimension is smaller than the effective width:

Focus width 0.9mm
Focus length 0.7mm,
generated on a target with 12° angle

(The focus aspect as quoted in SL871007 is not correct)

2. The tubes will be used under up to 80% duty cycle for extended periods. The peak load will be limited to 3.5 KW. (We may have the power available to run under higher peak load if the focal spot size would allow it).
3. The fan-angle used will be 60°. The angle is limited by tube and housing ports and should be slightly larger than 60° in order to facilitate mechanical tube adjustment on the scanner gantry. In order to minimize off focus radiation a focus vignetting effect could be tolerated of about 10% at the edges of the fan.

FIGURES

- 1 Photo of the FMS 5000
- 2 FMS 5000 in Isoshelter
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- 4b Gantry Rotation Components
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- 7 CMS Block Diagram
- 8 PCMS Block Diagram
- 9 CMR Block Diagram
- 10 PCMR Block Diagram
- 11 HVIC Block Diagram
- 12 DAS Block Diagram
- 13 Patient Table Motion System
- 14 Patient Table and Gantry Dimensions
- 15 X-ray Tube Rating Curve, 1.5 MHu target, GS15 series
- 16 HVPS Block Diagram
- 17 Dual Computer System Block Diagram
- 18 Console Layout
- 19 Time Required to Scan a Patient



Figure 1 Photo of the FMS 5000

Figure 1

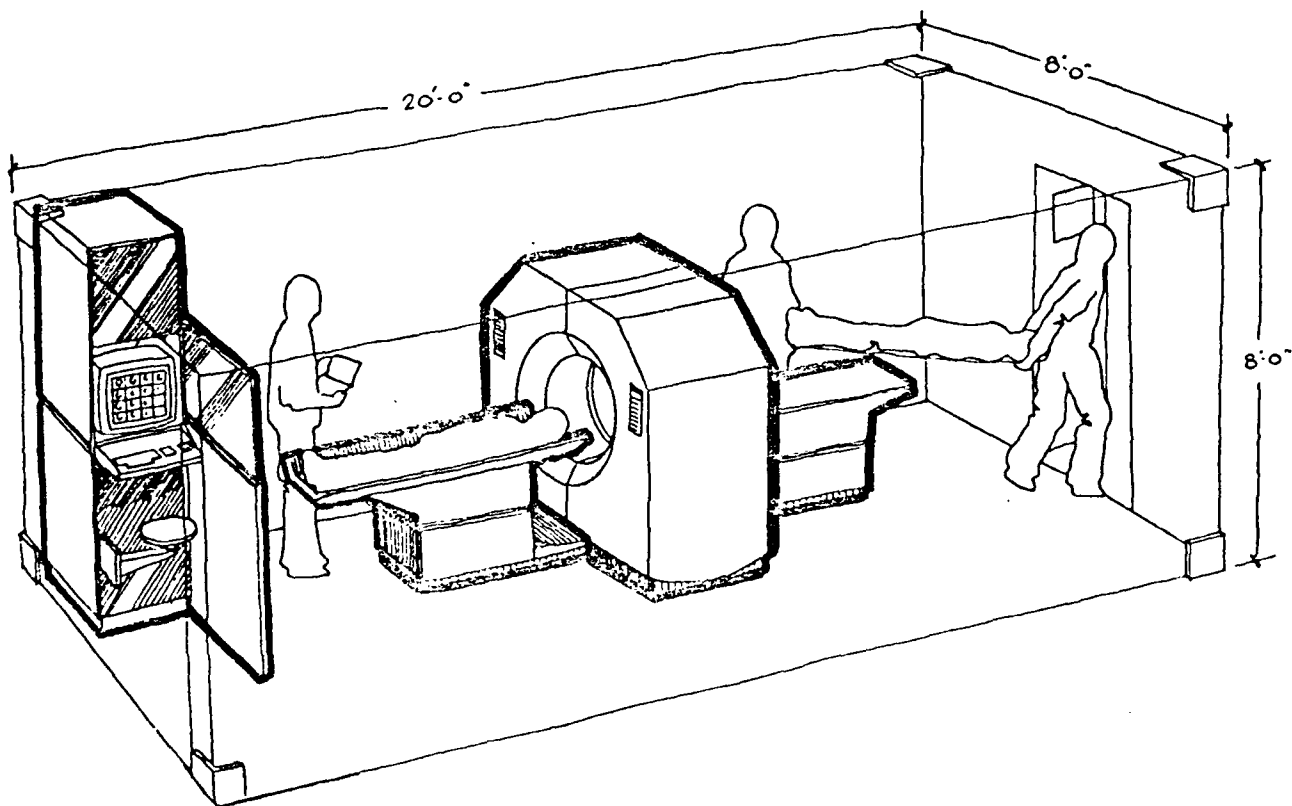


FIGURE 2. FMS 5000 IN AN ISOSHELTER

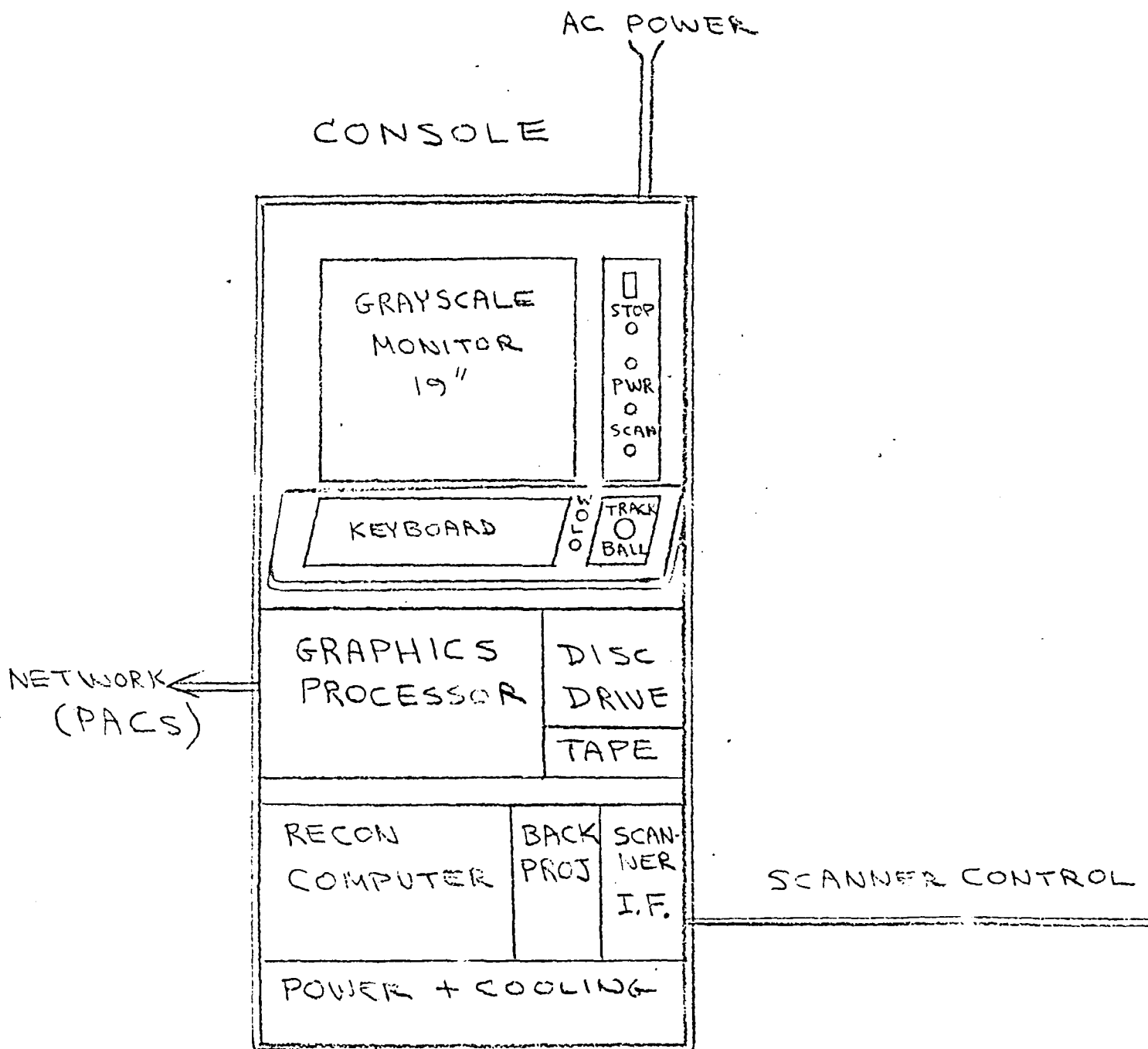


FIGURE 3. SYSTEM CONFIGURAT

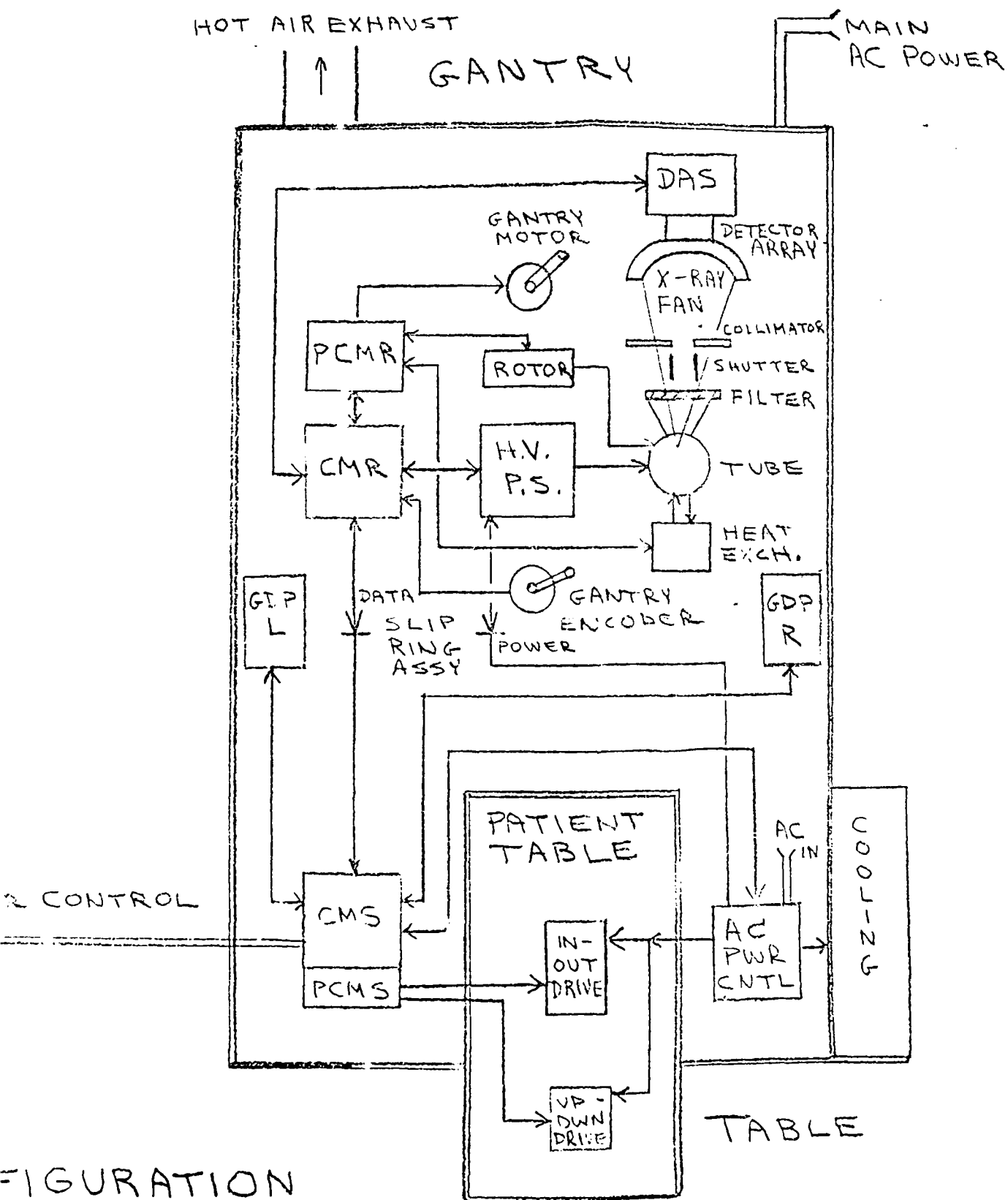


Figure 3

FIGURE 4a GANTRY COMPONENTS

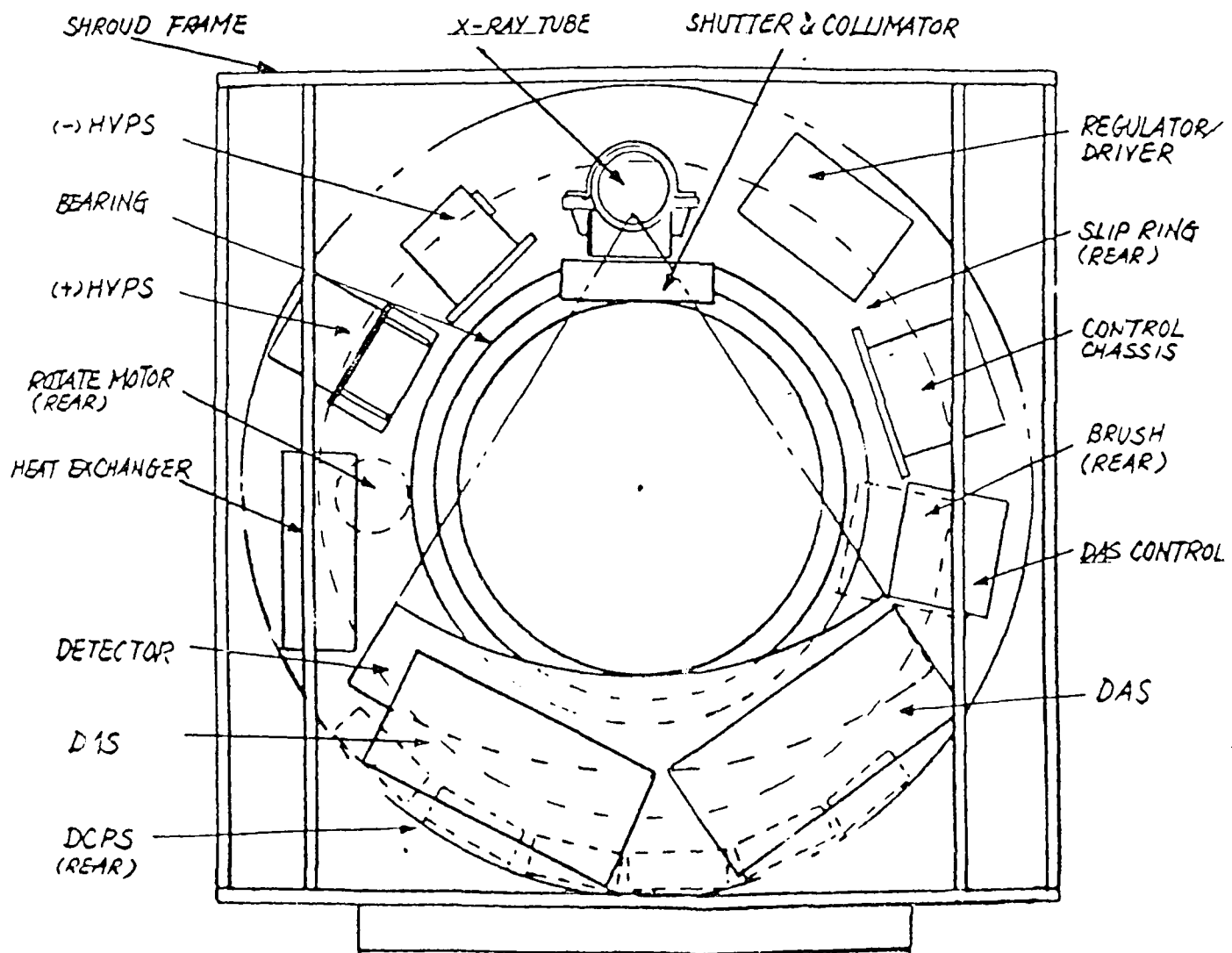


Figure 4a

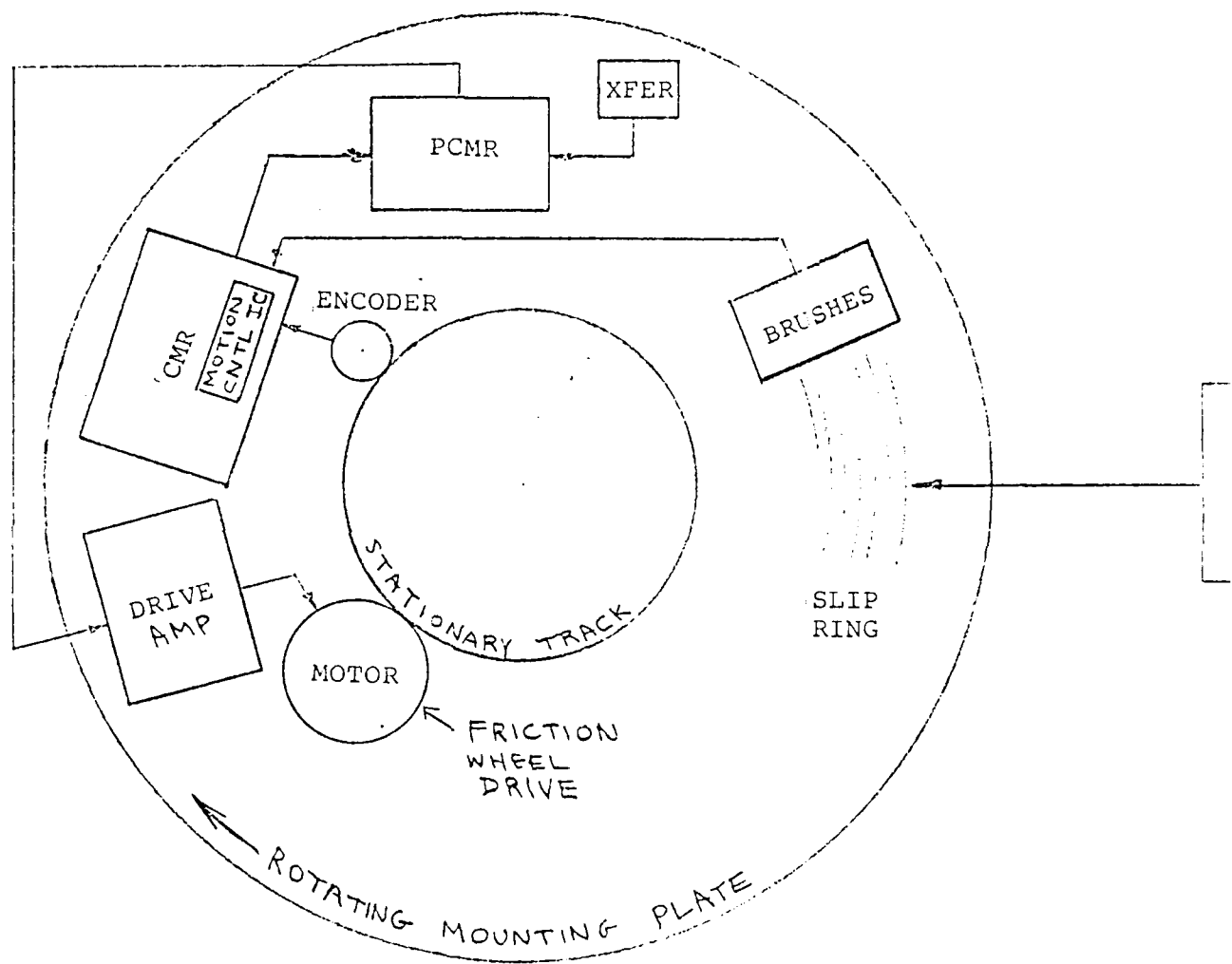
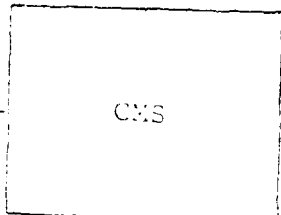


FIGURE 4b. GANTRY ROTATION COMPONENT

ROSHES

SLIP
RING



FROM COMPUTER

ION COMPONENTS

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Date: February 13, 1954 Sheet 2 of 1		

Figure 4b

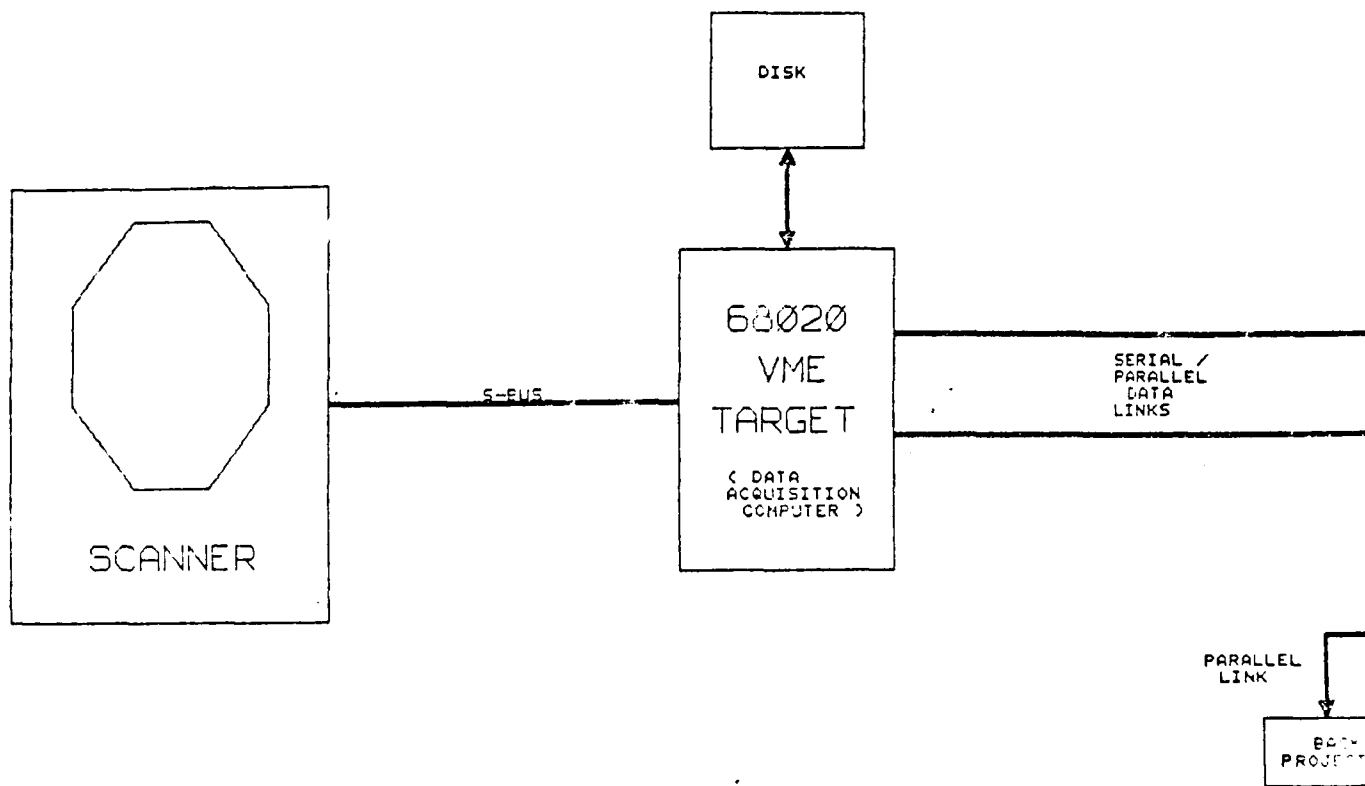


FIGURE 5 : DEVELOPMENTAL COMPU

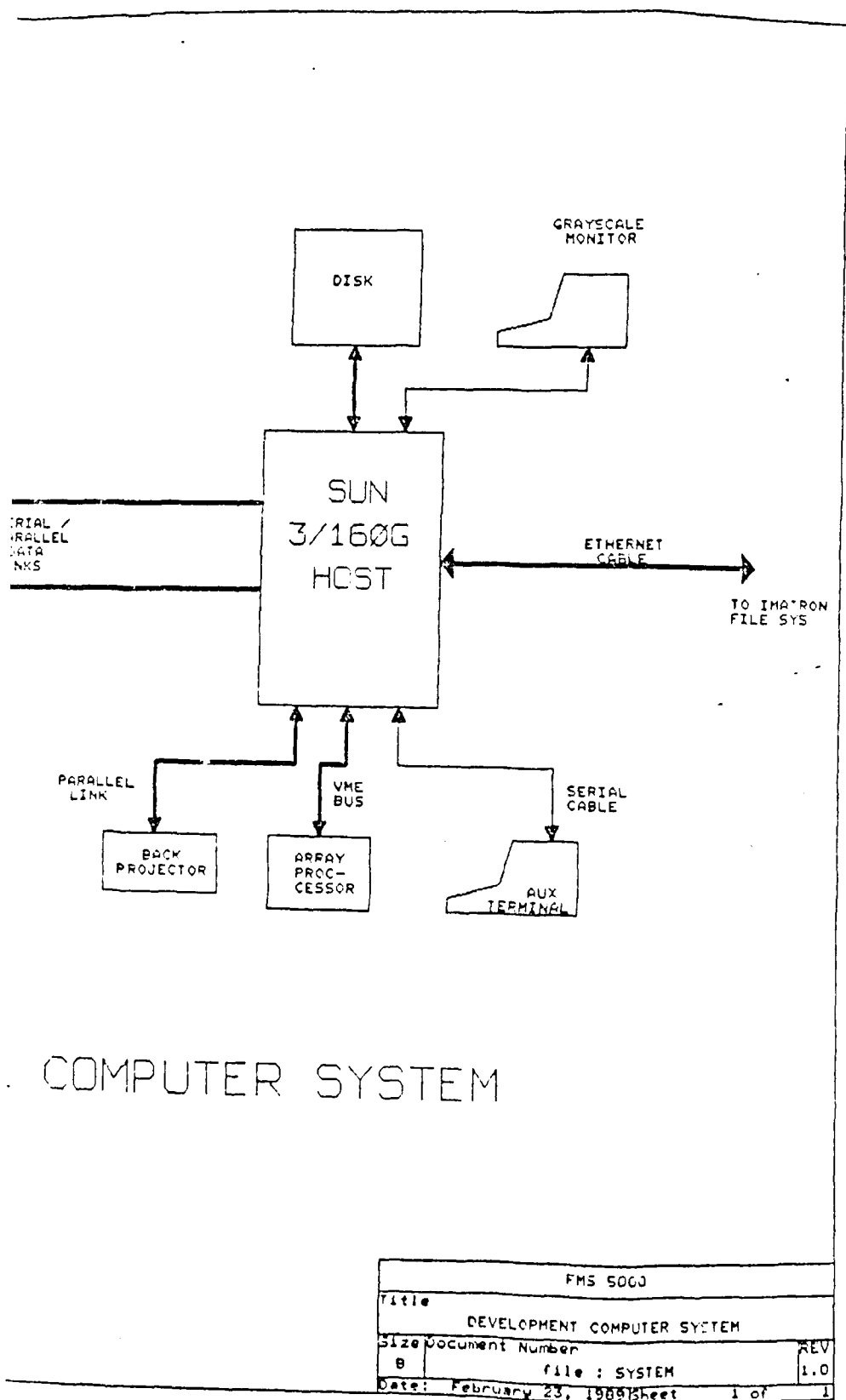


Figure 5

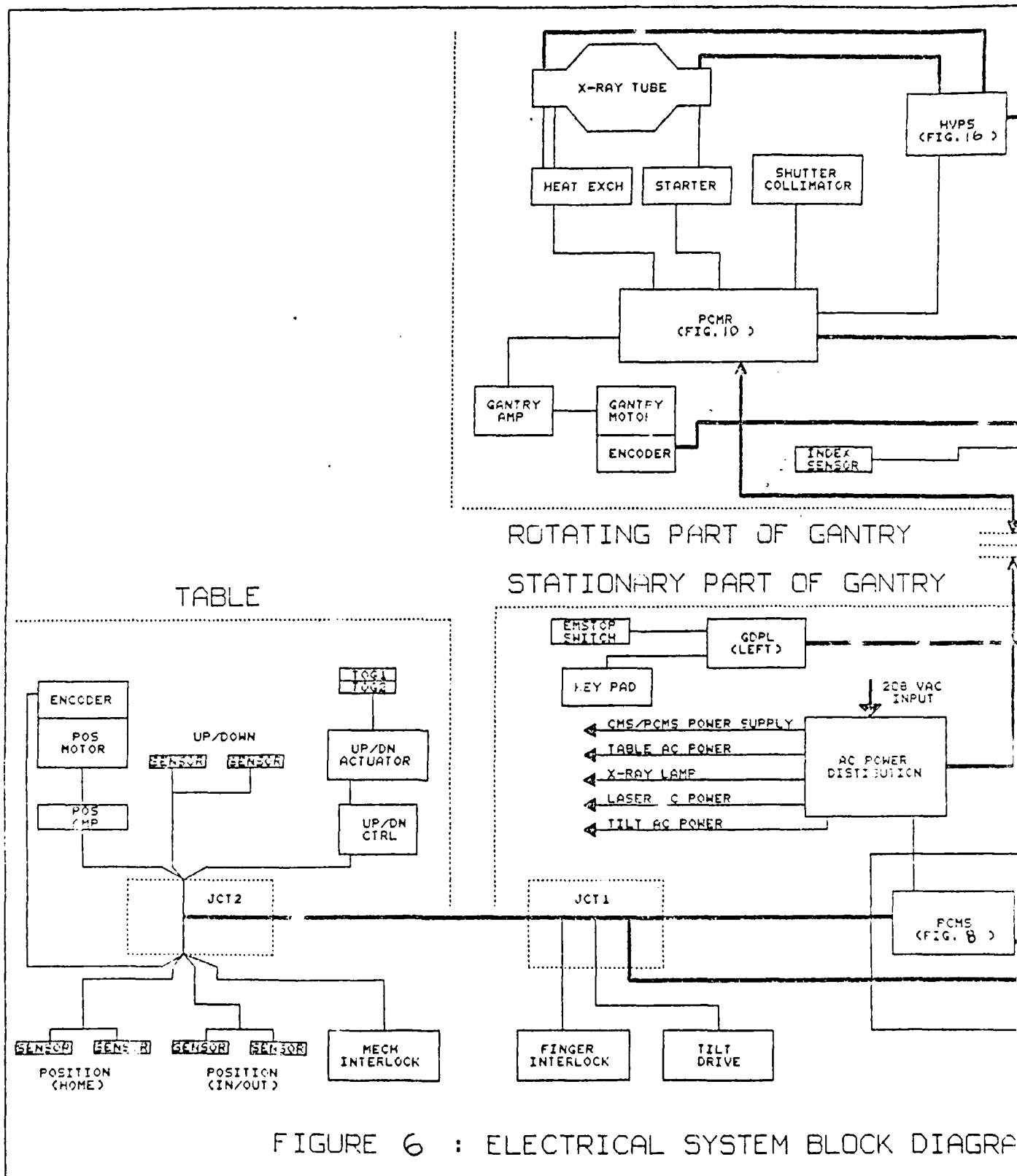


FIGURE 6 : ELECTRICAL SYSTEM BLOCK DIAGRA

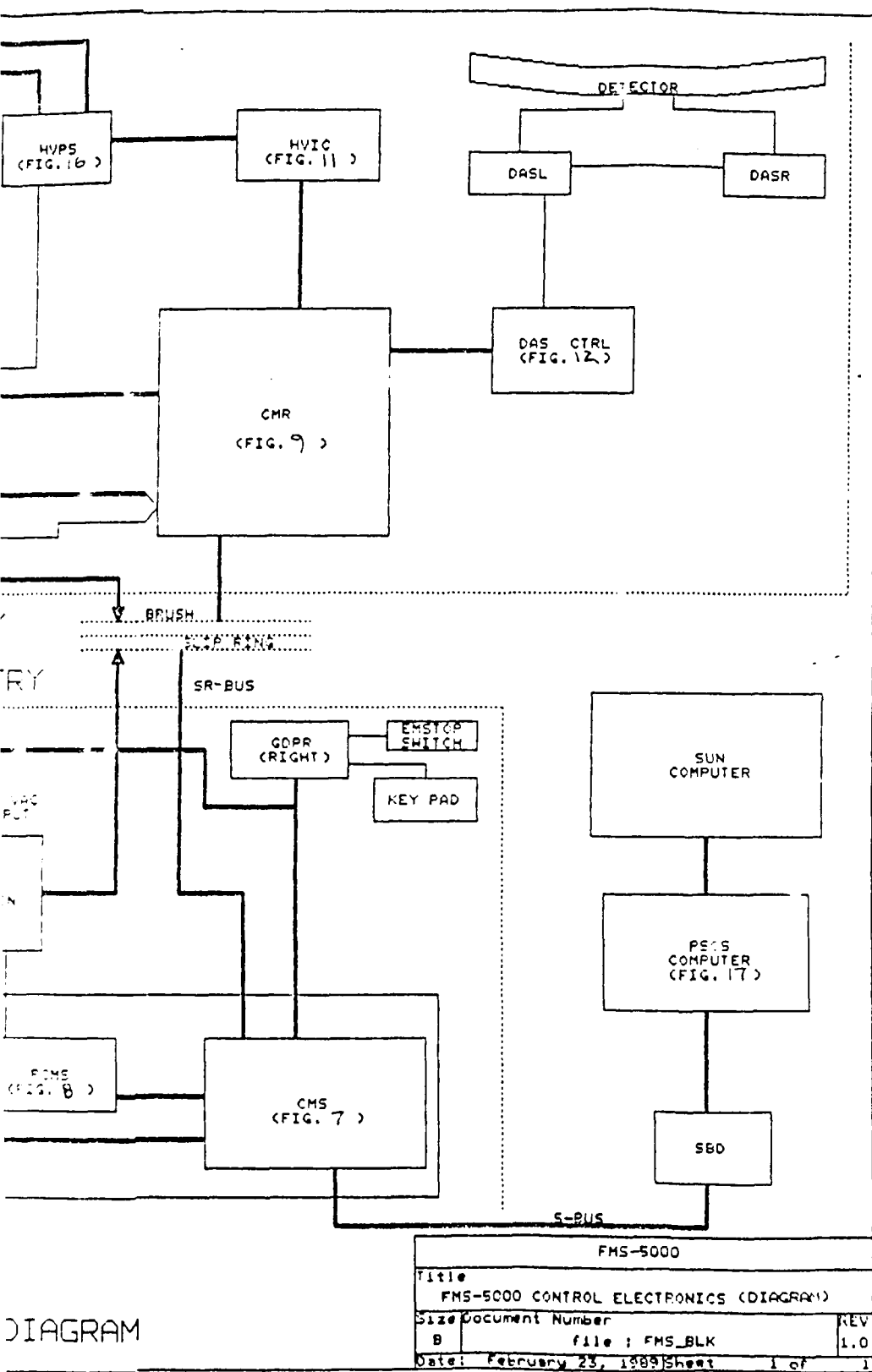


Figure 6

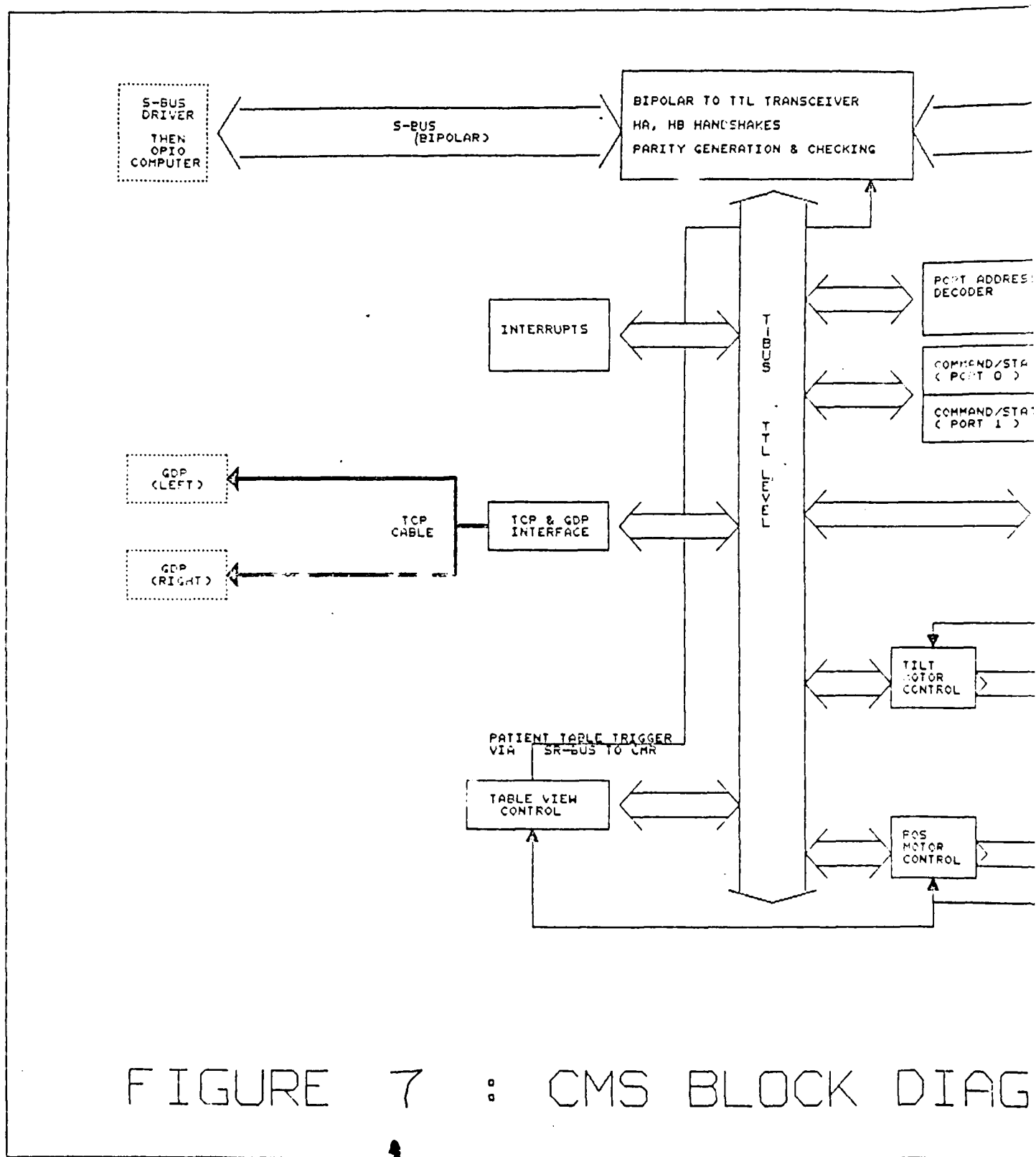
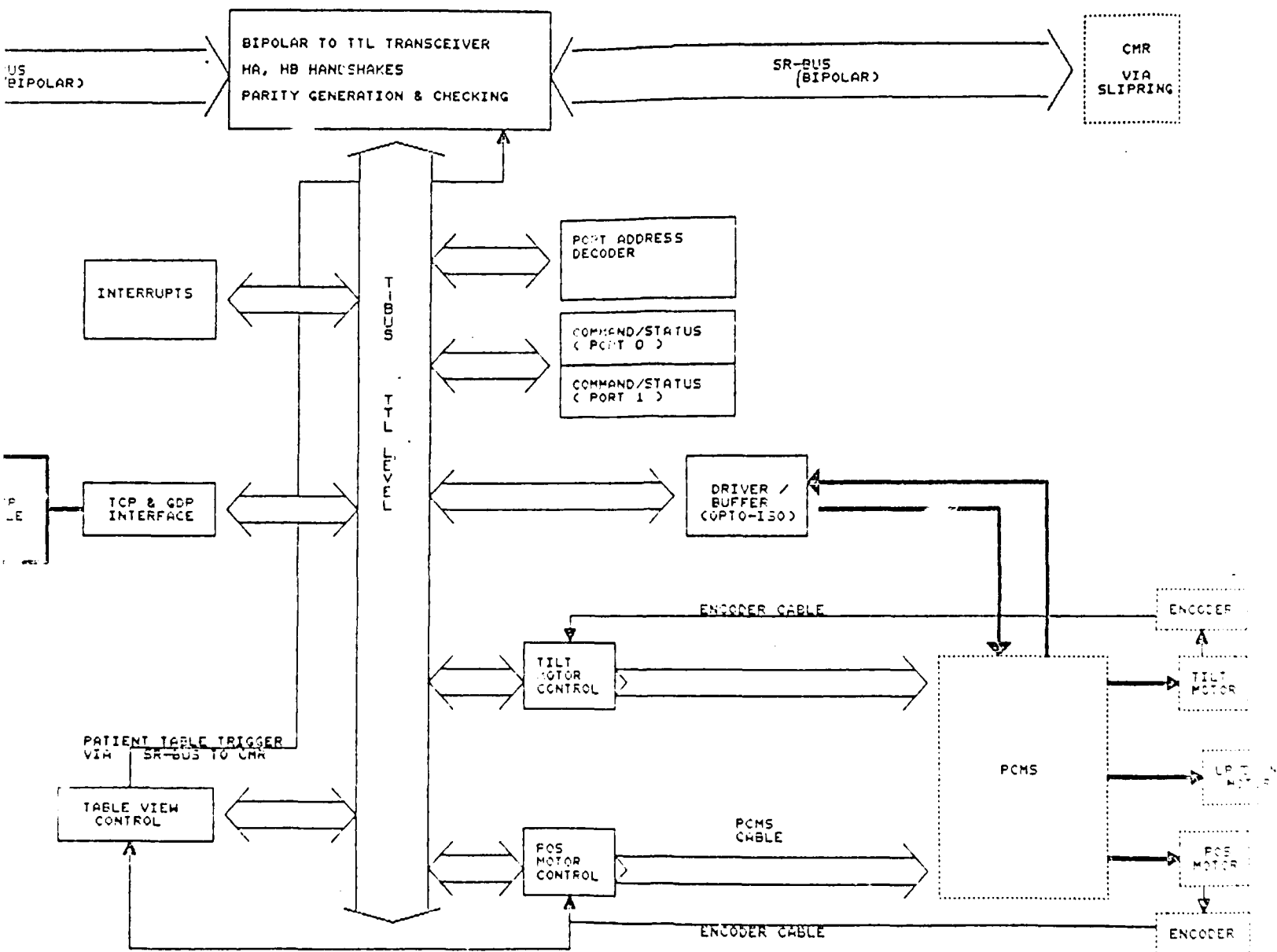


FIGURE 7 : CMS BLOCK DIAG



CMS BLOCK DIAGRAM

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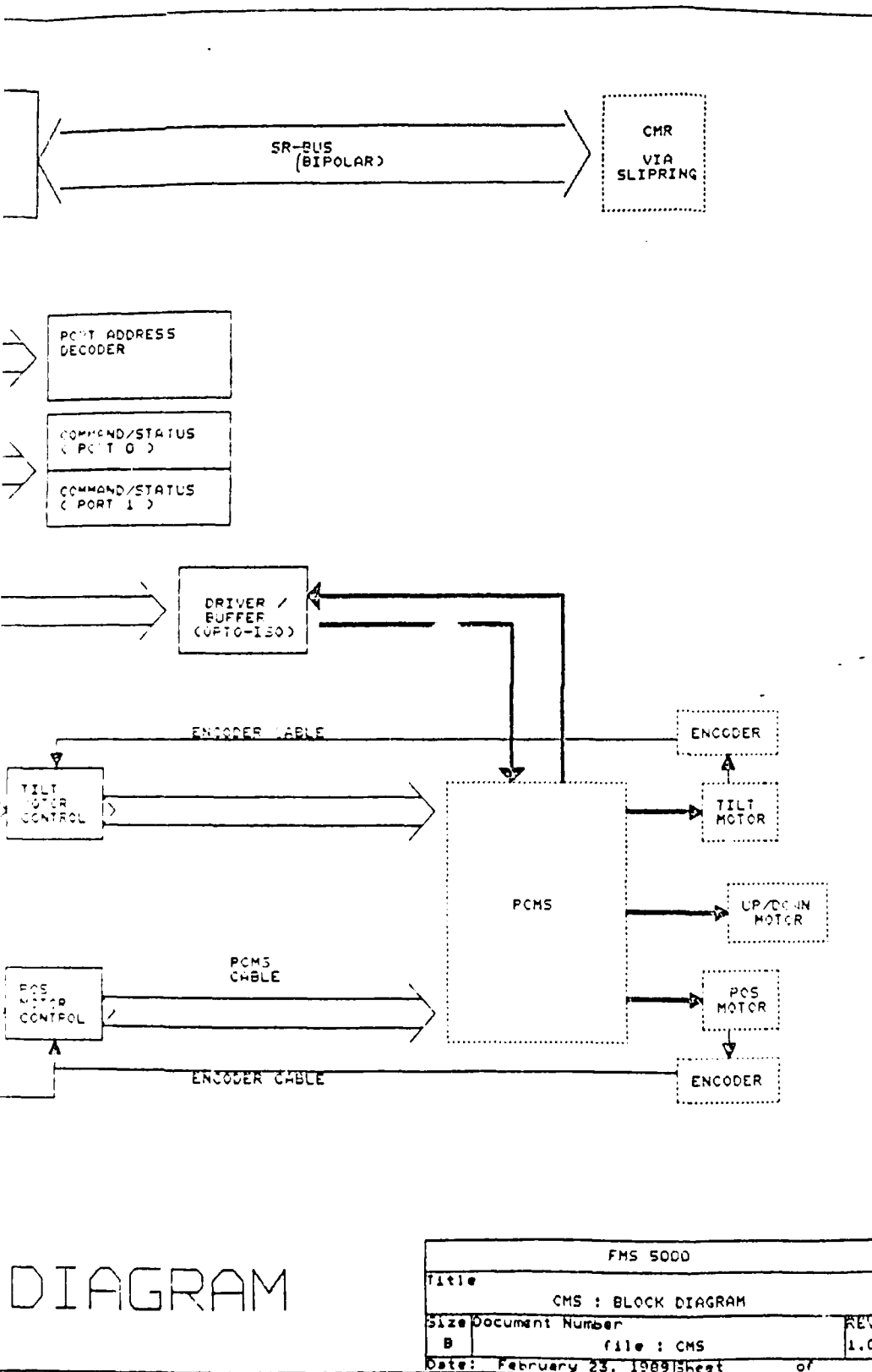


Figure 7

PCMS BLOCK DIAGRAM

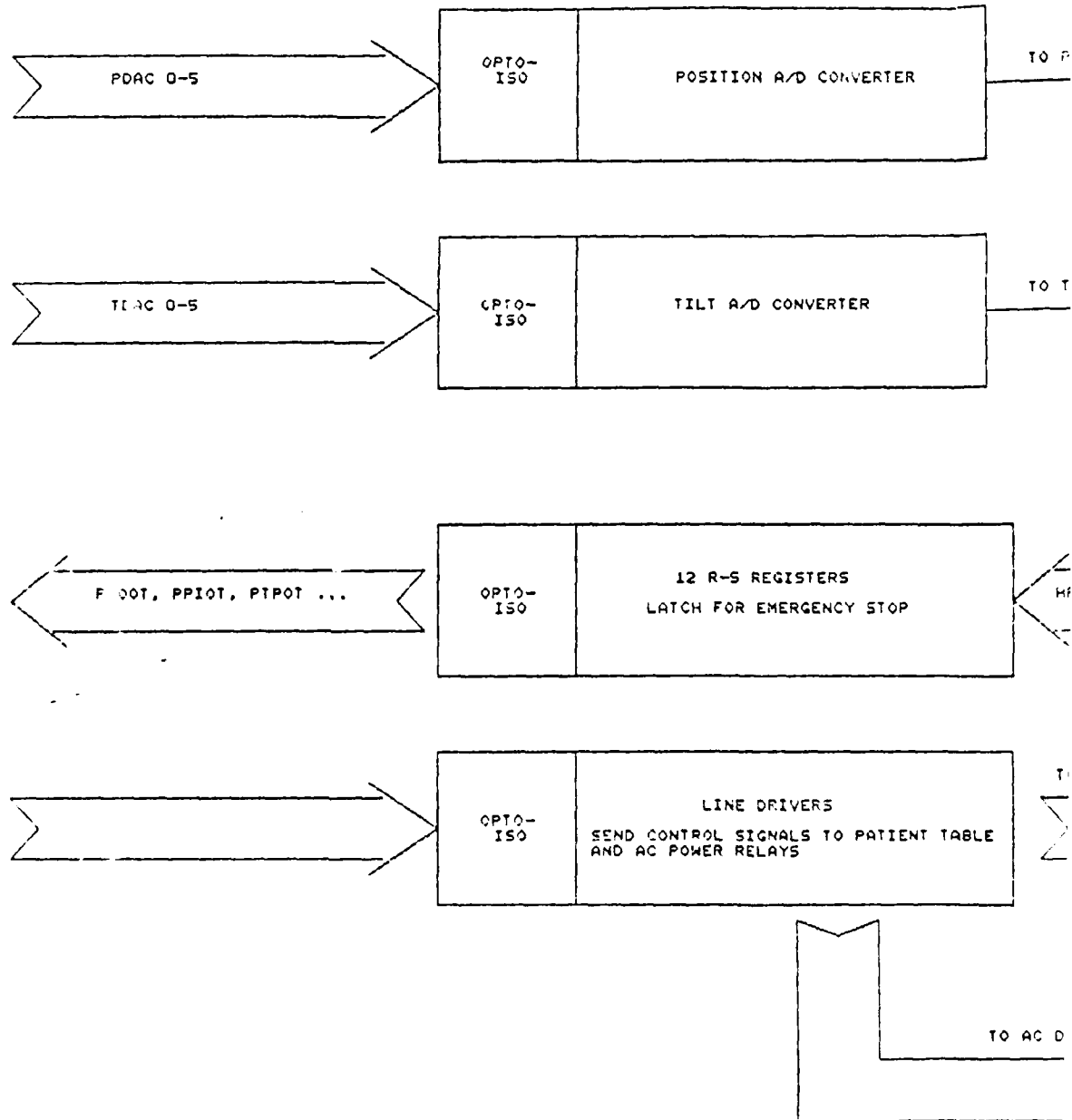


FIGURE 8 : PCMS BLOCK DIAGRAM

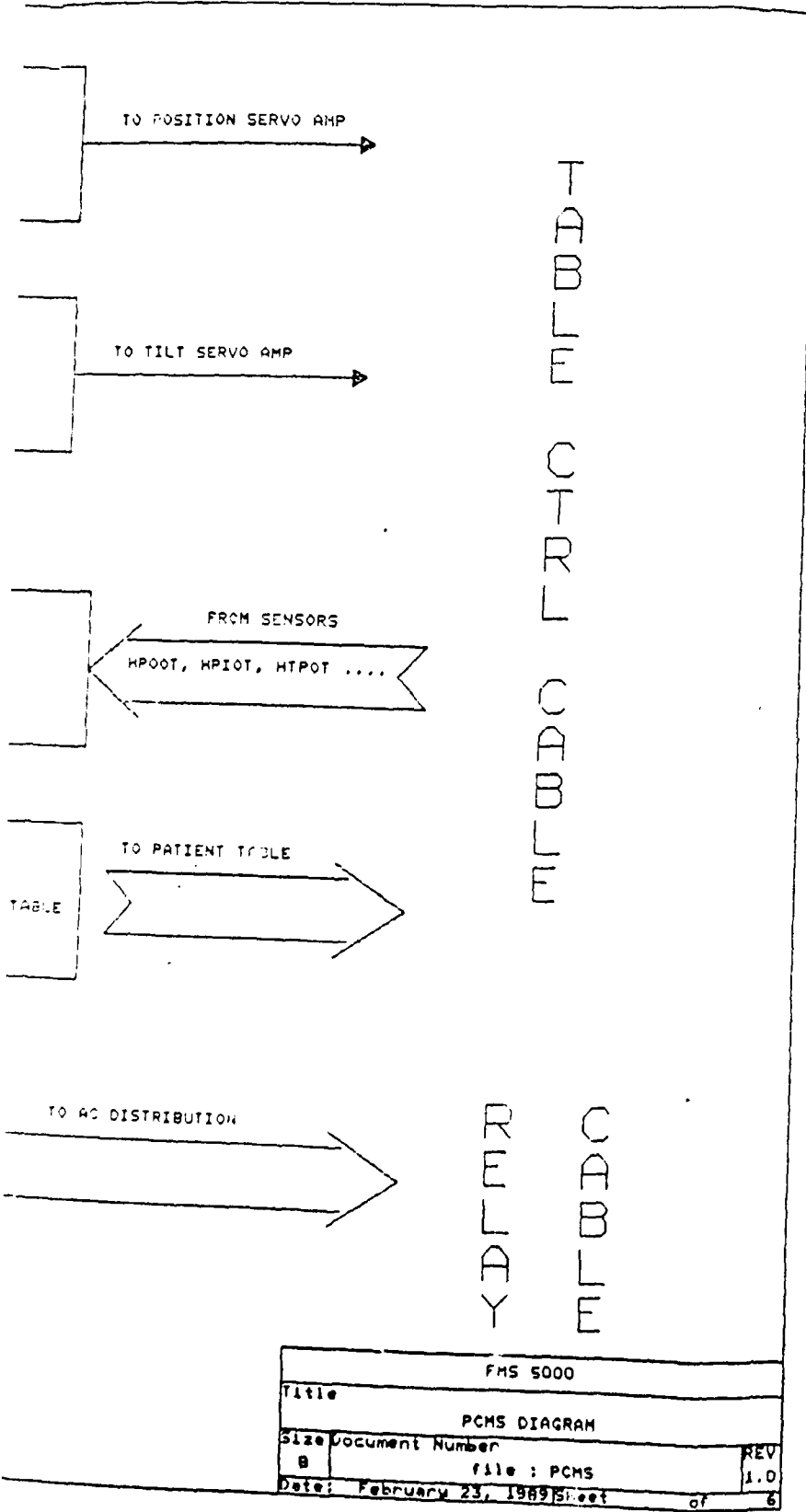


Figure 8

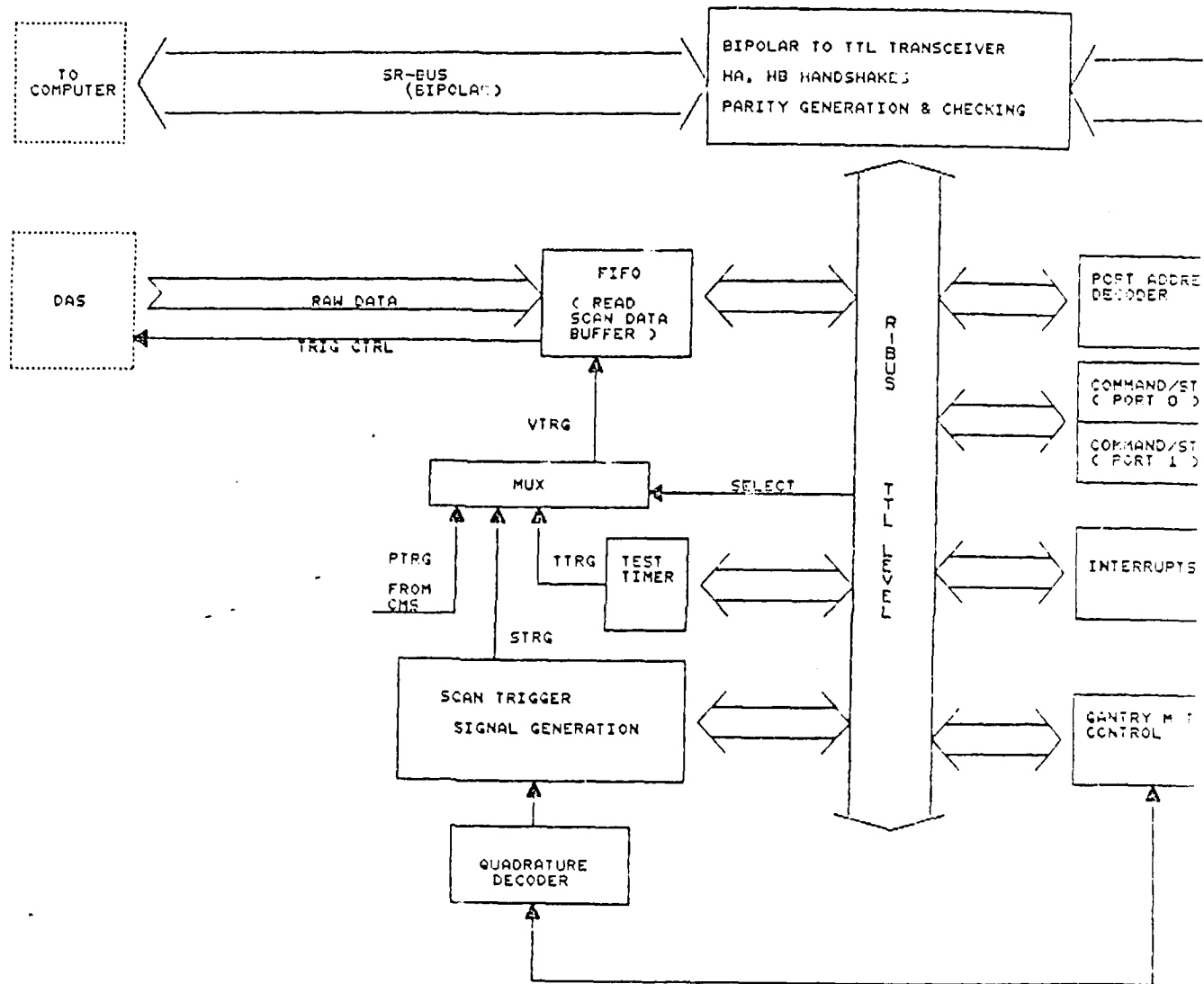
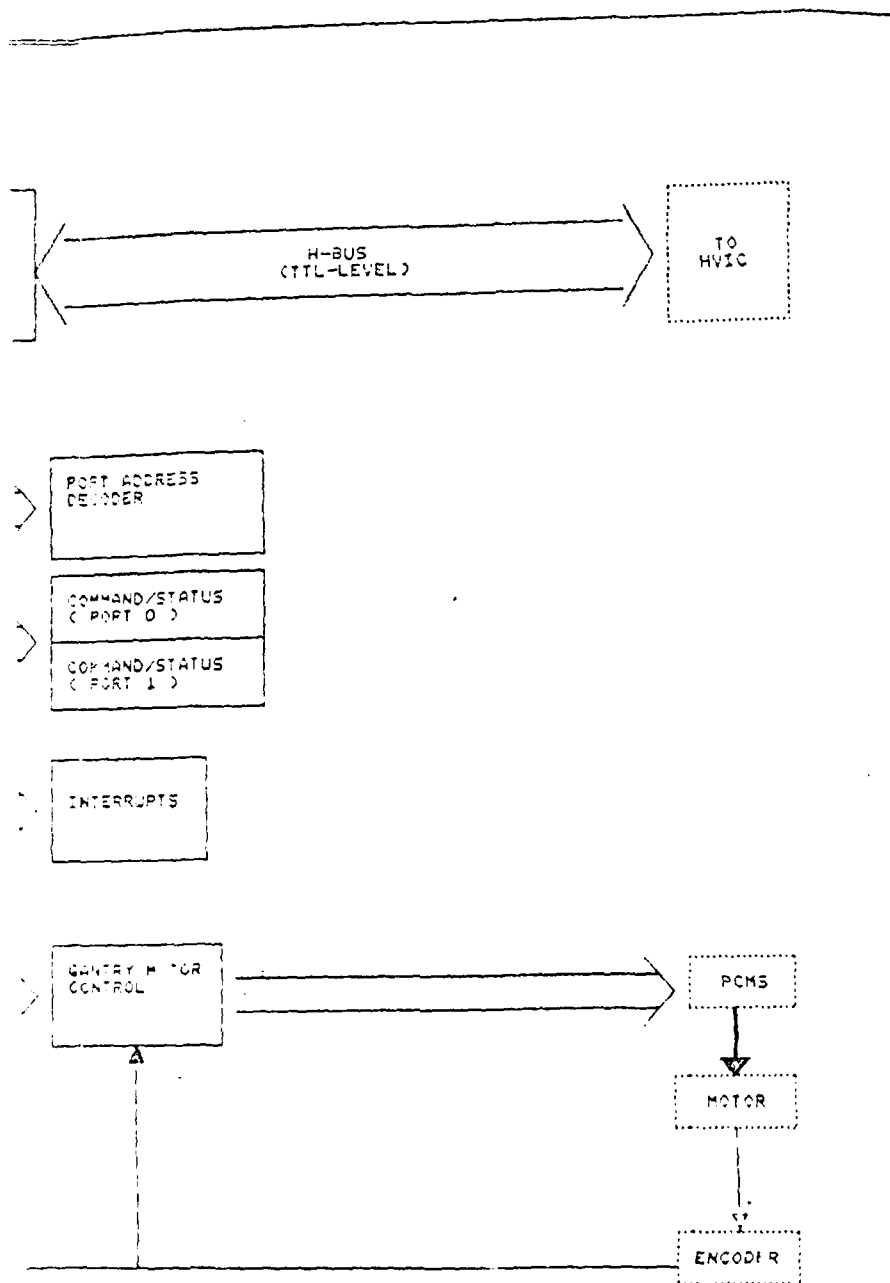
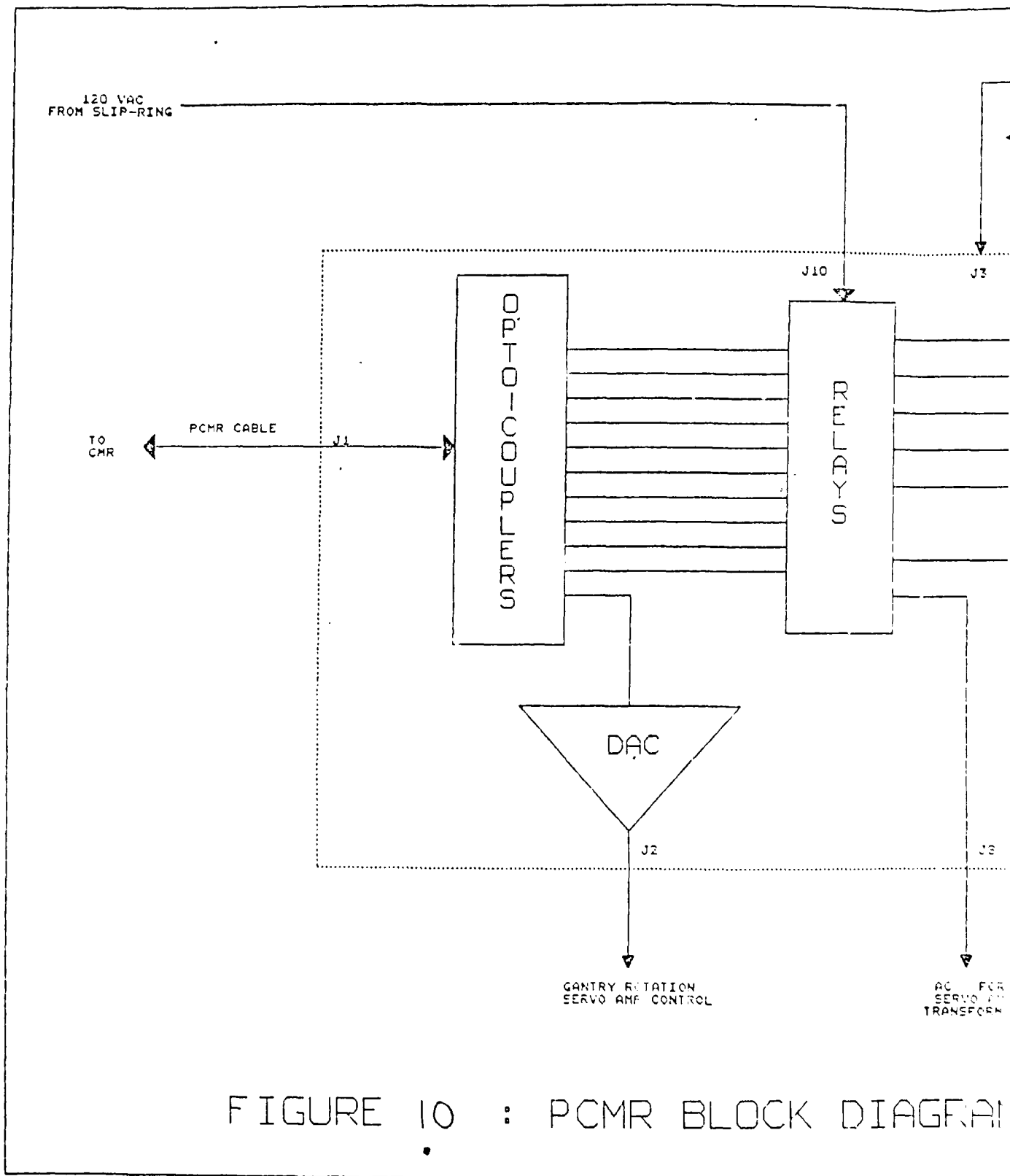


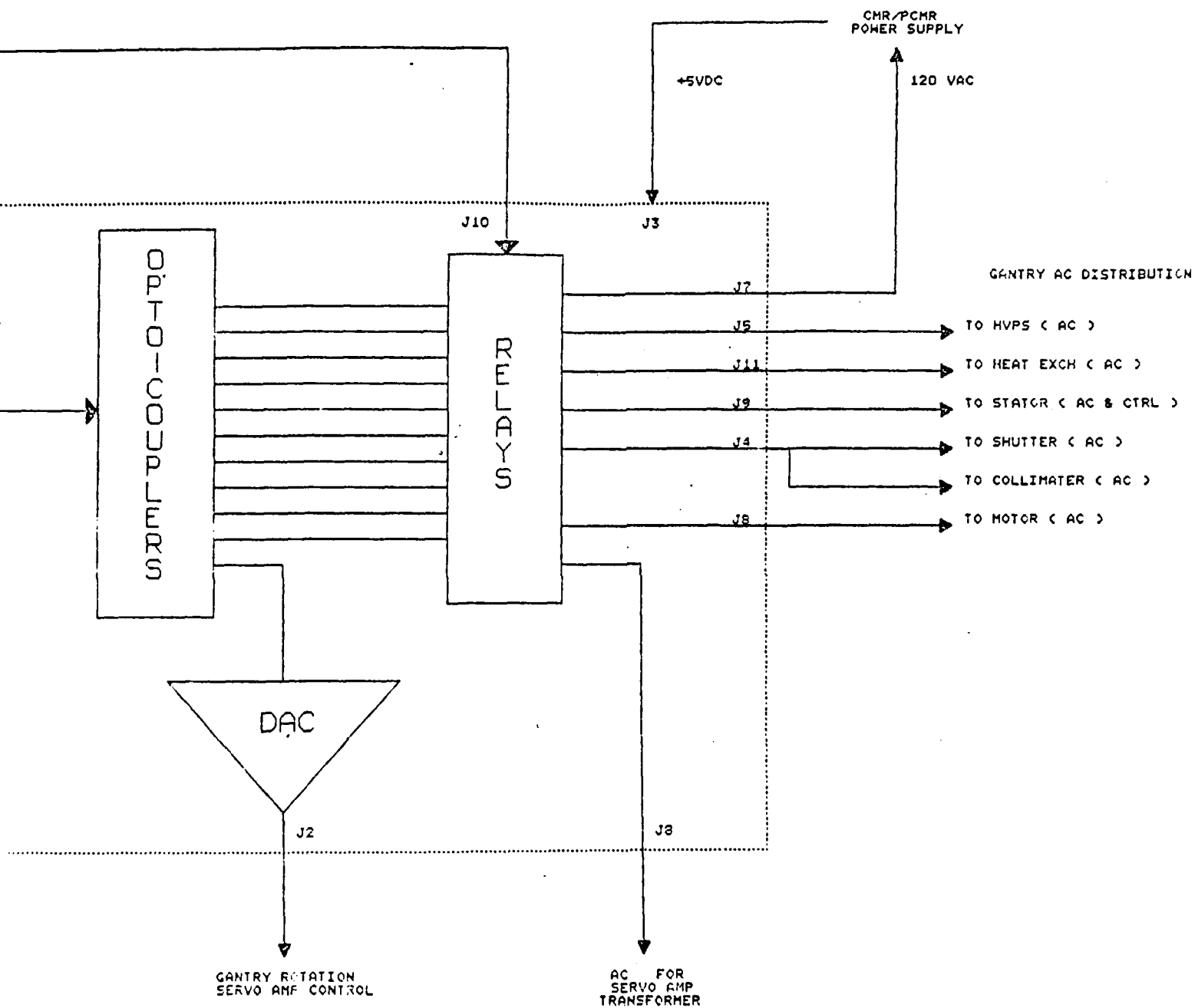
FIGURE 9 : CMR BLOCK DIAGRAM



FMS 5000	
Title	CMR : BLOCK DIAGRAM
Size	Document Number
B	file : CMR
Date: February 23, 1989	next of

Figure 9





E 10 : PCMR BLOCK DIAGRAM

FMS 5000	
Title	PCMR : DIAGRAM
Size	Document Number
B	file : PCMR
Date:	February 23, 1989 Sheet

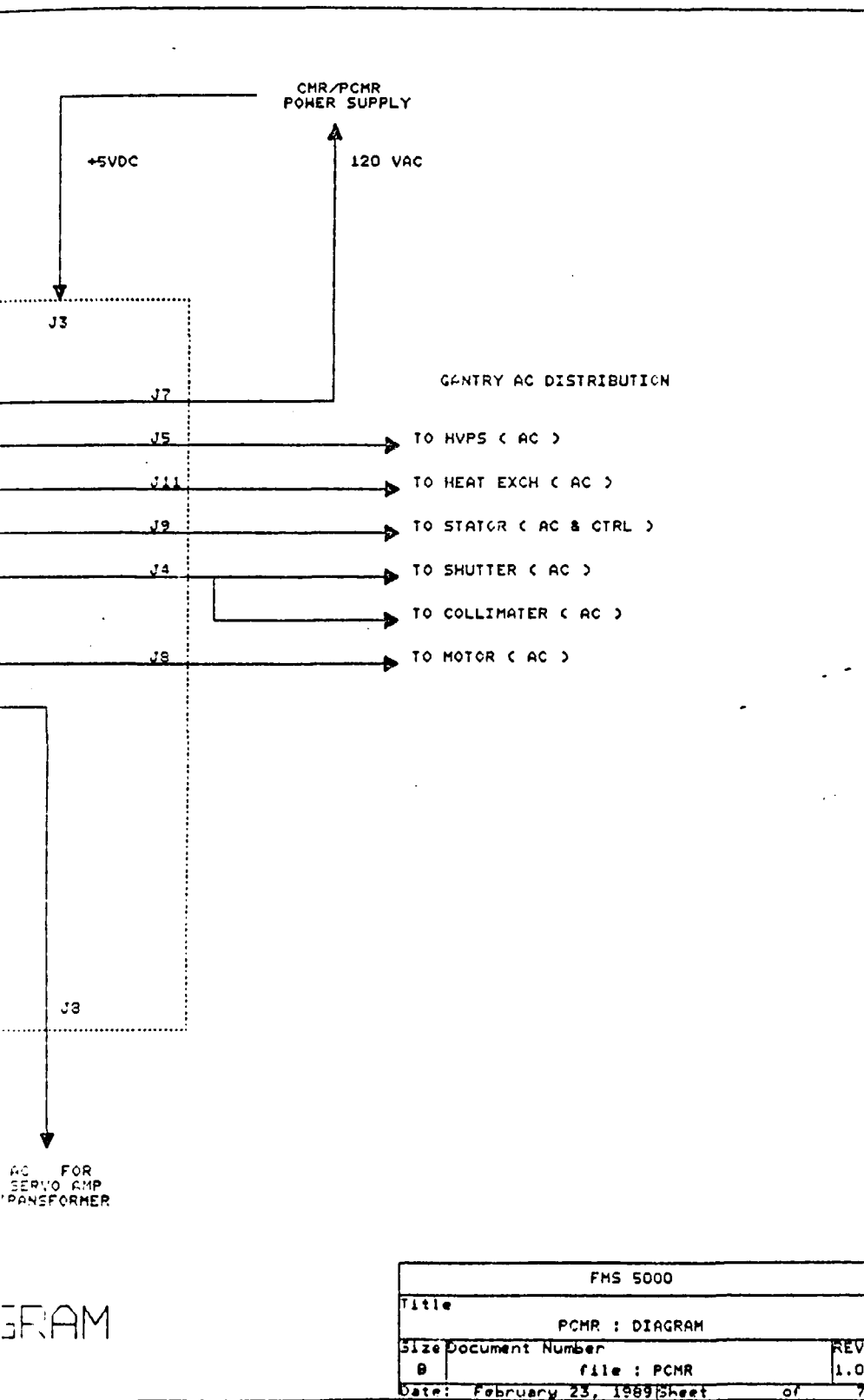


Figure 10

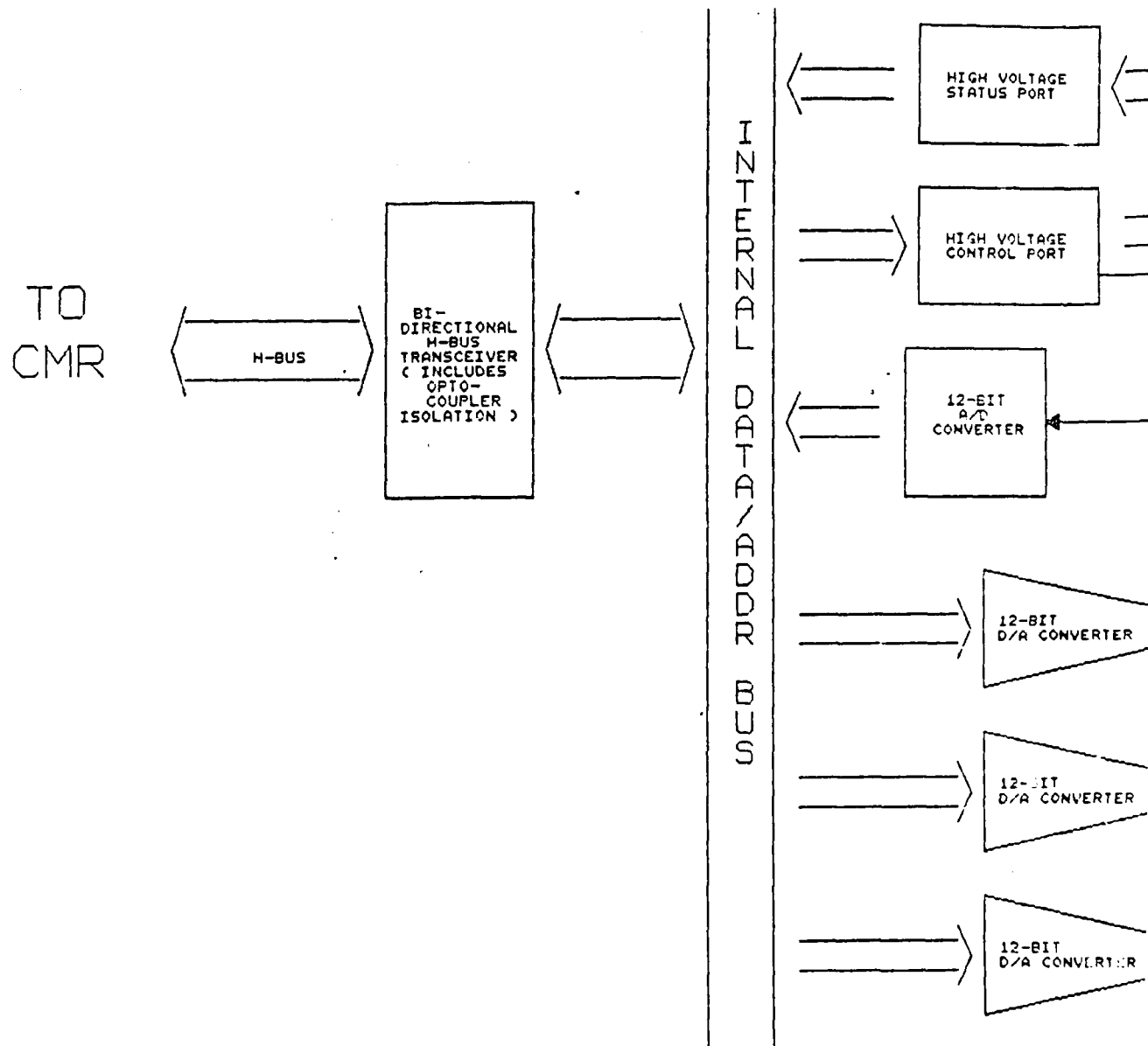
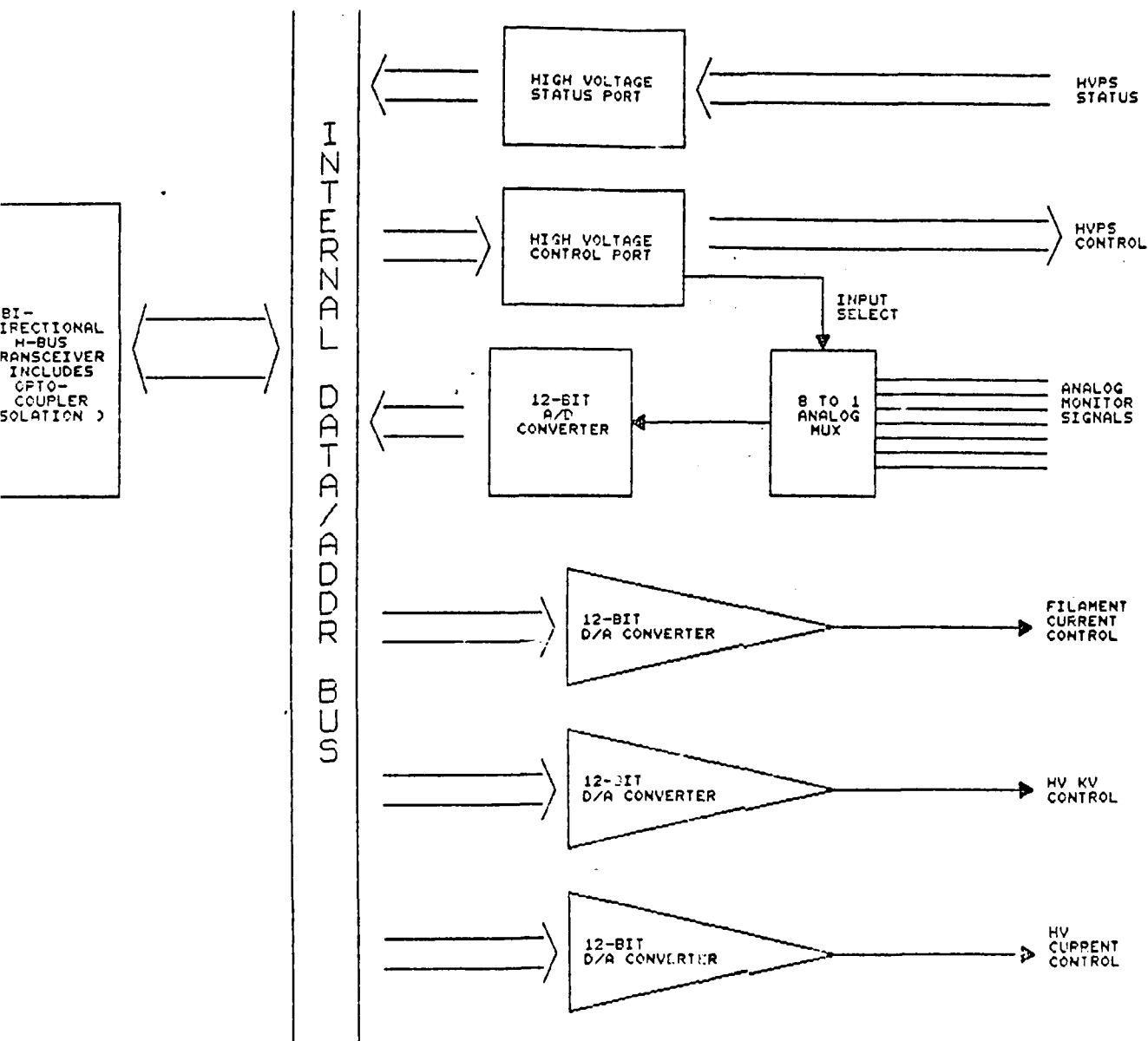


FIGURE 11 : HVIC BLOCK DIAGRAM

TO HVPS
INTERFAC



1 : HVIC BLOCK DIAGRAM

FMS 5000	
Title	HVIC DIAGRAM
Size Document Number	
B	file : HVIC
Date: February 23, 1989	Sheet 1 of 1

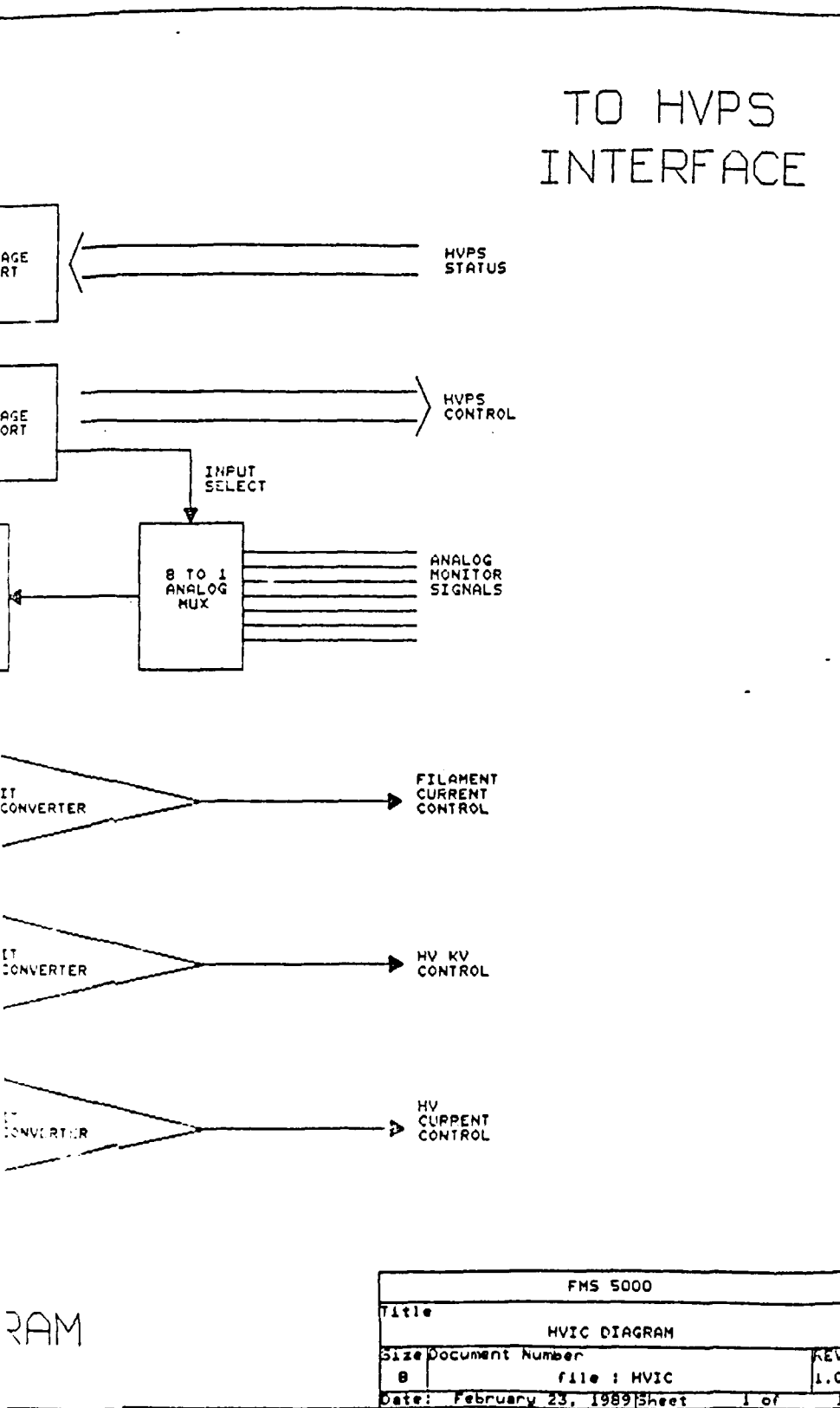


Figure 11

FROM DETECTOR MODULE
SIGNALS

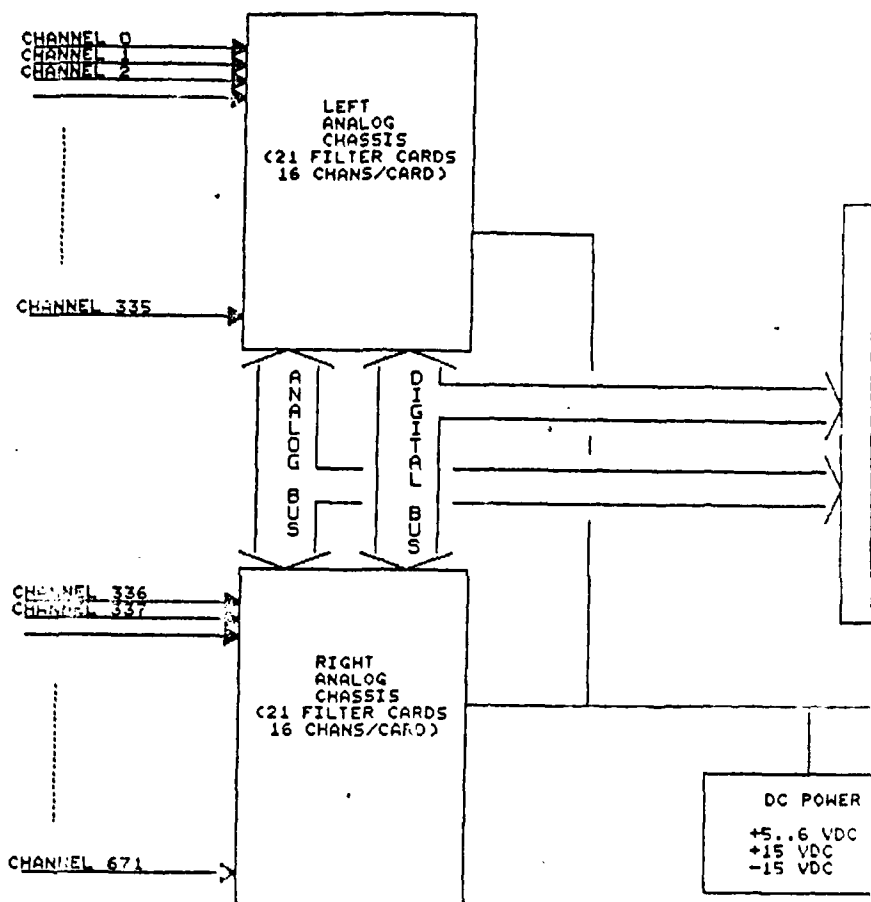


FIGURE 12 : DAS BLOC

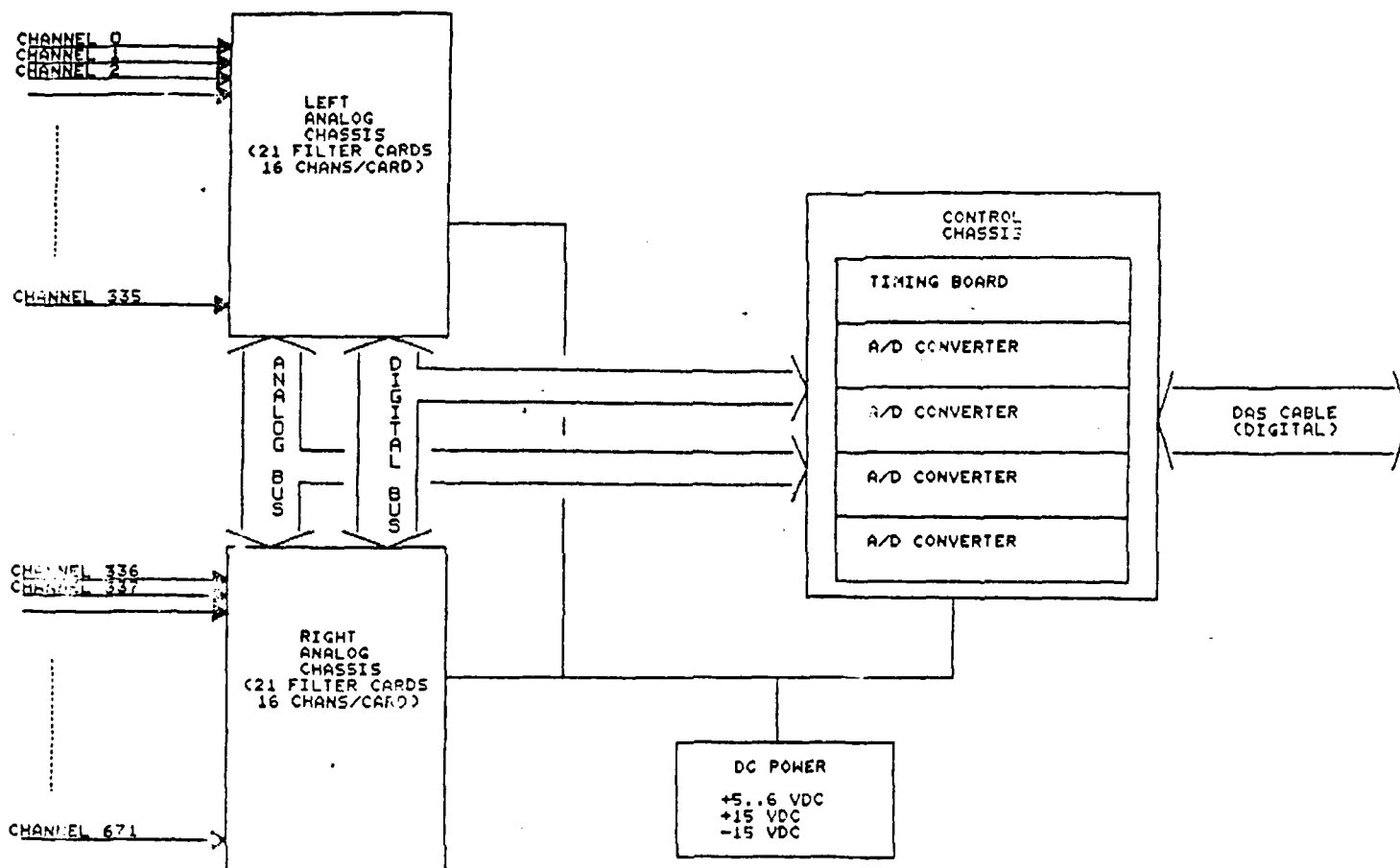


FIGURE 12 : DAS BLOCK DIAGRAM

FMS 5000	
Title	DAS BLOCK DIAG
Size	Document Number
B	File : DAS
Date:	February 23, 1983

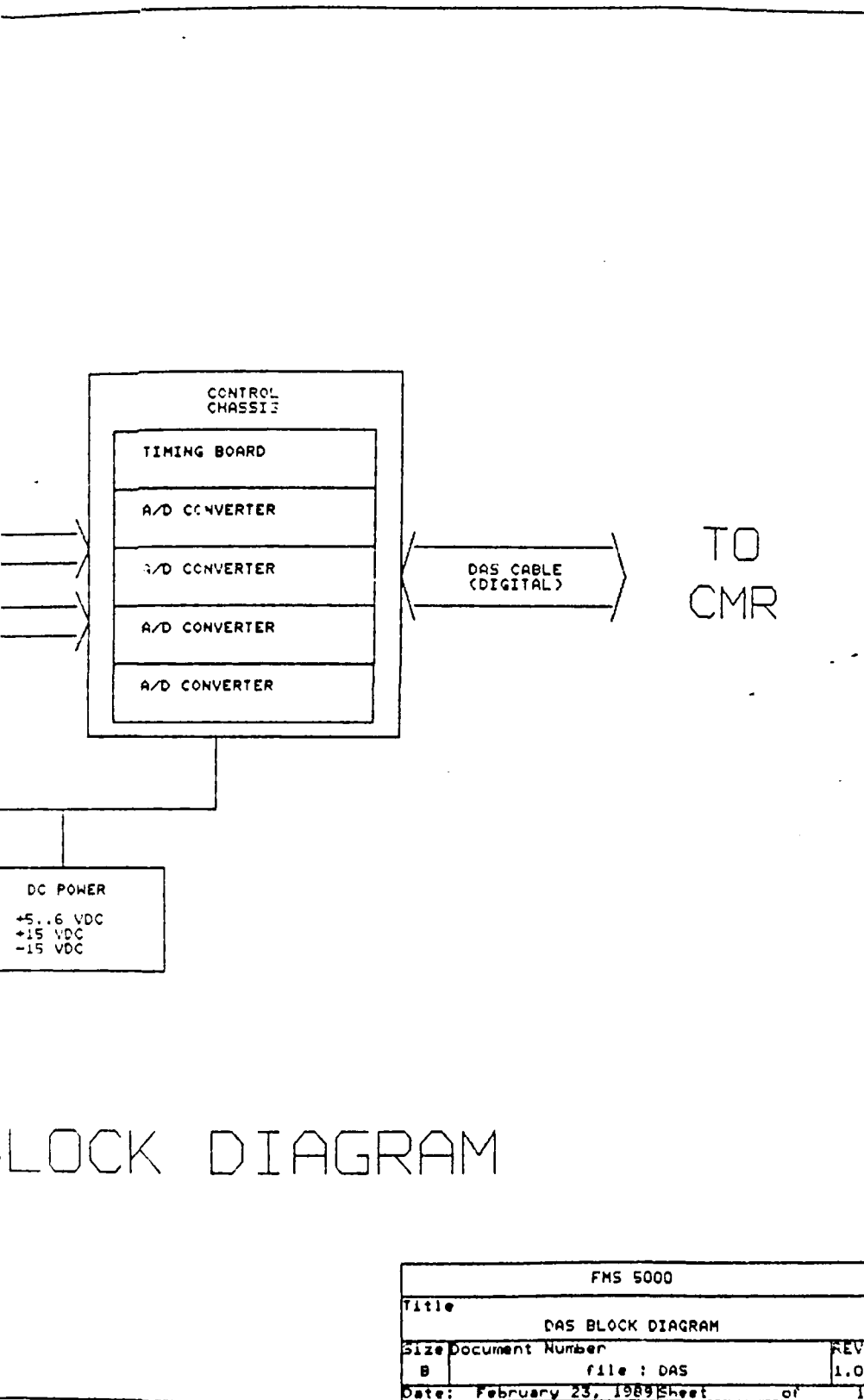
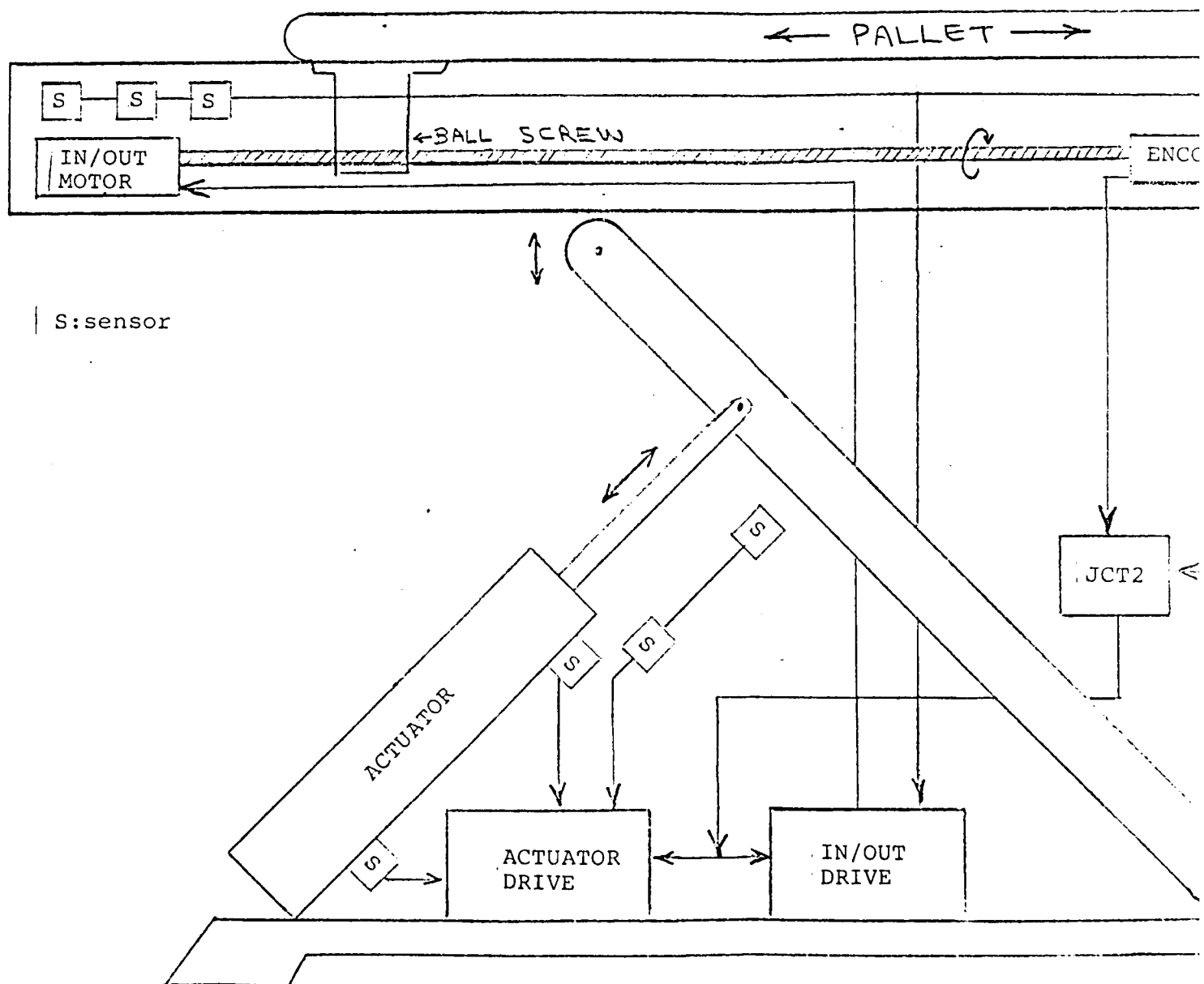
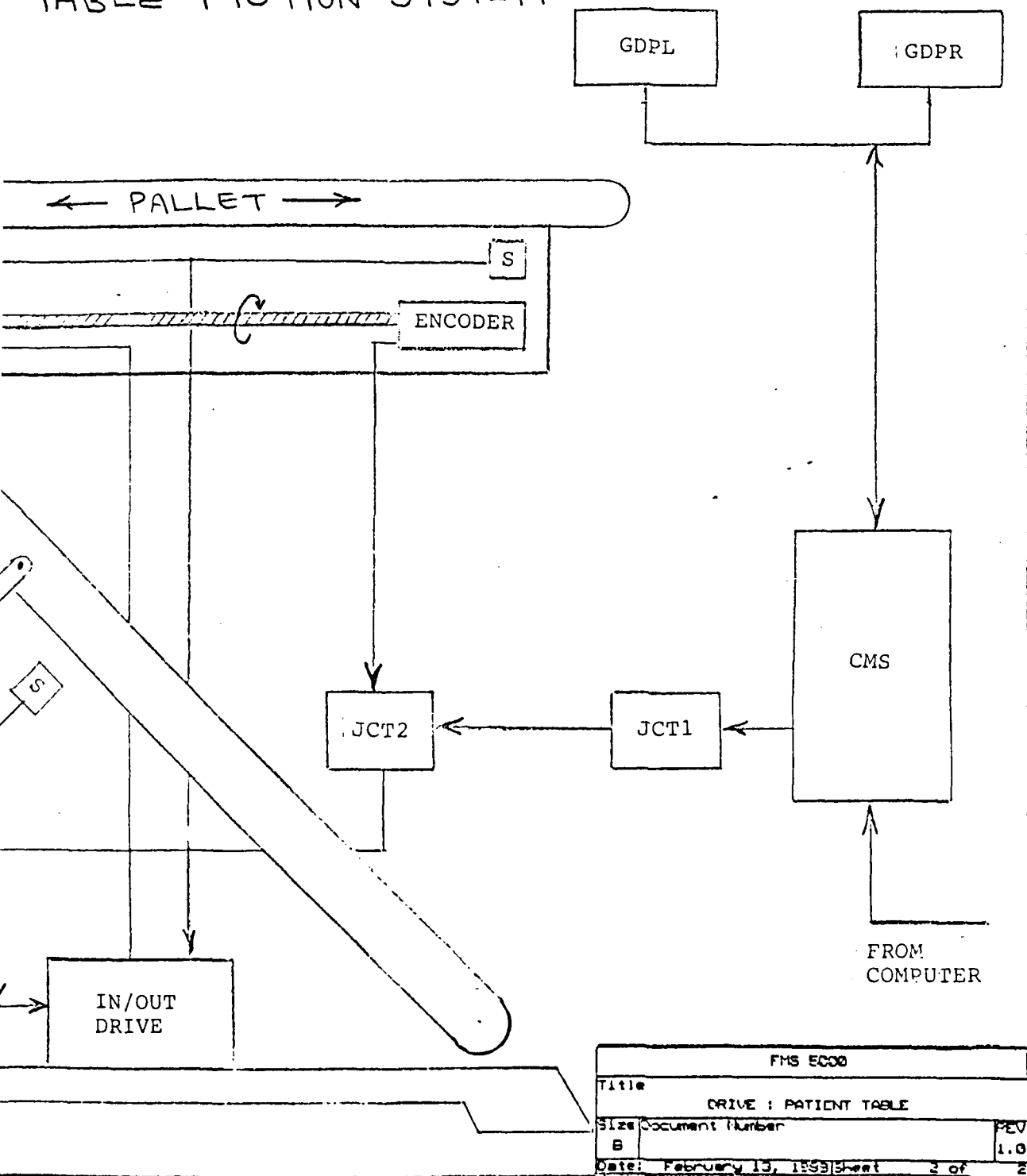


Figure 12

FIGURE 13. PATIENT TABLE MOTION SYS



-TABLE MOTION SYSTEM



FMS 5000		
Title	DRIVE : PATIENT TABLE	
Size	Document Number	REV
B		1.0
Date:	February 13, 1993	Sheet 2 of 2

Figure 13

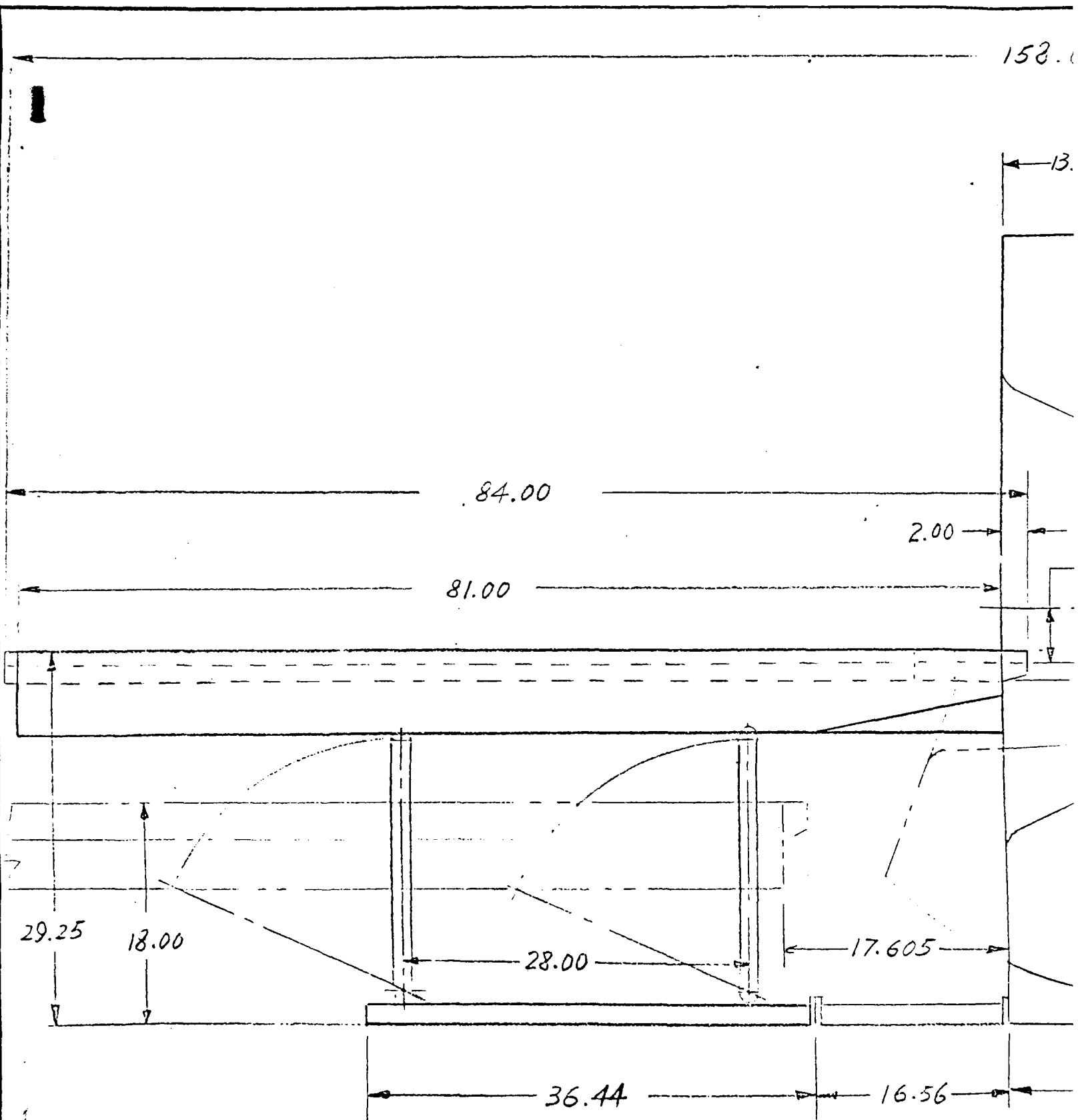


FIGURE 14. PATIENT TABLE & GANTRY DIMENS

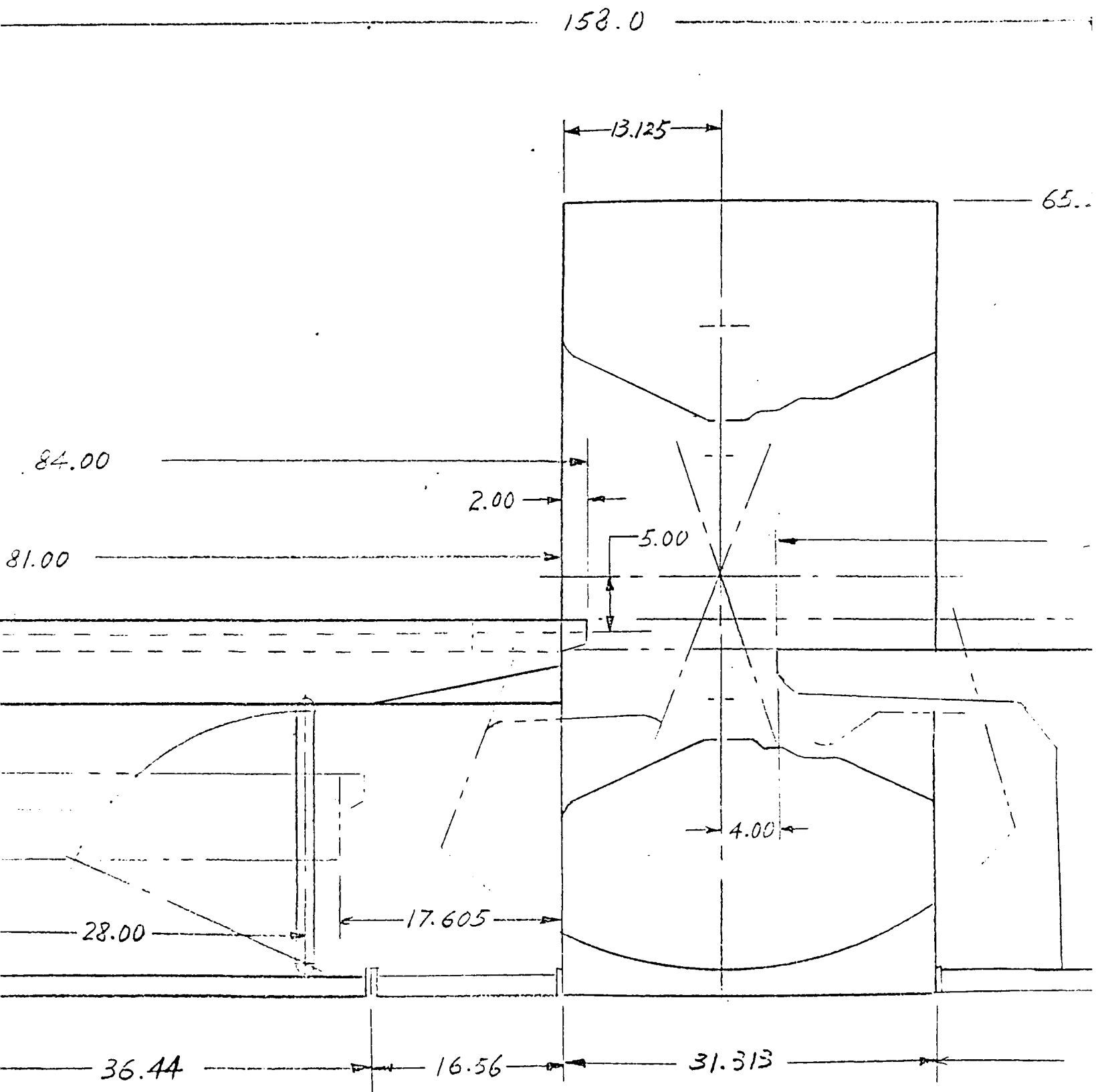
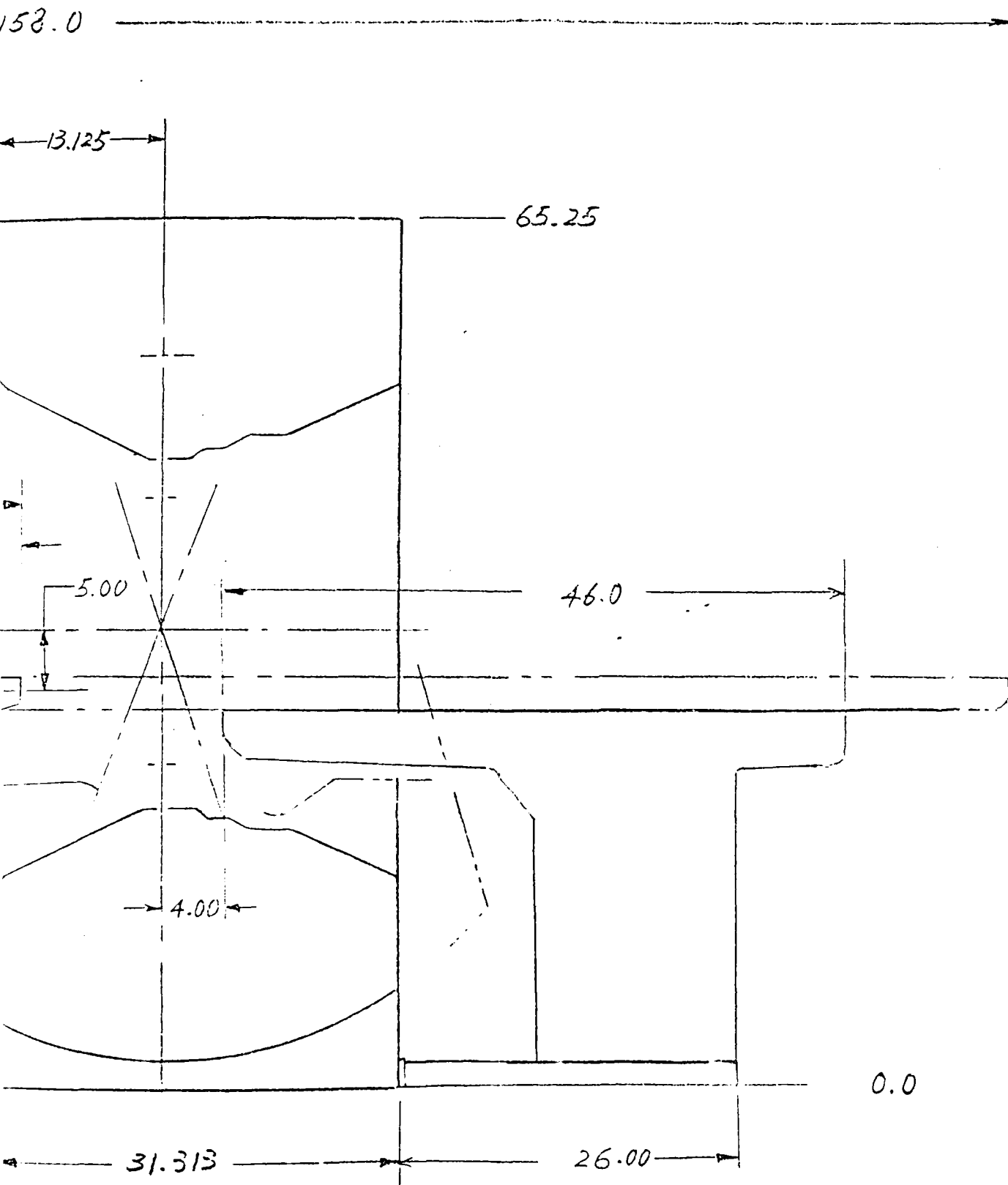


TABLE 8 GANTRY DIMENSIONS



ENSIONS

DWG NO.			REV
SCALE: 1/10	SHEET	/ OF 2	/

Figure 14

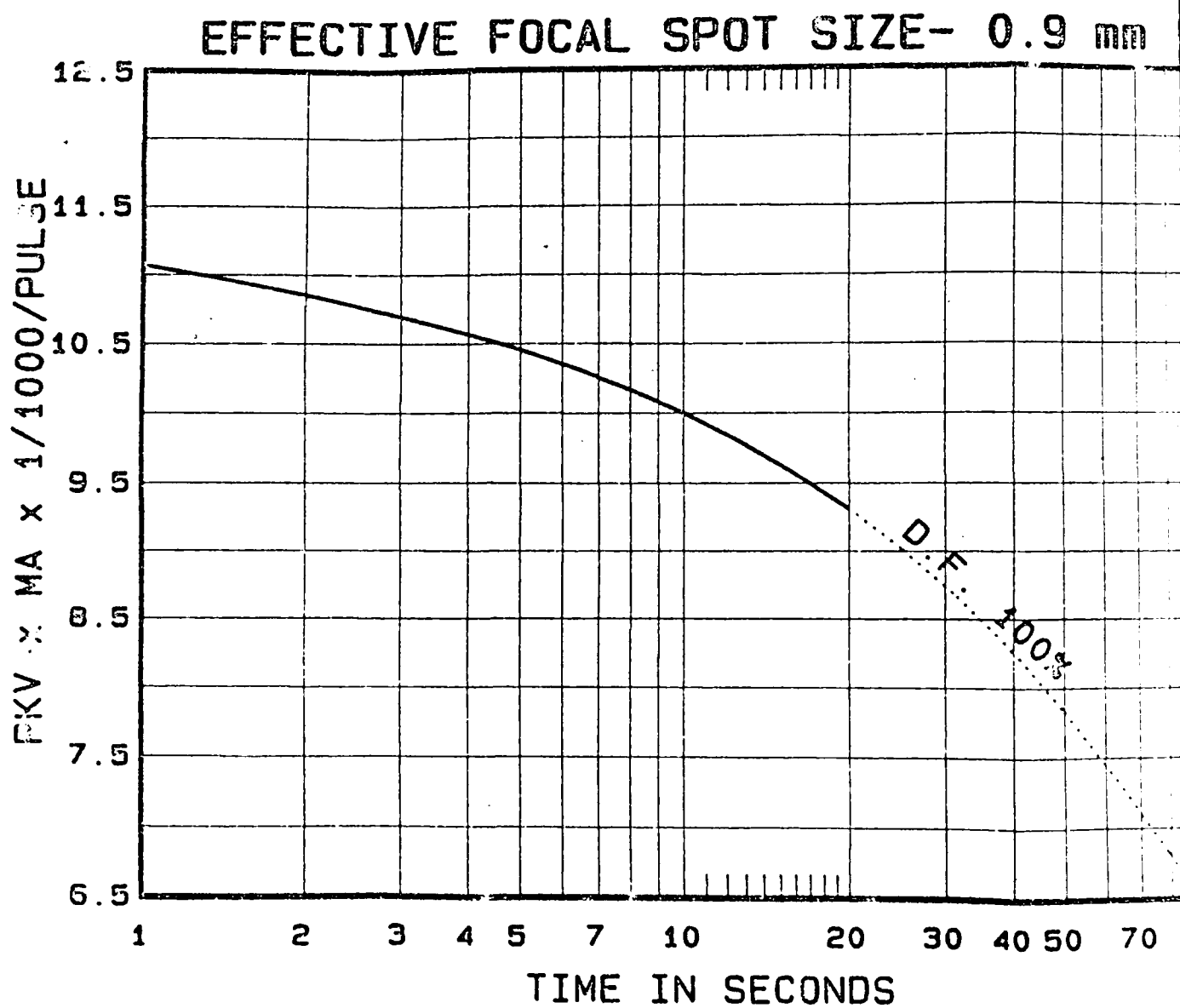
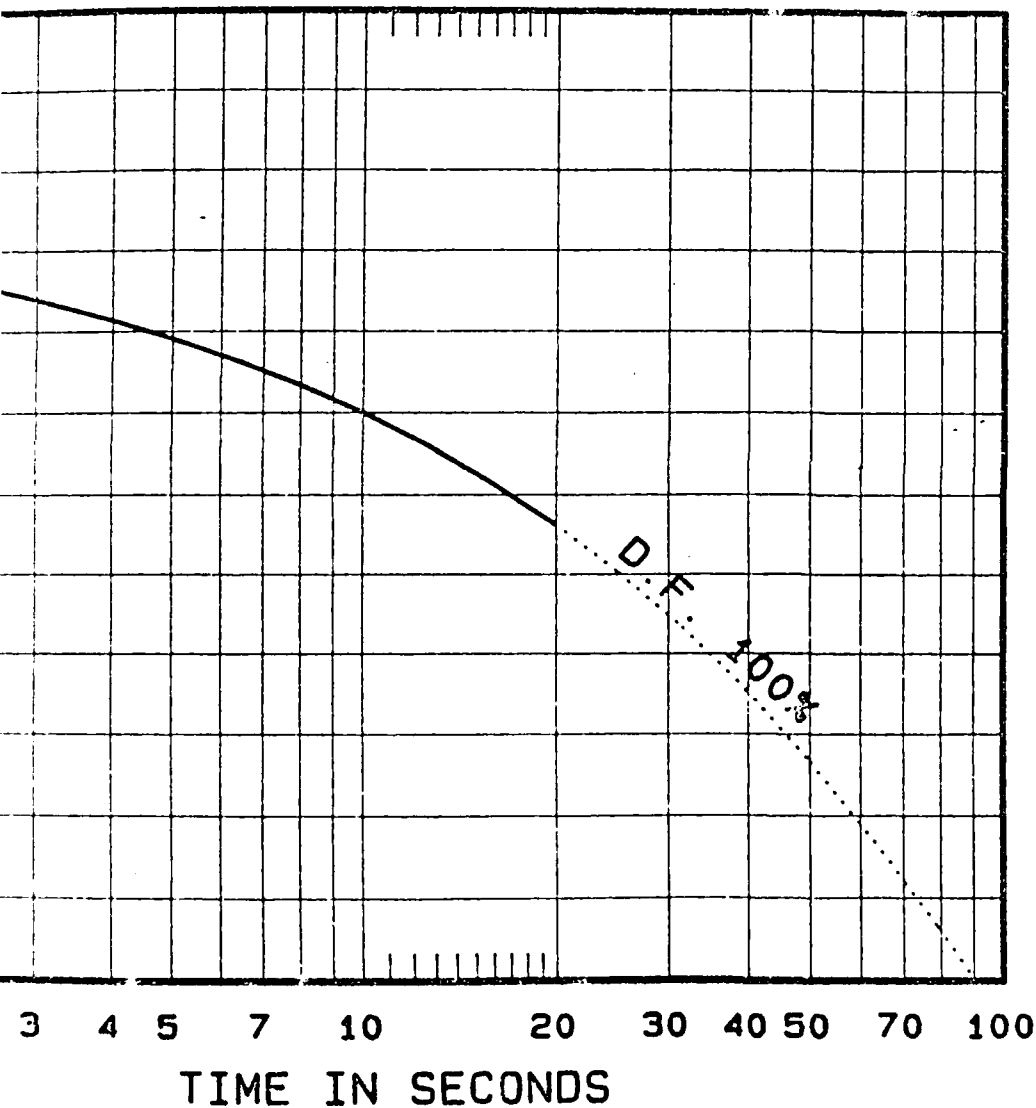


FIGURE 15. X-RAY TUBE RATING CURVE

IVE FOCAL SPOT SIZE- 0.9 mm



15. X-RAY TUBE RATING CURVE

gs-15xx

CINE

SPEED 3800 RPM

GENERATOR 3 PHASE

FOCAL SPOT

WIDTH .9 MM

LENGTH .7 MM

TRACK DIA 118 MM

F.H.S. .8

TARGET ANGLE 12.5

RHOxVxC 1872

1.5 MHV
ANODE

Figure 15

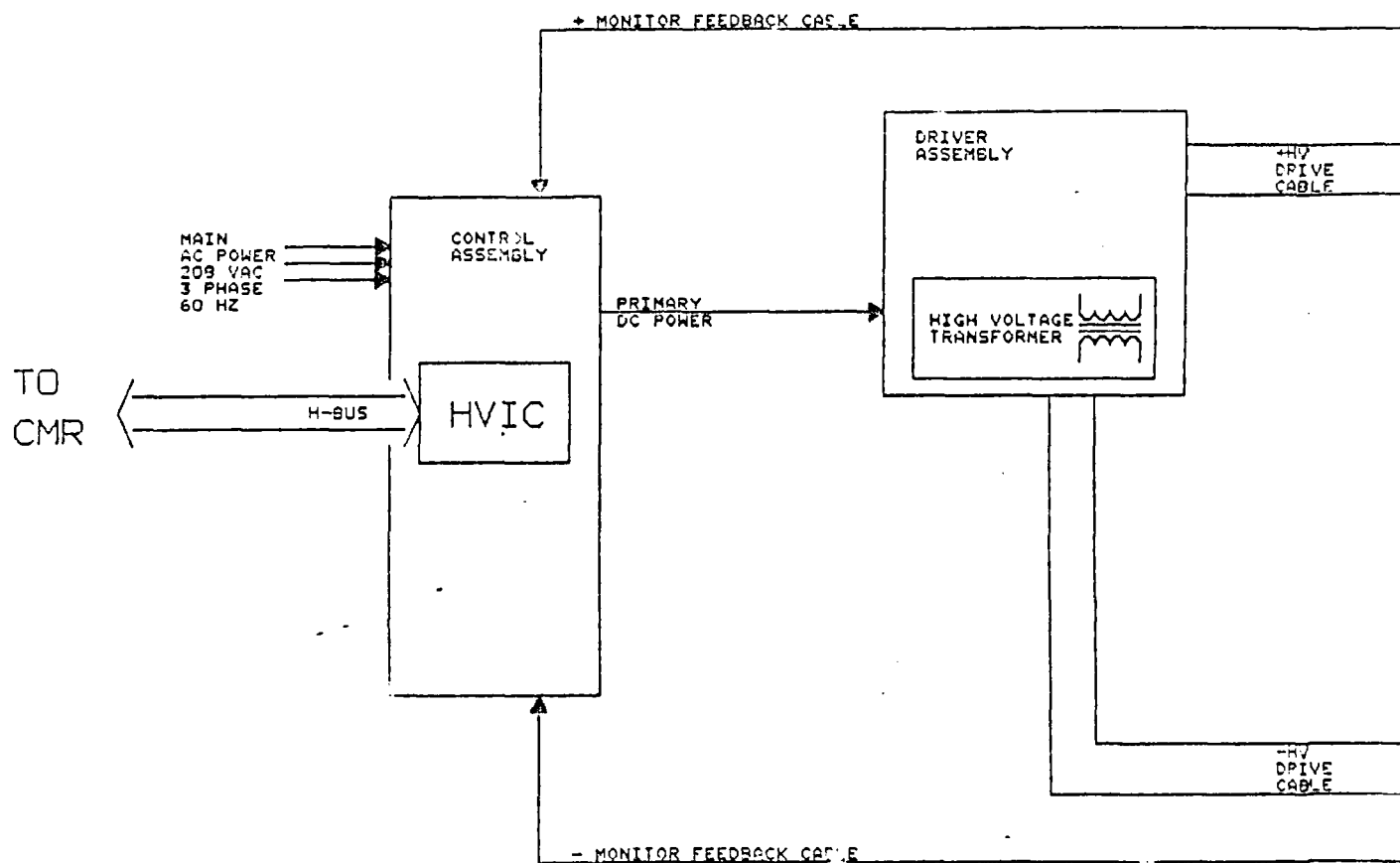
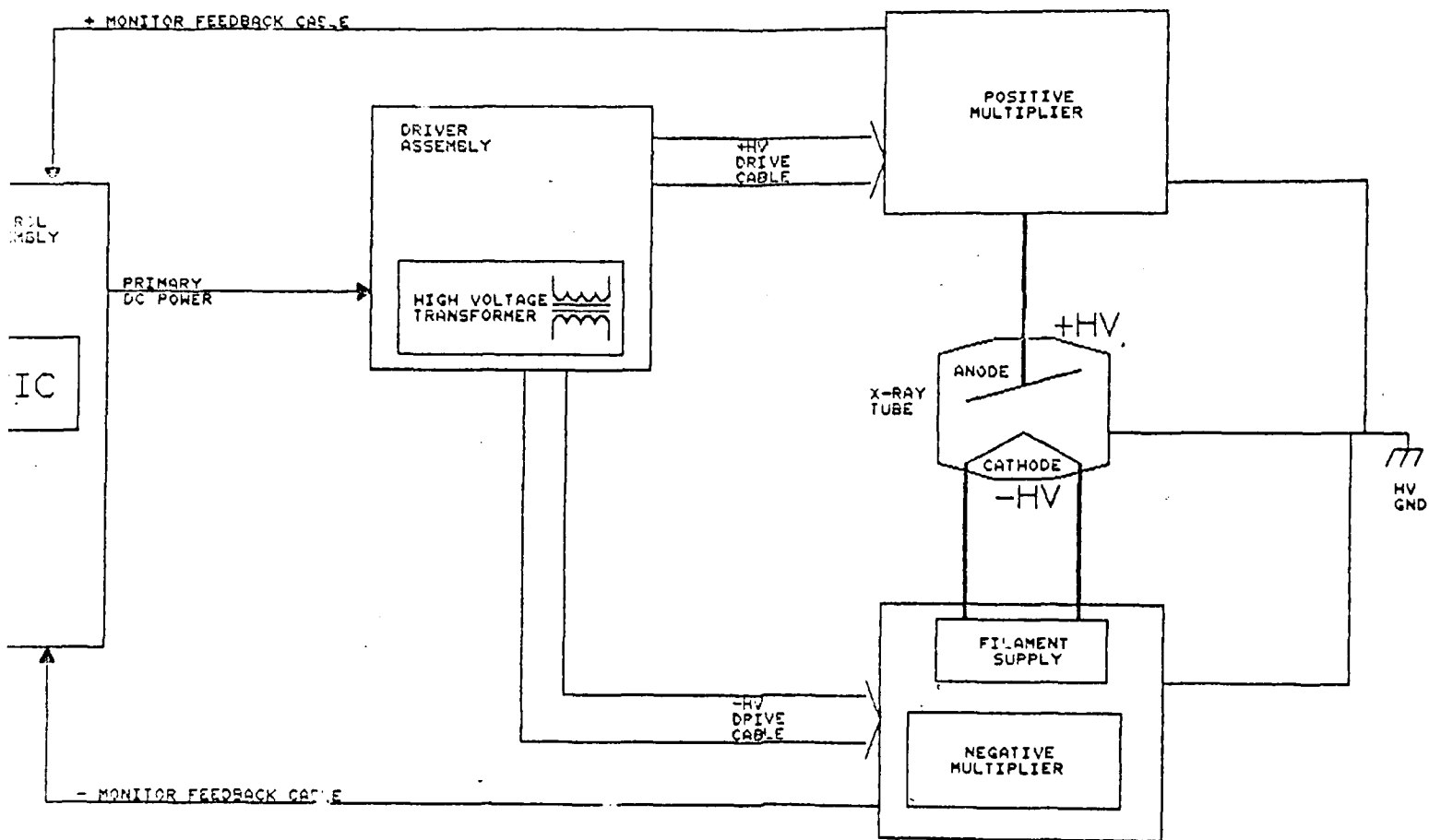
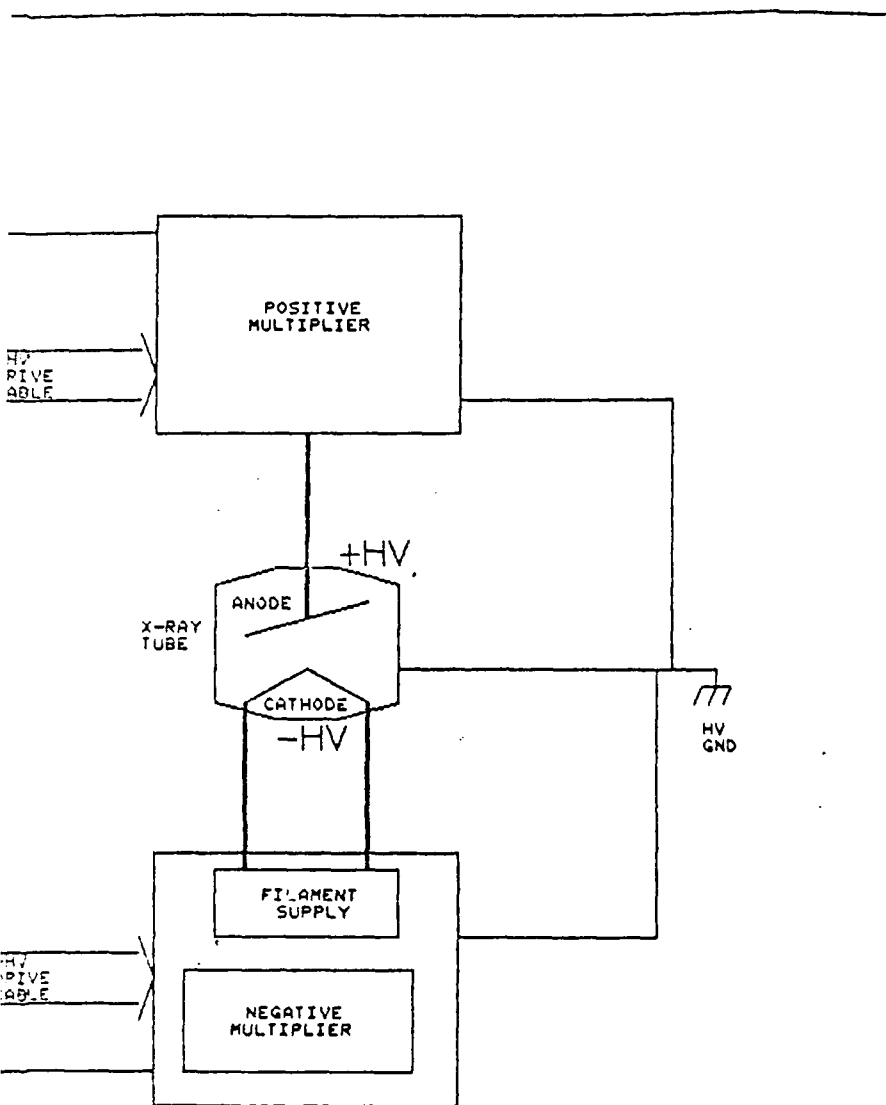


FIGURE 16 : HIGH VOLTAGE POWER SUPP



: HIGH VOLTAGE POWER SUPPLY BLOCK DIAGRAM

FMS 5000	
Title	HVPS BLOCK DIAGRAM
Size Document Number	
B	file : HVPS
Date: February 23, 1989	Sheet 1 of 1



SUPPLY BLOCK DIAGRAM

FMS 5000		
Title HVPS BLOCK DIAGRAM		
Size Document Number	file : HVPS	REV
B		1.0
Date: February 23, 1989 Sheet 1 of 1		

Figure 16

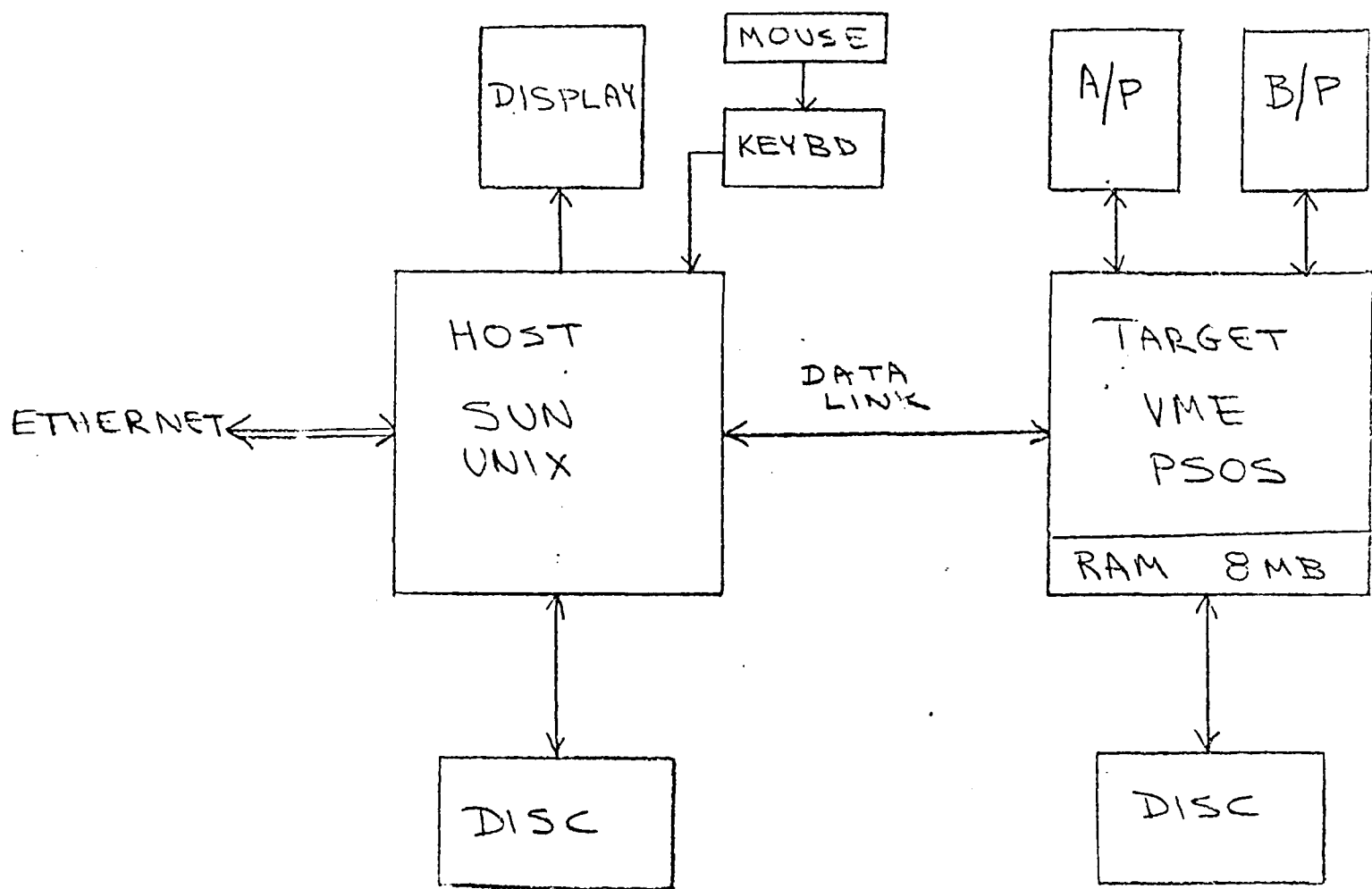


FIGURE 17. DUAL COMPUTER

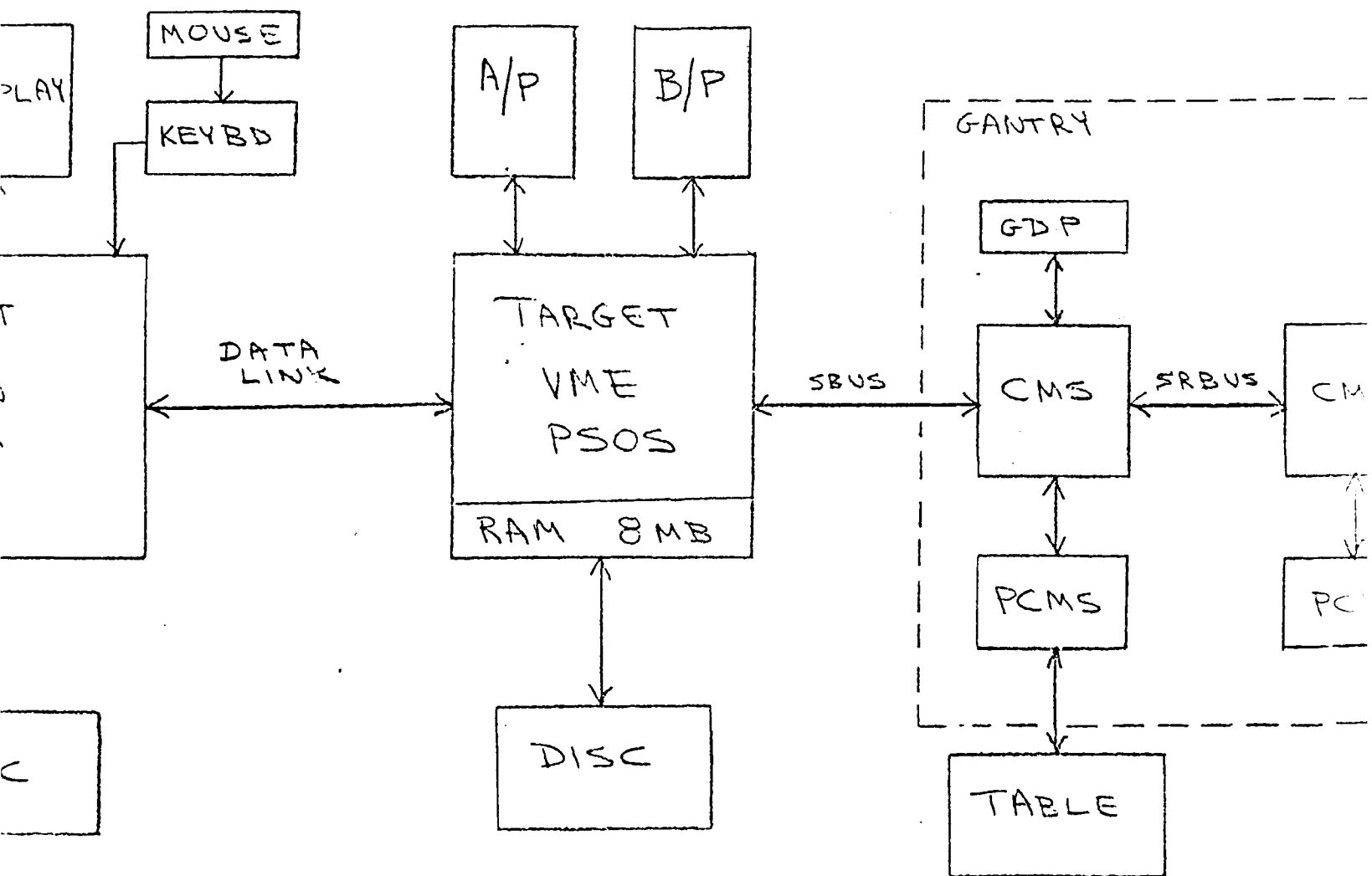
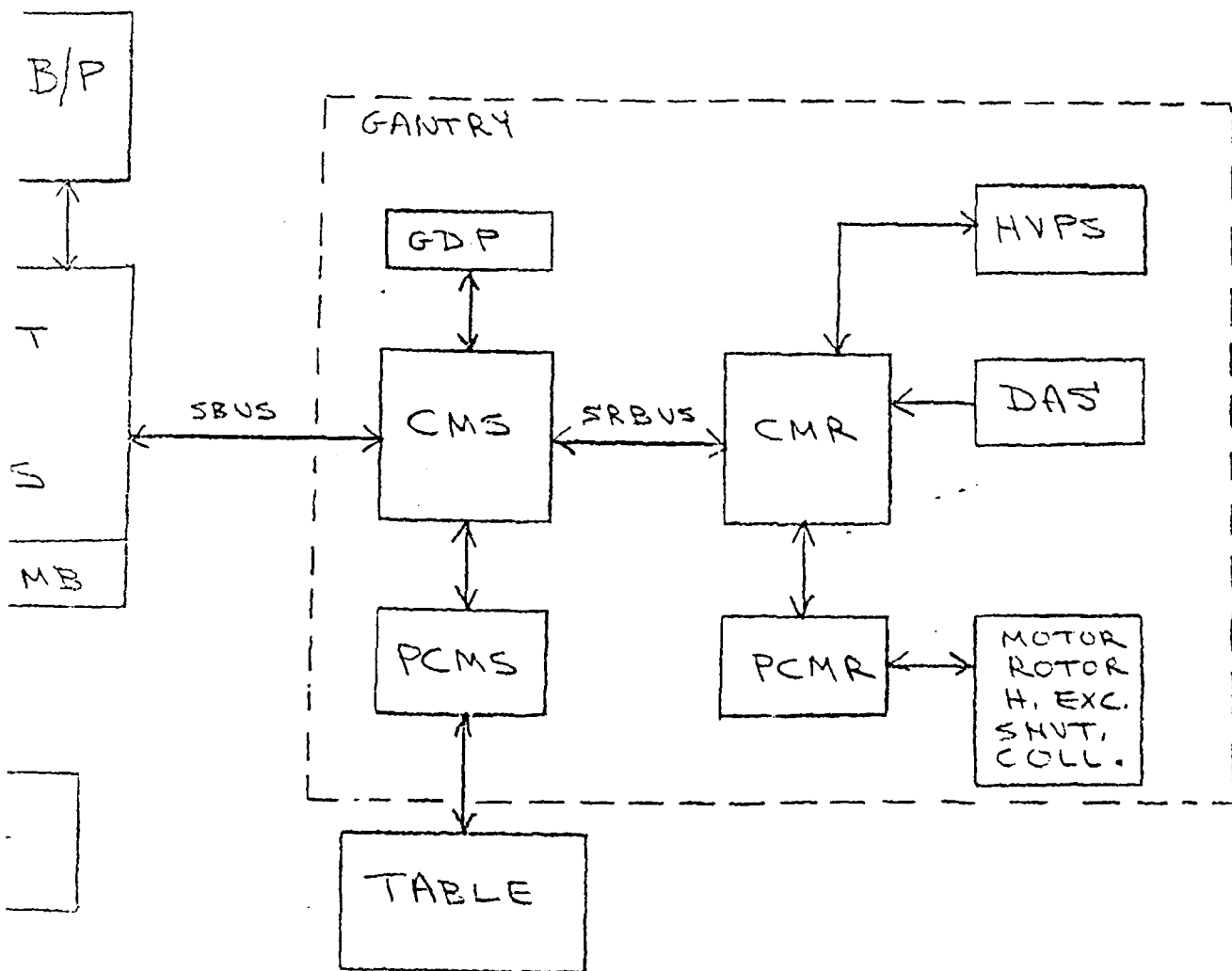


FIGURE 17. DUAL COMPUTER SYSTEM BLOCK DIAGRAM



TER SYSTEM BLOCK DIAGRAM

COMPUTER CONSOLE - COMPONENT DESCRIPTION

1. MONITOR - 19" diagonal gray scale, analog input, high resolution 1024 V by 1280 H, shock mounted with Lexan faceplate. Images and scanner control on one integrated screen utilizing a windowing user environment.
2. SCANNER CONTROL PANEL - Controls primary functions like:
 - a) System main power on switch and indicators
 - b) Start and Abort scan sequence via lighted pushbutton
 - c) X-Ray on warning indicator
 - d) Emergency Stop pushbutton
3. KEYBOARD - full alpha-numeric keyboard with function keys and numeric/cursor keypad
4. TRACKBALL (or Mouse) for cursor positioning and graphics pointing functions. Three button select feature. Continuous window and level controls via optical potentiometers.
5. FOLD-UP DRAWER - For keyboard and trackball, protects components, and covers display monitor for transport.
6. CONSOLE BASE - contains all electronics hardware.

MODULE - COMPONENT DESCRIPTION

19" diagonal gray scale, analog input, high
24 V by 1280 H. shock mounted with Lexan faceplate.
inner control on one integrated screen utilizing a
environment.

CONTROL PANEL - Controls primary functions like:

ystem main power on switch and indicators

start and Abort scan sequence via lighted pushbutton

-Ray on warning indicator

Emergency Stop pushbutton

- full alpha-numeric keyboard with function keys
ic/cursor keypad

(or Mouse) for cursor positioning and graphics
functions. Three button select feature. Continuous
level controls via optical potentiometers.

POWER - For keyboard and trackball, protects
and covers display monitor for transport.

GE - contains all electronics hardware.

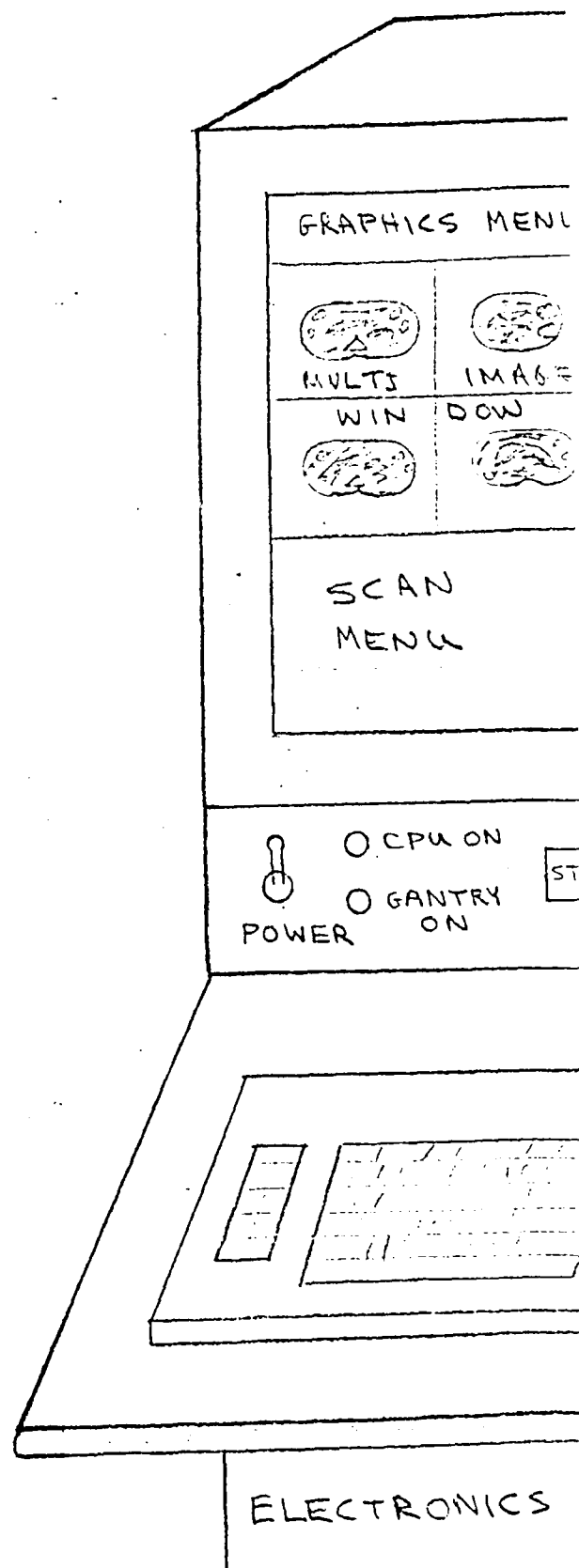


FIGURE 18. CONS

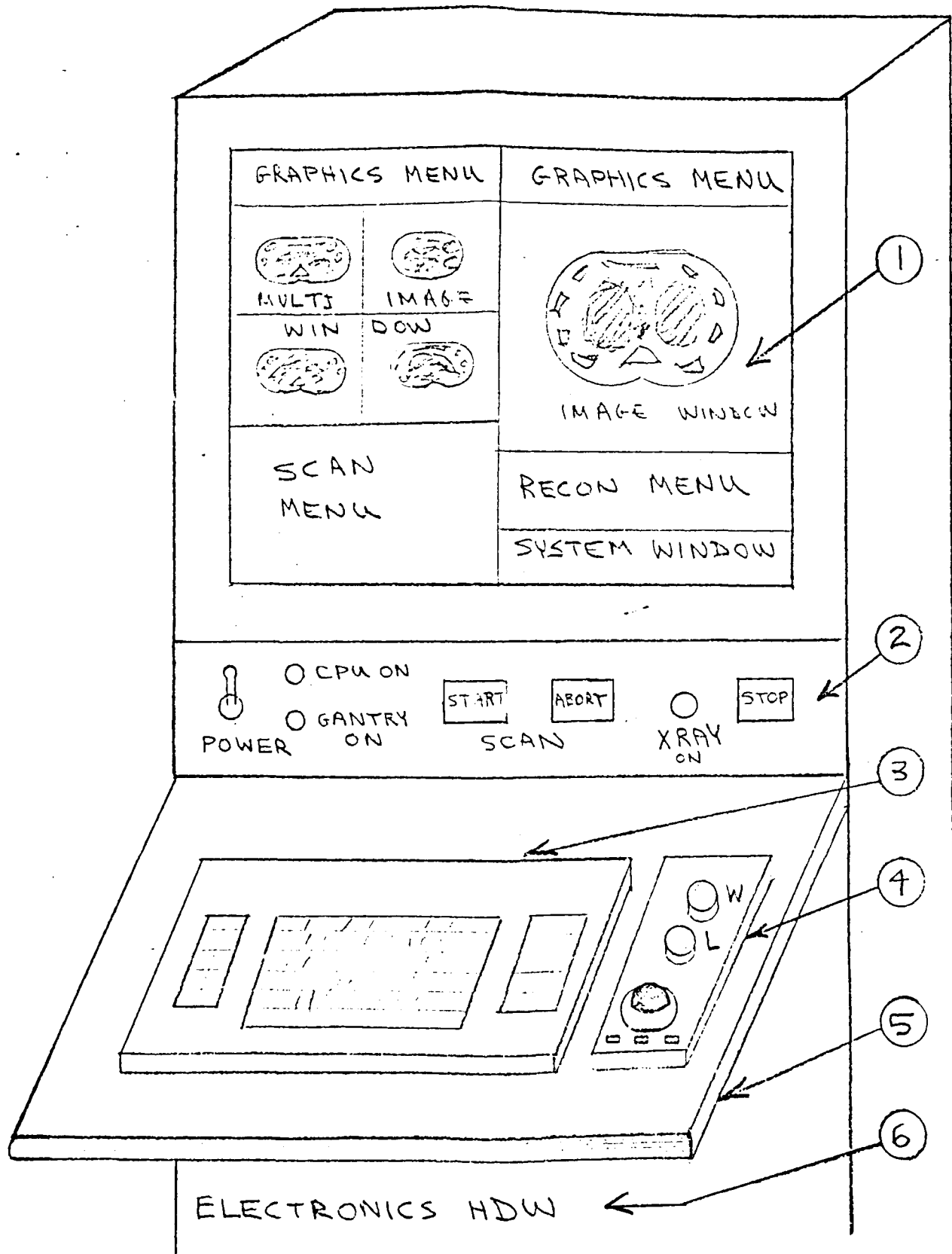


FIGURE 18. CONSOLE LAYOUT Figure 18

Time Required to Scan a Patient

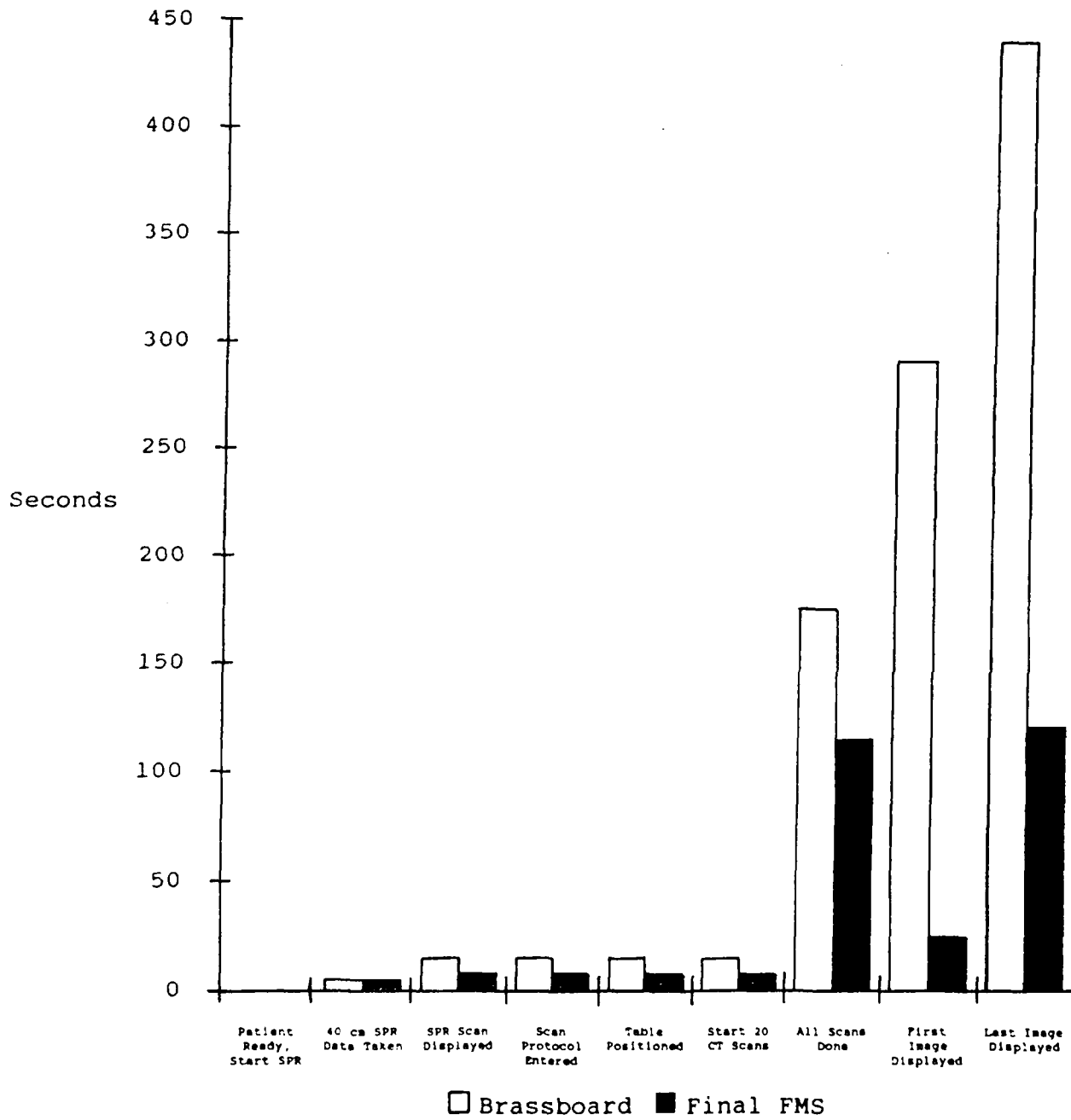


Figure 19