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FILMLESS RADIOGRAPHIC SYSTEM FOR FIELD USE

·FINAL REPORT

12 Feb 1988

Melvin P. Siedband
Douglas C. Kramp
Frank C. Grenzow
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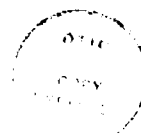Frank C. Grenzow
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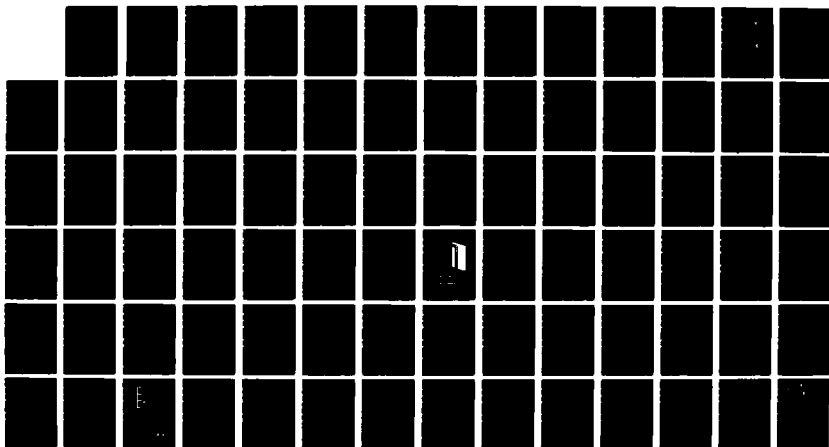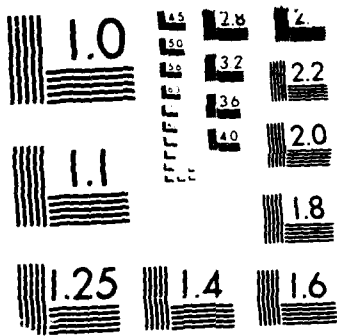
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A portable x-ray machine comprising a power pack and arm assembly has been developed for use in the field. Energy from a rechargable NiCd battery is accumulated in an electrolytic capacitor to produce a short, powerful exposure. The arm assembly contains electronic circuits, x-ray tube head, and receptor assembly. The image receptor can be a conventional x-ray film-screen cassette, a new Polaroid cassette, or an eraseable electrophoretic image display, EPID, made by Philips Research Laboratories.

A study was performed to determine a useful configuration of a filmless radiographic system based on stimulable x-ray phosphors and optical data cards. When exposed to x-rays, a phosphors plate will store a latent image until read by a laser beam. The image is digitized when read, transfered to a small computer, and displayed on a monitor for review. Optical digital data cards, which are credit card size and which store several MBytes of data similiar to music compact discs, will then permanently store up to 12 images and several pages of text. Advantages are a 100x reduction of volume of supplies, film and development chemicals are not needed, immunity to severe environments, and long storage times.

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I. INTRODUCTION

The contract between the University of Wisconsin and the U.S. Army Medical Research and Development Command, DAMD17-86-C-6039, was for the study of small x-ray systems and filmless x-ray systems. Items to be delivered were a demonstration model of a small x-ray machine, a Technical Report describing a filmless radiographic system based on optical digital data cards (DDC's) and a Final Report describing the results of the studies.

A portable x-ray machine comprising a power pack and arm assembly has been developed for use in the field. The principle of operation is that energy is accumulated in an electrolytic capacitor to produce a short but powerful exposure. The energy source is a NiCd battery. The arm assembly contains the electronic circuits, the x-ray tube head, and the receptor assembly. The image receptor can be a conventional x-ray film-screen cassette, a new Polaroid cassette, or an eraseable electrophoretic image display, EPID, made by Philips Research Laboratories.

A study was done to determine a useful configuration of a filmless radiographic system based on stimulable x-ray phosphors and optical data cards. The stimulable phosphors can be exposed to x-rays and will store the latent image until read by a laser beam. The image is digitized when read by the laser beam and can then be stored as digital information in the random access memory, RAM, of a small computer and displayed on the monitor. Optical digital data cards (DDC's) use the same data storage means as music compact discs where a laser burns a pattern of "micropits" in a reflective layer. The computer can send and receive image data by treating the DDC as a write-once/read-many (WORM) RAM. The credit card size DDC's can store up to 12 images and several pages of text. Practical advantages of the DDC scheme are the reduction of volume of supplies of more than 100 times, no film or development chemicals are needed, the cards are immune to severe environments (especially low level radiation), and tolerant to long storage times.

The general ideas of the filmless system are that each major element has its own image RAM and that communication between the RAM's will be via the small computer systems interface, SCSI. Communication between complete systems, e.g. teleradiology, would be via the DIN/PACS interface. Other medical imaging sources such as CT, MRI, and ultrasound machines could be connected to the system via the DIN/PACS interface. A complete assembly with such interfaces would be the basic Army Medical Imaging System, ARMIS. Major components would include a cassette reader with several cassettes, a computer/controller, a DDC reader/writer, an independent viewer, a DIN/PACS interface, and a data link interface.

II. PORTABLE X-RAY SYSTEM

A small portable x-ray device comprising a power unit and arm assembly has been designed for use in the field. The principle of operation is analogous to a photographic flash gun in that energy is accumulated in electrolytic capacitors and discharged to produce a short but powerful exposure. Capacitor discharge energy systems have the problem of diminishing voltage on the capacitors during discharge. This system uses a special form of switching regulator so that the voltage to the x-ray circuit is constant during discharge and so that up to 70% of the stored energy can be used for the production of x-rays. The primary power source is a NiCd battery which can be recharged from almost any source: powerline, vehicle battery, mobile power generator, etc. The arm assembly contains the electronic circuits, the x-ray tube head and the receptor assembly. The arm assembly is designed for use with a standard Army litter when elevated 45 cm from the ground. The tube head and the receptor holder can be folded against the arm for convenience of storage and transport. A radiation sensor is used as part of an automatic exposure control (AEC) to terminate the exposure when sufficient radiation has been received by the receptor. The image receptor can be a conventional x-ray cassette, a new Polaroid film cassette, an eraseable display device (the Philips electrophoretic image display), or a new filmless cassette using a stimulable phosphor.

II.A. Purpose

There is a need for a small x-ray machine, hand-held, with a self-contained power source, for use in combat casualty care or at the scene of common accidents. Since the accident scene may be chaotic, the need for a machine of considerable simplicity is required. For this machine, exposure control can be automatic for full field images, similar to an aim-and-shoot camera. All that is necessary is to turn on the machine, insert the receptor (film or eraseable display panel), verify that settings are in the automatic mode and that the "Ready" light is on, then aim and shoot.

II.B. General Description

The arm assembly and the power pack are connected by a short cable as shown in Fig.1. The arm assembly comprises the tube head, the receptor assembly, the arm and the control panel. The tube head consists of the x-ray tube, the high voltage circuits and the beam-limiting cone. The arm contains the electronic circuits. The receptor assembly contains the x-ray grid, cassette holder or EPID panel and the sensor panel for the automatic exposure control. Both the tube head and receptor assemblies are hinged so that they can be folded against the arm. The power pack contains the battery, the energy storage capacitor and the capacitor charging circuit. By separating the two assemblies, the weight of the arm assembly is held to a value where one operator can easily position it over the patient. The control panel permits operation in the automatic mode as well as manual setting of the exposure factors. Switches and signal lights are used to indicate operating conditions. The anode voltage of the x-ray tube can be adjusted, as well as the exposure time and density. An optional cone restricts the x-ray field for taking dental radiographs. When the arm assembly is disconnected from the power pack, the connector is exposed for charging the battery. External battery chargers or cables can be used to charge from the regular power line, vehicle battery, or electrical generator. Recharging time is less than 12 hours or, with fast-charge cells, as short as 2 hours.
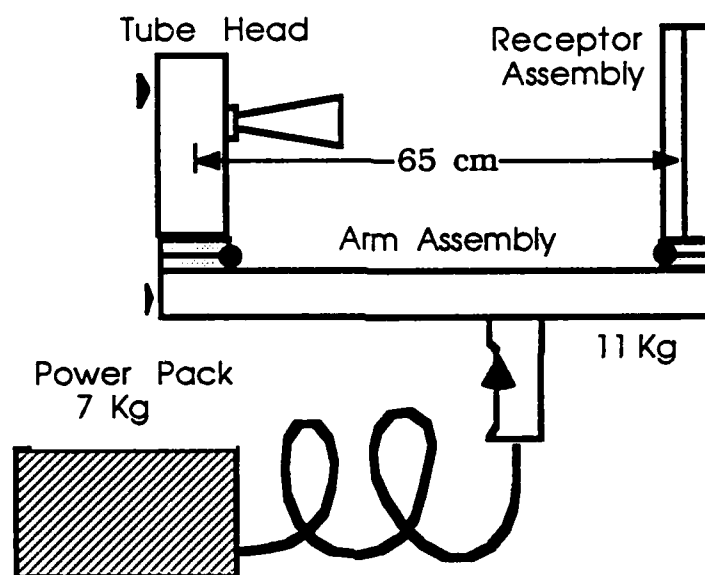
Fig. 1 Hand Held X-Ray Unit

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II.C. Requirements

The x-ray power level must be adequate for a motion-stopping image of the chest and capable of penetrating an average abdomen. The image field size must be large enough to see the region of interest and relevant body landmarks. In emergency care situations, it is important that operation of any device be as simple and fool-proof as possible.

The portable x-ray system was designed for use with an Army litter fitted with extension legs which elevate the litter about 45 cm above the ground. It is intended for use by a single, unassisted operator. The arm assembly is used by resting the tube head on the ground and positioning the receptor over the injury as shown in Fig. 2. For cross-table and other angles, the tube head may be rested on any stationary device or held by hand. The position of the handle and trigger require the operator to be positioned for reasonable radiation safety. The x-ray factors can be set over a range sufficient to image soft tissues, bone extremities, the chest, or abdomen. An aperture restricting device at the collimator would permit conventional dental radiography.

II.C.1. Specifications

The handheld x-ray machine performs as well as more powerful single phase conventional x-ray machines. There are two reasons for this: the reduced focus/film distance requires half the energy and the constant potential on the tube increases the effective output/mAs. The tube current of 35 mA for the handheld machine is equivalent to about 150 mA of a single phase generator. The limitation imposed by reducing the focus/film distance is that a full 14 x 17 inch field cannot be covered; a 10 x 12 or 8 x 10 inch field is used. The constant potential circuit means that energy is used more efficiently by the x-ray tube.

The internal battery is capable of powering up to 50 exposures and can be recharged from almost any external source. Set-up time, unfolding the arm assembly and charging the energy storage capacitors for the first exposure, is less than three minutes. Additional exposures can be taken at 30 second intervals. A battery saver circuit reduces battery current when the capacitors are fully charged. When either Polaroid x-ray cassettes or the Philips eraseable display panel are used, no bulky film processor is required.

The specifications are:

1. 60 to 90 kVp
2. 0.5 to 12 mAs. Larger capacitors can increase the upper limit to 50 mAs.
3. 3.0 kWp, 1.2 kJ
4. 69 cm focus/film distance
5. 11 kg (arm assembly), 7 kg (power pack)
6. 150 sec charge time to first exposure, 20 sec to following exposures
7. 50 exposure battery capacity
8. 8 x 10 or 10 x 12 inch receptor size
9. Standard Cassettes, Polaroid Cassettes, EPID panel
10. Automatic/manual exposure control

II.C.2 Field Supplies/Support

As described in previous paragraphs the handheld x-ray machine consists of an 11 Kg arm assembly and a 7 Kg power pack. For ease in positioning, a standard Army litter with extension legs should be used. For long term operation a power source for recharging the batteries will be required. The power source could be the standard power line, vechicle battery, portable generator, or a portable solar electric generator (ie. Sovonics model MP-3010).
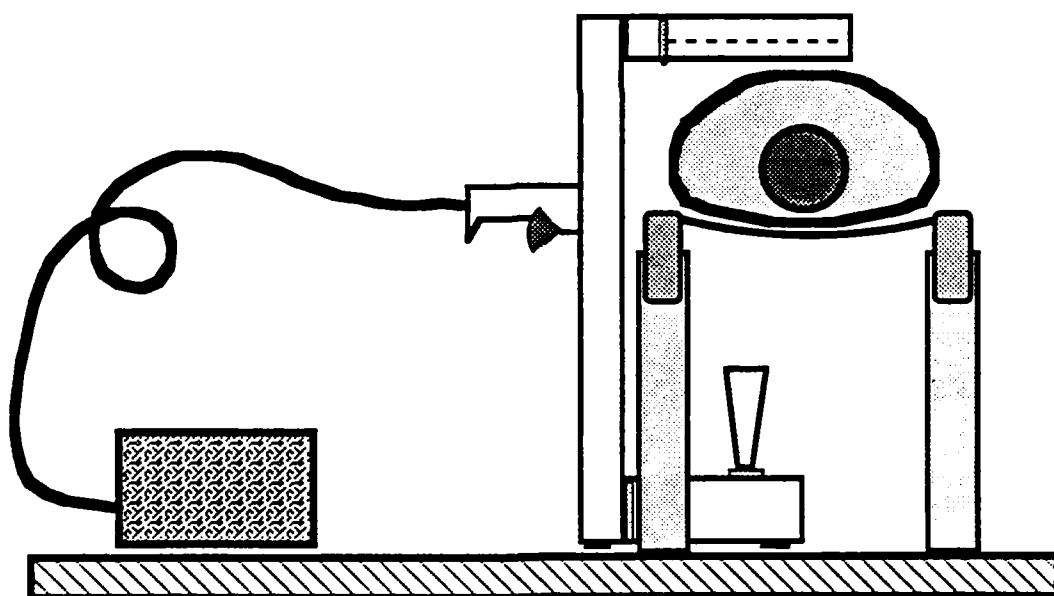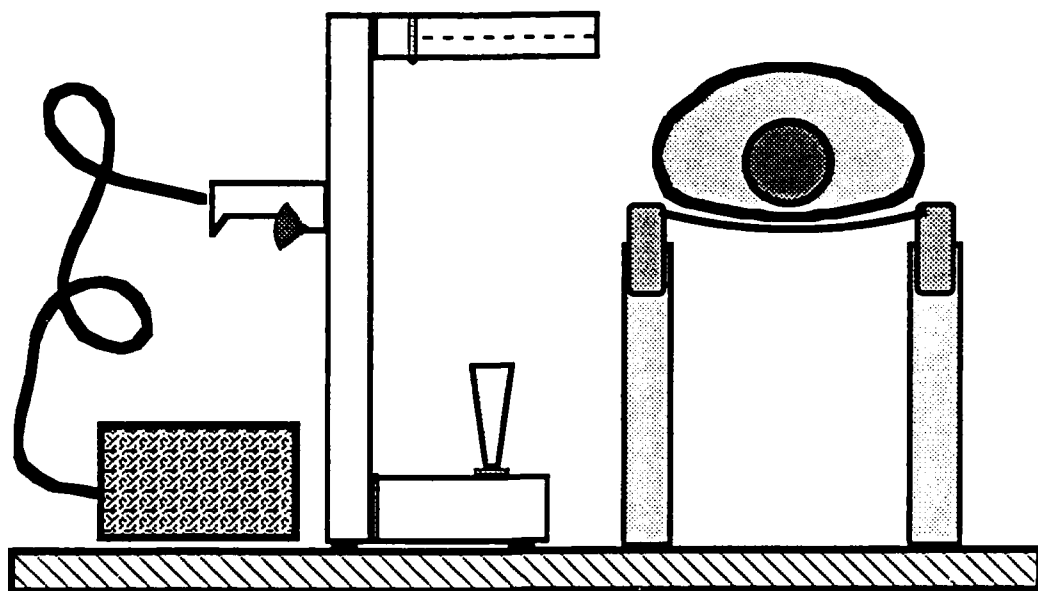
Fig. 2   Handheld X-Ray Positioning Diagram

A variety of image receptors can be incorporated. If the ususal transparent film is used, the bulky wet processing equipment and chemicals will be needed. A more portable alternative is the use of Polaroid coaterless film. In addition to the positive and negative film sheets and cassette, a small self contained processor, requiring no external power is manufactured by Golden Engineering, Model 150-P.

The Phillips EPID panel is the third receptor alternative. It has the advantage of not requiring additional supplies but does has some short comings as discussed in section II.D.4.

II.C.3 Radiographic Procedures

The x-ray generator is capable of short exposures for chest radiography and will stop the motion of the heart. The reduction of focus/film distance restricts the image size so that two images would be required to see the entire chest. In general, the lower focus/film distance and other factors mean that about 25% of the usual hospital mAs values will be required for exposure. The automatic exposure control would be effective for chest imaging but will not operate properly for extremity images as unattenuated x-rays will terminate the exposure too soon. Manual exposure settings and a simple technique chart can be used. For most imaging, it is important that both the machine and the body part are supported to avoid motion artifacts. With use, it is probable that various support clamps and rests will be developed for both the patient and the x-ray machine. With such devices, most of the common x-ray imaging requirements would be accomodated by the machine. The energy stored in the capacitors is more than sufficient for radiography of the head. A special cable can be made which will permit parallel operation of power packs to double the energy/exposure capability.

II.C.4 Radiation Safety

Operator safety from direct x-ray exposure has been taken into the design considerations. The x-ray tube is shielded with a Litharge cylinder, the cathode end is shielded with lead. A stainless steel collimating cone restricts the x-ray field to an area no larger than the receptor. The receptor assembly is backed with lead shielding.

The exposure switch is located in a position that reduces the operator exposure to a low value of backscattered radiation. The machine also accommodates a remote control exposure switch for even greater protection.

Calculations were made to estimate exposures to an operator of the portable x-ray machine for several common procedures. Measurements were made using TLD (thermoluminescent dosimeters) chips when exposures were made of water and plexiglass phantoms. The results show that the proper use of the machine falls within the safety limits of the National Council of Radiation Protection, NCRP.

Exposure estimates were based on calculating the incident exposure in R-cm^2, assuming 10% scatter, estimating the absorbance of the patient and the distance to body parts of the operator. The calculations are summarized below:

Estimated Exposure to Operator Body Part/100 Exams

Procedure	Incident/exp	Legs and Feet	Genital	Face and Neck
Chest (90kV, 3mAs)	1.1x10^2 R-cm^2	70mR	27mR	17.5mR
Abdomen (90kV, 8mAs)	2.9x10^2 R-cm^2	187mR	72mR	47mR
Head (80kV, 6mAs)	1.7x10^2 R-cm^2	111mR	43mR	27mR
Extremities (70kV, 3mAs)	0.7x10^2 R-cm^2	43mR	17mR	10mR

Measured exposure to five operator phantom sites (feet, legs, genitals, chest, neck) were all less than 10 mR, based on 10 exposures: 90 kv, 0.20 sec, 63 mAs approx/10 exp., 15 cm phantom, 69 cm FFD. The very low readings of less than 2x background are not reliable and are interpreted as less than 10 mR. These measured values are consistent with the estimates. A radiation detector next to the phantom read 22 mR (water) and 12 mR (plexiglass) after 10 exposures.

NOTE: No extra operator shielding was used. For non-emergency uses, a sheet of lead loaded plastic similar to lead apron material, would further reduce exposure to the operator. Exposure values are small when compared to conventional x-ray machines as a result of the smaller field size, positive beam barrier and placement of the operator at the patient exit beam side. These exposure values are less than that received by an operator of a convential radiographic/fluoroscopic machine operating in the spot film mode for the procedures described.

The water phantom was a 15 cm thick water layer in a 5 gallon plastic "jerry can". The plexiglass phantom was 30 x 30 x 15 cm. The radiation detector was a Nuclear Associates RadChek.

II.D. Receptors

The small x-ray machine has the same radiation capability as a full-size generator. The receptor assembly can accommodate any of the usual film-screen combinations, a new Polaroid x-ray cassette, a stimulable phosphor screen for electronic radiography (filmless radiography), or the Philips electrophoretic image display (EPID). The automatic exposure circuit has a sensing switch so that changeover is automatic: any receptor can be used in the system without readjustment of the exposure factors.

II.D.1. Conventional X-Ray Cassettes

Any of the standard film-screen combinations may be used: standard screens for general purposes, high sensitivity (thick) screens for chest or abdomen imaging, or detail (thin) screens for extremities. Conventional x-ray film must be developed by wet processing. However, several compact processors exist for the smaller format films and may be suitable for many field applications where the environment is not severe. Hand tanks may also be used for film processing.

II.D.2. Polaroid Cassettes

Polaroid positive print type 803 film was tested using a single Kodak Lanex fine screen and compared to two commonly used Kodak film-screen combinations. The film-screens were XRP/X-Omatic Regular and T-Mat G/Lanex Regular. Sensitometry curves of the two films were then compared to the Polaroid images except that the Polaroid density values were halved to account for the light which must pass twice through the emulsion of a positive film. Speed/resolutions were:

XRP = 1000 R / 5.6 lp/mm, TMG = 2700 R / 5.0 lp/mm,
803 = 800 R / 5.6 lp/mm.

Thus, the resolution values of the three combinations were close but the sensitivity of the TMG combination was about three times greater than the XRP or Polaroid. The maximum effective density of the Polaroid was less than that of the conventional films. A radiologist who reviewed the test films said that the Polaroid images were certainly of diagnostic quality.

To use the Polaroid 803 film, a sheet of negative film is first loaded into the x-ray cassette and exposed. The exposed film and a sheet of Polaroid 803 positive film are placed in a small film processor and the two parts are rolled through a "wringer" assembly to spread the developing gel. After one minute, the two parts are separated and the negative image is discarded. A smaller film processor, about 2 kg, is available for field use.

The screen of the Polaroid cassette was changed to Lanex Regular and several of the tests were repeated. The speed increased by a factor of five and the resolution decreased by less than two. Grid lines were still resolved. The appearance of fine details was altered but most of the diagnostic value was retained. The choice of the screens must be made by the using radiologist. The x-ray generator and automatic exposure circuits are capable of operation with either screen.

II.D.3. Storage Phosphors

A storage or stimulable phosphor screen is used in an x-ray cassette without film. Exposure to x-rays causes an initial fluorescence, which is ignored, and also drives some electrons into traps. Later scanning with a red laser induces a blue fluorescence. The blue light can be sensed with a photodiode to produce an electrical signal for digital processing and storage. The laser scanning erases and primes the screen to make it ready for the next exposure. Because the storage phosphor screen is mounted in a conventional cassette and has the same sensitivity as conventional screens, the small x-ray machine can use them without modification.

The stimulable phosphors will be used in future filmless radiographic systems, in particular, in the ARMIS system described elsewhere in this report. The small x-ray system is compatible with that system and would require only a simple resetting of the automatic exposure sensitivity control.

II.D.4. Electrophoretic Image Display, EPID

The EPID, developed by the Philips Research Laboratories, consists of two transparent plates containing an opaque dielectric fluid and an x-ray sensitive layer. The potential of the plates can be set so that small charged pigment particles within the fluid can be moved. The front plate will appear either black or yellow, depending on whether the pigment particles have been moved toward or away from the plate. The charge distribution of the x-ray sensitive layer will affect the motion of the particles to form the image. The image can be erased by electrical cycling of the plate electrodes.

The advantages of the EPID are that the image appears within seconds of exposure, the image remains for several hours (actually, several months) until erased, and it can be used again. Image sensitivity is about half that of film-screens and resolution is on the order of 2 lp/mm. Thus, although image quality is only fair, it is of diagnostic value. An obvious advantage is that no supplies are required. Disadvantages are the instability of the panels and the limited contrast scale. The instability appeared as a redistribution of the pigment particles and loss of sensitivity. This was corrected, in part, by several hours of electrical cycling. Several panels developed leaks and had to be returned to Philips.

The EPID panels would not function properly after being transported short distances in an automobile. Much of the sensitivity was restored after electrical cycling for 24 hours but dead areas or areas of poor imaging remained even then. At this time it appears that the EPID panels require further development before becoming practical for use in the field.

II.E. Circuit Operation

The portable x-ray system uses NiCd batteries to charge three 0.01F electrolytic capacitors to 305V. The capacitors are discharged through a switching regulator to produce a constant output voltage of -65 to -160V, depending on the selection of x-ray tube voltage. That voltage is applied to a saturated high frequency (25 kHz) power inverter which feeds the high voltage transformer in the tube head. A voltage multiplier in the tube head converts the high frequency energy to a constant potential to operate the x-ray tube. The filament transformer also operates at a high frequency to permit it to be made very small. Timers, battery chargers, automatic exposure control, EPID control and interlocks complete the circuit.

The following paragraphs describe the circuits. The system block diagram of Fig. 3 shows the interconnections between each of the circuits. Some terminology and syntax particulars should be clarified in order to easily understand the following descriptions. First note that signals (which interconnect the circuits) are capitalized. Most of the signals can be thought of as binary digital signals. That is, a signal is either high (1) or low (0). A signal is said to be asserted when it is in the active state (which may be either high or low). The name of a signal by itself (SIGNAL) means that the signal is active high and the name of a signal with a bar (SIGNAL*) means that the signal is active low.

II.E.1. Battery Charging

Ten 1.2V NiCd cells are arranged in two banks of five cells each. The banks are in series for use and in parallel for charging. The parallel/series connection is made at the cable connector of the power pack. When the cable to the arm assembly is removed, a charging cable can be connected. This cable can be fed from a variety of charging circuits ranging from a series resistor/cigarette lighter plug to charge from a passenger vehicle, or a small appliance charger, to a regulated fast-charger device. A rack could be designed to hold the power pack and connect to a power unit in an ambulance to keep the battery on continuous trickle charge.

II.E.2. Battery Indicator Circuit

The battery indicator circuit consists of 1/4 of an LM324 quad op-amp IC and various other components as shown in Fig. 4. The purpose of this circuit is to indicate the status of the battery voltage to the user and to prevent exposures when the battery voltage is below a set threshold.

When the battery voltage is greater than approximately 9.5V (full load), the op-amp is held in the inverting state via the voltage divider (150k and 180k resistors) and the 5.1V reference on its inputs. The 5.1V reference voltage is the VREF output of the SG3525 IC used in the floating power supply circuit (Fig. 20). In the inverting state (normal operation), when the output of the op-amp is low, the PWR/BAT LED on the front panel is lit. The low BATTERY signal has no effect on the ready circuit due to the high impedance of the reverse biased 1N4148 diode.
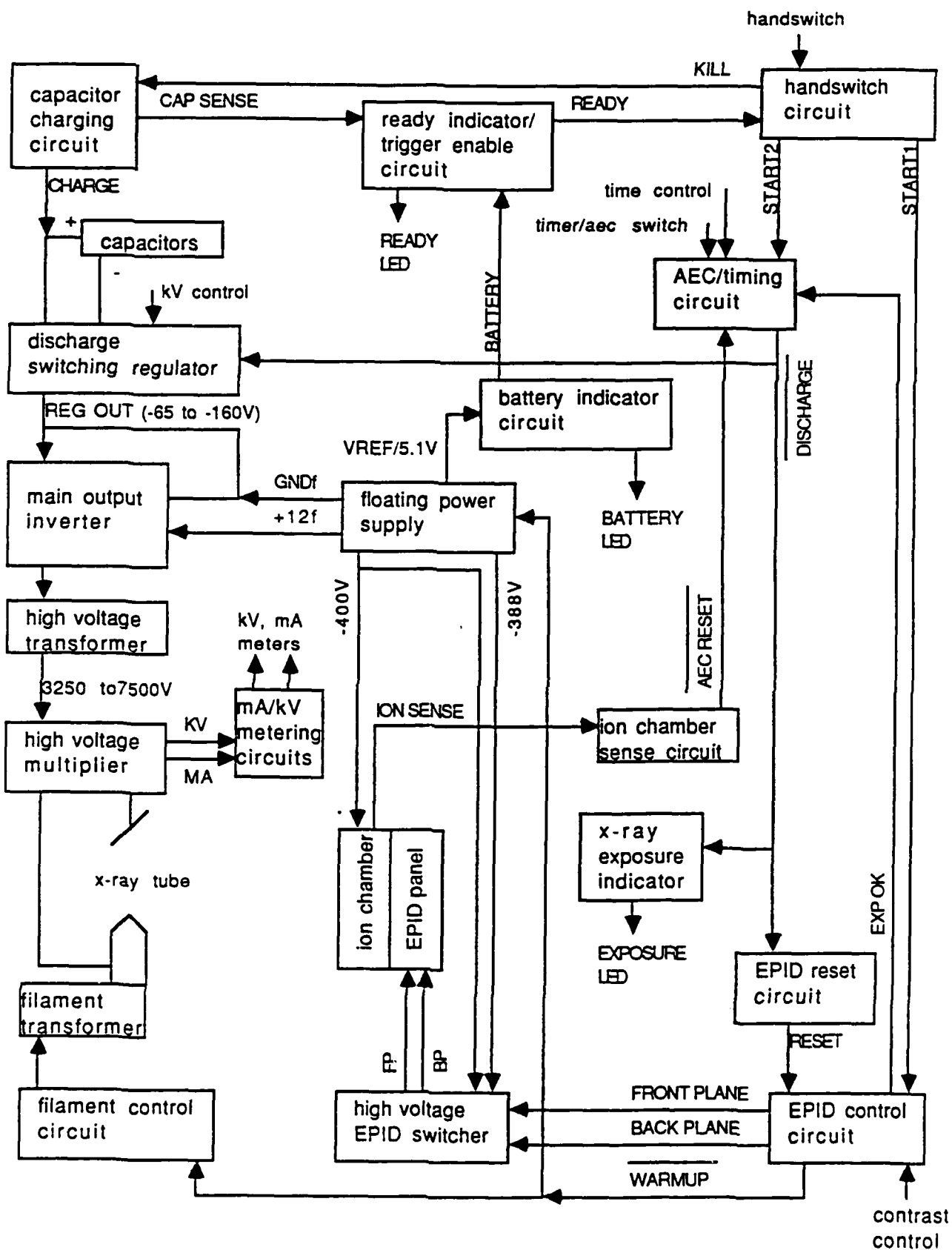
Fig. 3 HANDHELD X-RAY SYSTEM BLOCK DIAGRAM

VREF/5.1V

+12V

10k

150k

100k

+12V

BATTERY
LED

13
−
1/4 324

180k

12
+

14

2.2k

100 Ω   1N4148

BATTERY

.1uF
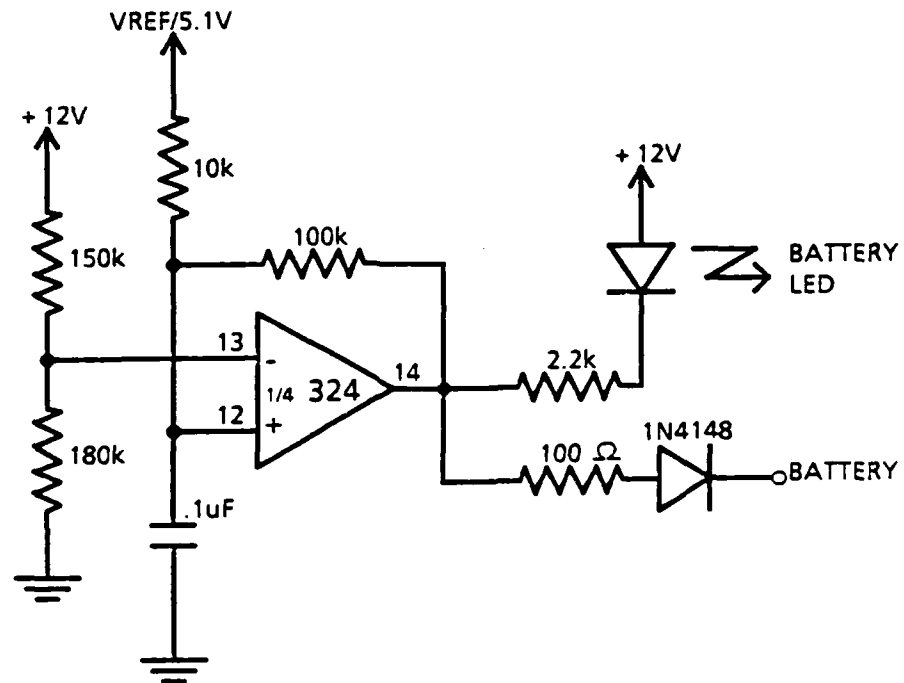
Fig. 4   BATTERY INDICATOR CIRCUIT

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When the power supply voltage drops to less than 9.5V, the op-amp switches into the non-inverting state. Note that the 5.1V reference voltage on the non-inverting input does not drop unless the power supply voltage falls below 8V. In the non-inverting state (low battery), the LED is extinguished due to the high-level on the output. The high BATTERY signal causes the READY signal to be low, consequently disabling any exposures. The 100k resistor and 0.1uF capacitor provide noise immunity.

II.E.3. Capacitor Charging Circuit

The capacitor charging circuit (Fig. 5) maintains the required voltage level on the energy storage capacitors. The circuit is enabled when the power is turned on. A 555 timer and 2N3906 transistor provide the gating pulses to the IRF530 MOSFET switch. The MOSFET switch is part of a forward converter which supplies the 400 volt charging spikes to the storage capacitors (see Fig. 8) via the CHARGE line. A CA3160 op-amp is configured as a comparator to disable the 555 when the storage capacitor voltage has reached a preset level.

The 555 timer is configured for astable operation to produce a 20kHz pulse train when pin 4 is held high by the CA3160 op-amp output. The 2N3906 pnp transistor and connecting resistors and capacitor were incorporated to generate a pulse train with a duty cycle of less than 50%. A duty cycle of less than 50% is not possible with the standard astable configuration.

The forward converter consists of a single IRF530 MOSFET switch, a 0.22 ohm resistor, a 1000uF filter capacitor, three 1N4937 fast recovery diodes, a step-up transformer, and output filter components. The 1N4937 diode connected to the primary of the transformer serves to clamp the reset winding current. The 0.22 ohm power resistor provides over current protection. The step-up transformer consists of a 10 turn primary with a 50 turn flux reset winding wound over it. Part of the 400 turn secondary is also wound over the primary to maximize coupling. The 2.5mH inductor in the output filter can either be a commercially wound toroid or a 2 x 2616 pot core with 40 turns of 24 AWG wire and a 6 mil air gap.

The CA3160 op-amp comparator compares the CAP SENSE voltage (voltage divider value of the storage capacitor voltage) to the 1N5235 zener reference voltage. The op-amp output is high until the desired storage capacitor voltage is reached. The maximum storage capacitor voltage is determined by the 5k pot setting. The hysteresis provided by the 820k feedback resistor and the 18k input resistor allows the storage capacitor voltage to drop 10 volts below full charge before the output of the op-amp toggles high again. To reduce loading on the batteries, the charging circuit is disabled when the filament is enabled. This is accomplished when the KILL signal from the handswitch (see Fig. 13) is asserted. The KILL signal pulls the inverting input of the op-amp high which toggles the output low which in turn disables the 555 timer.

The storage capacitor charging characteristics are presented in Figs. 6 and 7. Fig. 6 shows the capacitor voltage vs. time when the capacitors are initially being charged up. The charging time varies depending on the power source used. This particular data was obtained using a high current 12V power supply. The graph shows that the capacitor voltage reaches the required 300V in approximately 180 seconds (3 minutes). With 10 General Electric NiCd 1.2V 2.2AH (AmpHours) 1/2 D cells, the charging time is significantly faster (2 min. 25 sec. when the cells are "fresh"). With 10 Panasonic NiCd 1.2V 4.0 AH D cells the charging time is also faster than that of the power supply. The reason that batteries are initially faster is that when they are freshly charged, their combined voltage averages closer to 15V than the 12V of the power supply. As the cells are used over an extended period of time, the battery voltages drop and the capacitor charging time gradually increases.
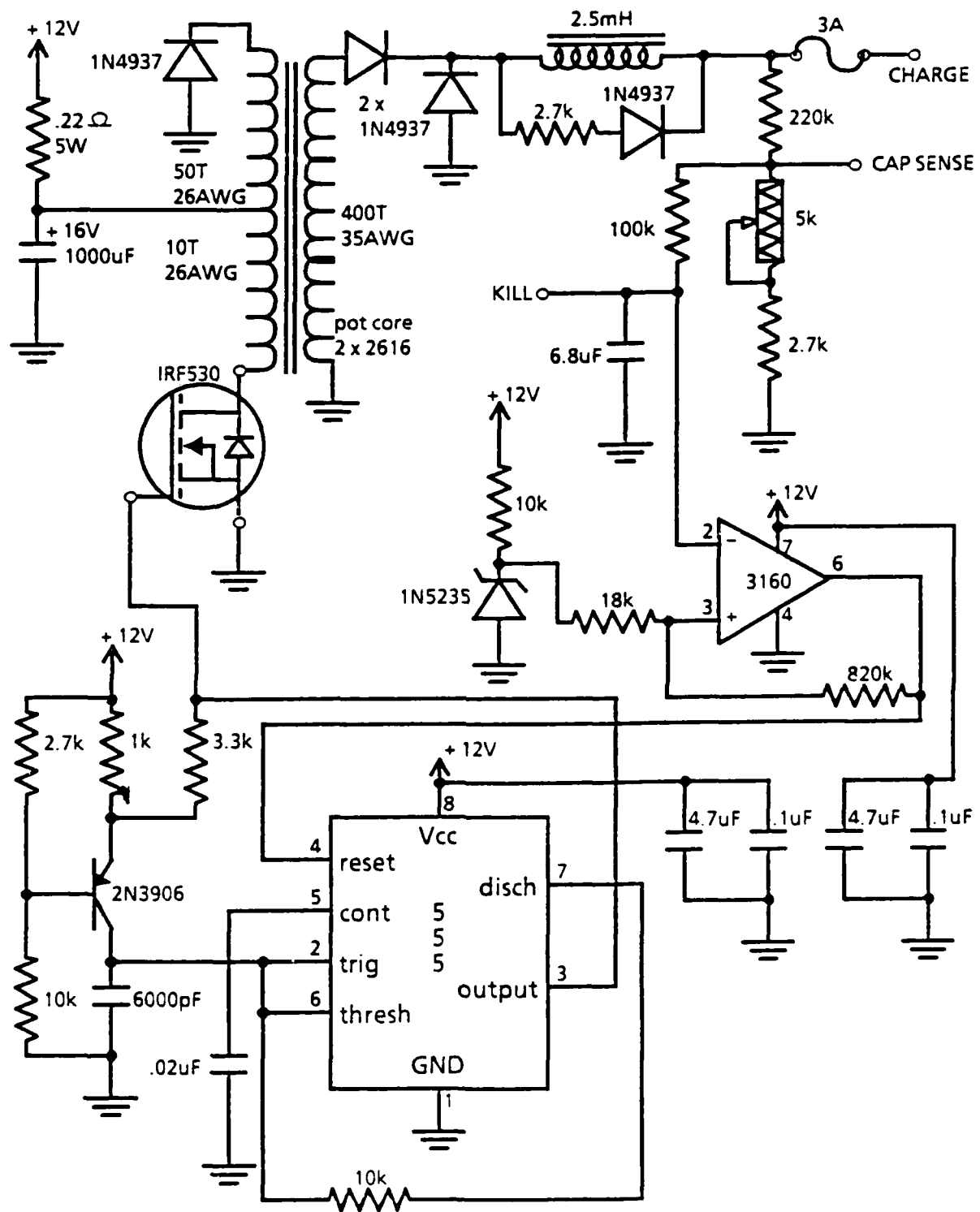
Fig. 5   CAPACITOR CHARGING CIRCUIT

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Fig. 6 STORAGE CAPACITOR CHARGING CHARACTERISTICS

note: system idles
at 80 mA
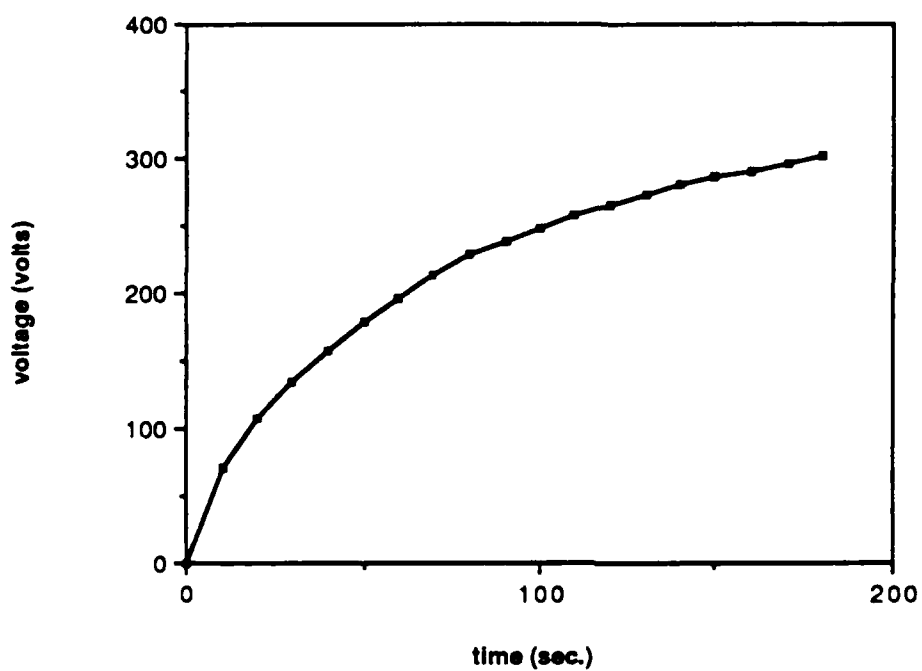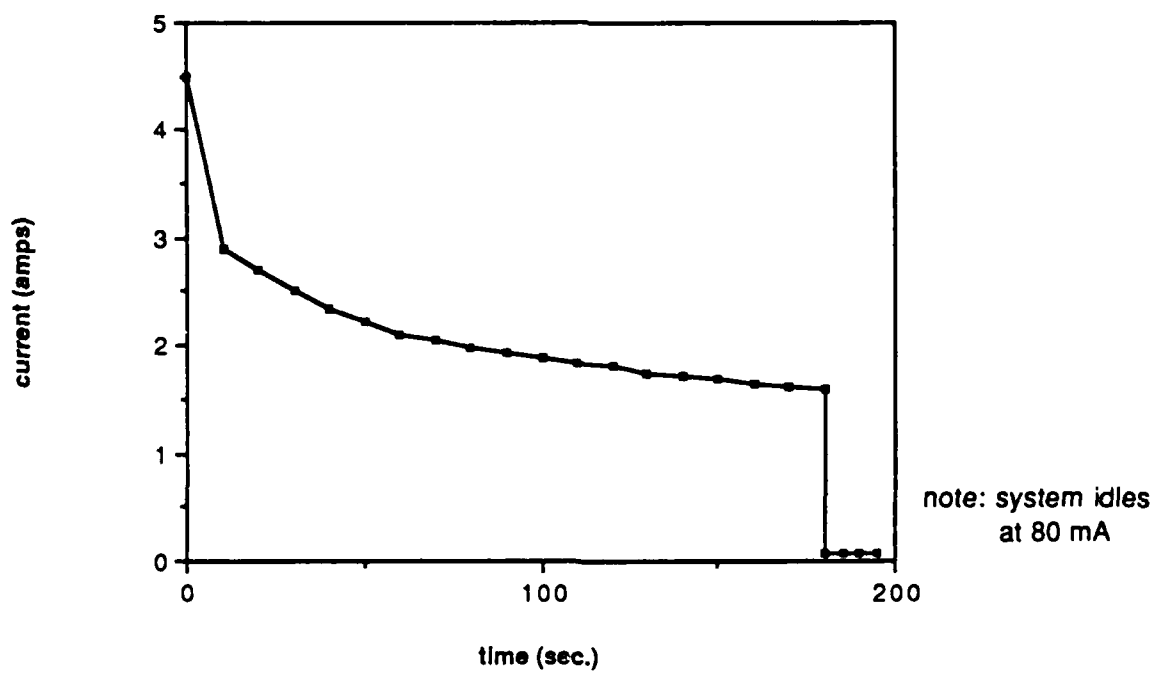
Fig. 7 BATTERY CURRENT VS. CAPACITOR CHARGING TIME

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Fig. 7 shows the battery current drain during storage capacitor charging. The initial drain of 4.5A quickly drops to less than 2A for the rest of the charging cycle. After the storage capacitor voltage reaches the required level (approximately 300V) the charging circuit shuts down and the entire system idles with a current drain of only 80 mA.

II.E.4. Discharge Switching Regulator Circuit

The energy needed to power the x-ray tube comes from the energy storage capacitors. The voltage on the energy storage capacitors diminishes exponentially as energy is withdrawn. The discharge circuit (Fig. 8) is a switching regulator which produces a constant voltage output when discharging the energy storage capacitors.

The switching regulator scheme is far more efficient than a linear regulator, but has an inherent negative characteristic of generating radio frequency interference (RFI). This means that more attention must be given to power supply bypassing, grounding, shielding, and printed circuit layout. Power MOSFET's are employed as the switching devices rather than bipolar transistors. Less circuitry and current are needed to drive the MOSFET's.

In the traditional step down converter scheme, a p-channel FET or pnp bipolar transistor is used as the switch between the DC input and inductor. P-channel FET's are not yet manufactured with sufficient current and voltage ratings for this application. Therefore, to incorporate n-channel FET's with simple drive circuitry and to permit switching to ground (a practical consideration to reduce interference and coupled noise) an unconventional scheme is used. This basically consists of placing the DC input source (storage capacitors) after the MOSFET switches rather than before. The negative terminals of the storage capacitors are no longer tied to ground. This results in the DC output pulse being negative with respect to ground.

An SG3525 pulse width modulation (PWM) IC alternately gates the MTM15N50 MOSFET switches. Each FET switches at 10kHz for an effective regulator switching frequency of 20kHz. By alternately firing the FET's, each FET carries the load current for half the length of time than if a single FET were used operating at 20 kHz; thus *reliability is increased.*

When an FET switches on, energy is transferred to the load. When an FET switches off, energy stored in the 7mH inductor is fed to the load. The 51k resistor closes the loop between the variable output load voltage (-65v to -160v) and the PWM controller. The on time of the gating pulses is varied to regulate the output voltage. The kVp across the x-ray tube is proportional to the regulator output and is adjusted by the 10k potentiometer.

The outputs of the SG3525 are low until pin 10 of the chip is pulled low from its normally high state. When pin 10 is pulled low by the DISCHARGE* signal an exposure is taken for the duration that pin 10 is held low. The 0.1uF capacitor connected to pin 8 controls fall time of the negative output pulse and, to some degree, leading edge overshoot. The 10k resistor between pins 1 and 9 determines the gain of the internal amplifier of the IC. The RC network consisting of the 0.0022uF capacitor and 33k resistor determines the switching frequency. The 2.2k resistor across the 20uF filter capacitor serves to hold the output near ground when the capacitor charging circuit and discharge circuit are idle. If not included, the output will drift and the charging circuit will not turn off when the storage capacitor voltage level has reached the desired full charge level. The toroid inductor connected between the regulator output and the main inverter filters out RFI.
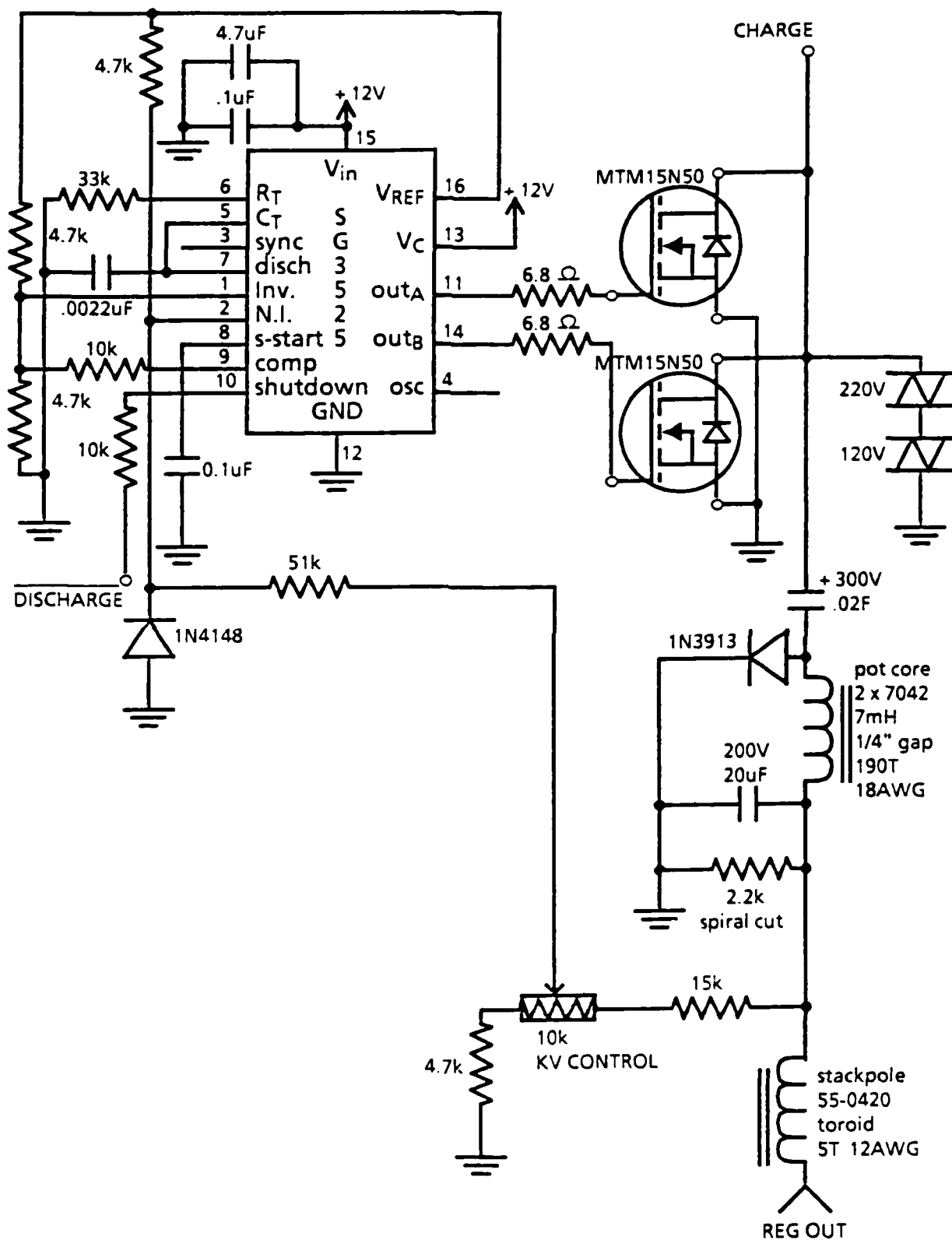
Fig. 8   DISCHARGE CIRCUIT

II.E.5. Main Output Inverter Circuit

The negative DC voltage pulse from the discharge regulator is fed to the main output inverter shown in Fig. 9. The inverter converts the DC voltage to an AC voltage so that the voltage can be stepped up by the high voltage transformer and voltage multiplier.

The main output inverter is a saturated inverter operating at 25kHz. The drive circuitry for the four MTM15N50 power FET's is powered by the 12v floating power supply (see Fig. 20). The inverter is enabled when the floating power supply is enabled by the WARMUP* signal.

The two outputs of the SG3524 PWM IC each switch with the maximum duty cycle of 45%. The switching frequency is established by the RC network consisting of the 10k resistor and 0.0022uF capacitor connected to pins 6 and 7. Each output of the SG3524 feeds the non-inverting inputs of each SG3627 high current driver. In addition to providing high drive current, the two outputs of each SG3627 allow paralleling the drains and sources of two FET's without paralleling the gates. This eliminates oscillations that are sometimes set up on paralleled gate signals. The pot core in parallel with the 5 ohm resistor provides a resonant impedance to reduce current flow during FET switching as the distributive capacitance of the high voltage transformer is charged and discharged. The two 0.45 ohm resistors provide over current protection in case the x-ray tube sputters.

II.E.6. High Voltage Multiplier Circuit

The high voltage multiplier circuit is shown in Fig. 10. The circuit is constructed on a separate printed circuit board so that it may be mounted in the tube head with the other high voltage components. The multiplier circuit takes the 3250-7500V output of the high voltage transformer and steps it up to 40-90kV across the x-ray tube. The high voltage components are arranged in a standard multiplier configuration to give a multiplication factor of 12.

The high voltage transformer is made with a 2 x 7042 pot core. The primary winding is 20 turns center tapped of 18AWG wire. The secondary winding is 500 turns of 30AWG wire. Distributed capacity is the cause of power loss in the transformer and can also be destructive to the FET's driving the transformer. When the FET's switch, energy stored in the distributed capacity causes a current surge through the FET's which may exceed the current rating of the FET's, consequently causing breakdown. The greater the separation between winding layers, the smaller the distributed capacity of the transformer. Thus, five layers of 5 mil kraft paper are used to provide insulation between the primary and secondary and each layer of the secondary winding, and to reduce the distributed capacity.

The 1000Mohm resistors used in the circuit are Murata Erie #MHR1538DA105K and have a 15kV voltage rating. The 1000pF capacitors, Murata Erie part #DHR20Y5P102M15K, are rated for 15kV. The diodes are made by Varo, part #VG20X, and have a voltage rating of 20kV. The circuit board is designed to maximize separation between the components of adjacent stages in order to prevent arcing.

Since each stage of the circuit carries the cumulative current of each of the following stages, the losses become significant in the capacitors of the initial stages. Paralleling several capacitors in the initial stages, as shown, lowers the impedance of those stages and thus reduces losses. Two MOV's are included in the circuit to prevent the KV and MA outputs from rising to the same voltage as the x-ray tube.

Fig. 9   MAIN OUTPUT INVERTER CIRCUIT

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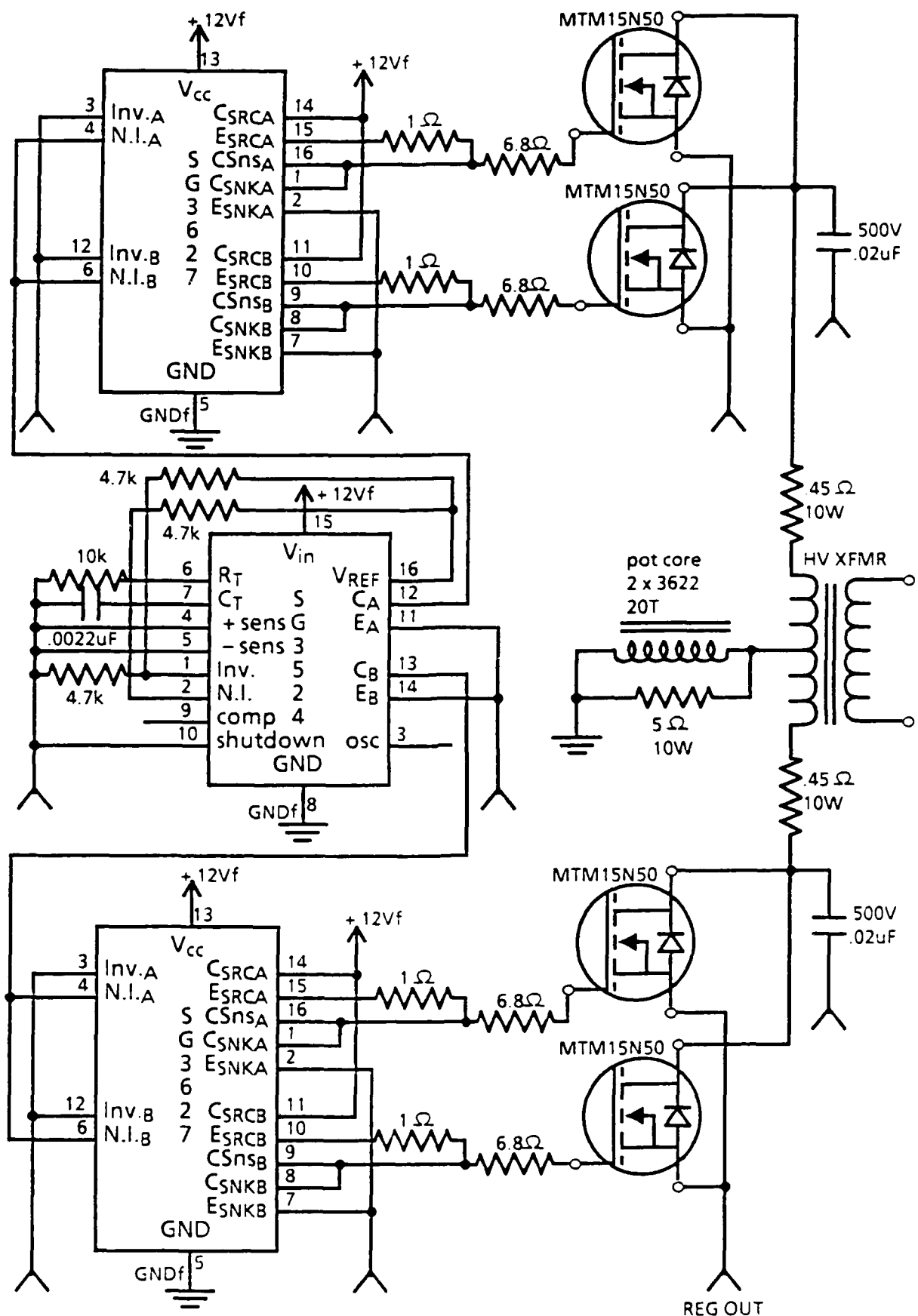
Fig. 10   HIGH VOLTAGE MULTIPLIER CIRCUIT

II.E.7. Ready Indicator/Trigger Enable Circuit

The ready circuit consists of 3/4 of an LM324 quad op-amp IC and various other components as shown in Fig. 11. This circuit provides a READY signal which is used to enable an x-ray exposure and to indicate (via the READY LED) that an exposure can be taken. A voltage divider (see Fig. 5) provides a voltage signal, CAP SENSE, which is proportional to the voltage level on the storage capacitors. This signal is used to determine whether or not enough energy is available to make an exposure.

In the startup phase, when the storage capacitors are initially being charged up, the READY signal is not asserted. The first op-amp is in the non-inverting state due to the 1N5235 zener diode maintaining a higher voltage than the CAP SENSE signal. The high output of this first op-amp holds the second op-amp in the inverting state. This means that the output of the second op-amp is low, which causes the last op-amp to be in the inverting state. Thus, the READY signal is low, the READY LED is not lit, and the machine is incapable of making an exposure (see handswitch circuit Fig. 13).

When the storage capacitors have been charged to approximately 290V the first op-amp switches to the inverting state. This causes the second op-amp to switch into the non-inverting state barring a low battery signal (ie. BATTERY is asserted, see Fig. 4). In the non-inverting state the second op-amp charges up the 22uF capacitor through the diode and switches the last op-amp into the non-inverting state. The READY signal is thus asserted, the READY LED lights, and the handswitch circuit is enabled.

The READY signal is prevented from switching states due to small flucuations in supply or storage capacitor voltages. Feedback resistors on the first op-amp provide a significant hysteresis range. The hysteresis range permits a 10V change on the storage capacitors (280-290V assuming the maximum storage capacitor voltage is set to 305V). Note that the storage capacitor charging circuit 10V hysteresis range (ie. 295-305V) is set higher than the above ready circuit range so that no overlap of the two ranges occurs. This prevents unwanted interactions between the two circuits and allows the ready circuit to stay enabled during idling since the storage capacitor voltage is never allowed to leak to less than 295V. Increasing the 220k resistor on the first op-amp causes the hysteresis range to become smaller.

A delay is included between the second and last op-amps so that an exposure which discharges the storage capacitor voltage below 280V is not terminated prematurely. The 22uF capacitor, 680k resistor, and diode provide for approximately 8 seconds of delay between the time the second op-amp switches into the inverting state and the time the last op-amp switches into the inverting state.

II.E.8. Ion Chamber Sense Circuit

The ion chamber sense circuit consists of two CA3160 op-amps and several other components as shown in Fig. 12. This circuit takes the ION SENSE signal from the ion chamber as an input and sends the AEC RESET* signal to the AEC/timing circuit (Fig. 19). During an exposure the ION SENSE signal proportionally reflects the number of ions created in the ion chamber. When enough ions for the proper exposure have been collected the AEC RESET* signal is asserted to terminate the exposure.
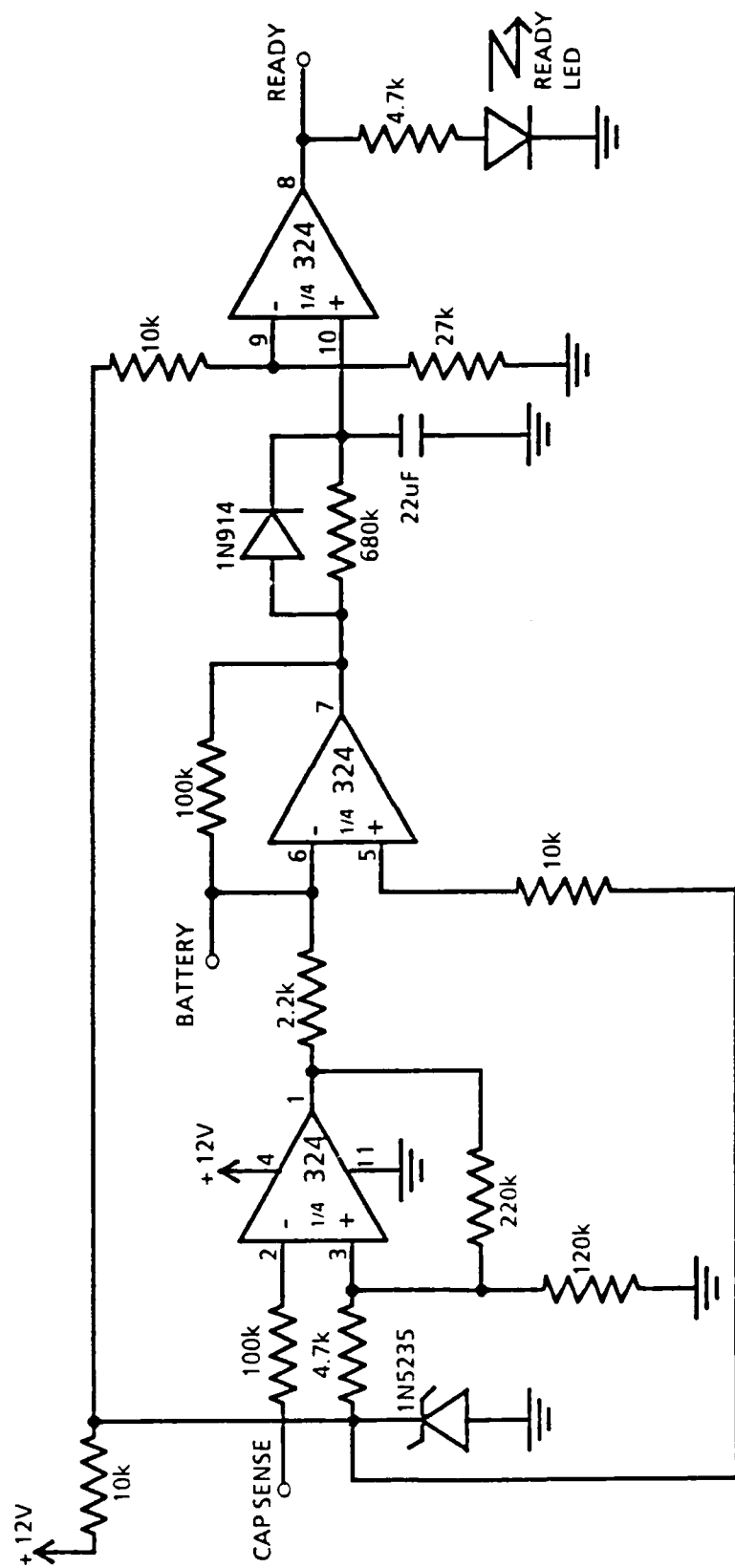
Fig. 11 READY/TRIGGER ENABLE CIRCUIT

Fig. 12   ION CHAMBER SENSE CIRCUIT

Initially the output of the first op-amp is low which then holds the second op-amp in the non-inverting state. This means that the AEC RESET* signal is not asserted. As the ions are collected during an exposure the output of the first op-amp rises proportionally. This is because the first op-amp is configured as an integrator. The 47pF capacitor and 10M resistor determine the slope of the rising output and the 10k offset null pot is used to set the sensitivity. When the output of the first op-amp rises past the reference level on the non-inverting input of the second op-amp, the second op-amp switches states. The level at which the second op-amp switches states is determined by the pot setting of either the cassette density pot or EPID density pot depending on which one is selected by the density pot selection switch. When the second op-amp switches into the inverting state, AEC RESET* is asserted thus terminating the exposure.

The 2.2k resistor and 1000uF capacitor on the power supply lead of the first op-amp are used to isolate it from noise on the power supply lines. Since the ION SENSE signal is very small (on the order of 10^{-10} Coulomb) a shielded cable must be used to route it from the ion chamber to the ion chamber sense circuit. Guard areas are also used around the inverting input on the printed circuit board to avoid RF noise interference.

II.E.9. Handswitch Circuit

The handswitch circuit shown in Fig. 13 is used by the operator to trigger an EPID cycle. The circuit receives the HANDSWITCH and READY signals as inputs and has the START1, START2, and KILL signals as outputs. START1 is used to initiate the EPID circuit cycle (see Fig. 15), START2 is used to qualify the DISCHARGE* signal (see Fig. 19), and KILL is used to "kill" the storage capacitor charging during an exposure (see Fig. 5).

When the handswitch trigger is pulled to make an exposure, the HANDSWITCH signal is asserted. If the READY signal is being asserted then the 2N3904 transistor passes the HANDSWITCH signal and the START1, START2, and KILL signals all become active. If the handswitch is released after triggering an EPID cycle then all of the output signals become inactive and the exposure phase of the EPID cycle is ignored. The handswitch trigger must be held in throughout the entire EPID cycle for the exposure to complete correctly.

II.E.10. X-ray Exposure Indicator Circuit

The x-ray exposure indicator circuit is comprised of a 555 timer IC configured as a reset timer as shown in Fig. 14. The purpose of this circuit is to alert the user that an exposure is in progress via the EXPOSURE LED. The only input to the circuit is the DISCHARGE* signal from the AEC/timing circuit (Fig. 19).

Initially the output of the 555 is low and the EXPOSURE LED is not lit. When the 555 is triggered the output immediately goes high lighting the LED. The 10uF capacitor also begins charging up through the 100k resistor. When the capacitor voltage reaches 2/3 of the supply voltage the 555 is reset to its initial state. The EXPOSURE LED is then extinguished. The 10uF capacitor and 100k resistor were chosen to give an exposure signal of approximately 2 seconds.

II.E.11. EPID Control Circuit

The EPID control circuit is shown in Fig. 15. The two main parts are a CD4017 decade counter IC and a 555 timer IC. The purpose of this circuit is to provide the proper signals to the EPID panel and to synchronize the EPID panel cycle with an x-ray exposure. On power-up, the circuit is reset to its initial idle phase by the EPID reset circuit (Fig. 17). When an EPID cycle is triggered via the START1 signal, the circuit produces the proper FRONT PLANE and BACK PLANE waveforms for the high voltage EPID switcher circuit (Fig. 18). The high voltage EPID switcher circuit then provides the correct FP and BP voltages for the EPID panel.
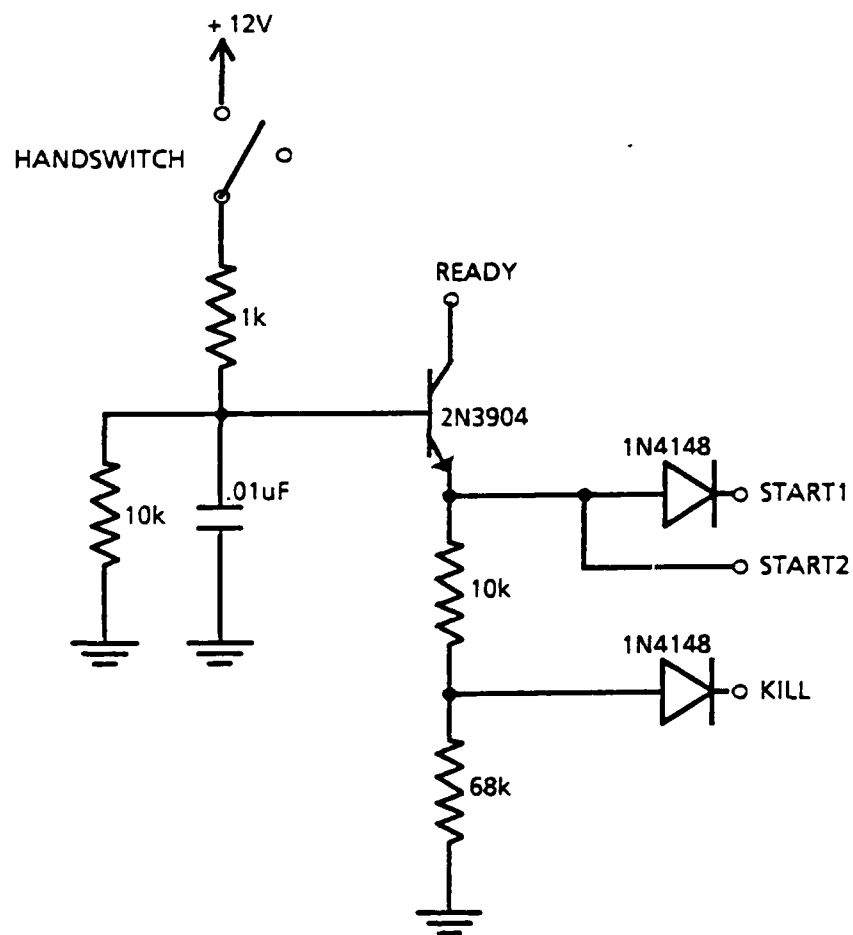
Fig. 13   HANDSWITCH CIRCUIT

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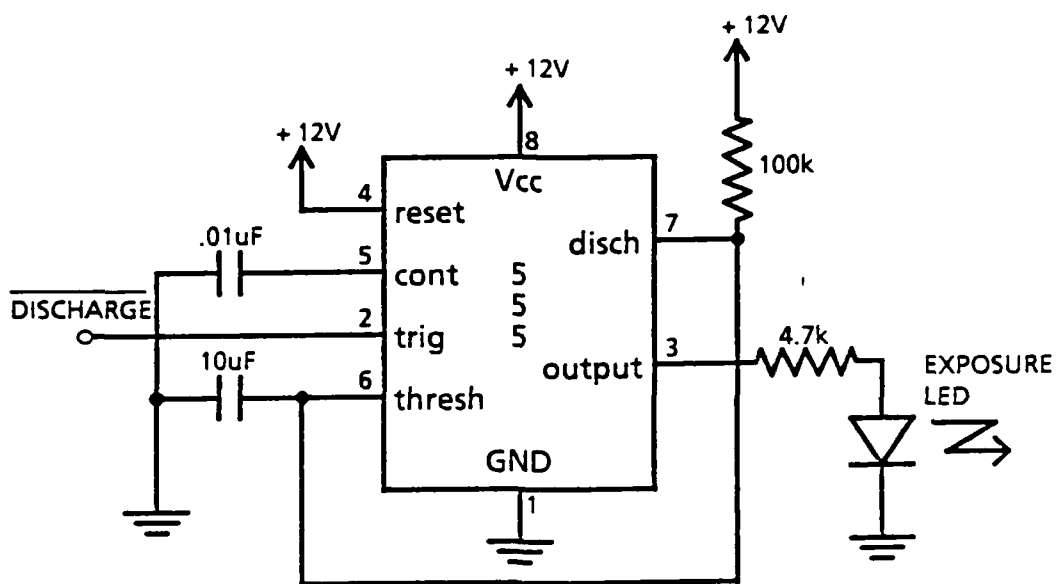
Fig. 14   X-RAY EXPOSURE INDICATOR CIRCUIT
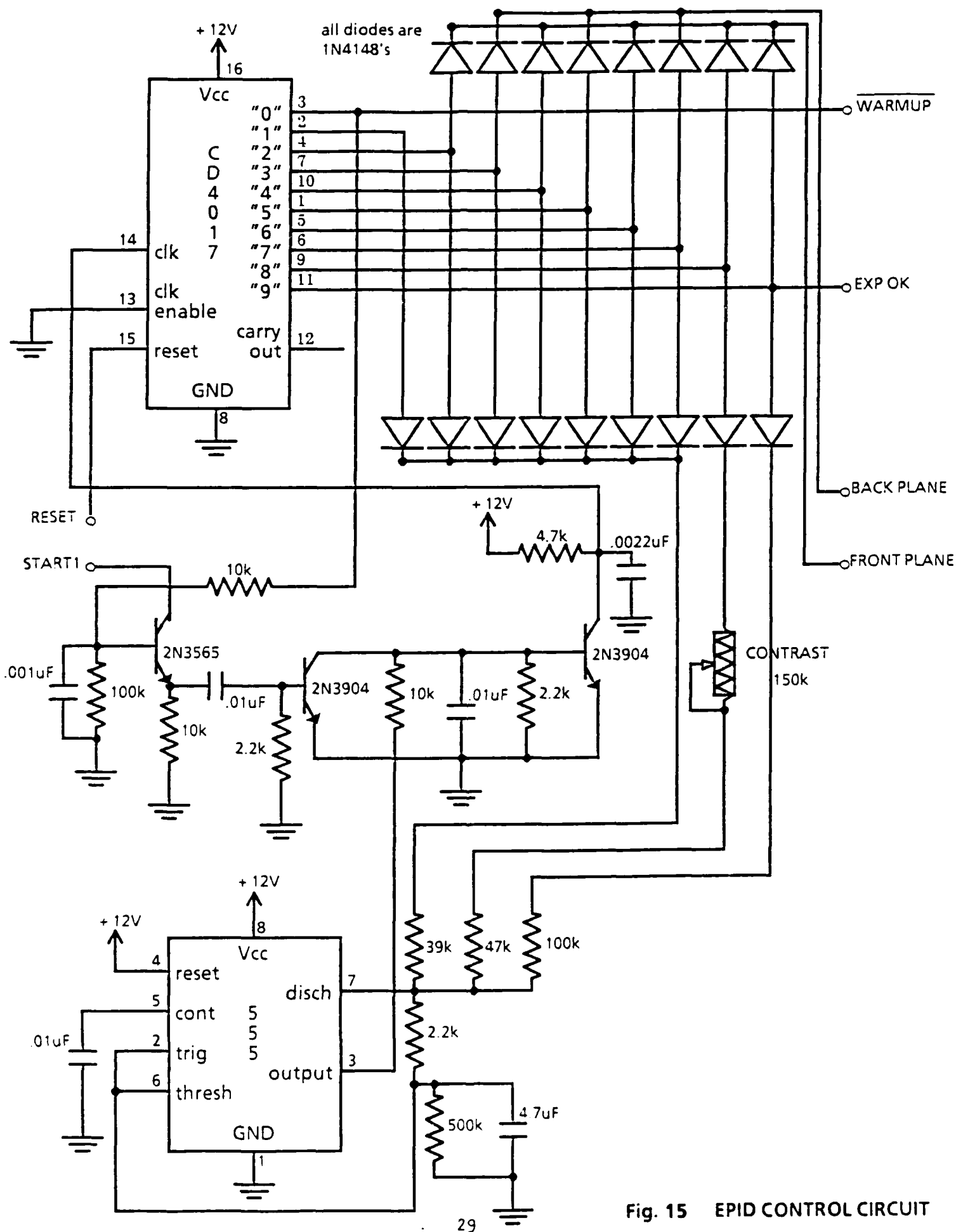
Fig. 15 EPID CONTROL CIRCUIT

Inputs to the circuit consist of the RESET and START1 signals. The WARMUP*, EXP OK, BACK PLANE and FRONT PLANE signals make up the outputs. The RESET signal is used to reset the CD4017 counter to its initial phase (count 0). In this phase the WARMUP* signal, which is used to ready several other circuits before an exposure, is not asserted. The START1 signal from the handswitch circuit is used to trigger an EPID cycle. EXP OK signals the beginning of an exposure by starting the exposure timer (see Fig. 19). The BACK PLANE and FRONT PLANE signals run the high voltage EPID switcher which cycles the EPID panel.

There are several phases of the EPID cycle as shown in Fig. 16a. The first is the initial phase during which the circuit is idle. When the circuit begins cycling the setup phase is entered. This provides a short time for the 555 timer to stablize. The next is the erasure phase during which the voltage across the EPID panel is switched between 0 and -400V to erase the panel. The voltage across the panel is then held at -400V for the contrast phase. The length of the contrast phase determines the contrast of the image to some extent. The voltage across the panel then remains at -400V for the exposure phase which follows. After the exposure, the circuit is once again held in the initial idle phase.

In Fig. 16b the actual voltages applied to the front and back planes are shown. When one plane is switched from 0 to -400V at the same time that the other plane is switched from -400 to 0V, the effect is the same as switching the second plane from 0V to 800V. This effect is used throughout the EPID cycle so that a -400V supply may be used in place of an 800V supply. The phases and the corresponding plane voltages are reiterated in Fig. 16c.

The 555 timer IC is configured for astable operation. In this mode of operation the circuit free runs as a multivibrator. When the circuit is in its initial phase (count 0), the lines to the discharge input of the 555 are all in the high impedance state. The 555 thus sits idle. As soon as the CD4017 gets clocked into any of the other phases, the level on the discharge input will be of sufficient voltage for the 555 to free run. The pulse width of the 555 output is determined by one of the three resistors (39k, 47k + 150k pot, 100k) connected to the discharge input, the resistor (2.2k) between the discharge and threshold inputs, and the capacitor (4.7uF) on the threshold input. The 39k resistor gives an erasure phase pulse width of 200mS, the 47k resistor and 150k pot combination give a variable pulse width of 220-1420mS, and the 100k resistor gives a maximum exposure phase pulse width of 500mS. Increasing the capacitance or the resistor values will make the corresponding pulse width larger.

The CD4017 is setup to count through the different phases of the EPID cycle. After the CD4017 has been reset by the EPID reset circuit it is in the initial phase (count 0). In this phase the WARMUP* signal is not asserted and the clock circuitry is enabled for triggering. When the START1 signal is asserted the CD4017 is clocked into the next phase (count 1) by the clock circuitry. This phase allows the 555 to run as in the erasure phase but the CD4017 output is not used for switching the EPID panel since the 555 pulse width is initially unstable. The WARMUP* signal also becomes asserted during this phase. The next 6 counts (counts 2-7) make up the erasure phase. The length of each count pulse is determined by the 555 timer as explained previously. The following phase (count 8) is the contrast phase. This is usually the longest phase with a typical time length of 1000mS (variable between 220 and 1420mS). When the exposure phase (count 9) is entered, the EXP OK signal is asserted. This signals the AEC/timing circuit to begin timing the exposure. As a backup safety feature, the feedback loop (100k resistor) from the CD4017 count 9 output to the 555 will cause the exposure phase to automatically timeout after 500mS (filament is turned off via WARMUP*). In normal operation the AEC/Timing circuit controls the length of the exposure by turning the discharge circuit on and off and by reseting the CD4017 which turns the filament and main output inverter off via the EPID reset circuit (see Figs. 19 and 17).
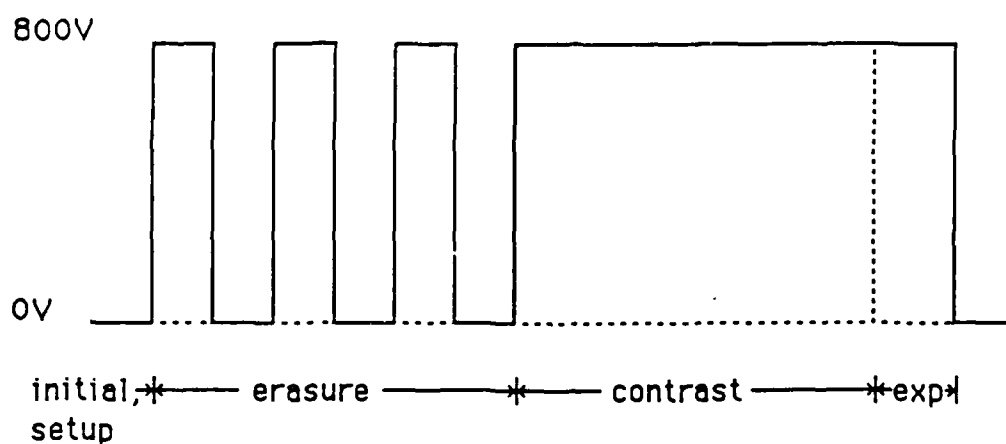
(a)
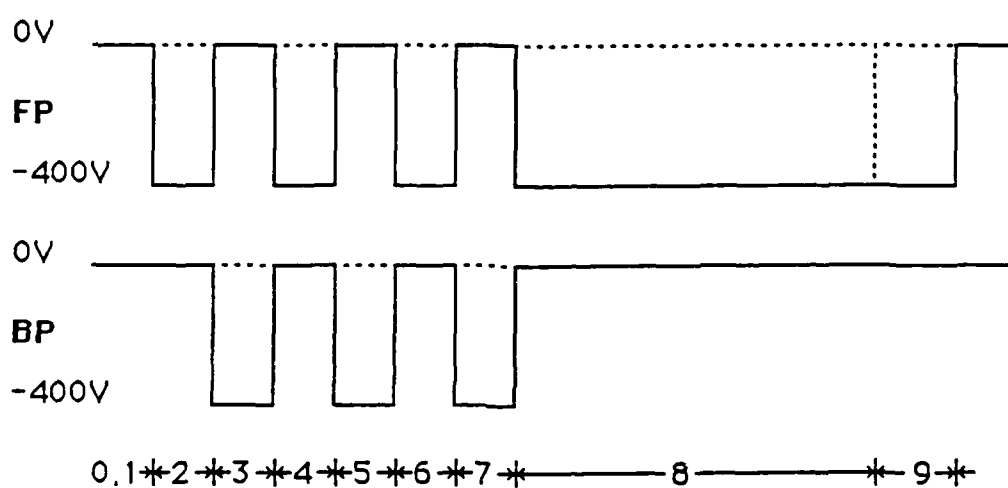
(b)

4017 count	cycle phase	FP voltage	BP voltage
0	initial	0	0
1	setup	0	0
2	erasure	-400	0
3	"	0	-400
4	"	-400	0
5	"	0	-400
6	"	-400	0
7	"	0	-400
8	contrast	-400	0
9	exposure	-400	0

(c)

Fig. 16 EPID Panel Waveforms

The clocking section of the EPID circuit is responsible for creating the clock pulses which clock the CD4017 through its cycle. If the CD4017 is in the initial phase (count 0), then the base of the first 2N3565 transistor is at a high level. When the START1 signal is asserted, the low to high transition is passed to the base of the first 2N3904 transistor through the 0.01uF capacitor. This causes the 2N3904 to switch on, momentarily pulling its collector low. The collector is normally held high by the output of the 555. When the collector is pulled low then the second 2N3904 switches off causing its collector to be pulled high. This results in a positive going clock pulse being fed to the clk input of the CD4017. Once the CD4017 has started its cycle then subsequent clock pulses are generated via the 555 timer output.

II.E.12. EPID Reset Circuit

The EPID reset circuit shown in Fig. 17 is constructed from several transistors and other components. The purpose of this circuit is to reset the CD4017 to its initial phase under two conditions. On power-up the RESET signal must be asserted for approximately 100nS in order to properly reset the CD4017. The CD4017 must also be reset to its initial phase immediately after an exposure ends as determined by the AEC/timing circuit.

RESET is asserted immediately after the machine is turned on. Since the 2N3904 is initially in the off state it will not pull RESET low. When the 0.01uF capacitor has charged up to approximately 1V through the 100k base resistor, the 2N3904 becomes biased on. This brings the RESET signal low. The 2N3904 will be allowed to remain on since the 2N3565 pulldown transistor connected to its base is off, except momentarily at the end of an exposure.

One requirement of the EPID panel is that the panel voltage must be zero immediately after the end of an exposure. This is accomplished by reseting the CD4017 to its initial phase when the exposure has ended. The DISCHARGE* signal from the AEC/timer circuit (Fig. 19) indicates the exposure phase. When DISCHARGE* goes high at the end of an exposure the first 2N3565 turns on. The initial positive-going edge of the waveform which is produced is passed through the 33k resistor and 0.1uF capacitor to the base of the second 2N3565. This temporarily biases it on causing the base of the 2N3904 to be pulled low. The 2N3904 then temporarily turns off causing a RESET pulse to be passed to the CD4017. The RESET pulse width, determined by the 33k and 10k resistors and the 0.1uF capacitor, is of sufficient length to reset the CD4017.

The diode on the base of the second 2N3565 is included for negative glitch protection. The 0.01uF capacitor paralleled with the diode is for noise bypass.

II.E.13. High Voltage EPID Switcher Circuit

The high voltage EPID switcher circuit shown in Fig. 18 provides the -400V pulses required by the EPID panel as shown in Fig 16b. It consists of two 4N33 opto-isolators, two MGP20N50 power FET's and other components. The FRONT PLANE and BACK PLANE inputs are provided by the EPID circuit (Fig. 15) and the FP and BP outputs are routed to the EPID panel contacts.

The sequence and duration of the pulses are controlled by the EPID circuit, the high voltage switching circuit translates the 10V EPID circuit pulses to -400V pulses. The FRONT PLANE and BACK PLANE input pulses feed the bases of two 2N3565 transistors. The 2N3565 transistors are used as emitter-followers in order to increase the current supplied to the opto-isolators. When one of the input signals is asserted, the corresponding opto-isolator switches on, pulling its emitter high. This turns on the connecting FET which then switches either the FP or BP output to -400V.

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Fig. 17 EPID RESET CIRCUIT
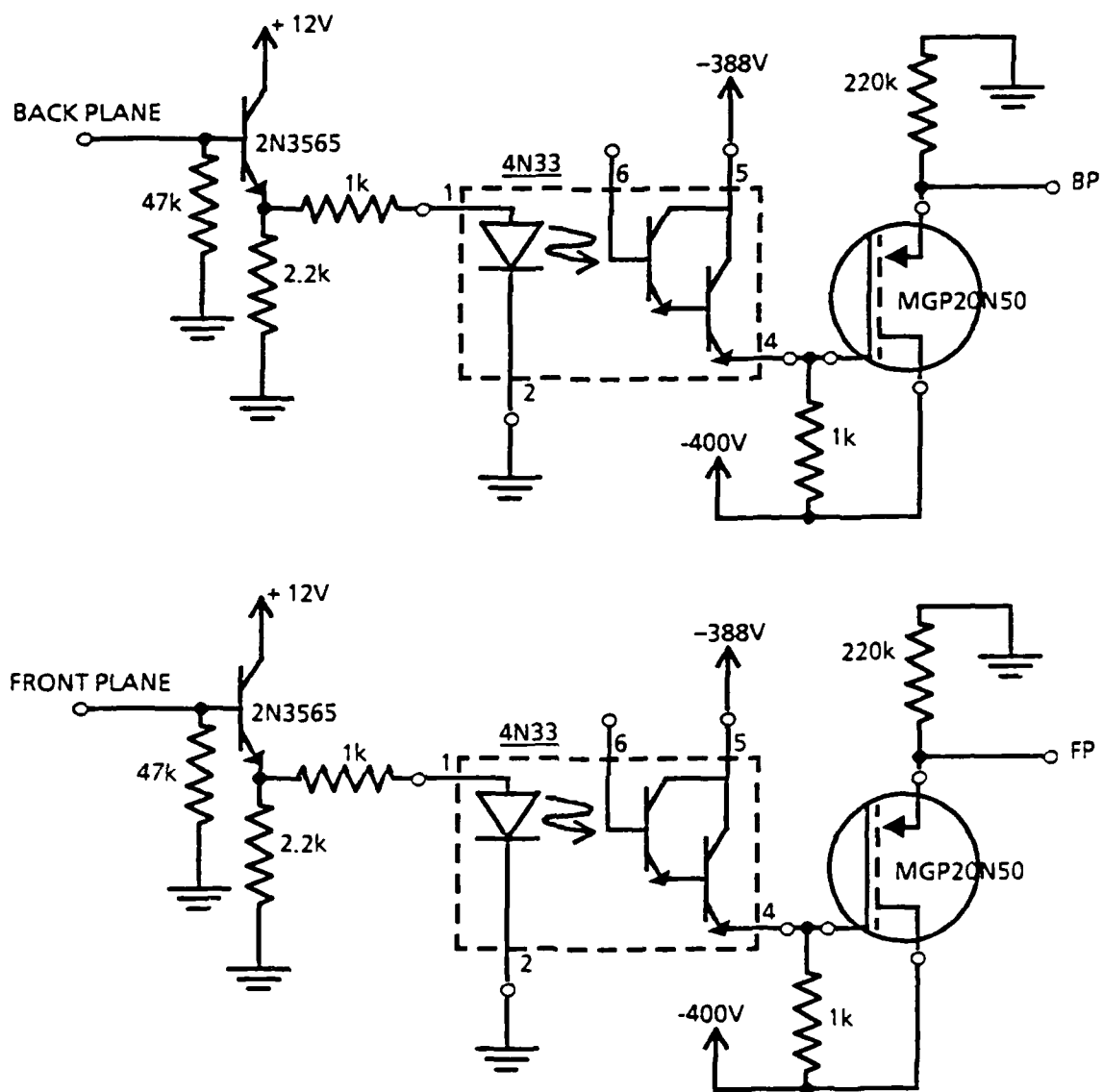
Fig. 18   HIGH VOLTAGE EPID SWITCHER CIRCUIT

II.E.14. AEC/Timing Circuit

The AEC/timing circuit is presented in Fig. 19. The main part of the circuit is a CD4538 dual precision monostable multivibrator IC. The purpose of this circuit is to determine the timing mode and to time the x-ray exposure in the selected timing mode. In the AEC (Automatic Exposure Control) mode, the length of the exposure is determined by the ion chamber and the ion chamber sense circuit. See Fig. 12 and its accompanying paragraphs for a complete description of how the ion chamber controls the exposure time. In the timer mode, the CD4538 and the TIME control on the front panel determine the exposure time. The front panel TIME control consists of a potentiometer to regulate the exposure length in the timer mode and an integrated switch to determine the timing mode.

Inputs to the circuit consist of the EXP OK, START2, and AEC RESET* signals. DISCHARGE* is the only output signal. EXP OK initiates the start of an exposure in either timing mode. START2 is an exposure qualifier from the handswitch circuit (Fig. 13). If the handswitch trigger is not continuously held in the on position, the START2 signal will not be asserted and the exposure will not be allowed. In the AEC mode, asserting AEC RESET* will reset the AEC half of the CD4538, thus ending the exposure. The DISCHARGE* signal is passed to the discharge switching regulator (Fig. 8) to control the exposure length.

An exposure is initiated and terminated as follows. When EXP OK is asserted, both halves of the CD4538 are triggered. The Q1 and Q2 outputs then become active. The CD4011 quad nand gate and TIME switch then determine which signal is to be used and inverts it, presenting it to the discharge circuit as DISCHARGE*. When the half of the CD4538 which is being used times out, the corresponding output, Q1 or Q2, becomes inactive causing DISCHARGE* to be reset. This signifies the end of the exposure.

The 2.2uF capacitor, 6.8k resistor, and 100k TIME potentiometer setting determine the pulse width of the timer half of the CD4538. The maximum pulse width of the AEC half is determined by the 1.0uF capacitor and 330k resistor whereas the actual pulse width is controlled by AEC RESET*. In the timer mode the pulse width range is 10-440mS (determined by the potentiometer) while the AEC mode has a maximum pulse width of 330mS.

When the TIME control is in the AEC position there is no bias applied to the gate of the VN10KM. The off state of the VN10KM in combination with the logic of the 4011 qualifies the exposure length control of the AEC half of the CD4538. This means that the high AEC pulse is qualified and the timer pulse is disqualified. When the TIME control is in the timer position, the VN10KM is biased on, the timer pulse is qualified, and the AEC pulse is disqualified. The second stage of the nand gate network combines the signals from the first two nand gates. The last gate then qualifies this combined signal with the START2 signal and outputs the DISCHARGE* pulse.

II.E.15. Floating Power Supply Circuit

The floating power supply circuit appears in Fig. 20. The main component is an SG3525 regulating pulse width modulator IC. This circuit provides the floating supply voltages that are required by some of the other circuits. A floating +12V supply is required by the main output inverter circuit (Fig. 9). An additional +12V floating supply is required by the high voltage EPID switcher circuit (Fig. 18) as is a -400V supply. The -400V supply is also used to bias the ion chamber. The only input to the circuit is the WARMUP* signal which turns the floating power supply on when asserted. The circuit is not run continuously in order to conserve battery power.

Fig. 19   AEC/TIMING CIRCUIT

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Fig. 20   FLOATING POWER SUPPLY CIRCUIT

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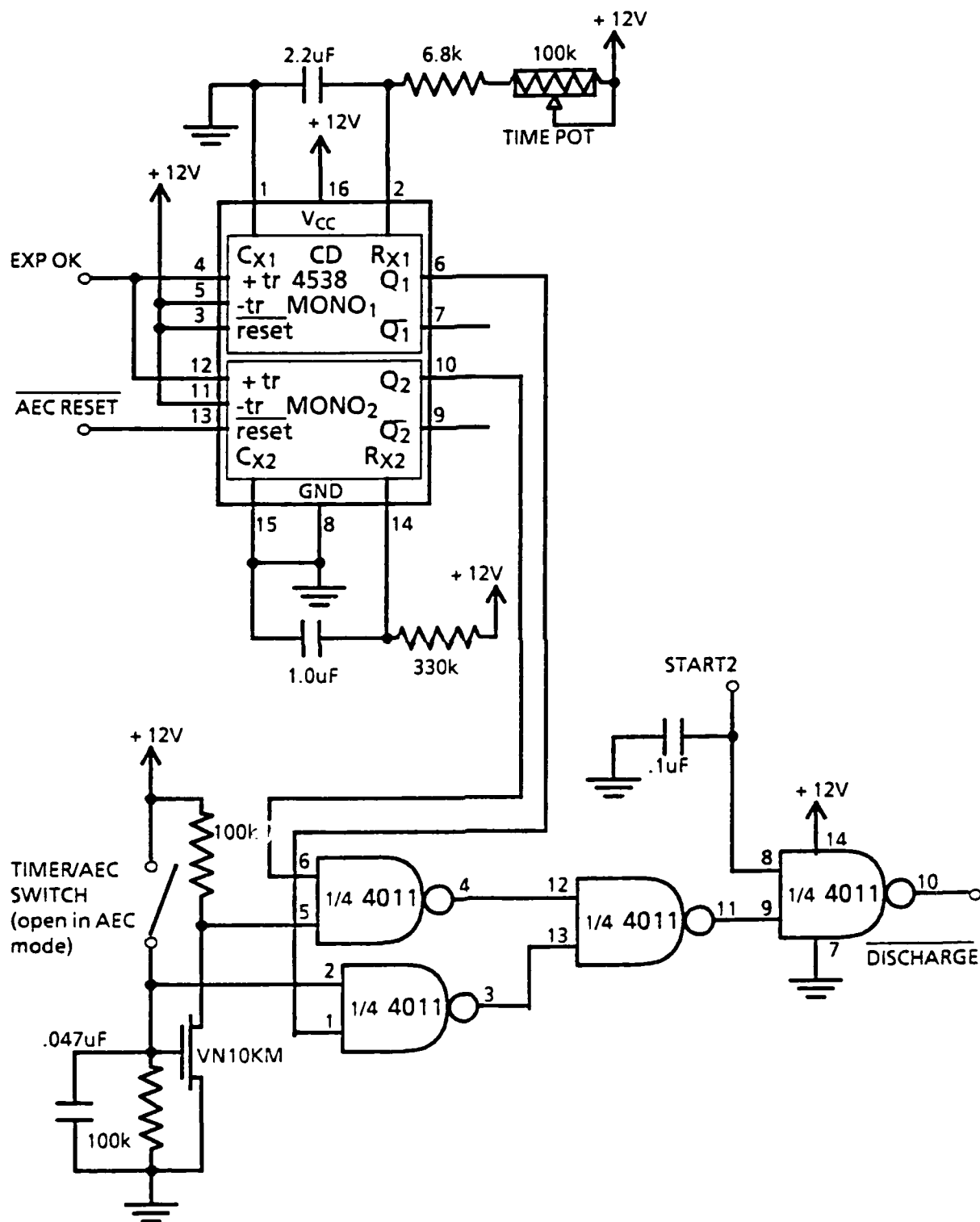
The various components connected to the SG3525 serve several purposes. The 15k resistor and 0.0022uF capacitor determine the switching frequency of the outputs, which is 50kHz. The 4.7k resistors form a voltage divider for the error amplifier inside the SG3525. The non-inverting input (pin 2) is biased at 5.1V while the inverting input (pin 1) is biased at 2.55V by the voltage divider. The effect of the biasing is to keep the error amp in the non-inverting state. This causes the SG3525 modulator to operate with the maximum duty cycle and to run continuously as long as the shutdown input is low (ie. WARMUP* is asserted).

The totem-pole outputs of the SG3525 are connected to IRF643 FET's through 22 ohm resistors. The FET's are arranged so that they are alternately switched on and off. During the first half of a cycle one FET is switched on and provides a current path through half of the primary winding of the transformer. During the second half of a cycle, the first FET is turned off and the second FET is switched on. The deadtime adjustment feature (both outputs off between switching) of the SG3525 is not used so no resistor is included between the CT (pin 5) and discharge (pin 7) inputs of the IC.

Two low capacity, low leakage, fast recovery, VA25 diodes are part of a voltage doubler in the -400V supply. Two 1N4937 fast recovery diodes are configured for full wave rectification in each of the 12V supplies. The 10k resistor across the 12V high voltage switcher power supply loads the 2200uF filter capacitor to maintain better regulation. The 18k resistor and 49pF capacitor snubber is included across the -400V secondary to eliminate switching spikes.

In order to maintain control over the secondary voltages, a feedback loop is included. The -400V is fed back into 1/2 of an LM358 op-amp via a voltage divider. The voltage divider is adjusted with the 100k potentiometer. All of the secondary voltages change together so only one of them will be optimally adjusted (the prototype units have the 100k potentiometer set so that the -400V secondary supplies exactly -400V). The output of the LM358 op-amp varies in proportion to the voltage on its inverting input. This in turn varies the gate voltage of the IRF9531 FET which acts as an adjustable resistor between the 12V supply and the primary center tap of the transformer.

II.E.16. Filament Control Circuit

The filament control circuit is shown in Fig. 21. This circuit consists of an SG3524 pulse width modulator, an SG3525 pulse width modulator, an SM600 switching regulator, two IRF530 FET's, and several other components. The purpose of the circuit is to provide the tightly regulated current needed for the x-ray tube filament. The single input to the circuit is the WARMUP* signal from the EPID control circuit (Fig. 15). The only outputs of the circuit are the three filament transformer leads which go to the high voltage multiplier circuit (Fig. 10). The filament transformer is shown in both Fig. 21 and Fig. 10 for clarity. The filament transformer specifications are given in Fig. 10.

The circuit is divided into two major parts: a voltage regulator and a saturated inverter. The voltage regulator portion of the circuit provides an adjustable and extremely stable voltage to the saturated inverter. The saturated inverter converts the DC regulator voltage to a 20kHz square wave which is then fed to the filament transformer. The transformer provides isolation between the control circuitry and the filament as well as lowering the average DC voltage level supplied to the x-ray tube filament.
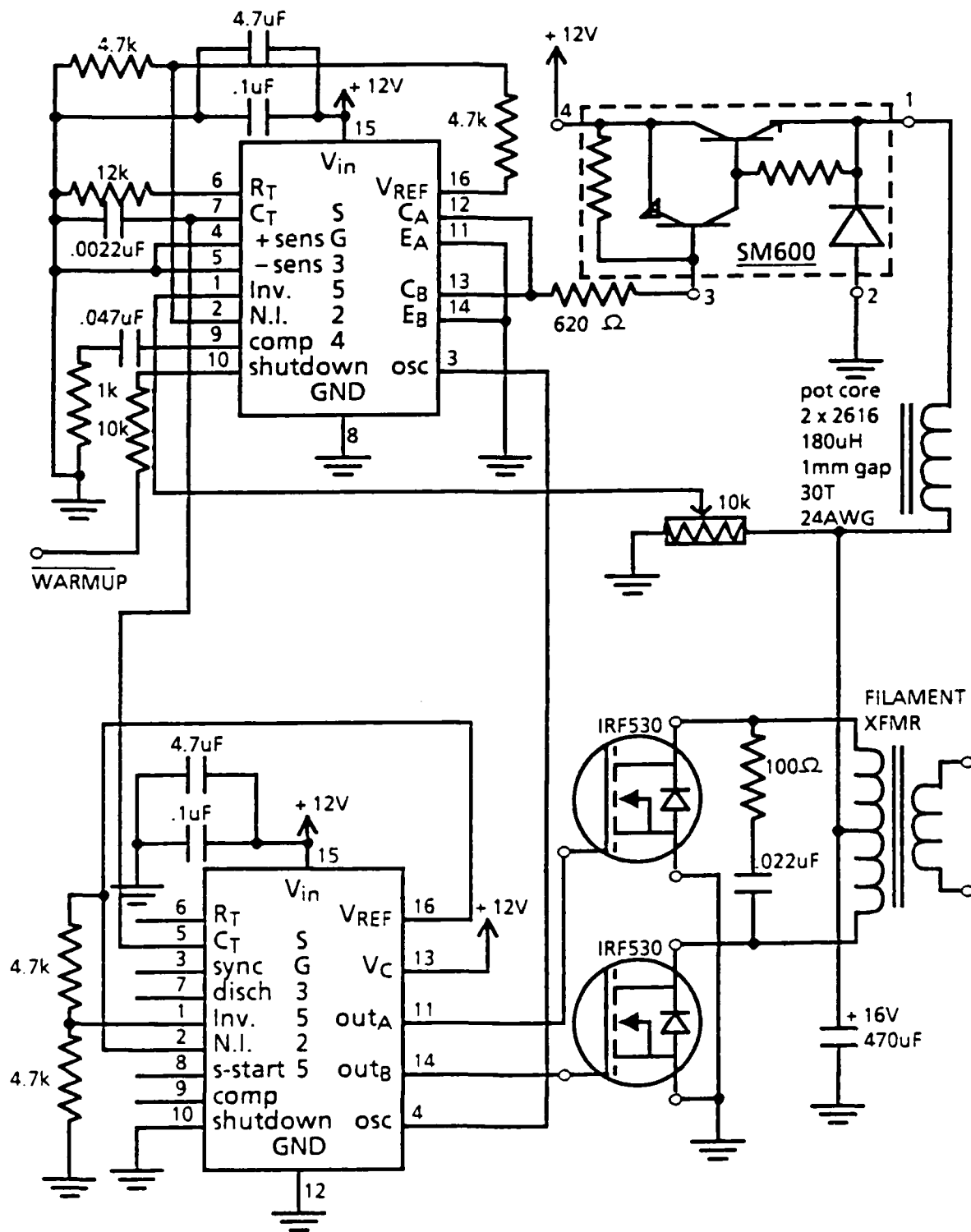
Fig. 21   FILAMENT CONTROL CIRCUIT

The SG3524 and the SM600 are the major components of the switching regulator. The SG3524 provides a pulse width modulated signal which is used to gate the SM600. The SM600 is an integrated package consisting of a pnp power transistor and a clamp diode. When the SM600 is gated on (SG3524 outputs are low) energy is transferred to the load. When the SM600 is switched off, energy stored in the 180uH inductor is fed to the load. The DC regulator voltage is monitored and adjusted via the 10k feedback pot connected to the inverting input of the SG3524. The DC voltage is proportional to filament current, therefore the 10k pot is used to set the filament current.

The internal output transistors of the SG3524 are connected in parallel for single ended output operation. With the outputs paralled an effective duty cycle of 0-90% is attained and the frequency of the internal oscillator is the frequency of the output. The 12k resistor and 0.0022uF capacitor provide for an internal oscillator frequency of 40kHz. The WARMUP* signal is connected to the shutdown input of the SG3524 so that the circuit can be switched on just prior to an exposure.

The saturated inverter consists of the SG3525 IC, two IRF530's, and the filament transformer. The SG3525 is synchronized to the SG3524 oscillator and is configured for push-pull operation. In this configuration the two outputs are alternately switched with 45% duty cycles and an overall frequency of one-half the oscillator frequency (20kHz). The filament transformer steps the regulator voltage down to the required 2-4V. The snubber across the leads of the transformer (100 ohm resistor and 0.022uF capacitor) are needed to suppress the switching spikes on the outputs of the IRF530's.

II.E.17. mA/kV Metering Circuits

The mA/kV metering circuits shown in Fig. 22 are for external monitoring of the mA and kV levels during an exposure. The mA circuit consists of a mini-plug, which provides access to the MA signal from the high voltage multiplier (Fig. 10), and a 15uF tantalum capacitor in parallel with a 0.47uF ceramic capacitor to suppress leading edge overshoot and noise. An mAs meter connected to this circuit will give an mAs reading of a given exposure. This reading can then be divided by the time length of the exposure to get the mA reading. Note that the MA signal is grounded by the mini-plug when an mAs meter is not in the circuit.

The kV circuit also consists of a mini-plug and other components. The 60k resistor attached to the KV signal line is used to provide the correct scaling factor between the KV signal current and the kV meter (oscilloscope) voltage. The KV signal current ranges from 0 - 15uA as the voltage across the x-ray tube ranges from 0 - 90kV. Thus the voltage drop across the 60k resistor provides for kV meter readings between 0 and 0.9V (15uA x 60k = 0.9V). The 0.1uF capacitor is included to suppress spikes on the leading edge of the kV waveform.
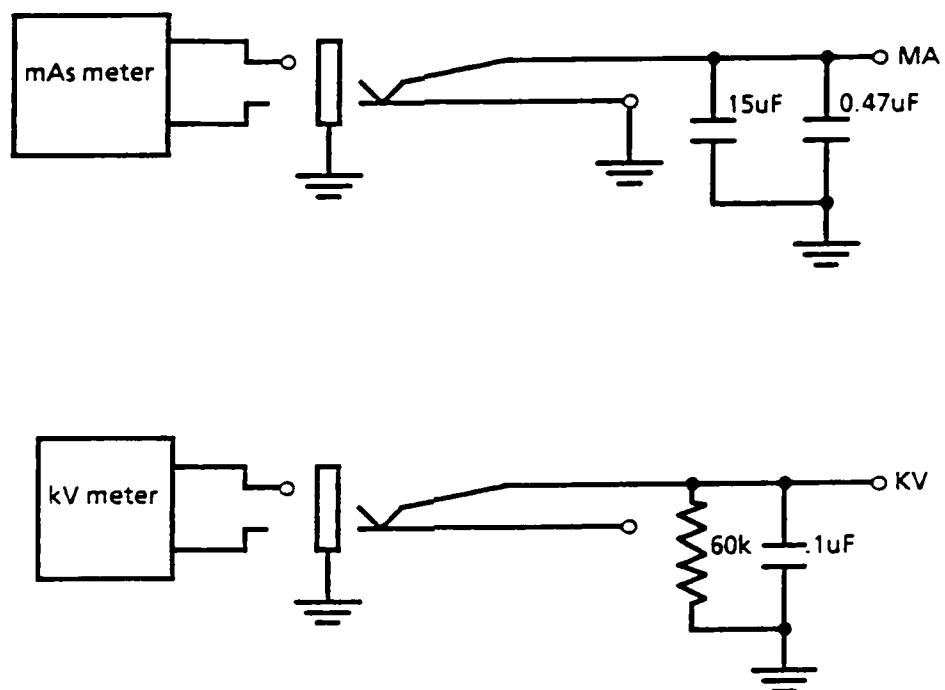
Fig. 22   MA/KV METERING CIRCUITS

II.F. Mechanical Design

The handheld x-ray machine was designed for use with an Army litter fitted with extension legs. The machine consists of a 7Kg power pack and an 11Kg arm assembly. Figure 2 illustrates how the single operator would position the arm assembly for use.

The mechanical design of the portable x-ray unit is broken up into six major sections: arm assembly, tube head, receptor assembly, ion chamber, battery/capacitor power pack, and transformers and inductors. The arm assembly section covers the design of the main channel and the handle. The tube head section describes the design of the tube head container including how heat dissipation and oil expansion are handled. The receptor assembly section describes the mounting of the various receptors as well as the different electrical interfaces required. Section 4 describes the design of the ion chamber used for automatic exposure control (AEC). The battery/capacitor power pack section describes the box used to house the batteries, storage capacitors, and associated electronics. The transformer and inductor section gives part numbers of the cores and bobbins used, and the winding procedures.

II.F.1. Arm Assembly

The main channel of the arm assembly is made from 3/32" sheet aluminum and is 31" long, 4 1/2" wide, and 2 1/2" high. Aluminum is used because of its relatively light weight and excellent electrical conductivity, which allows the arm assembly to be used as a system ground plane. The 3/32" sheet aluminum is used to provide the channel with sufficient strength to support both the tube head and the receptor assembly at opposite ends of the channel and to allow mounting of the handswitch handle. The height of the Army litter with extension legs was the main factor in determining the length of the channel. The litter will elevate the patient about 18" above the ground, and the channel will hold the x-ray receptor assembly about 11" above the litter. The width of the channel is designed to accommodate 4" wide printed circuit boards and the associated metal card guides. The 2 1/2" channel height gives sufficient clearance to the discharge circuit switching regulator inductor which is the highest component in the channel.

The exposure switch is located in the handle which extends from the bottom of the main channel. The handle and switch are manufactured by Black & Decker, part #4046.

II.F.2. Tube Head

The tube head enclosure is manufactured by Rose Enclosures, part #01162609. The enclosure is cast aluminum with a neoprene rubber gasket mounted in the lid and weighs 4.32 pounds. The outside dimensions of the enclosure are 10.2" x 6.3" x 3.5". The enclosure houses the high voltage transformer, the filament transformer, the high voltage multiplier circuit board, two metal oil expansion bellows, and the Eureka OIX-15 x-ray tube.

The tube head is filled with Shell Diala AX transformer oil to prevent high voltage arcing and to dissipate x-ray tube heat. The oil filler hole is located on the top of the enclosure. The amount of oil volume change caused by temperature change can be calculated from the thermal coefficient of volume expansion. The definition of the thermal coefficient of volume expansion for liquids is the ratio of the change in volume per degree to the volume at ^{0}C. The thermal coefficient of volume expansion of the Diala AX oil is 0.0007 ml/ ^{0}C /ml.

To compensate for the oil volume changes, two metal bellows are incorporated. The metal oil expansion bellows, part #0011542101, are manufactured by Robertshaw Controls Company. The bellows are sweat soldered onto mounting plates which are then mounted to the inside of the enclosure with o-ring seals. Holes through the enclosure and mounting plates allow air to pass between the inside of the bellows and the environment as the bellows expand and contract with changing oil volume.

Electrical power is brought into the tube head through a Detoronics hermetically sealed connector, part #DT07H-12-10PN. The male Detoronics connector mates to a female Bendix connector, part #MS3116F-12-10S. The seal between the Detoronics connector and enclosure is by a neoprene o-ring. The x-ray tube is strapped on a Delrin craddle, with the x-rays exiting through a 9/16" hole in the cradle and enclosure wall. A brass plate with a plexiglass covered porthole and double o-ring seal is mounted over the x-ray port. The brass plate has four mounting studs for the stainless steel x-ray collimator.

II.F.3. Receptor Assembly

The receptor assembly is designed with the intention of allowing several different types of receptors to be used. The receptors supported include a standard x-ray film cassette, a stimulable phospher screen cassette, the Philips EPID panel, and the Polaroid film cassette. Design of the receptor assembly not only takes into account the different sizes of the receptors but also has to allow for the different electrical interfaces required. Another requirement of the assembly is that it fold down and latch onto the channel to facilitate ease of transport.

The receptor assembly consists of a U-shaped aluminum frame that the ion chamber is dropped into and secured with flat head screws. The standard cassette, EPID panel, or Polaroid cassette can be dropped in behind the ion chamber. The standard cassette with film or phospher screen is 9 1/8" x 11 1/8" x 9/16" (W x H x D), the prototype EPID panel is 10 1/8" x 10 5/8" x 1", and the Polaroid cassette is 9 5/16" x 12 3/8" x 5/8". The difference between the receptors is accounted for by making the receptor frame large enough for the EPID panel and then constructing a separate adaptor frame for the standard and Polaroid cassettes that slides into the receptor frame. Later versions of the EPID panel and Polaroid cassette should match the standard cassette in size.

The receptor frame is mounted behind the control panel and hinged so that it will fold down and latch onto the channel. Four electrical control signal wires are brought in through the bottom of the frame. One wire is for the -400V ion chamber bias voltage. A shielded coaxial cable carries the ion sense signal from the ion chamber to the ion chamber sense circuit. Two wires with molex connectors carry the EPID control voltages. A 6:1, 60 lines per inch grid is mounted to the frame on the x-ray entrance side.

II.F.4. Ion Chamber

The ion chamber is used by the automatic exposure control (AEC) circuitry in order to automatically time an exposure. The ion chamber is sandwiched between the x-ray grid and the x-ray receptor (EPID panel, film cassette, Polaroid cassette, etc.). X-rays thus go through the patient and the grid, then pass through the ion chamber, and finally strike the receptor. The ion chamber remains mounted in the receptor assembly and needn't be removed even if the AEC option is not being used.

Operation of the ion chamber is quite simple. As x-rays pass through the chamber, ion pairs are formed in the air space of the chamber. Since a high electric field is present (created by applying -400V to one of the inner electrodes) the ion pairs will tend to separate and drift toward the electrode of opposite charge. If two ions of opposite charge recombine to form a neutral charge, then the charge is lost and cannot be collected. Recombination is minimized by making the electric field large. If recombination is negligable and most of the ions can be efficiently collected, then the steady-state current produced can be considered an accurate measure of the ion pairs created. As negative ions reach the signal electrode (opposite the -400V electrode), a small negative charge is created. This charge is the ION SENSE signal, which is integrated by the ion sense circuit (see Fig. 12).

The ion chamber is made with an aluminum frame and two sheets of mirrorized acrylic as shown in Fig. 23. Dimensions of the chamber are 11 1/8" x 9 1/8" x 11/16" (H x W x D). Attaching the acrylic sheets to the aluminum frame as shown forms an air chamber which is where the ions are formed. The mirrorized surface of each sheet of acrylic is on the outside of the chamber. An electrical connection is made between each outer surface of the chamber (the mirrorized surface is conductive) and the aluminum frame. The frame is then grounded so that the sensitive inner signal electrode is not contaminated with RFI (radio frequency interference).

II.F.5. Battery/Capacitor Power Pack

The battery capacitor power pack contains the power source for the x-ray machine. A Zero Corporation, model #ZC-7080, deep drawn aluminum carry case holds the ten D-size NiCd batteries, three Sprague model #36DX982F300DJ2D energy storage capacitors, and the capacitor charging circuit board. The interior dimensions of the case measure 11" x 7" x 6.9".

Electrical power and control signals are brought into the case through a 10-pin, female, Amphenol connector, model #AN3100A-18 1S. This connector mates to a screw-on Amphenol connector, model #MS3106A18-1P. Energy storage capacitor current is carried to the arm assembly through stranded, 2-conductor, shielded, 16 AWG wire. The 12V battery current and two control signals (KILL, CAP SENSE) are fed to the arm assembly through stranded, 5-conductor, 20 AWG wire.

II.F.6. Transformers and Inductors

This section describes the winding procedures and specifications of all the transformers and inductors used in the handheld x-ray unit.

NOTE 1:   Permag is a distributor for several manufacturers of ferrite cores and bobbins. All of the cores can be cross-referenced except the 70 x 42 pot cores.

NOTE 2:   When ordering pregapped pot cores, care must be taken to specify the proper gap. The pot core specifications in this report (for those gapped with spacers only) give the actual gap distance between the two halves of the core. The effective air gap is twice this gap distance since both the center leg and rim of the core is gapped. Production cores have only the center leg gapped, so one must double the gap distances in this report to get the correct gap distances.

II.F.6.a. Capacitor Charging Circuit

Transformer
   core size: 26 x 16 pot core
   Permag (Siemens) core   #B65671-L0000-R028
   Permag (Siemens) bobbin   #B65672-A0000-D001

The primary is wound first using 26 AWG wire. The first 10 turns can be wound and the tap brought out next to the starting lead . The remaining 50 turns are then wound and the lead is brought out the opposite end but on the same side.

A single layer of kraft paper or masking tape separates the primary and secondary, and each layer of the secondary. The secondary is wound with 400 turns of 35 AWG wire. The leads enter and exit from opposite ends, and the side opposite from the primary leads.

mirrorized acrylic (outer surface is mirrorized)

aluminum frame

Aquadag coating

-400V

ION SENSE
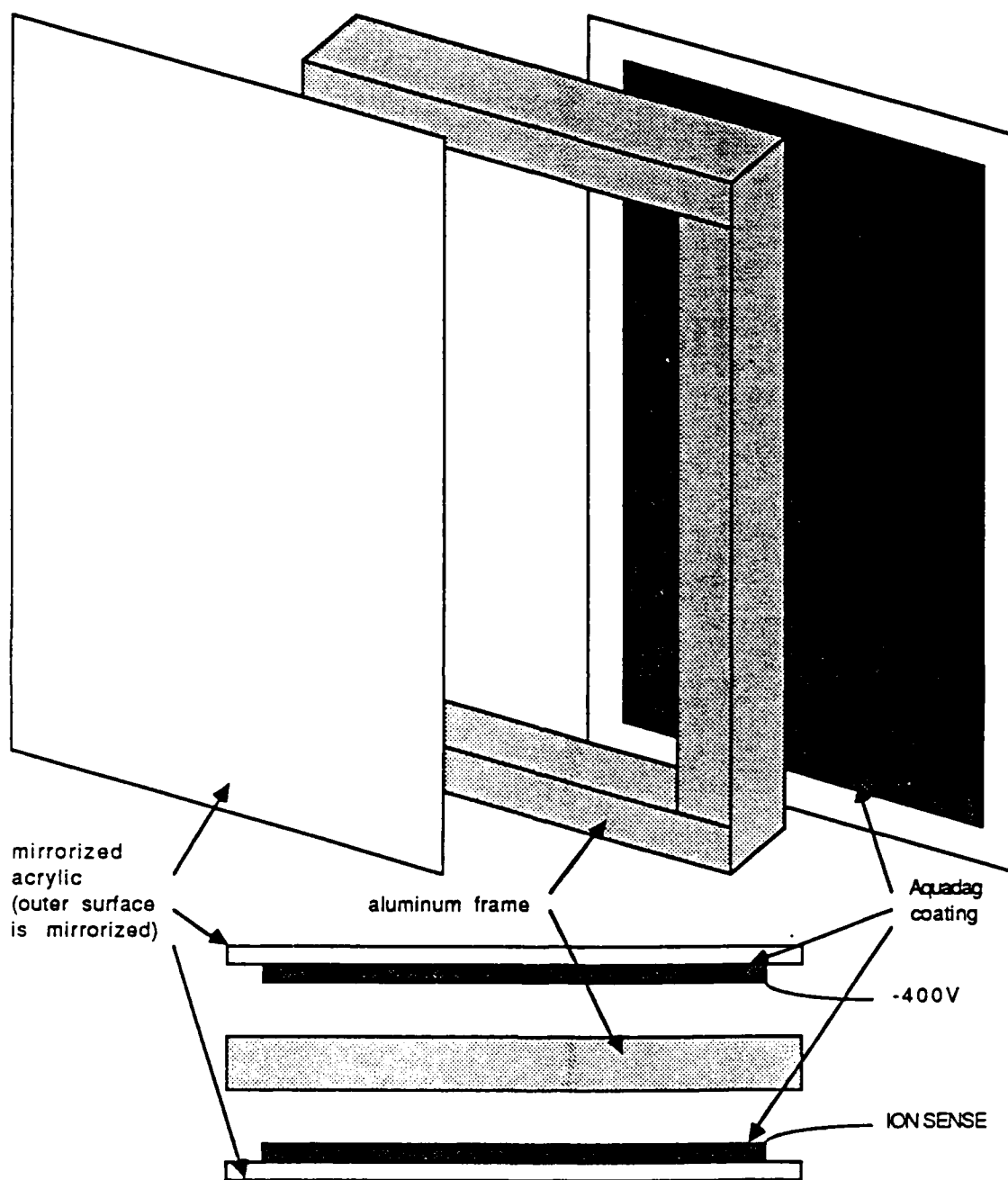
Fig. 23   ION CHAMBER CONSTRUCTION

Inductor
    core size: 26 x 16   pot core, or a commercially wound toroid of
                  similar mass with the required 2.5mH inductance.
    Permag (Siemens) core   #B65671-L0000-R028
    Permag (Siemens) bobbin   #B65672-A0000-D001

The inductor is wound with 24 AWG wire, 5 layers, 15 turns per layer. Each layer is insulated with 5 mil kraft paper or masking tape. The leads are brought out opposite ends but on the same side.

The air gap is 6 mils wide, formed by 2 layers of 3 mil mylar. Mylar sheet was cut into small washers and placed in the center leg of the core.

II.F.6.b. Tube Head

High Voltage Transformer
    core size: 70 x 42 pot core
    Permag (Indiana General) core   #IR8003-1
    Permag (Indiana General) bobbin   #B679

The primary is wound bifilar with 18 AWG wire. The 20 turns CT fill the bobbin with one complete layer of wire. The winding is held in place with a layer of packaging tape, the kraft paper type that has glue on one side. The glue is wetted with water to activate it. Five layers of 5 mil kraft paper are wound over the packaging tape.

The secondary leads are located on the opposite side of the bobbin from the primary leads. The secondary is wound with 500 turns of 30 AWG wire. The ground lead is wound starting approximately 1/4" in from one end of the bobbin. Each layer is wound with 50 turns, which allows for approximately 1/4" of space between the edge of the wire layer and each end of the bobbin. Each secondary layer is separated with 5 layers of 5 mil kraft paper. The last several turns of wire are brought back over the last layer of wire so that the lead can exit in the center of the bobbin. These last several turns are wound over a couple layers of kraft paper. The secondary is held in place with the kraft paper type packaging tape.

Filament Transformer
    core size: X30 cross core
    Permag (Indiana General) core   #IR8003-1
    Permag (Siemens) bobbin   #B65672-A0000-D002
                  (same as 26x16 bobbin)

The primary is wound bifilar on one-half of the bobbin, with 24 AWG wire, 10 turns center tapped. Teflon tubing can be slid over the leads for added protection.

The secondary is wound with Belden 25,000 volt cathode-ray tube cable, part #8868. Heat shrink tubing is placed over the cable for extra protection. The 3 secondary turns are loosely wound over the bobbin and held in place by the core structure.

II.F.6.c. Discharge Switching Regulator

7mH Inductor
    core size: 70 x 42   pot core
    Permag (Indiana General) core   #IR8047
    Permag (Indiana General) bobbin   #B679

The inductor is air gapped by grinding away 1/4" of material from the center leg of one-half of the core. The bobbin is wound with 189 turns of 18 AWG wire. There are 9 wire layers with 21 turns per layer. Wire layers are separated with a single layer of 5 mil kraft paper. The outside layer is secured in place with the kraft paper type packaging tape.

> NOTE: In gapping the 70 x 42 pot core for the discharge switching regulator the center leg of just one-half core was ground down, half of the material could have been removed from two halves.

Output Filter Toroid
    core size: 1.250"OD x .740"ID x .435"H   toroid
    Permag (Stackpole) core #55-0420

The toroid is wound with 5 turns of 12 AWG stranded, vinyl insulated wire.

II.F.6.d. Main Output Inverter

Current Limiting Inductor
    core size: 36 x 22 pot core
    Permag (Indiana General) core #F1152-1-TC9-400 (factory gapped)
    Permag (Indiana General) bobbin #B481-1

The bobbin is wound with 20 turns of 16 AWG wire. Wire layers are separated with a single layer of 5 mil kraft paper and the kraft paper type packaging tape is used to secure the last layer. The air gap of the core is approximately 24 mils.

II.F.6.e. Floating Power Supply

Floating Power Supply Transformer
    core size: 26 x 16 pot core
    Permag (Siemens) core #B65671-L0000-R028
    Permag (Siemens) bobbin #B65672-A0000-D002

There are 4 sets of windings in the floating power supply transformer. All leads exit from the bottom end of the bobbin, the primary leads and the +12V supply leads for the main inverter exit from the one side of the bobbin, the +12V secondary winding for the high voltage EPID switcher and the -400V secondary leads exit from the opposite side.

The primary is 14 turns center tapped, wound with 26 AWG wire. The +12V floating secondary for the main inverter is 20 turns center tapped, wound with 26 AWG wire. The +12V secondary for the high voltage EPID switcher is 20 turns center tapped, wound with 28 AWG wire. The -400V secondary used for the high voltage switcher and ion chamber is wound with 156 turns of 32 AWG wire.

The primary is wound bifilar across the entire width of the bobbin. Masking tape is used to insulate and hold the leads in place, as the center tap and one lead are brought back down to the bottom of the bobbin. The +12V secondary for the main inverter is wound bifilar and occupies part of the bottom half of the bobbin. A single layer of masking tape is placed over this winding. The +12V secondary for the high voltage EPID switcher is wound bifilar on the upper half of the bobbin. A single layer of masking tape is placed over the winding and the leads which are brought down to the bottom of the bobbin. The -400V secondary is wound across the entire width of the bobbin. A single layer of masking tape is used for insulation over every 52 turns.

II.F.6.f. Filament Control Circuit

Filament Inductor
      core size: 26 x 16 pot core
      Permag (Siemens) core   #B65671-L0000-R028
      Permag (Siemens) bobbin #B65672-A0000-D001

The core is air gapped approximately 15 mils, 5 layers of 3 mil mylar washers in the center leg. The bobbin is wound with 30 turns of 24 AWG wire.

Filament Transformer (description is given in Tube Head section).

II.G. Potential for Improvement

The goal of future improvements to the handheld x-ray machine are mainly directed at reducing the weight and size, and increasing the ruggedness. Weight and size can be reduced by using several improved electronic components and by changing some of the mechanical design features. A potted tube head incorporating a ceramic x-ray tube will both ruggedize the unit and make it more compact.

II.G.1. Ceramic X-Ray Tube

The conventional glass x-ray tube is relatively fragile because of the heavy anode assembly and re-entrant glass seal. Most x-ray tubes can not survive shock in excess of ten g's. A ceramic x-ray tube would be far more rugged than conventional glass tubes and would permit potting.

An x-ray tube design was made of a simple ceramic cylinder having furnace brazed end seals to mount the internal components. A flanged anode structure can be brazed to a metallized ceramic cylinder and should tolerate shock levels of hundreds of g's. Calculations showed that the thickness of the alumina ceramic cylinder provides the required x-ray beam filtration, obviating the use of additional filtering. This method of construction was discussed with several manufacturers and one was selected to build two tubes. Unfortunately, the tubes have arrived too late to be used in the model tube heads. A cylindrical lead oxide shield was also designed to fit closely around the tube. These tubes and shields will be ready for use in production versions of the handheld x-ray machine.

Experiments are being conducted to determine the possibility of making a ceramic using a mixture of tungsten oxide and alumina. If the experiment is successful, the tube body could be made of this material and obviate much of the external x-ray shielding. Shielding would still be needed to block radiation from the ends of the tube cylinder but the main shield would not be required for a substantial saving in the volume of the tube head.

II.G.2. Potted Tube Head

During the development of the tube head, various types of potting compounds were tried as alternatives to oil insulation. Oil has ideal electrical and thermal properties but allowance must be made for expansion. Two metal bellows were used in the models. The oil also attacks certain plastics and wire insulation; silicone wire and coatings cannot be used. When silicone potting compounds were tested, a monolayer of gas at the surface of the glass x-ray tube caused a reduction of the breakdown voltage. When breakdown did occur, devitrification of the glass destroyed the insulating properties. This happened at voltage levels of less than half the peak working voltage of the machine.

The use of silicone potting compounds such as Dow-Corning 184 obviates expansion bellows and permits the use of silicone and vinyl insulation. While the electrical properties of the potting are excellent, thermal conductivity is poor. One method of dissipating tube heat would be the use of a tapped beryllia slug between the anode and the metal housing. The thermal conductivity of that ceramic approaches aluminum and the insulating properties are excellent. Beryllium compounds are dangerous to machine and have become difficult to obtain. A new material, boron nitride, is harmless to people and is available as machinable cylinders or in powder form and may be miscible with silicone gels to improve thermal conductivity. Although not completed during this study, development of components which would allow potting in silicone gels would permit the construction of more rugged and compact tube heads.

II.G.3. Components

Some of the electronic components used have been improved upon in recent months, there are also alternative components which will allow production versions of the handheld x-ray machine to be made smaller and lighter in weight.

There are several switching regulators and several inverters in the handheld x-ray machine. All of these circuits require transformers or inductors with ferrite cores, pulse width modulation (PWM) IC's, and power MOSFET's. The size of the ferrite cores can be reduced by increasing the operating frequency. But switching the MOSFET's faster requires a greater drive current, which is supplied by the PWM IC.

There are new ferrite materials which allow a higher operating frequency with lower core loss and in a smaller package. To increase operating frequency requires greater drive current from the PWM IC or the use of a high current driver IC. There are new PWM IC's which offer increased drive current as well as different regulating features. The high current buffer drivers are also relatively new. The improvements to power MOSFET's are announced almost monthly. Several companies have MOSFET's with current ratings significantly higher than that of the MOSFET's used in the discharge switching regulator and main output inverter. This means that the number of components can be reduced by not having to connect MOSFET's in parallel.

The three Spraque 0.01uF storage capacitors occupy 3/4 of the space of the power pack. Both Spraque and Capacitor Technology claim to have the technology to build special capacitors with the same ratings but half the size.

The two x-ray machine models built each used 10 high capacity (4.0AH) standard size NiCd D cells as the power source. Another battery investigated was the General Electric NiCd 1/2 D cell. These cells are about half the size and weight of standard D cells, yet have a discharge rating of 2.2AH. Gates Energy Products have since purchased the General Electric Battery Division and continue the manufacture of the 1/2 D cell. Gates Energy Products is the only American manufacturer of the 1/2 D cell. The high capacity NiCd D cells have a rating of 4.0AH which is about twice that of a standard D size NiCd cell. There are three American manufacturers of the high capacity D size cell.

A graph of the continuous discharge characteristics of 10 General Electric NiCd 1/2 D cells into a dummy load is shown in Fig. 24. This data was taken merely to verify the 2.2AH rating of the 1/2 D cells and to get an idea of their voltage stability. The 6.4 ohm dummy load used, approximately matches the load of the handheld x-ray unit during capacitor charging. The cells were initially cycled two times to bring them up to full capacity after storage. They were then discharged, 10 in series, through the 6.4 ohm load. The discharge was terminated when reversal was first noticed on two of the cells. The graph shows that the battery capacity measures approximately 1.9AH (1 hour x 12V / 6.4 ohms = 1.875AH) vs. the 2.2AH rating claimed. The 2.2AH capacity rating is obtainable at slower discharge rates (ie. higher resistive load).

NOTE: The battery discharge graph, which is plotted over 70 minutes of continuous discharge, does not mean that the batteries will only last for 1 hour in the x-ray unit! The handheld x-ray unit is not operated continuously and the battery drain in the system reaches that in the test only when the capacitors are being charged (the system idles with a current drain of 80mA which is about 25 times less than the 1.9A drain during charging).
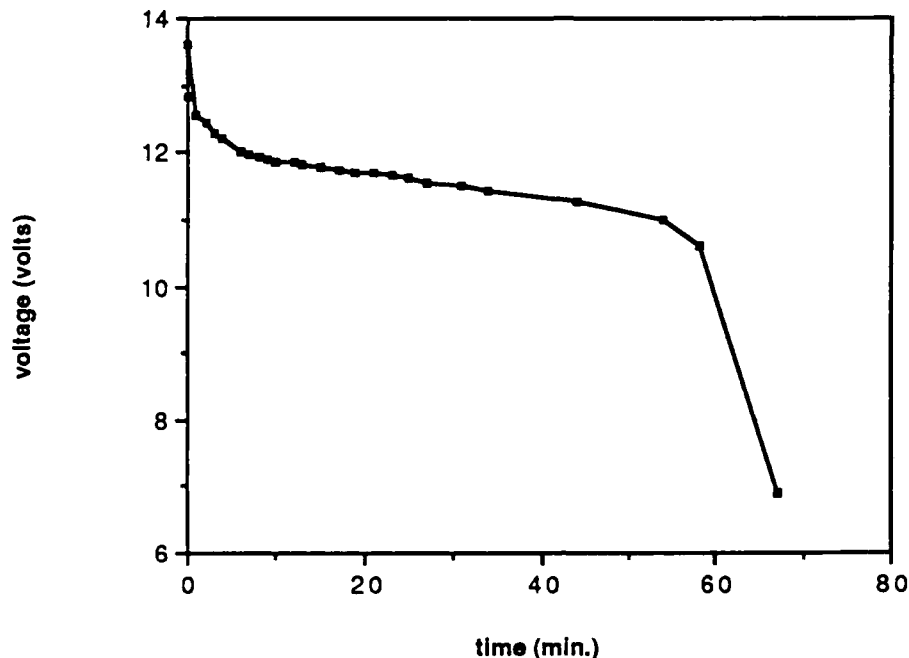
Fig. 24   NiCd 1/2 D BATTERY CONTINUOUS DISCHARGE CHARACTERISTICS INTO A 6.4 OHM DUMMY LOAD

II.G.4. Mechanical Assembly

The purpose of future improvements to the mechanical assembly of the x-ray machine would be to reduce the overall size and weight or to enhance the use of the machine. Some possible improvements are a shoulder carrying strap, folding and/or removable assemblies, variable film size receptors, and lighter construction materials.

One model was built with the receptor assembly and tube head hinged. Spring latches were used to hold the receptor and tube head assemblies in both the upright and lowered positions. The use of hinges allows the assemblies to be folded down to the main channel thus reducing the size of the machine for transport. The size of the x-ray machine could be further reduced for transport if the collimator cone and handswitch handle were able to snap on and off. If the tube head and receptor assembly were constructed with quick release mechanisms they could be completely removed from the arm assembly. These features would again allow for more compactness in transport and would reduce the size requirements of storage containers.

Another useful feature might be a shoulder strap for steadying the arm assembly while taking an exposure and for ease in carrying. In a hospital, a rolling stand to which the x-ray machine would attach would greatly facilitate steadying the machine. A rolling stand would also make moving the x-ray machine about the hospital very easy.

The current models take 8" x 10" films. To take 14" x 17" films a snap on arm assembly extending the focus to film distance and incorporating the larger film cassette could be used.

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An additional snap on cone that restricts the x-ray field for taking dental radiographs along with the required receptor assembly is an additional option that could be added.

As mentioned in section II.D.4., the EPID panel suffers from an instability in pigment dispersion when the panel is handled or stored for relatively short periods of time. To redisperse the medium, the panels must be electrically cycled as is done when erasing the panel. Therefore, if the EPID panel is incorporated, a circuit should be added to the machine which will cycle the panel when not in use. This would keep the pigment particles dispersed with a uniform consistency.

III. FILMLESS RADIOGRAPHIC SYSTEM

Medical imaging systems are usually based on photographic film. When used for combat casualty care, the films would be transported with the soldier through all levels of medical care. Supply requirements include film, development chemicals, clean water and the need to rotate stocks of supplies as a result of the rapid aging of photographic materials. The aging effects are increased under conditions of high temperature or low levels of radiation.

New methods of radiographic image acquisition based on stimulable or storage phosphors can produce images suitable for computer processing and storage on magnetic tape, disc or cards. However, magnetic data storage is affected by moderate electromagnetic field interference. Such fields are produced by unshielded electrical machinery and would be encountered if nuclear weapons were used even at moderate distances. Other by-products of nuclear weapons would certainly affect all photographic films.

The Army Medical Imaging System, ARMIS, is based on the use of optical digital data cards (DDC's) to store the digital radiographs. Other image sources, such as CT or MRI devices, could also feed digital image data to the computer controller for processing and storage on the DDC's. Images could be recalled from the DDC for display or transmission to remote sites or stored on an archival image storage device using a high capacity optical disc.

The central idea is that a stimulable phosphor screen is mounted in an x-ray cassette and exposed to radiation using the same factors as a conventional film screen cassette. Exposure causes the screen to fluoresce and drives electrons into traps. The initial fluorescence is ignored as no film is used. Scanning the screen with a laser beam lifts the electrons out of the traps to cause a second fluorescence which can be measured with a photodiode or photomultiplier tube. This action erases the screen and makes it ready for the next exposure. The amplified light signal can be digitized and stored in the RAM of the cassette reader. A computer/controller would receive a signal indicating that image information is now available in the reader RAM. The reader could not read another cassette until the computer/controller has transferred image data from the reader RAM into the computer RAM. The computer/ controller would display the image and accept operator commands for adjustment of contrast, brightness, edge enhancement, expanded region of interest, and to add annotations (cursors, markers, text, etc.), patient data, diagnostic information, etc. The computer image could also be entirely self-generated as a page of text or a standardized data entry form. The computer/control could send and receive images from the DDC reader/writer, to a local archival image storage device or to and from a DIN/PACS interface. The DIN/PACS interface could be connected to any other DIN/PACS compatible image source device or to a communications link to send and receive data from distant sites.

Each major component of a local ARMIS would have its own RAM so that component operation would proceed at its own rate. Reading and writing of the data cards may be slow and particular data coding methods may be used. Data is transferred between each device RAM and the computer/controller RAM via the small computer systems interface or SCSI bus. The computer may compress or expand the digital data to/from the DDC devices in order to conserve bandwidth, image storage capacity and increase the effective reading/writing speed of the device. The DIN/PACS interface would also incorporate a RAM and SCSI connection to the computer/controller. If other image sources are close enough, then their data may also be placed in RAM and transferred via the SCSI bus. If they are not close, then the DIN/PACS interface may be used. More than one DIN/PACS interface may be connected via the SCSI bus so that communication links and a variety of image sources may be integrated in the ARMIS.

III.A. Image Requirements

Image quality has two components: the appearance of the image and the utility of the image as measured by the error rate or receiver operating characteristic, ROC. The ROC curve is a means of plotting the four quadrant probabilities of diagnosis: true/given that the event is true, true/given that the event is false, false/given that the event is false, and false/given that the event is true. Success is measured by the ratio of true positives and negatives of diagnoses to the false positives and negatives. For an object of a certain contrast and resolution, increasing the capability of the imaging chain beyond that required to just map the object in the image plane may improve the appearance but not the probability of success. Insufficient ranges of resolution or contrast will certainly reduce the success rate. Because the human eye is quite adaptive, many techniques for the contrast enhancement of edges, or shaping the spatial frequency response to emphasize certain shapes, have resulted in making the images more attractive but also increasing the rate of false positive diagnoses. As one radiologist described the effect, "When I tuned the system for gallstones, everybody had 'em!" Perhaps the ideal approach is to avoid image losses but to add little that is new. Image enhancement techniques must be used with skill and care.

In order to recognize subtle signs of damaged or diseased tissue, radiologists have demanded resolution on the order of 2 lp/mm. The eye can recognize almost 100 levels of intensity (7 bit depth). In order to associate the area of interest with anatomic landmarks, a field diameter of at least 25 cm is required. The nearest standard radiographic image sizes are 25 x 30 cm (10 x 12 inch) and 28 x 35 cm (11 x 14 inch). To meet the resolution requirements, images could be scanned using one of the industrial standards of 1024 lines and 1024 picture elements (pixels or pels) per line. Each image pel would be acquired with circuits having 12 bit capability to allow for errors of initial exposure and adjusted at the computer to 8 bit depth. This would be 1.0 MB of digital data, a convenient value. Increasing the information capacity of the chain may not neccessarily result in improvement of the ROC values but will increase the requirements for RAM and computer capacities.

Large field, 35 x 43 cm (14 x17 inch), radiographs of the chest are affected by x-ray scatter which tends to reduce image resolution. Such radiographs are usually made with high sensitivity/medium resolution screens as a practical compromise of image data and patient exposure. Scanning chest images with a 1024 x 1024 matrix should be sufficient for most diagnostic purposes. For those diagnostic applications where greater resolution is required, two smaller field images of higher resolution may be acquired. Thus, to keep things simple, only two stimulable phosphor cassette sizes are proposed: 25 x 30 cm and 35 x 43 cm.

Data space is expensive and determines the dimensions of the random access memory, RAM, or other data storage and communication means required for each image. While it would be desirable to have very high resolution images every time, the hardware and data costs dictate that image data must be minimized. However, technical parameters must be chosen so that diagnostic information is preserved. i.e., ROC values and success rates must be comparable to those of standard diagnostic imaging methods.

III.A.1. Component Link - SCSI

There are several standards used to interconnect devices with a computer. These include: RS-232, RS-422, IEEE-488 (GPIB, HP-IB), SCSI, ESDI, and SMD. Transfer of large image files within a reasonable time requires a high speed parallel interface. Practical considerations also require that it be widely supported by many vendors for a variety of products of interest, and that it can be easily incorporated, and perhaps later modified, into a new special device.

RS-232 and RS-422 are low speed serial interfaces. The IEEE-488 is a moderate speed (1 M bps maximum, 400 K bps typical) parallel bus for interconnection of lab instrumentation. The other interfaces are high speed parallel data links designed to transfer bytes between hard disc drives and a computer. ESDI and SMD are high performance links (2-4 Mbps) designed for super-minicomputers and require care in implementation.

The SCSI interface (small computer systems interface) was designed as an intelligent interface so that different hard disc drives, which have diverse response rates, storage capacities, and file storage formats, could be easily interchanged or added to a system. A different version of hard disc controller would not be required for each drive type. It employs logical, rather than physical, addressing for all data blocks. Consequently, intelligent peripherals from different manufacturers can be connected through a SCSI interface to a computer system as long as they adhere to the American National Standards Institute ANSI X3.131 standard. Devices such as disc drives, tape drives, printers, and communication devices can be easily connected.

Several vendors produce chips which support the current maximum data rates of 1.5 M bps asynchronous, 4 M bps synchronous. Second generation chips are available and will be further developed in order to take advantage of revisions of the ANSI standard to expand the SCSI command set to accomodate additional peripheral devices, and greater data rates.

III.A.2. Storage Phosphors

Storage phosphors are also called memory screens or photostimulable phosphors. When exposed to x-rays, the screen fluoresces and electrons are driven into traps. When later scanned by a red laser, a second blue fluorescence occurs. A blue filter separates the laser light from the fluorescence light which enters the detector where the signal of the second fluorescence is amplified. That signal can be digitized and stored as digital data.

Cassettes using storage phosphors could be exposed using the same exposure settings as conventional x-ray cassettes. In general, x-ray factors are determined by acceptable noise limits of the radiograph which, in turn, are functions of the quantum statistics of the x-ray photons and the quantum efficiency of the detector. Conventional x-ray screens are thick for high sensitivity/low resolution and thin for high resolution/low sensitivity. Obviously, the thickness of the screen determines both resolution and sensitivity. A conventional cassette uses two screens (except for mammography) as tests have shown that two thin screens exposing both surfaces of a double emulsion film are better than one thicker screen of the same total thickness exposing a single emulsion. A storage phosphor cassette would use only one screen because of the scanning process. The quantum efficiency and resolution would be similar to the two screen system as the laser light tends to scatter less than the fluorescence. If the memory screen were made thicker to improve quantum efficiency, then a problem of laser beam penetration versus scattering might occur: certain picture elements might not be sufficiently stimulated by the laser to fluoresce and there would be some image carry-over to the next image. This could be reduced by a light flooding operation after laser scanning.

Several companies have been evaluating storage phosphor systems where the scanned image is digitally processed and reproduced on single emulsion photographic film. Clinical results have been excellent and costs/image are reduced. Exposure/image is about the same as conventional radiography but the appearance of the images and retake rates have been improved. In conventional radiography, several film sizes are used to save film costs. In this system, it is assumed that only two formats are required as electronic image processing can expand the final image. Thus, only 25 x 30 cm (10 x 12 inch) and 35 x 43 cm (14 x 17 inch) cassettes are proposed. The scanning parameters would be the same as larger formats would always have lower resolution as a result of large area scatter and the effects of patient thickness.

III.A.3.   Cassette Reader

The cassette reader should provide daylight loading. Insertion of the cassette should initiate the reading action and the cassette should not be removable until read or released by an override mechanism. The dynamic range of processed images should be within a range of 8 bits. However, errors of exposure or a need to examine some region of interest in more detail suggest that initial acquisition should be at the greater depth of 12 bits. When the 12 bit image is viewed at the computer/controller, the operator will reduce the range to 8 bits by selection of contrast, brightness and gradient.

The configuration of the cassette reader should be such that both cassette sizes can be read. While several commercial stimulable phosphor systems scan at 2048 lines or higher, their images are copied onto single emulsion films. Such screen to film systems do not have a data storage limitation imposed by digital data storage capacity. The reduced resolution of this system should mean a lesser requirement for precision of the scanning mechanism. If an existing commercial 2048 line scanning device is modified for this application, then either the scanning parameters must be changed or data must be accumulated by pixel averaging. Merely accepting alternate pixel data on alternate lines would increase patient exposure; such methods are not acceptable.

In summary, the cassette reader should: (1) provide a manual reset or initialization button, (2) accept x-ray cassettes of sizes 25 x 30 cm and 35 x 43 cm, (3) read and digitize the radiological image at 1024 x 1024 x 12 bit resolution within 10 - 20 seconds, (4) store the image in a local image memory RAM of 1.5 M Bytes (minimum), (5) permit removal of the storage phosphor cassette after it has been read, (6) provide a SCSI interface for transmission of the image to the computer/display upon command, (7) prevent the reading or scanning of a second radiograph image before the first has been sent to the computer *unless* the local reset or initialize button has been pressed, and (8) be about the size of a desk-top copying machine.

III.A.4.   Computer / Display

Desirable factors in a computer/controller/display are: cost, easy to learn and use, large RAM capacity and hard disc storage, adequate computing capacity for manipulating large image data files and capacity to simultaneously display up to 4 images.

The environment and tasks required of the equipment are similiar to the requirements of high resolution graphics display of CAD/CAM engineering workstations which are now standard equipment in manufacturing research and development, or for systems for electronic publishing. The wide acceptance and large demand for computer work stations within industry has created a large, very competitive market with systems offering a wide range of price and performance ranging from simpler 2-D displays to elaborate "real-time" 3-D object animation displays.

The ARMIS filmless radiograpic system is a system for the 1990's. Thus it is desirable to look at advanced workstation designs currently available or planned in order to get a glimpse of the technology and capabilities which will be commonplace, and hence expected by knowledgable radiologists. A current lower performance work station, which has design features which permit a path to the highest performance, must be considered.

Some general characteristics of advanced microcomputer workstations are: a UNIX or UNIX-like multi-tasking operating system; Motorola 68020 CPU, Intel 80386 CPU, or Micro-VAX II, with newest top of the line systems now based upon a RISC (Reduced Instruction Set Computer) architecture; a 10 MHz minimum bandwidth (VME or proprietary) backplane bus; multi-windows with pull-down mouse options (i.e. Xerox, Macintosh design), linear address space CPU to permit arbitrary sized, variable bit depth, multiple high resolution images.

Computer systems considered for the ARMIS proposal were: IBM PC/AT, IBM PC/RT, IBM PS/2, Digital Equipment Corp. (DEC) VAX Station series, SUN 3 series, and Apple Macintosh II workstations. High performance 2-D and 3-D UNIX workstations based upon VME or MultiBus backplane architecture, or the specialized data acquisition MASSCOMP Unix workstation, were not considered due to price, physical size, and capabilities that are greater than currently necessary.

IBM PC/AT - This is a very popular system because of its price. It has limited performance for high resolution display of graphics/images. This has induced many third party vendors to offer a large variety of specialized, medium resolution plug-in boards. However, its older design has been superseded by the IBM PS/2 series of machines.

Single board computers, some of which are based on PC/XT or PC/AT designs, may be used for special applications. These applications may be part of the control of the independent viewer or part of the data handling of an interface device. In any case, such applications will be constrained to a dedicated or repetitive function and would not be visible to the operator.

IBM PC/RT - While this machine has better performance than the AT, due to a RISC type architecture, it does not appear to offer enough additional advantages to justify the higher cost. It has not met wide acceptance in the market and hence it can be expected to be modified for special applications or discontinued.

IBM PS/2 - This system uses new manufacturing technology and hardware designs to bring higher performance to its line of PC's, to inhibit reverse engineering of the system, and delay the development of non-IBM clones. The model 80, which will be available shortly, contains the advanced 80386 CPU chip. The proprietary 10 MHz 'Micro Channel Bus' is better than the older PC/AT backplane bus. However, some hardware board developers remain concerned that the micro channel bus was not designed with sufficient bandwidth and may require some form of redesign/enhancements in the near future. This, coupled with proprietary aspects of the bus architecture, has inhibited development of new board products.

While the technology is new, it does not run software significantly faster than many of the PC/AT clones. The 286DOS operating system, which is designed to fully support the older 80286 CPU chip is finally expected by late 1987; it only partially supports the newer 80386 chip.

A key aspect of the PS/2 system is the development of a new operating system, OS/2, with initial versions due in 1988/1989. It is to be compatible with the older PC's, conform to the IBM System Application Software (SAA) which will permit programs to run on any size IBM computer and which is not yet fully defined, incorporate a window presentation manager, provide multi-tasking, and liberate users from the 640K memory limitation. Applications which will take advantage of the 80386 inside the PS/2 model 80 can then be developed. However, there may be pressure to ship OS/2 as soon as possible, which could increase the programming difficulties. It is expected that 3 years will pass before OS/2 is completed. Although the initial version is due next year (1988). OS/2 memory overhead requirements are now at 2-3 MBytes and increasing while response time decreases.

The display system uses special IC chips which have an inherent resolution of 640X480 pixels but can be bypassed by third party board vendors for other resolutions. Adding multiple monitors and controlling their display is awkward. The IBM PC/AT and IBM PS/2 have been weak on graphics and image display applications support due to their architecture.

While the hardware is possibly satisfactory for imaging, there is considerable confusion about the operating system even by professional software houses who have large installed bases of IBM based software. This confusion, as well as the present unavailability of a high level operating system, makes the PS/2 system currently unattractive for a new imaging workstation.

VAX Workstation Series - There are several models in this series. The lowest priced version (Vax Station 2000) has a "closed" structure, i.e. it does not have slots to accomodate specialized boards, does not have a disk for temporary storage of images, and its cost is higher than other systems. The higher performance models of the series are even more expensive, heavy, and bulky.

SUN 110/LP - Sun is a leader in the design of advanced computer workstations and would be a preferred supplier for a high performance system. However, its entry level system is also a diskless, closed system. Its higher performance models set standards that other vendors emulate but which are too expensive and include excessive performance capabilities that are unnecessary for this application.

Apple Macintosh II - (The system of choice) -The new version of the Macintosh series has desirable features not found in earlier versions or other systems. It contains the 68020 CPU and 68881 math coprocessor. Its backplane is a high speed 32 bit, 10 MHz bus based upon the NuBus, IEEE 1196 standard developed by Texas Instruments.

The visual icon based environment is fast, convenient, and grasped very easily by inexperienced users. The user interface with the computer is uniform and consistent across hundreds of Macintosh programs. Thus, reference to the manual of a *new* application is typically unnecessary until the experienced user desires a special feature. This represents a strong advantage over UNIX and MS-DOS computer users where the same button combinations have different interpretations in different applications. A computer tool is less effective when its use is inconsistent to the people who must manage it. The consistent Macintosh operating system will permit easier training of staff as imaging applications are designed. The trade off of a simple interface is the increased effort required for programming.

The SCSI interface is standard and is used for data transmission between external hard disk drives (or any other attached SCSI device) and the computer at 1.4 M bps. This will be convenient for interfacing the digital data card reader/writer and the cassette reader.

The display does not have a default size but can be any resolution for which there is a video board i.e. 300x200 to 4096x4096. As many as 6 different types of video boards can be inserted into the NuBus backplane which would allow an image to be displayed on up to 6 different monitors, i.e. each of different resolutions and/or black/white or color.

A further advantage is the ease with which the keyboard, mouse, track ball, or other devices can be linked in a daisy chain to a serial I/O port. Only one serial port to the computer is required even if there are several input devices on the system (nine is maximum). Multiple RS-232 ports on a serial I/O board, with each separate input device associated with one specific port, are not necessary. A device that became defective would be removed from the chain, even if the computer is on, fixed or replaced (the other devices would continue to work), and then be reinserted into the chain at a later time.

Apple can upgrade the Macintosh II to a model that incorporates the more advanced 68030 CPU which will be available shortly. Further, it is hinted that a RISC based machine is planned. One vendor has indicated it has available, special boards based upon multiple INMOS transputer chips, which could invite performance comparisons with mini-supercomputers for special applications. While such performance is not currently necessary, radiological demands of the 1990's may require it.

In summary, the platform for the computer/display will be a Macintosh II from Apple. Hard disks with a low access time and high storage capacity for temporary image retention will be selected from several possible vendors. Image display boards with a software programmable resolution of 640 x 480 up to 1024 x 768 pixels are currently available and will be selected for preliminary development. As the 1024 x 1024 pixel versions of the display boards become available, they will be evaluated for satisfactory characteristics before

a final choice is made for inclusion in the prototype systems. Monitors which match the corresponding video display boards must also be evaluated.

III.A.5. Digital Data Cards

The optical digital data cards, DDC's, operate on the same principle as compact music discs. A laser beam is focused to less than 5 um and used to erode a thin metal film used as an internal mirror. The mirror is protected by an overlay of polycarbonate. About 0.25 uJ is required to burn a small pit; a 50 mW laser can write 20 k pits or bits per second. In theory, a 1.0 W laser should be capable of writing data at 400 k bits/sec. A scanning reading laser (of lower power) is used to read the pattern of reflected light. The reading code requires about 13 bit spaces to read one byte in order to track the data pattern. A 5.25 inch compact music disc can store almost 50 MB of digital data. The first version of the credit card size DDC can store 2.0 MB, and a new version more than 4.0 MB of digital data. This should be sufficient to store either 4 uncompressed 1.0 MB images or 12 or more compressed images, plus several pages of text.

The writing action at the reflective surface of the DDC occurs at a very high local temperature. Photographic processes are not used so that the card is immune to extremes of temperature and to low level ionizing radiation. The polycarbonate overlay is quite rugged and sufficiently thick so that the laser beam, focussed in the plane of the reflector, will not resolve fine scratches at the surface. The card could be placed in a thin vinyl envelope and accompany the soldier through various levels of combat casualty care. Cards could be mailed or filed without special care or handling. The ARMIS system can copy the contents of the DDC's to produce duplicate cards.

As compact discs, CD's for music, spin, the circular data tracks are read by two reading circuits. The digital data is encoded to limit the size of gaps in the data stream. This is necessary for the operation of the tracking circuits. Minor positional or tracking errors are compensated for as part of the reading process. The reading data rate is in excess of 120 kbps. The DDC data is recorded in rectilinear form and requires a reciprocating motion with error compensation to read and write. A spinning motion would not require the rapid acceleration of the mechanism and the consequent increase of the positional errors. However, the x-y coordinates of the data tracks allow better control of the placement and categorizing of the data on the card. This ability to place data at random positions may be essential to perform the control and addressing functions so that information may be added as one image or one page of text at a time. The cost appears to be a reduction of the maximum data rate. At present, data may be written at 10 k bps and read at 100 k bps. Several manufacturers have indicated that new machines will have twice that speed and future machines will double that rate again. With 4x compressed data, this translates to writing one image in 200 sec (now) and 50 sec (future). The goal is 10 sec. write and 2 sec. to read an image.

Alternative optical data cards are also being developed by other companies. These cards incorporate a dye layer in front of the internal reflecting surface. The energy required to convert the dye layer from transparent to opaque is less than that to erode the reflecting layer. There may be questions of the resistance to radiation and aging effects of this method. One company advocates the use of a spinning laser head assembly with arc segments on the data card.

III.A.6. Card Reader / Writer

Several commercial DDC reader/writers are available on an experimental basis with production of the simpler models scheduled for later this year. These commercial models are available with a SCSI and sufficient RAM for packet communication, i.e., where one line of stored information (about 1 kB) is sent at a time. In order to transfer complete compressed images, the RAM and associated circuits must be increased to 125 to 250 kB, depending on the whether 4x or 8x compression is used. A small amount of additional RAM capacity is required

for data management to keep track of data location and contents of each DDC.

If the device cannot be modified to add the additional RAM capacity then some type of interface will be needed to accumulate packet data to the full compressed image. In most applications of similar devices, the computer accepts the "sliced" data and accumulates the packets to the full image value. In the ARMIS, each peripheral device could have the same requirement so that simultaneous operation of all elements of the system would mean that the SCSI data stream would be a melange of non-synchronous packets and control signals. It would also mean that each peripheral device could not be tested independently of the system computer/controller. Even if the data were transmitted in packets, the central computer would still require the equivalent of a full-image RAM for each device. For those reasons, the first approach will require that each peripheral device incorporate a full-image RAM.

The error rates of present and proposed DDC reader/writers is very low. The data encoding methods require a repeat of the reading cycle of a packet or image line if the parity data is not correct. The available commercial models are intended for business applications and are low cost production devices. In order to gain experience on the noise tolerance and general characteristics, a machine of this type will be used for early experimentation while waiting for the development of machines of increased data capacity and higher speed.

III.A.7.   Independent Viewer

It is often necessary to examine medical images to confirm a diagnosis or verify the precise location of an anomaly. It is assumed that the review process of a radiograph or multiple CT film does not require annotation or alteration but only a simple display of that image. The independent viewer is a simple device to display the contents of a DDC.

Each DDC would have a data management section containing a list of card contents and locations. The independent viewer would consist of a DDC reader, data expander to convert a compressed image to a form suitable for display and a monitor. The independent viewer would be of the same complexity as a small computer. Only one image RAM would be required as the card contents could be read, expanded and displayed with minimum processing. It would resemble a monitor with lower added section containing the card reader and the dedicated computer components.

Additional image RAM circuits could permit the independent viewer to display more than one image. The independent viewer could be quite simple. Insertion of the DDC will cause the display of the file directory of the card: perhaps 12 images and 12 pages of text. Three keys will permit selection of the image by moving the cursor: up/down/enter. For text, the up/down keys will scroll the display. Pressing the enter key will select the catalog item or return to the directory. One of the items of the directory, when selected, will return the DDC.

III.A.8.   DIN/PACS Interface

The DIN/PACS interface will provide the 50 pin connector and software which will permit local communication with another DIN/PACS system. This will be accomplished by building an internal "black box" device with a DIN/PACS port on one side and the SCSI communications port to the computer/controller on the other. Since the device requires: two dissimiliar I/O ports, 1 MB of local image RAM, intelligence to convert data message protocols between two formats, and be programmable to permit evolutionary modification of the DIN/PACS standard, it will require implementation by a (Macintosh) computer.

When developed, research will not only indicate if the funtions of this device can be simplified to a single board computer, but also if the host computer has sufficient capability to assume these additional functions.

A data communications device will be developed which will connect the DIN/PACS port to a long distance communication channel. This will provide long distance transmission of patient images and data to another DIN/PACS system. A high speed (56 K bps) dedicated phone line is the media of choice at this time. However, integrated services digital network (ISDN) developments of the phone system are progressing at a very rapid rate. Hence, development will keep current of ISDN developments so that the communications link can migrate to the

newer system when it becomes nationally available.

III.A.9. Optical Disk Device

The standard 5.25" optical disk has: random access, high storage density (200-600 MB/disk equivalent to 800-2400 compressed high resolution images), non-volatile, physically compact, well understood/proven technology, easily handled/stored/mailed, reasonably fast data transfer rates (1 Mbps), and finally offers a continually improving and very competitive cost/MByte. Larger, 14", CD disks are available which can store 6 gigabytes of data. Further, the University of Wisconsin's Physical Sciences Laboratory has designed a computerized optical archival storage device that fits within a small room and stores 2 terabytes of data. This is equivalent to aproximately 8 million compressed, high resolution images.

There are two types of optical disk technologies currently on the market: WORM (write once / read many) and CD-ROM (compact disk read only memory). A double sided WORM disc can store more than 200 MBytes of data, about 120 MBytes on each side. The removable cartridge is only slightly larger than the 5.25" disc which makes it easy to store. Data is written using an "embedded servo" in which the disk is formatted by burning additional laser tracks which guide the read/write head. A CD-ROM disk can hold 600 MBytes of data. The reason for the greater data storage is that it is produced under ideal recording conditions. Further, the data storage format is different as servo tracks are not required.

Several vendors now offer WORM devices that can be interfaced to a SCSI bus but with differing levels of software driver support. Storage can be as great as 400 MBytes per unit (200 MBytes / side). As additional vendors develop products for this marketplace, local archival storage will become very practical as well as large global archival storage.

III.A.10. Hard Copy Device

There may be situations where an image must be examined outside of one of the electronic systems. A hard copy in the form of a film or diagnostic text can be made. Because the computer/control will have a printer port, the ability to print text information is built-in. Images can be printed by photographing the monitor or by various forms of line-scanning printers using conventional or "dry" films.

Multi-format cameras are in common use in medical imaging. These incorporate a monitor, a film camera, and optical components to permit taking one full-size image or various combinations of multiple smaller images on a single large sheet of film, one of the standard medical sizes. The film must be processed after exposure.

Several new films and papers have been developed which have low light sensitivity but which can be thermally developed. The film is exposed by means of a scanning laser and developed by passing over heated rollers in the scanner. Such devices are available commercially which exceed the requirements of the ARMIS system and which can be converted from their present IEEE-488 standard to the SCSI bus.

III.B.   Data Links

Data links are the communication hardware and software protocols that standardize reliable transmission of data or files from one host device to another. Transmission distances may be internal, local, or wide area. Of particular interest in radiology is the DIN/PACS standards as well as local and wide area networks.

III.B.1.   DIN / PACS   Interfaces

The DIN/PACS interface is a set of hardware specifications and software protocols which permit the transmission of digital images from one imaging system to another (ACR-NEMA No. 300-1985). With the rapid proliferation of mechanisms to transmit data between computer systems, the timely development of a standard interface for radiological imaging systems is benifical. These standards imply that it will not be necessary for every vendor to develop interfaces between their proprietary system bus and all other communication protocols. The effort can be used to impove the reliability and effectiveness of all complete systems and communication capabilities thru a standard interface.

III.B.2.   Communication Link Interfaces

To simplify initial development of the ARMIS prototype system, the DIN/PACS communications interface subsystem will be developed independently of the cassette reader, host computer/controller, and digital data card reader/writer. This is motivated by several concerns. (1) It is desirable to have the DIN/PACS interface send/accept an image file to/from a remote DIN/PACS sytem without performance penalty from the ARMIS host system. This implies that the interface must contain sufficient image RAM to store a typical image. (2) The DIN/PACS implementation of the International Standards Organization / Open System Interconnect (ISO/OSI) software communication protocols, which permit transparent data transmission, requires an intelligent (i.e. computer based) interface. (3) For independence from the chosen host computer, which permits future upgrading to another computer system, it is desirable to have the DIN/PACS "black box" appear to be a SCSI device, i.e. communicate to the host computer via the SCSI interface.

These features imply that the interface to the DIN/PACS system must itself be a small computer/controller, with local image RAM, and with specialized I/O ports being a SCSI interface on one side and a DIN/PACS interface at the other. After successful integration of the DIN/PACS-SCSI subunit with the host, simplification of the design may be possible by having the host computer assume some of the responsibilities of the interface. However, such simplification of hardware will be measured against the increase of complexity in the host software, loss of host response, and interchangeability and maintenance of subcomponents.

III.B.3.   Types of Communication Links

Communications between computers is becoming an increasingly important issue in their utilization. The rate of development of hardware and software communication devices for computers is proceeding as fast or faster than development of their hosts. Some reports expect that computer communications equipment will account for 30-40% of the total system. Current necessities and future expectations has created a diversity of solutions directed to specific applications. High level computer communication applications include: file transfer, mail, and remote log-on.

Computer communication developments have proceeded in three interrelated areas: gradual conversion of the analog public telephone into a digital network offering a variety of communication services, i.e. voice, data, fax, etc., local area networks (LAN's), and wide area networks (WAN's).

The public phone network was the earliest wide area network and is familiar to most people. Since it provided convenient, easy communication between thousands of sites, the phone network was exploited early as a media for data exchange. The public phone system still offers the simplest procedures and means to connect widely separated systems. It is

comparitively easy to connect a computer to a modem, and dial up (or lease a dedicated line to) a computer with modem at a remote site and use a simple log-on procedure to control the data transfer. Increased data rates and additional but limited services can be obtained at somewhat non-competitive prices.

The phone system is in a period of transition while converting from historical analog service to a totally digital network. This new digital service is called "integrated services digital network" or ISDN. The ultimate goal of the system is to provide multiple 64 K bps digital lines to all sites now currently equipped with a telephone. Specific terminal access units, TA's, will encode either voice, fax, computer, or other special data or imaging equipment to the phone network. Leased lines used only several hours a day will will become unnecessary. Circuits will be digitally switched; it is not an X.25 packet network (see below). While this system can offer new options for imaging communications, it may not occur as desired. AT&T is no longer in a position to set and implement a single interconnect standard for the United States. Several competing designs differ slightly but significantly, i.e. incompatable. While several regional trials of systems are in progress, competition between designs will delay ultimate implementation. Implementation will evolve regionally, beginning with major customers in early 1990's. The large financal investment by the regional phone companies depends upon utilization by large accounts who will be increasingly unable to wait for national implementation and may opt for an alternative communication system. While this would be an ideal system to interconnect imaging and other equipment using high bandwidth channels, it may be delayed without implementation of full capability.

Difficulties of low data rates via the phone network, as well as the need to link computers, has led to development of increasingly standard local and wide area data communications networks. Local area networks offer modest to extreme data rates with low error at a compromise of requiring specific hardware devices, data encapsulation, network protocols, and increased expense, over a limited area. Setup and reliable maintenance of this network by a network administer is becoming increasingly attractive, even commonplace. Many local area networks offer an additional level of service by connecting into a broadband LAN (not quite local area service), which may in turn have a gateway into a major wide area network such as ARPA, or BitNet. This could provide data communications to a similiar installation at a very remote location. In some future form, this type of pathway via high bandwidth channels should be seriously considered for routine transmission of radiological images. However, the effort to initially setup (and maintain) the errorless delivery of image files through these various interconnections should not be underestimated.

III.B.3.a. Local Area Networks (LANs)

LANs provide a high bandwidth data communication system that spans a physically limited area (usually less than 1 mile), have full connectivity among stations, are administered by the owner (not the FCC), and connect via inexpensive cable. Cable may be twisted pair, shielded twisted pair, or one of several grades of coax or triax shielded low loss cable, or fiber optic cable. In principle, transmission may be via RS-232, RS-422, RS-485, IEEE- 488, ... etc. Most LANs use twisted pair cable (ala RS-422) or high grade coax cable.

Hardware and electrical specifications for network communications are only part of the *physical* and *data link* layers of the seven layer Open Systems Interconnect (OSI) model. The other five layers are software protocols which via "divide and conquer", isolate related protocol details within each communications layer which include: data formats, node addressing, subnet protocols, communication packets, etc. While not so long ago, computer connections via "RS-232" was sufficient, and many details were ignored or not necessary, the burden of a proper network has now shifted to standard software protocols of interconnection with details of actual hardware components and electronic modulation procedures related to the physical media of data exchange being insulated from all other layers and hence the user. This permits the details of technological improvements and

hardware replacement to be transparent to the application.

Network Topologies. The physical and electrical interconnection of nodes.

star - easy routing of data but central node must be reliable with excess speed to route traffic.

starLAN - special IC chips are making this a less expensive, but slower system

ring (loop) - all transmissions in one direction, no routing. Each node passes message until it returns to sender. Easy to implement. Requires care to insert node. Possible snag if a node fails.

bus - data on medium must be directional, nodes do not route or forward messages, hence data is broadcast to all stations. The LAN lives if a node fails. Easy to add nodes (taps).

Access Protocols. Local area networks are distinguished by the method of sharing (arbitrating) the channel among nodes. Some access protocols may be applicable to more than one topology. A variety of protocols may be used, but the most popular are the TCP-IP protocols because of their availability on super-minicomputers (VAX), workstations (SUN, Apollo, HP), and on IBM PC's. Because many department LAN's use TCP-IP protocols, many universities have adopted these protocols as the campus standard. Other protocols of increasing popularity are IBM's token/ring for PC systems, and StarLan (special IC's have decreased the cost of each node).

Polling. (Star). A master polls each slave/node. Time consuming. All complexity for hardware, timing delays, etc. concentrated at single point. Each node gets equal access to network.

Token/ring. A "token", a special bit pattern, is passed around the ring. If a node has a message, it inserts the message in front of the token and passes it on until it returns. Easy to check for message corruption. Fast, as two nodes do not simultaneously request network. Example is IBMs Token Ring for the PC (4 Mbps, twisted pair cable). Another is ProNet (20/80 Mbps). Standard is IEEE 802.5.

Token/bus. Similiar to above except that token is passed address to address. Example is ARCnet or GM's MAP on broadband. IEEE 802.4 protocol. Nodes do not collide in time; every node has equal access to net.

Bus (branching bus or tree). Bidirectional data, no routing, each node contends with each other for the network. Protocol is "carrier-sensing multiple access with collision detect", CSMA/CD, as standardized in IEEE 802.3. This is the basis for Xerox's Ethernet . If two nodes simutaneously request the bus, then data collision occurs. Each node detects the collision, ceases transmitting for a random period, then attempts to retransmit if the line is free.

III.B.3.b. Wide Area Networks

ARPANET. This began in 1969 as an R&D project by DARPA (Defense Advanced Research Projects Agency). This is an operational network supporting DOD, Dept. of Energy (DOE), and some NSF computer science and supercomputer research on high bandwidth (56kbps) communication links. Gateways to the ARPA network exist at most DOD installations.

IP is the internet protocol which permits different technologies and connection protocols to be linked together. This allows networks of computers to be linked into a net. Transmission Control Protocol (TCP) is a complicated protocol at a higher software level than IP which is designed to correct: transmission errors, duplicate packets, out of sync packets,...etc. of the network. Hence the ARPA protocol is usually known as TCP/IP. The original protocol NCP, or NCP/IP, was designed presuming a perfect subnet.

Mail, test files, and ultimately image files could be communicated from a radiological site on an ethernet subnet, to a gateway on ARPA, and on to a second gateway and ethernet subnet at a remote site. Communication with most, if not all, other DOD sites and research areas could be established via this wide area network. This net is good for messages and a limited number of small, compressed images; not as efficient for transmitting uncompressed or large images.

Other communication links include:

BITNET. A "store and forward" net often used for electronic mail between research institutions using leased telephone lines at 9600 bps. Simple connection. Uses software initially developed by IBM.

CSNET. Used to communicate advances in computer science research.

MFENet. DOE magnetic fusion energy research network.

MILNET. Long haul military network.

SPAN. Network communications for space physics studies. NASA.

UUCP and **USENet.** Electronic mail and file transfer between Unix systems.

III.B.3.c. Public Packet Telephone Network Services

Digital data transmission service is available from local and national telephone companies. Data is sent via packets across the network, which is similar to ARPAnet for the DOD. The data is encoded by a Packet Assembler/Dis-assembler (PAD) using an X.25 standard format and transmitted/routed at 4800, 9.6 K, or 56 K bps into the packet switching network. Users can connect into a PAD provided by/at the phone company which then routes the data into the network, or a user can provide their own PAD and connect directly into the packet switching network. Service is best designed for interactive or remote log-on to a remote computer site. A major limitation restricts the local telephone company from sending data packets across an LATA boundary. In order to cross an LATA boundary, data packets must be switched through a gateway to a national packet carrier network. The two principle nets are TymNet (TymNet Inc., San Jose,Calif) and TeleNet (GTE). However, TymNet and TeleNet recommend that a leased line be purchased to connect from the users site to the nearest port of entry of their network. Consequently, rather than require each of N remote sites obtain 2 or 3 dedicated lines to only selected main facilities, each site would require (i.e. highly recomended) a single dedicated line into the network permitting data transmission capability to any facility on the net. Throughput and response time of transmission of a large image file via a packet network is unclear as not all links between nodes may be high bandwidth.

It is technically possible to send data from one packet switched network through a gateway into other packet switched networks such as ARPA, TymNet, or TeleNet. A station connected to one of these nets can, in principle, transmit data to any other station connected to one of the nets.

Tariffs are charged by a fixed amount for the line plus the number of packets sent through the system. It is not dependent upon source to destination distance. Hence, for limited numbers of packet to be transmitted, this service may be more cost effective than a long distance dedicated line.

III.B.3.d. Standard Phone Services

Common Carrier Leased Lines   Leased lines may be analog or digital. Service is available at up to 9600, and 56 K bps (digital only). They also offer digital packet switched services.

Dial-up. Analog transmission service. Data rates up to 4800 bps.

Bell Channel Service (BCS). Analog service on 2 or 4 wires at data rates up to 19.2 K bps.

Local Area Data Service. (LADS).   Digital 2 or 4 wire service. Point to point service for distances limited to within a central office. Data rates to 19.2 Kbps. Good for several departments or units physically separated but within a local area.

Basic Digital Service (BCS).   Synchronous digital transmission at data rates of 2.4, 4.8, 9.6, or 56K bps.

Direct Digital Service (DDS).   Same as BDS but higher performance, i.e. guaranted low error rates, at tariffs about 25-40% greater than BDS.

High Capacity Digital Service (HCDS or Hicap).   Synchronous digital transmission at 1.544 M bps on a 4 wire circuit. "T1" point to point service anywhere in country. Long haul common carriers (i.e. MCI, AT+T) must be used for service crossing a Local Access and Transport Area (LATA).

III.B.4. Hybrid Systems

The most common system for digital communication uses four tones representing the 0's, and 1's in the originate and answer modes. Standard Universal Asynchronous Receiver-Transmitters, UART's, use particular sequences of 1's and 0's to mark the beginning, end, and validity of each digital character which may range from four to twelve (or more) bits in length. For example, the Intersil IM6402 UART can transmit an 8 bit character, one start bit, one parity bit and 1, 1-1/2 or 2 stop bits. Usually, one space is left between character transmissions so that an 8 bit character requires 13 bit spaces. Parity is defined as even if the number of 1's of the character is even. The chip parity flag or output signal is energized if the received parity bit does not match the parity of the received data. Parity is a simple method of verifying that the data channel is clean.

Digitized image data is often transmitted in some type of coded sequence to mark the start and end of each character, even when a UART is not used. If the data channel is particularly clean, then a longer sequence of bits can be transmitted between the start and stop bits. One practical limitation is the phase error between the terminals of the communication link. These phase errors are caused by random or thermal variations of signal velocity during packet transmission. If 10 K bits comprise the sequence, the phase error must be less than 1 part in 4x100k to assure that each bit remains in its proper time slot. Phase or received diversity errors of this magnitude or greater are common and force limits on the packet size. To accomodate these errors, data links will "fragment" the packets into pieces small enough to tolerate the phase errors. For example, the ARPAnet would fragment a 1024 byte packet into 11 fragments of 1008 bits or less. The hardware must accept packets, fragment them, transmit/ receive them, put them back together and check for errors. Obviously, elegant and precise long-distance digital transmission of images is expensive.

A less expensive, and less precise means for image transmission is based on the Ginsberg method used in most video tape recorders. With this method, a start pulse is generated at the beginning of an image scan line. The time to the next pulse is inversely proportional to the signal amplitude sampled at the time of the pulse. If the polarity of these pulses is alternated and smoothed, the effect is similar to a frequency modulated, FM, signal where the higher frequencies correspond to higher amplitudes. The ratio of the highest to lowest frequencies is less than two and the lowest frequencies actually overlap the higher video spatial frequencies. This overlap would cause a moire pattern of interference except that the signal amplitudes are low in the region of overlap so that the moire pattern is also of low amplitude and not significant. One problem is that the sample intervals vary. A digital image, once transmitted this way, would lose pixel registration between transmitted and received images and some resolution of the lower amplitudes. The quality of differential images, differences of paired images, would be rather poor. The quality of single images would be fair. Common real-time TV images permit the eye to average over several frames so that the errors of single images are less obvious. As this method is used for TV broadcasting, a number of commercial devices are available such as phase error correctors and image enhancers.

Several companies market inexpensive slow-scan systems to generate the FM signal for transmission. A TV camera is scanned slowly, the signal converted and a computer image storage card is used for accumulating the image for display. Within its limitations, this FM transmission system may be an inexpensive alternative to the elegant digital data transmission schemes if no further processing of the images is required and if the demands on image quality are not stringent. It is not proposed for regular use with the ARMIS. However, such images, once received by another system, could be entered in the ARMIS, displayed and stored on DDC's.

III.C. Data Compression

Compression of digital image data has two very desirable features: (1) data storage requirments can be considerably reduced. This reduces chip counts, power supply needs, heat dissipation, physical size and bulkiness, and thus can improve overall reliability of the system. (2) Required bandwidth and/or transmission times of the data through external communications links and internal system buses is reduced. For transmission of large data files, i.e. images, data manipulation times can easily be in the range of tens of seconds to many minutes. Hence image compression helps to maintain operator/technician efficiency and alertness during extended, repetitive, perhaps tedious image transmission periods. Lower bandwidth requirements may make additional, probably lower cost, transmission channels available.

Undesirable features of image compression are: (1) distortion may be introduced into the image. The distortion may or may not be negligible. (2) The requirements for hardware, software, and processing time.

Of considerable importance in selecting a compression algorithm are (1) the noise/error characteristics of potential communication channels or storage media, (2) the sensitivity of the algorithm to reproduce the original image from a corrupted data file, and (3) the effect that mis-interpretation of a corrupted image may cause. There are many compression algorithms available which offer compromises for: compression ratio, hardware complexity vs. software complexity, computation time, and sensitivity to channel noise. Hence, a suitable compromise for the application must be determined and implemented.

III.C.1. Compression Methods

There are two main approaches to data compression. (1) Remove redundancy and predictability of the data as used in differential pulse code modulation, predictive coding, or block truncation coding procedures. (2) Energy preserving transforms such as Fourier, Cosine, Hadamard, Haar, and Karhunen-Loeve procedures. Generally, pulse code modulation and predictive coding can achieve high compression ratios, quickly, without the necessity for complex hardware or digital signal processors. However, they are usually sensitive to noise. The transform methods are not as sensitive to noise but computation times are long unless assisted by special hardware such as newer digital signal processing chips.

Block truncation coding techniques of the first approach offer modest compression ratios of 4:1 or 6:1, are moderately fast without special hardware, minimally alter absolute pixel values and have low sensitivity to noise errors. Variations of this technique will be implemented in software, and, if results are satisfactory, can be· implemented using a dedicated processor chip to make computation times negligible.

The fast cosine transform has been successfully used to achieve high compression ratios of medical images. This transform has been highly regarded because (1) it is a good approximation to the optimal Karhunen-Loeve transformation, and (2) processing time is orders of magnitude less. However, compression or reconstruction of a single high resolution image still requires many minutes of processing time. This long processing time has restrained widespread adoption of the method. A board containing digital signal processing chips may reduce this time to several seconds. At a later time, trade offs of using this more sophisticated method can be compared to the block truncation method. A transform method of image compression would require inclusion of a digital signal processing array processor within the independent viewer, would be a major hardware addition, and would increase the cost.

III.C.2. Images / Text.

Images will be compressed using the algorithm of choice. However, the option will be available to store or perhaps transmit images in an un-compressed state or in an alternate compression format.

Diagnostic text used to document important parameters of the image and patient, and stored as ASCII characters, will be a small fraction of the total storage required for an image set. Since compression of text data will yield only small relative savings in storage for the effort and complexity expended, text compression will not be implemented.

III.D.   Research Plan

At the present time, all components of the proposed system are commercially available in some form. While the components will function in some fashion, they will not be efficient, the quality of their images may be poor, their operating time per image cycle may be far too long, or there may be a deficiency in some other characteristic. The tasks will be to improve these characteristics and make the complete system easy and practical to use. The existence of these components means that the assembly of the system need not wait for their perfection. Rather, a system could be assembled and evaluated in order to test the strong components and features as work continues in areas requiring improvement. Even though the present writing and reading speeds of the DDC reader/writer are far too slow, techniques could be tested for data compression/restoration as development continues on that device.

For example, the Apple Macintosh computer is available with a 1024 x 768 pel image board; the goal is 1024 x 1024 pel. The writing time of a compressed image of either the Nipponcoinco or CSK DDC device is more than 100 sec and the goal is less than 15 sec. Present 2400 bd modems require more than several minutes to transmit a compressed image. The goal is 38 sec with the 56 K bps standard; less time is required if the 1.544 M bps link becomes more easily available. Image processing is possible but slow and cumbersome; it must be fast and transparent to the operator.

The general approach will be to specify a system based on the present capabilities of the components, yet designed in such a way that present components can be used and the specifications adjusted as component development and programming proceed. This means that a system will be assembled early and images processed, stored and transmitted, perhaps inefficiently, slowly or at reduced resolution, but operating conditions can be tested. The research plan involves the assembly of an operating system as soon as possible and replacement of key components as improvements are made. The major components will be described in terms of their ideal performance as well as what is achieveable within the first year of the development project.

III.D.1.   System Configuration

The planned configuration of the system is shown in Fig. 25. The computer/controller will be a Macintosh II computer with small computer systems interface, SCSI. The standardized interface structure of SCSI will unite the dissimiliar imaging equipment into a unified I/O system. Minor variations of the SCSI standard by each vendor are anticipated.

Fig. 25 indicates additional options to the system which will be considered, and investigated, but for which implementation is not planned.

It is planned that each device on the SCSI bus will have its own separate image RAM in order to facilitate system response and development. Part of the research plan will be to test this proposal in order to verify optimum RAM requirements for each device versus the increased mechanical and electrical and programming complexity, power requirements, and price.
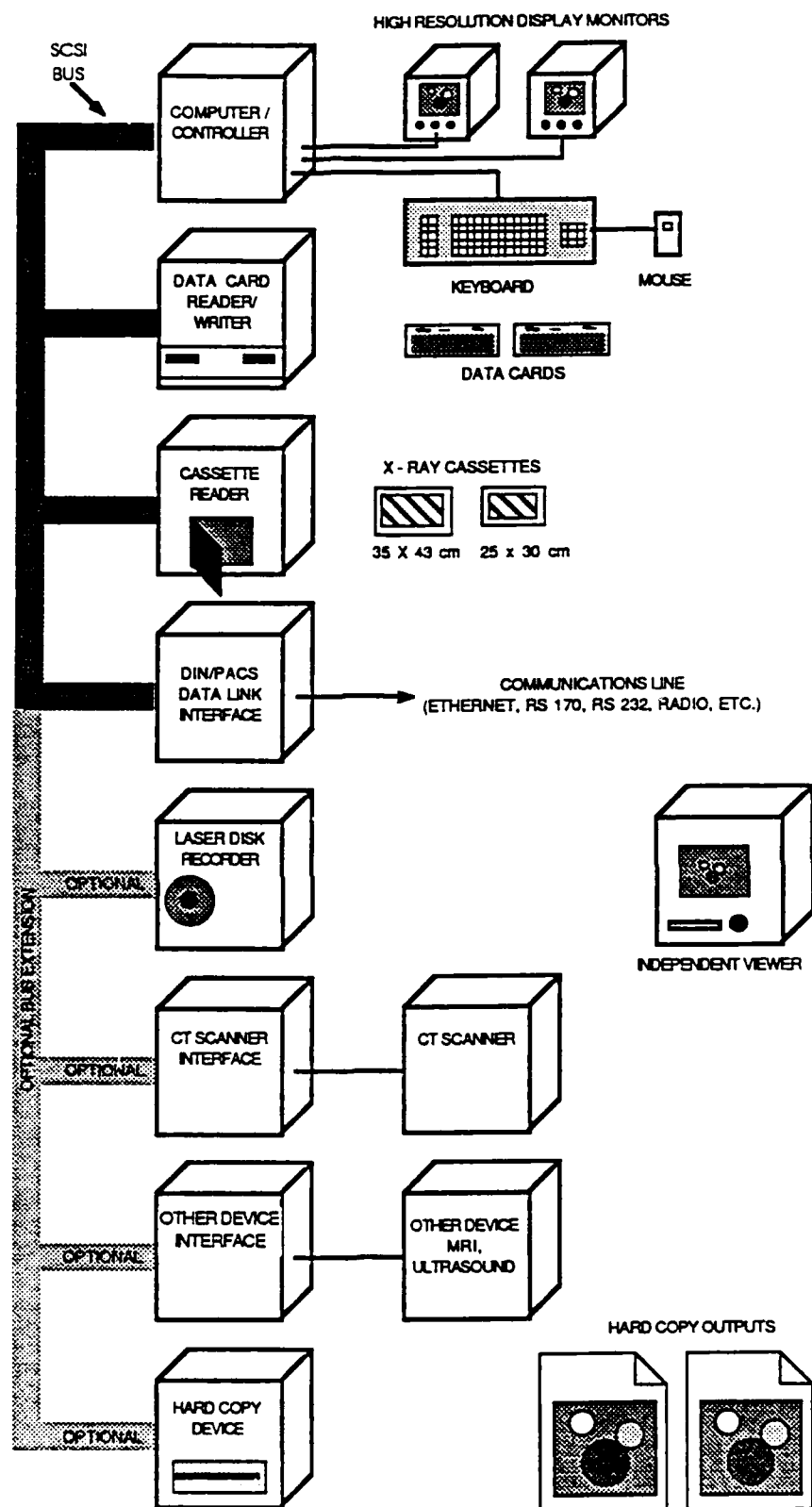
Figure 25   ARMIS Filmless Radiographic System

Each device requires an explicit software driver algorithm at the host computer which controls the functions of the device. Since the cassette reader and digital data card are new devices, initial versions of the driver programs will not be expected to be optimized for response time nor take advantage of all possible functions available on the device. Initially, the algorithm will be simple and adequate while further research and experience with the devices will permit increased sophistication.

III.D.2. Schedule

There is no doubt that an operating system can be assembled. The level of performance and the practicality of the system are the main issues. The schedule will depend on the responses and timely performance of the bidders for the cassette reader and the DDC reader/writer. The technical approach may have to change depending on the results of the early studies. If it appears that the data rates of the DDC cannot be improved, then alternate sources will have to be developed quickly. In general, the first year verifies the methods and choices and the second year completes the design and assembly.

First Year: The devices will be specified and puchased. They will be assembled into the system and compatibility between components will be assessed. The standards which define the programming environment of the Macintosh will be learned and used to create the subprograms which will be used to control each device. By the end of the first year major image display and data handling should be ready to permit image transfer between cassette reader, digital data card, and computer/controller and image file transfer between two computer/controllers.

Second Year: The communication interface will be fully developed and tested. Inital testing will indicate which protocols are unacceptably slow and require improvment. The system should be working but sub-optimally, and effort will be expended for improvements in the response and user ease of operation.

III.D.3. Build / Buy

Where possible, all units will be purchased. When the units do not fully meet design considerations, an attempt will be made to obtain the desired modifications from the vendor or from another viable third party. However, in cases where this is not possible, or where flexibility of design parameters is required, building prototype devices will be necessary. The overall goal will be to acquire the diverse products, and then assemble them mechanically, electrically, and then logically into a strong, effective system.

III.D.4. Subcontracting

Two major subcontracts are anticipated: for the x-ray cassettes and their reader and for the DDC reader/writer (and separarte reader only). A minor subcontract within the University of Wisconsin to the Physical Sciences Laboratory, PSL, will be for the assembly of finished devices after breadboard testing. Preliminary technical information for the major subcontracts can be found in Section III.E. Final specifications will be prepared during the early part of the first year.

The goal of final mechanical assembly of sub-units into an ergonomically designed structure will be subcontracted to the University of Wisconsin's Physical Sciences Laboratory, PSL.

III.D.5. Technical Testing

Testing of units and assemblies at all phases of the development will verify that equipment and designs are operating as expected and meeting all design criteria. This will require hardware test equipment, (i.e. pulse generator, logic analyzer, oscilloscopes, etc.) and software development tools. When technical testing indicates that a device or function is not operating as specified, the vendor will be consulted.

In development and assembly of a complex system from several devices that are in final stages of development, unanticipated difficulties will occur. This could be due to: unannounced

changes of specifications or implementation of functions, differences in opinion concerning methods of implementation or specifications, or incomplete or errored documentation. Close collaboration with main vendors, visits when necessary, will minimize technical problems.

III.D.6. Phantom Testing

Phantom testing will be initiated as soon as possible as part of overall testing. Test phantoms will contain resolution grills, step wedges, low contrast fibers and other test objects. The test phantoms will be radiographed and the images examined to measure the image characteristics of contrast, resolution, noise, detectibility of anomalies and general appearance. Some comparisons will be made relative to conventional film-screen combinations. This will also verify functional aspects of the cassette reader.

III.D.7. Preclinical Testing

Preclinical testing will commence in the second year after successful phantom testing and when software development has reached a stage sufficient to verify that the effectivness of the procedures are acceptable for radiological personnel. Responses from this testing will subsequently be used in modification and further implementation of procedures. Preclinical phantoms will include acrylic models and tissue simulating materials as well as some animal images. Several radiologists will be asked to review these images and comment on the operation of the system.

III.E.   Preliminary Purchase Specifications

Several commercial filmless radiographic systems are undergoing evaluation in hospitals. A number of optical digital data card devices have been developed and are in limited production. Rather than design entirely new devices, it is proposed that these commercial devices be examined and technical possibilities discussed with each potential vendor. Specifications would be based on the characteristics of each particular item. This is a departure from the common procedure of preparing a broad technical specification which could be met by most designs followed by selection just prior to purchase. Here, bidders would be informed that each product would be compared on the merit of the total assembly rather than that particular component or element. For example, one DDC device could have a RAM of 125 kB and another device could have 1 kB which would require an external circuit to increase the effective RAM to 125 kB. Obviously, the second device should be less expensive but the cost of the added circuits must be part of the selection criteria.

While the present design goals call for an image matrix of 1024 x 1024 x 8 bits, the Macintosh II computer has standard components of 1024 x 768 x 8 bits. System development could proceed with the slightly reduced matrix while waiting for completion of the 1 MB video RAM display boards.

III.E.1. Cassettes and Reader

Only two cassette sizes are proposed: 25 x 30 cm (10 x 12 inch) and 35 x 43 cm (14 x 17 inch). As both sizes will use the same scan matrix of 1024 x 1024 pels, the larger can use a thicker, more sensitive stimulable phosphor screen. Each system will have several cassettes of each size.

The cassette reader should be capable of reading both sizes. The reader will scan the cassette, place the contents in RAM and release the cassette. The next cassette would not be scanned until after the transfer of RAM data to the computer/controller.

Preliminary Specifications:

(1) Scan and Digitize image at 1024 x1024 x12 bit resolution within 10-20 seconds.

(2) Store the image in a local image memory RAM of 1.5 M Bytes (minimum).

(3) Accept x-ray cassettes of sizes 25 x 30 cm and 35 x 43 cm.

(4) Permit removal of the storage phosphor cassette after it has been read.

(5) Provide a SCSI interface for data transmission with host.

(6) Provide a manual (re)initialization or reset button.

(7) Prevent inadvertant opening of the unit during digitization. Prevent the reading or scanning of a second radiograph image before the first has been sent to the computer and the computer has issued a clear memory command *unless* the local reset or initialize button has been physically pressed by the technician.

(8) Size is approximately that of a desk-top copying machine.

(9) Display status using green and red lights/LEDS and English legends to indicate:
> (A) Cassette.
>> 1) Ready to load cassette.
>> 2) Not Ready - a cassette is loaded
> (B) Image digitization.
>> 1) Ready to scan and digitize image.
>> 2) Not ready - Previous Image stored in memory.
> (C) General.
>> 1) Reading of cassette in progress.
>> 2) Image transfer to host in progress.
>> 3) Error conditions.

III.E.2. Data Card Reader / Writer

Currently, only prototype digital data card read/writer units are available for systems development. Read and write speeds have not been optimized. The data card reader/writer has not demonstrated that it can easily read and write large data files. This represents a developing technology in which satisfactory standarized parameters for device operation have not yet been established, nor may be possible or obvious at todays current level of development. Experience with DDC operation will be gained by obtaining several prototype devices so as to insure future interchangeability and availability of data cards and reader/ writer devices from more than a single source.

Preliminary Specifications:

(1) Read and write Drexler Digital Data cards.

(2) Provide sample demonstration programs with source code.

(3) Card Data Storage of 4 M Bytes (minimum). Inital prototype may be 2 M Bytes.

(4) Writing rate is 100 K bps minimum. Inital prototype may be 10 K bps.

(5) Reading rate is 1 M bps minimum.   "   "   "   " 100 K bps.

(6) SCSI interface with SCSI driver source code.

(7) Ready and/or Reset button.

(8) Be able to continuously read/write data files of 1 MB in size.

(9) Have a suggested file and directory structure in lieu of industry standard.

(10) Have status lights.

III.E.3. Micro-Computer Workstation

The computer / display should contain the minimum devices:

(1) High speed backplane bus with minimum of 6 expansion slots.

(2) SCSI interface.

(3) Keyboard and mouse or trackball.

(4) 5 MB RAM.

(4) 80 MByte hard disc with minimum 30 msec access time .

(5) Standard video interface card and monitor for program development.

III.E.4. Image Storage Cards

The image storage cards must be equivalent to Drexler Data Cards. Alternative digital data card methods will be studied and may be used if early tests show that this type of card cannot be imploved for faster read/write data rates or if unforseen problems arise.

III.E.5. Monitor

(1) One or Two 1024 x 768 x 8 video boards per prototype system. At a later time, 1024 x 1024 x 8 (or possibly 1280 x1024 x 8) video boards and monitors will be obtained.
(2) Recommended matching display monitors.
(3) 50-60 MHz, 2 db., EIA 343 or equiv. minimum

III.E.6. Optical Disc Device

Several 5.25" disc optical storage devices for small computer workstations are currently available with storage capacities of 200, 400, and 800 MBytes. A compact 800 MB disc could potentially store 2,000 to 8,000 compressed, archived images. This is a rapidly developing area and new devices with improved response times and storage will be available as well larger 14" discs which store several giga-bytes. These devices are optional and may be evaluated.
Minimum specifications:
(1) SCSI interface.
(2) 400 M Byte storage for development.
(3) Driver interface software for computer.

III.E.7. Development Software

To develop the ARMIS user application interface, design and build the electrical and mechanical interfaces to external communication links, and document development, application software which facilitates these processes will be required. These include:
(1) Word processing.
(2) Assembly Language compiler.
(3) Pascal and "C" compiler environments.
(4) Computer communications.
(5) System debugging tools.
(6) System hardware technical specifications.
(7) SCSI driver development tools.
(8) Image Processing software.

III.F. Preliminary Design Specifications

Several of the major components will be unique to the ARMIS and will be designed and built at the University. Other major components can be purchased and, after modifications, used directly. Thus, it may be possible to modify the Apple Macintosh II by the addition of image RAM boards and high resolution monitors to perform the functions of system display and control. The development of software for operation and image processing will be a major task. Conversion devices to couple the system SCSI to DIN/PACS will need to be designed and built. Interface circuits between DIN/PACS and various communication links are required and are not available commercially. Data compression circuits must match the computer and should be transparent to the user. The following paragraphs are tentative specifications for the purchase and modification of standard apparatus or for the development of special apparatus.

III.F.1. Computer / Display

The computer display assembly will be a self contained device which holds the computer, hard disc, image compression/expansion circuits, digital data card device, two monochrome monitors, and DIN/PACS interface sub-assembly. All devices will be easily attached for ease in maintenance and repair. There will be external connections for the keyboard and mouse and communications interface.

III.F.2. DIN / PACS

The DIN/PACS device will be a smart, i.e. computerized, device with 1 MB RAM (minimum), and physical connections for the SCSI bus and the DIN/PACS connector (ACR/NEMA #300-1985). It will be programmed to convert SCSI commands and data blocks to the DIN/PACS format and vice versa. It will be an internal sub-assembly of the system and physically located within the computer/display unit. Future development may possibly permit it to become an integral part of the host computer/controller.

III.F.3. Communications Interface

A communications device to connect the DIN/PACS interface and transmit DIN/PACS format data and command information to a long distance communications line will be designed. The current best option for the long distance option is a 56 Kbps digital telephone line, although the the development progress of ISDN will be monitered. This sub-assembly will be physically separate from the DIN/PACS interface and will be external to the computer/display. As additional communications hardware is developed by other vendors, it may also become effective to implement an auxillary device which interfaces at a point closer to the host computer.

III.F.4. Independent Viewer

The independent viewer will be a smaller, self contained unit. It will contain the digital data card reader, a single viewing monitor, as simple a mechanical assembly as possible, and several push buttons and or selector switchs as required. Options for adding additional viewing monitors will be required.

III.F.5. Data Compression Circuits

Data compression hardware will be developed with digital processing integrated circuit devices to faciltate image compression and restoration. Algorithms chosen for implementation will be evaluated by software simulations. The image array processing hardware will be internal to the computer/display.

III.F.6. Test Devices / Simulators

Development of each sub-assembly and continued testing as each piece is sequentially added into the final device will require several pieces of equipment. These include:
  (1) Logic analyzer
  (2) Digital signal processor development system.
  (3) Other as required.

III.G. Typical Operation of the System

Operation of the system is dependent upon the choice of both the selection of hardware and the software application program. While the physical presence of high technology computer hardware is suggestive of advanced state of the art capabilities and analysis, it is the application program which "glues" the separate devices into a unified system. The successful computerized system is managed by a program which not only permits the user to be highly effective and efficient in their manipulation and control over each separate device, but also responds in a timely, and coordinated manner. Building this program is highly dependent upon the host computer, the ease with which external devices permit full utilization of their capabilities, the versatility of the program development environment to exploit the capabilities, and finally, the inspiration and understanding of the programming staff. The programing development environment must also facilitate modification of the program based upon feedback and requests for changes by users.

To make program development possible, the intended operation of the equipment must be clear. This section states the operating procedure and tasks which are planned for its utilization so that desirable modifications can be indicated at an early time. This definition directs development of the program. For simplicity and reliability, the program will expect that only one operator will perform a single operation at a time. Future development may include limited multi-tasking of certain combinations of operations.

III.G.1. Enter Image into ARMIS

In general, the cassettes will be exposed in the same way as conventional film-screen cassettes. As radiographic image quality is quantum limited, there should be no significant change in the exposure requirements or technique factors used.

X-Ray Cassette Reader.

The cassette will be inserted into the cassette reader. Status of the reader will be displayed by appropriate indicator lights. When the reader memory is clear, the computer/ controller is ready and functional, and when there are no other system difficulties, pressing a start button will initiate reading the phosphor screen within the cassette at 1024x1024x12 bit resolution. The acquired image will be saved in local image memory RAM. The computer will determine when the complete image is in image RAM, and release the cassette so that it can be extracted and reused. The image would be transferred to the computer hard disc via the SCSI bus for temporary non-volatile storage (in case there would be momentary system power loss). The cassette reader memory would be cleared for reading another cassette.

Image Check on Host Computer.

From a "Display Image" pull down menu the technician will select the monitor to receive the display, and then select the 8 bit range out of 12 bits to display. The bit selection process permits the operator to set brightness, contrast and gradient. These have the effect of selecting the mid-point or average brightness, the mean gain near that point and the change of gain as a function of brightness, i.e., log or linear amplitude response. Although the original is a 12 bit image, the resulting image will subtend 8 bits. The image is checked for positioning (erase image and retake), and contrast (select another 8 bit range).

<u>Store Image I.</u>

When satisfactory, a "Store Image" pull down menu will permit selection of either:
(a) Open new patient folder on hard disc; enter new patient ID information or select from a previous patient data base file with appropriate modifications,
(b) Image is appended to an existing patient folder file on the hard disc.
(c) Close patient folder.
(d) Copy patient folder to digital data card (compress images); delete folder from hard disc.
(e) Copy patient folder to DIN/PACS communications channel; delete folder in 1 (2,..?) days.

III.G.2. Diagnostic Examination of Images

The image is reviewed, diagnosis entered, and image stored. This process may be repeated up to 50 mimages (or more).

<u>Image Recall.</u>

A que of the patient folders is displayed. A folder is selected and the most recent radiographs are displayed on the high resolution monitors. The "Display Image" pull down menu can specify which images are to be displayed on each of the monitors for diagnostic examination. Alternatively, the patient folder from a digital data card reader/writer, or the image from the DIN/PACS device, can be selected for review.

A "Special Functions" menu can be selected to define a region-of-interest, and perform image processing functions upon the selected region(s). The Display Image menu can be used to restore the original image.

<u>Entering Diagnosis.</u>

An "Annotate" pull down window will permit text or a grahic sketch to be incorporated directly onto the image using the mouse or possibly a trackball. The window can also open and display the diagnosis text file for review. The radiological evaluation can be added to the file, or a secretary could add it later.

<u>Store Image II.</u>

When complete, the "Store Image" pull down menu will select either:
(a) Close patient folder; save on hard disc for later additions to folder.
(b) Copy patient folder to new digital data card; delete folder from hard disc.
(c) Copy patient folder to DIN/PACS communications channel; delete folder in 1 (2,..?) days.
(d) Archive folder to optical disc (optional); delete folder from hard disc.

<u>Independent Viewer</u>

The independent viewer will permit the examination of the contents of a DDC without the capability of modifying the contents. The device is intended for use by the surgeon or referring physician. The independent viewer will resemble a small computer with a slot for a small disc and only three control keys: up/down/enter. Insertion of the DDC will cause the catalog of the DDC to be displayed. The up/down keys will move the cursor for selection and the enter key will cause that item to appear. The up/down keys can be used to scroll text. Pressing the return key while viewing an image or text will return the screen to the catalog. One of the catalog items, when selected, will return the DDC. The independent viewer will have the expander circuit to view compressed digital images.

<u>DDC Duplication</u>

Under most conditions, the DDC will replace films in the sense of accompanying the patient, transmittal to the referring physician, placement in a patient folder, etc.. One method of duplicating the DDC will be to place the original DDC in the card reader/writer and transfer the data one image at a time to the computer display. A blank card can then be placed in the card reader/writer and the contents of the computer display transferred back to the reader/writer for entry onto the new card. A computer subroutine will control the entire sequence so that the contents of an original card can not be altered during the process of duplication.

III.G.3.   Special Functions

Special functions which are to be included in ARMIS system are:
(a) Identification of a region of interest.
(b) Unsharp masking using kernel size "A"
(c) Unsharp masking using kernel size "B"
(d) Gamma Compression / Expansion
(e) Line Averaging   (1024 --> 512)
(f) Line Interpolation   (512 --> 1024)

> NOTE: Kernel size "A" and kernel size "B" refers to application of a spatial filter (which is a mathematical spatial convolution of prechosen size and value) upon the region of interest which will enhance detection of edges associated with pathology type "A" or pathology type "B".

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