COAL THICKNESS GAUGE USING RRAS TECHNIQUES

By

J. Derwin King
W. L. Rollwitz

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FINAL REPORT — PART II AND PART III
SwRI Project 15-4967
Contract No. NAS8-32606

for

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 38512

September 1980

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I. INTRODUCTION

A. The Problem

The goal of the work under Contract NAS8-32606 has been the investigation of electron magnetic resonance (EMR) as a sensing technique for use in measuring the thickness of the layer of coal overlying the rock substrate. The ultimate goal is the development of a thickness gauge which will be useable for control of mining machinery to maintain the coal thickness within selected bounds. To be most suited for this purpose, a sensor must be non-contacting, have a measurement range of 6-in. or more, and an accuracy of 1/2-in. or better. In addition, the sensor should be insensitive to variations in spacing between the sensor and the surface, the response speed should be adequate to permit use on continuous mining equipment, and the device should be rugged and otherwise suited for operation under conditions of high vibration, moisture, and dust. Finally, the sensor measurement must not be adversely affected by the natural effects occurring in coal such as impurities, voids, cracks, layering, high moisture level, and other conditions that are likely to be encountered.

The work reported herein has been concerned with the continued development of the technique of electron magnetic resonance (EMR) for use as the basis for the coal thickness gauge. This technique offers many potential advantages over other methods that have been previously considered and, if properly implemented, provides a very practical solution to this measurement problem. The basic feasibility of the EMR method was previously established and the results described in Part I of the Final Report of Contract NAS8-32606. The goal of the work under Part II and Part III of the contract has been the development of an experimental model to further demonstrate the utility of the EMR technique for coal thickness gauging.

B. Background

The investigation conducted under the initial phases of Contract No. NAS8-32606 and reported in Part I of the Final Report included extensive laboratory measurements of the EMR response characteristics of coal and rock samples taken from locations near and across a variety of interface regions. An evaluation of the technique based on an analytical model of a thickness gauging concept was also carried out. The concept was experimentally studied using laboratory apparatus to verify analytical results. All the results obtained in this work confirmed the basic feasibility of using EMR as the basis for the development of a practical coal thickness gauge. A limited investigation of the nuclear magnetic resonance (NMR) characteristics of coal and rock samples was also conducted and, while additional useful information on coal characteristics was obtained, this method was not found to be as promising for thickness gauging as EMR.

The laboratory investigation of coal and rock samples indicated that the coal-rock interface as well as the coal-air interface are both readily discernible on the basis of the large difference in amplitude of the EMR response obtained from coal compared to that from either air or rock. Positive results in these characteristics confirmed the existence of a measurable EMR effect that could be useful in defining the location of the front and back surfaces and thus the thickness of coal overlying a rock substrate.

To further establish the suitability of the EMR technique for coal thickness gauging, an analytical study was conducted. This analysis was based on the findings of the foregoing sample studies and a conceptual model of a low-frequency EMR system which was considered to be basically suitable for use in the coal gauging application. This study provided information on (1) the effects of selected system design parameters on the detection range and other characteristics, (2) the attainable resolution in defining the location of the front surface (coal-air interface) as well as the back (coal-rock) interface, and (3) the detection sensitivity. The results of this analysis indicate the excellent probability of achieving coal thickness measurement resolution on the order of 1.0-cm or less, a thickness gauging range of 15-cm or more, and noncontacting operation. The study also indicated that the detection head required for such results could be of acceptable size, weight, and power requirements and basically suitable for use in the mining environment.

The basic suitability of the EMR technique to coal thickness measurement was verified by assembly and use of an experimental laboratory apparatus to confirm the important characteristics of the analytical models. This apparatus demonstrated the feasibility of detecting the EMR response in coal samples at the low magnetic field intensity (and corresponding low resonant frequency ranges) assumed in the analytical model. Tests were conducted with the apparatus to determine the available sensitivity and the linewidth of the EMR resonance at magnetic field intensities of 57 and 142 Gauss, corresponding to those used in the analytical model, and in coal samples located a short distance outside the physical extent of the detection coil.

While the results obtained in the initial work demonstrated the basic feasibility of the EMR method, further work was needed to develop a model of the EMR coal thickness gauge which would be suitable for evaluation of the measurement range, gauging accuracy, speed, and other characteristics. The laboratory model used to evaluate the concept in the initial work made use of a continuous wave balanced bridge type detection configuration which, if carefully adjusted, yielded very sensitive results. However, the problems of maintaining such balance in the mining environment were felt to be sufficiently severe as to preclude the development of an instrumentation system based on this approach. Other means of implementing the EMR detection function were considered necessary in order to obtain sufficient stability to allow the method to be applied to the coal gauging application. Further work in the analytical study was also needed to determine optimum system design parameters and to evaluate the influence of operational conditions on the speed, range and accuracy of the thickness measurements. Based on these findings, an experimental model of the coal thickness gauge needed to be developed for further evaluation of the EMR technique under laboratory conditions and then in a mine where tests may be conducted under controlled conditions. This additional work has been the goal of the program effort under Part II and Part III of the Contract. During Part II, the use of transient EMR detection methods were explored while the work under Part III was directed toward investigation of a dual frequency technique for sensitive detection of the EMR response from coal.

C. Results of Part II

To overcome the problems of instrumentation stability inherent in continuous wave balanced bridge detectors, alternate approaches to implementing the EMR detection function were considered. On the basis of prior experience at Southwest Research Institute in the use of transient methods for nuclear magnetic resonance (NMR) detection, this technique appeared to offer promise for achieving the desired improvements in the most simple, readily achievable manner. Since prior use of transient EMR (for special materials having favorable characteristics) had been reported in the literature, it was known that this method could be used for electron magnetic resonance detection. Use of the transient method was therefore recommended and demonstration of the transient method of EMR detection was specified as a contract requirement. The initial work of the Part II contract effort was directed toward meeting this goal.

In the transient method a short burst of radiofrequency energy at the resonant frequency is impressed upon the sample located in a magnetic field. Following the end of the burst, the decaying response (free induction decay or FID) induced in the resonant electrons or nuclei may be detected. The decay time for nuclear magnetic resonance typically ranges from a few microseconds to tens of milliseconds. Similarly, the sample materials used for the transient EMR tests previously reported had decay time constants on the order of microseconds. However, for the electrons in coal, the decay is much more rapid being on the order of 30 to 40 nanoseconds and the detection process from the beginning of the transmitted burst of energy to the sensing of the EMR response must be completed in a comparably short time period if optimum sensitivity is to be obtained. Thus, to detect a response from coal, the transmitter output burst was required to be only a few nanoseconds long and the detection recovery time following the transmitter burst was similarly limited to such short time periods. Obtaining such operating conditions while maintaining sufficient sensitivity to achieve the detection range that is necessary for coal thickness gauging applications proved to be a very difficult problem to overcome.

The majority of the Part II effort was devoted to finding practical solutions to the above problems. Successful detection of the transient EMR signals from coal at a center frequency of approximately 400 MHz was achieved and demonstrated. However, due primarily to recovery time problems, the useful sensitivity was not considered to be adequate for the application of this method to coal thickness gauging. The possibility of using more intense magnetic fields to allow the operating frequency to be raised to 1 GHz or greater was considered as a means for overcoming the sensitivity limitation as well as a means for enhancing the possibility of achieving a faster recovery time. This was not attractive for the intended application, however, because of the increased size, weight, and power requirements for the production of such intense magnetic fields over large volumes external to the magnet structure. In view of this, an alternate approach to the design of the experimental apparatus was considered.

The alternate approach to EMR detection makes use of a dual-frequency concept which offers the advantage of stability and freedom from the effects of the environment which are characteristic of the transient method. It does, however, provide these advantages without the requirements for rapid recovery time and other limiting factors encountered in the transient method. This dual-frequency method, shown in Figure 1, was demonstrated in the laboratory along with its capability to detect coal samples at distances up to 15 cm (6-in.) from the sensing coil. The basic concept for using this method of EMR detection for coal thickness gauging was also developed but, due to the previously described and unanticipated technical difficulties, demonstration was not possible within the available contract funds for Part II. Development of a model of the coal thickness gauge based on this concept now needs to be carried out to allow experimental evaluation of this concept in the laboratory and then in a mine suitable for controlled tests. Results of the preliminary investigation appear to warrant the further development of the EMR technique for this purpose.

D. Results of Part III

Under Part III of the contract, an experimental model of the EMR coal thickness gauge based on the dual frequency detection concept was developed and evaluated in the laboratory. The basic design of the model was similar to that shown in Figure 1, but differed in a few details to make it suitable for detection of the EMR response from materials outside the physical extent of the apparatus as is required for in situ coal measurements and to provide the depth resolution required for thickness gauging. Both of these features are basically realized by use of a U-shaped electromagnet instead of the parallel plate type shown in Figure 1. The poles of this magnet were spaced approximately 12" center-to-center and were 10" wide. By control of the current to this electromagnet, a field of the intensity required for electron magnetic resonance at distances ranging from zero up to 8-inches from the pole faces could be produced. As is described in Section II.A, the gradient in the intensity of the field of the magnet provided the spatial resolution required to establish the distance at which EMR detection occurred. The coils for the lower radiofrequency (5 MHz) were also made concentric with poles of the magnet. Other changes included provisions for using the same UHF detection coil (or antenna) for both transmitting and receiving, a slight increase in both the radiofrequencies, and the use of a sweeper to cyclically vary the distance range at which ESR detection occurred. The experimental apparatus is pictured and described more fully in Appendix C.

Tests with the system showed the capability to detect the EMR response from a block of coal at distances up to 2-inches above the uppermost part of the U-shaped magnet and antenna assembly and to resolve both the upper and the lower coal-air interfaces to within 0.04 inches (1.0 mm). Thus, except for the range, the technique was shown to be suitable for non-contact coal thickness gauging.

In efforts to resolve the reasons for the detection range being less than the desired 8-inches, further tests were conducted with the block of coal, modulation coils and sensing antenna located in a homogeneous magnetic field. The apparatus was otherwise the same. Under these conditions, the block of coal (approximately 3" thick x 10" square) could be detected at a range of 8-inches from the antenna with a usable (2:1) signal-to-noise

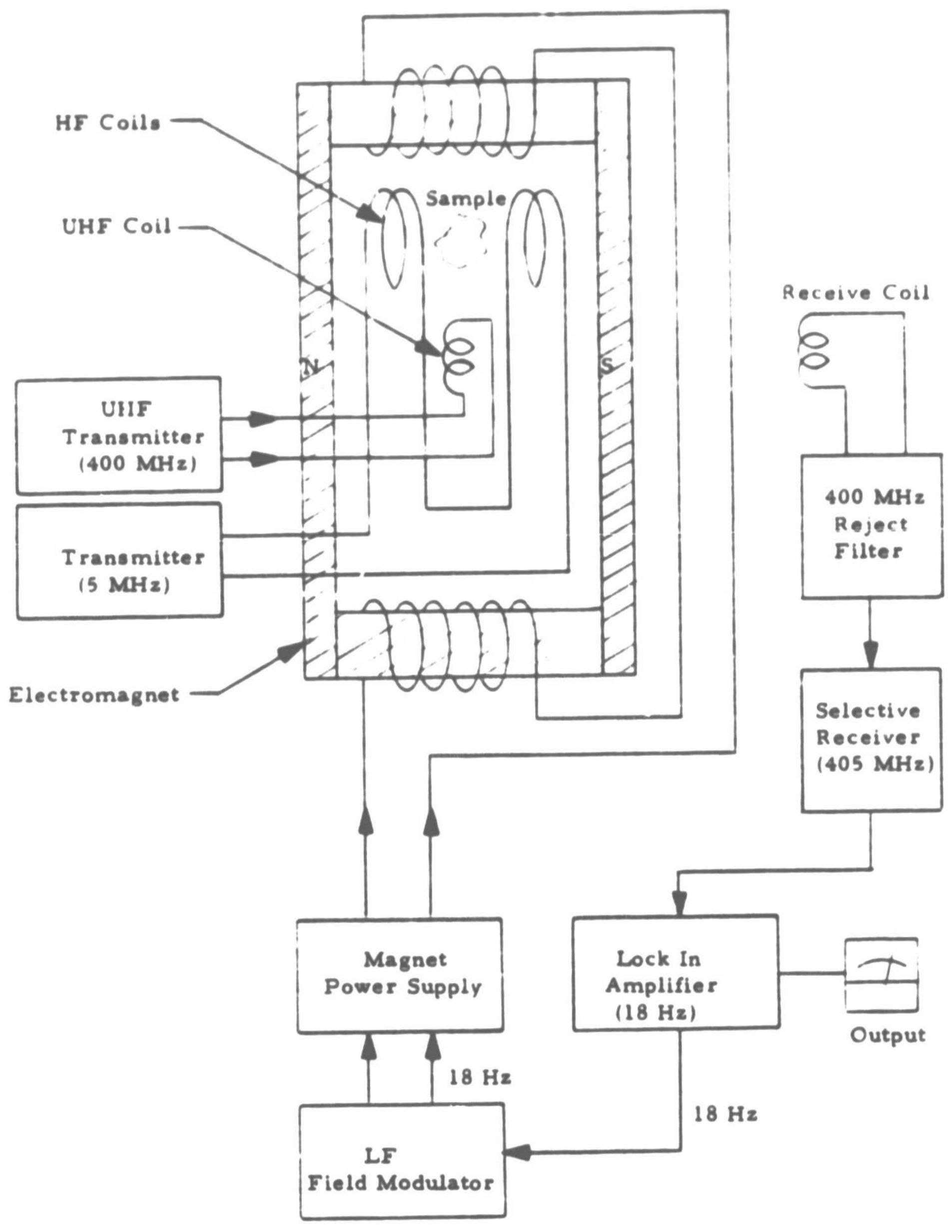

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FIGURE 1. BLOCK DIAGRAM OF DUAL-FREQUENCY EMR

ratio. This suggests that the primary reason for the inadequate detection range with the U-shaped magnet is the excessive gradient in the field which causes the effective volume of the coal within the appropriate field intensity band to be very small and the resultant EMR signal to be relatively weak. To overcome this problem and to otherwise optimize the detection sensitivity of the apparatus, the following steps are recommended:

1. Alter the magnet design to provide a lower field gradient at the measurement range. This will in-increase the effective volume of the coal which is sensed and thereby improve the signal-to-noise ratio. Even with this change, the thickness measurement resolution can still be made to be 0.5 inches or better.

2. Increase the magnetic field intensity and the associated EMR frequency to approximately twice that now being used. This will provide an S/N improvement of 4:1 and increase the measurement range by an estimated factor of 2:1.

3. Increase the modulation frequency to be more optimum for coal and proportionately increase the available modulation power.

4. Incorporate more advanced signal processing methods to better extract the desired signal from the noise.

With these changes, the detection range will be substantially increased and the probability of achieving the desired range of 8-inches is believed to be very high. This should allow the technique to be successfully used for in situ coal thickness gauging in mining applications.

II. SYSTEM DEVELOPMENT

A. Basic Concept

To make use of the EMR technique, the material under test must be both exposed to a magnetic field, H_o, and excited by an appropriate radiofrequency field, H_1. The detected response is also in the form of a radiofrequency signal having an amplitude proportional to the number of free electrons in the sample, a frequency proportional to the magnetic field intensity, and a form which is dependent upon the characteristics of the material and the detector throughput. The basic concept, illustrated in Figure 2, shows a sensor which uses a two-pole U-shaped magnet with a radiofrequency detection coil located between and in the plane of the two magnetic poles. The magnet structure produces the required magnetic bias field, H_o. The coil is connected to an appropriate transmitter, receiver and auxiliary apparatus to produce the required radiofrequency field and to detect the EMR response from material exposed to the field of the coil. The magnetic bias fields extend outward from the pole of the magnet and can interact with any unpaired electrons in the material located within the field to produce an EMR signal at frequency, f_o. The EMR frequency f_o is related to the magnetic field by

$$f_o = \gamma H_o / 2\pi \qquad (1)$$

where γ = gyromagnetic ratio of electrons = 17.61×10^6 for free electrons. H_o = particular value of magnetic field intensity required for resonance expressed in Gauss. For free electrons

$$f_o = 2.8 \times 10^6 H_o \qquad (2)$$

For example, if H_o is 100 Gauss the EMR frequency is 280 MHz.

For the U-shaped magnet of Figure 2, the field intensity H_o varies as functions of distance and direction from the plane of the poles. Thus, the EMR frequency for free electrons would vary as a function of location within the material, and, by adjusting the pole strength, the EMR frequency anywhere in the material can be made to be equal to any desired value f_o. Only those electrons located where the value of H_o is proper for resonance at f_o will be detected. By varying the pole strength over a selected range as a function of time, the field strength H_o required for EMR at frequency f_o can be made to sweep through the material as a function of time and permit detection of EMR in any region of the sample. At any one time the exact field intensity H_o required for resonance occurs along the line of constant flux density as illustrated in Figure 2. Since the EMR energy absorption curve has a finite width (linewidth), some response will be produced by electrons in the band of material extending on each side of the exact H_o line. Thus, the EMR thickness gauge concept is based on the use of a bias magnet which may be varied in intensity to cause EMR for a particular operating frequency f_o to sequentially occur over known distance ranges between the sensor unit and the depth within the coal layer.

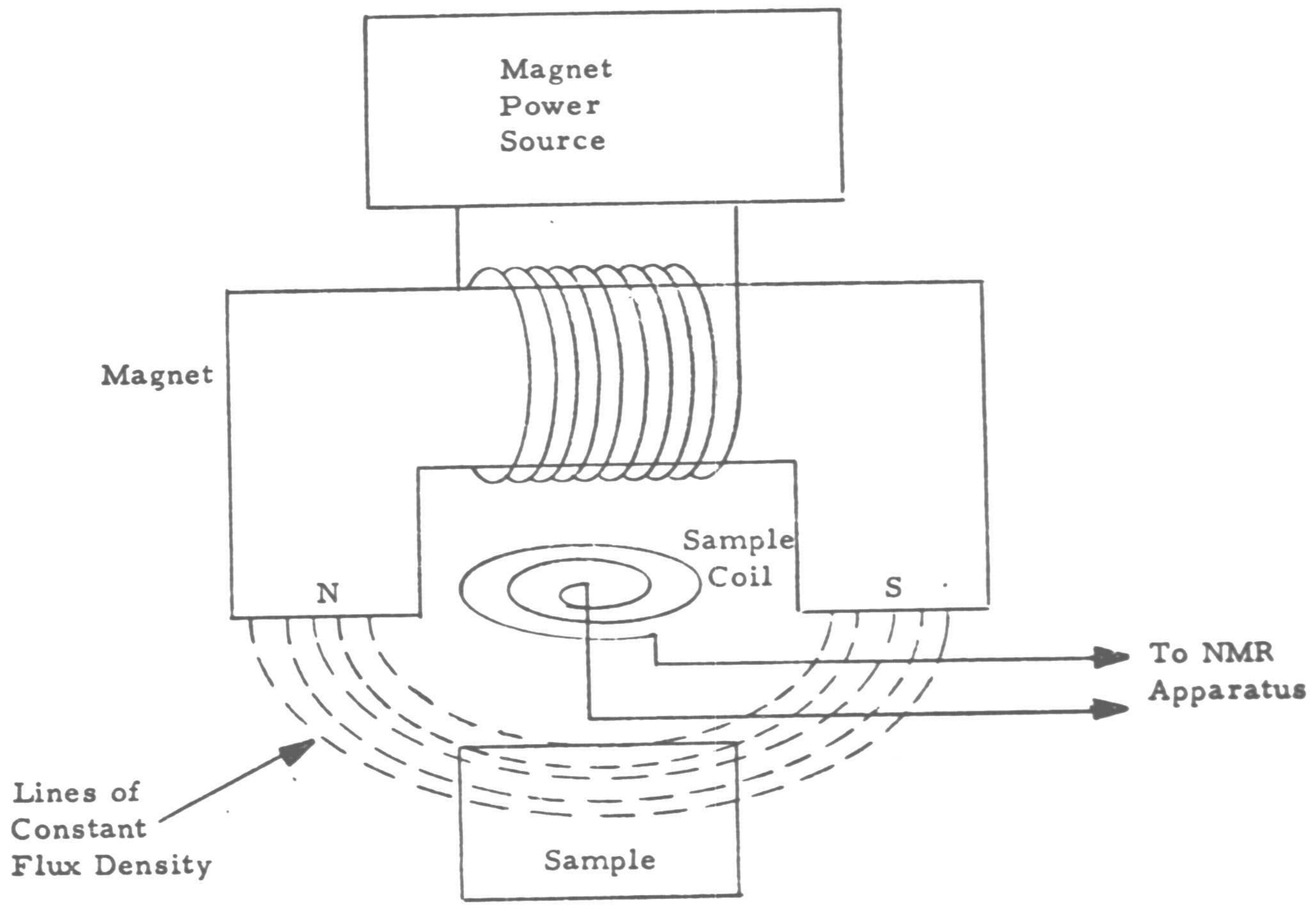

FIGURE 2. BASIC CONCEPT, COAL THICKNESS GAUGE

The radiofrequency coil and associated electronic circuitry detect an EMR response from the volume of material where the field intensity is within the EMR linewidth (about 5 to 8 Gauss in coal) of the resonance intensity H_o. Coal has been found to produce an EMR response of relatively large amplitude while rock exhibits only a very weak EMR characteristic and air produces no response. Thus, if the magnetic field intensity is such that H_o occurs within a region filled with coal then a relatively large EMR response will be obtained. Conversely, if the field is of such value that H_o occurs either in the rock or in the air then a small EMR response is obtained. If the magnetic field intensity is made to vary such as to cause the resonance value, H_o, to be swept over the air-coal interface and across the coal-rock interface there will be an abrupt change in the amplitude of the detected EMR responses at both of these points. This can be used to define the location of both the front surface of the coal and the coal-rock interface. Knowledge of the location of these points relative to the sensor allows the coal thickness to be measured.

Figure 3 shows a block diagram of the basic EMR system for thickness gauging. The transmitter provides the radiofrequency power to the sample coil to generate an electromagnetic field H_1. The receiver detects the EMR response produced by the free electrons in the coal and the display system provides an output in a form suitable for the intended application. The sequencer provides synchronization for the radiofrequency signal generated by the transmitter, the sweeping of the magnetic field, and the processing of the detected EMR signals. Several means of implementing the EMR detection function for this basic concept are available. Those that have been considered for use in the coal thickness gauge have included the balanced bridge continuous wave method, the transient method using both the free induction decay and the pulse-echo, and a dual-frequency method in which a resonant mixing occurs due in the free electrons as a result of the EMR characteristics. The continuous wave method was previously described and considered in the work described in Part I of the Final Report. Both the transient method and the dual-frequency method were considered and experimentally evaluated during the work on this portion of the program.

B. Transient System

1. General

The transient means of implementing the EMR detection offers the promise of providing high sensitivity and a means for overcoming the stability and proximity problem which are characteristics of the more commonly used balanced bridge (or equivalent) type steady-state designs. Such characteristics are required if the EMR technique is to be practical for use in a mining environment. While there are other possibilities for achieving the required system performance, the transient method appeared in the initial assessment to be advantageous and the preferred method based on simplicity and the expected performance. However, even though the transient approach had been widely used for nuclear magnetic resonance detection, it had only been applied to EMR in a very few cases. The lack of general use for EMR is not too surprising since the design requirements for such generally useful transient EMR call for the use of RF pulses of only a few nanoseconds duration and an appropriately wide

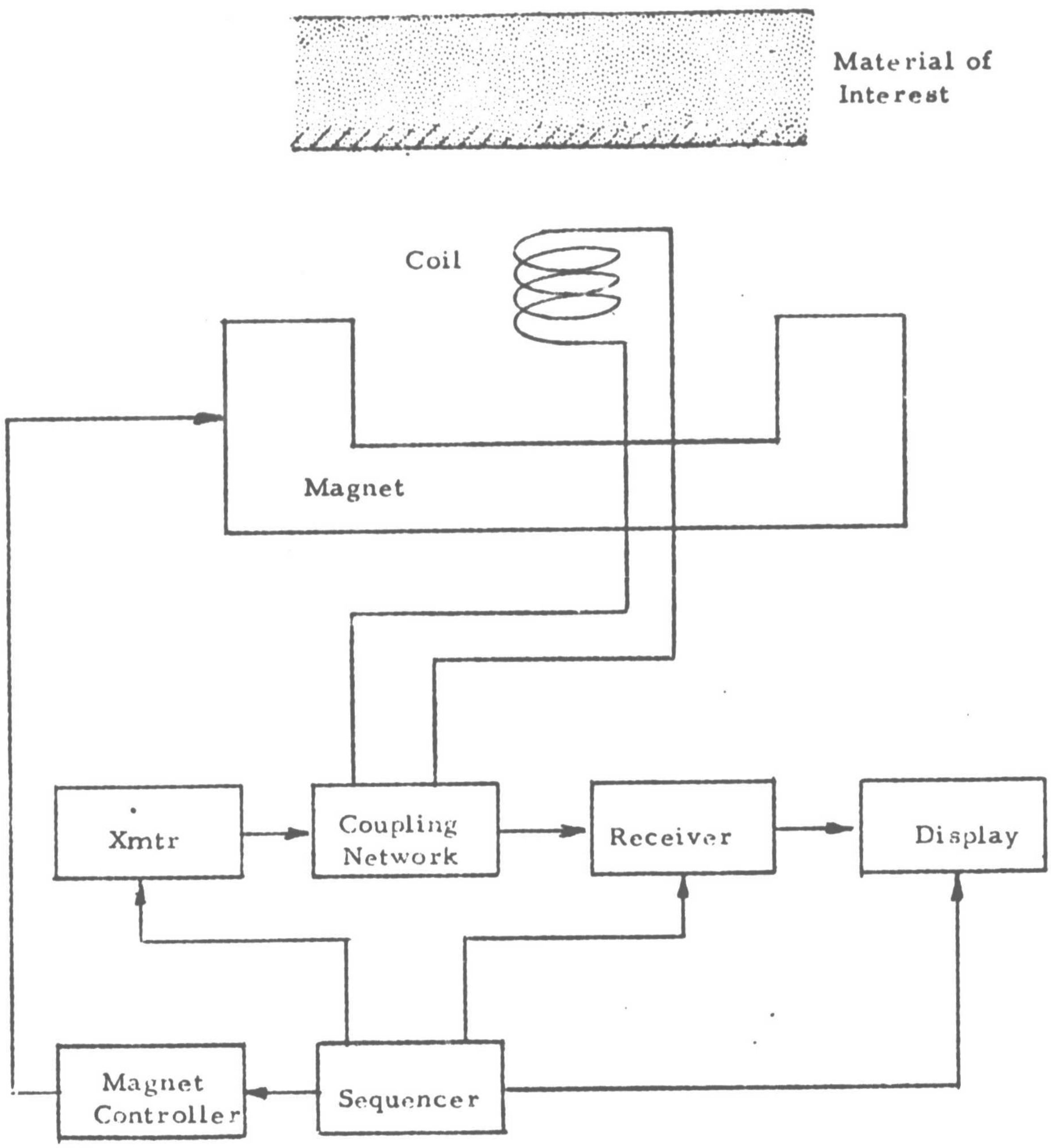

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FIGURE 3. BASIC ELECTRON MAGNETIC RESONANCE SYSTEM FOR THE COAL THICKNESS GAUGE

bandwidth in the coupling network, sample coil and receiver. Technology and devices to permit practical operation in the nanosecond regime have only recently been readily available. These were used in the initial contract effort to develop the transient method for EMR detection.

Several transient techniques are used in magnetic resonance work. The simpliest of these makes use of the free induction decay (FID) which follows a single transmitted burst of energy. This decaying response produced by the unpaired electrons in EMR and by selected nuclei for NMR is detected by the receiver and used to obtain information in regard to the EMR characteristics of the material in the sensing region of the apparatus. The spin-echo mode appeared to be more advantageous for EMR and was used as the basis for the transient system developed in this contract. With this method the sample is exposed to two short, closely spaced pulse bursts of radio-frequency energy having a frequency corresponding to magnetic resonance of the electron in the magnetic field. The EMR response obtained from the material is a short burst of RF which occurs at a time equal to the pulse-to-pulse spacing after the end of the second excitation pulse. This frequency of the response is at the resonant frequency of electrons in the magnetic field and is typically of a 20 to 30 nanoseconds in duration and occurs at similar time after the second transmitter burst.

A block diagram of the basic transient EMR system is shown in Figure 4. Based on several considerations and tradeoffs, a nominal operating frequency of 400 MHz was determined to be most optimum and was selected for use in the thickness gauge. These considerations included: (1) the low attenuation of electromagnetic waves of that frequency in coal; (2) the requirements for a magnet of reasonable size, weight, and power consumption; (3) adequate sensitivity; and (4) the requirement to have the time period for one cycle of the wave to be very short compared to the EMR decay time constant. Use of higher frequencies would yield improved sensitivity but would require larger magnetic structures to produce the higher field intensities. In addition, as the frequency of the waves is increased the attenuation of the radiofrequency waves in the coal becomes larger. Thus, a frequency in the vicinity of 400 MHz appeared to be optimum for this application. In the system shown in Figure 4, therefore, the radiofrequency generator provides a pulsed output centered on a frequency of 400 MHz. The output format may be either in the form of a single pulse for FID or a double pulse sequence to provide a spin-echo mode of operation. The length of each pulse is typically in the range of 25 to 40 nanoseconds and spacing between pulses is in the same time range. For maximum sensitivity, the repetition rate should be as large as possible but it is limited by the recovery time constant T_1 of the electrons in coal and typically may be on the order of 1 MHz or greater. For best sensitivity, the peak power in the output pulses from the RF generator should be made to be the specific value that causes a 90^o precession of the electron spin axis in the magnetic field. The requirements for this condition are discussed later but in practice it is very difficult to achieve a sufficiently high power level along with an adequately fast recovery time.

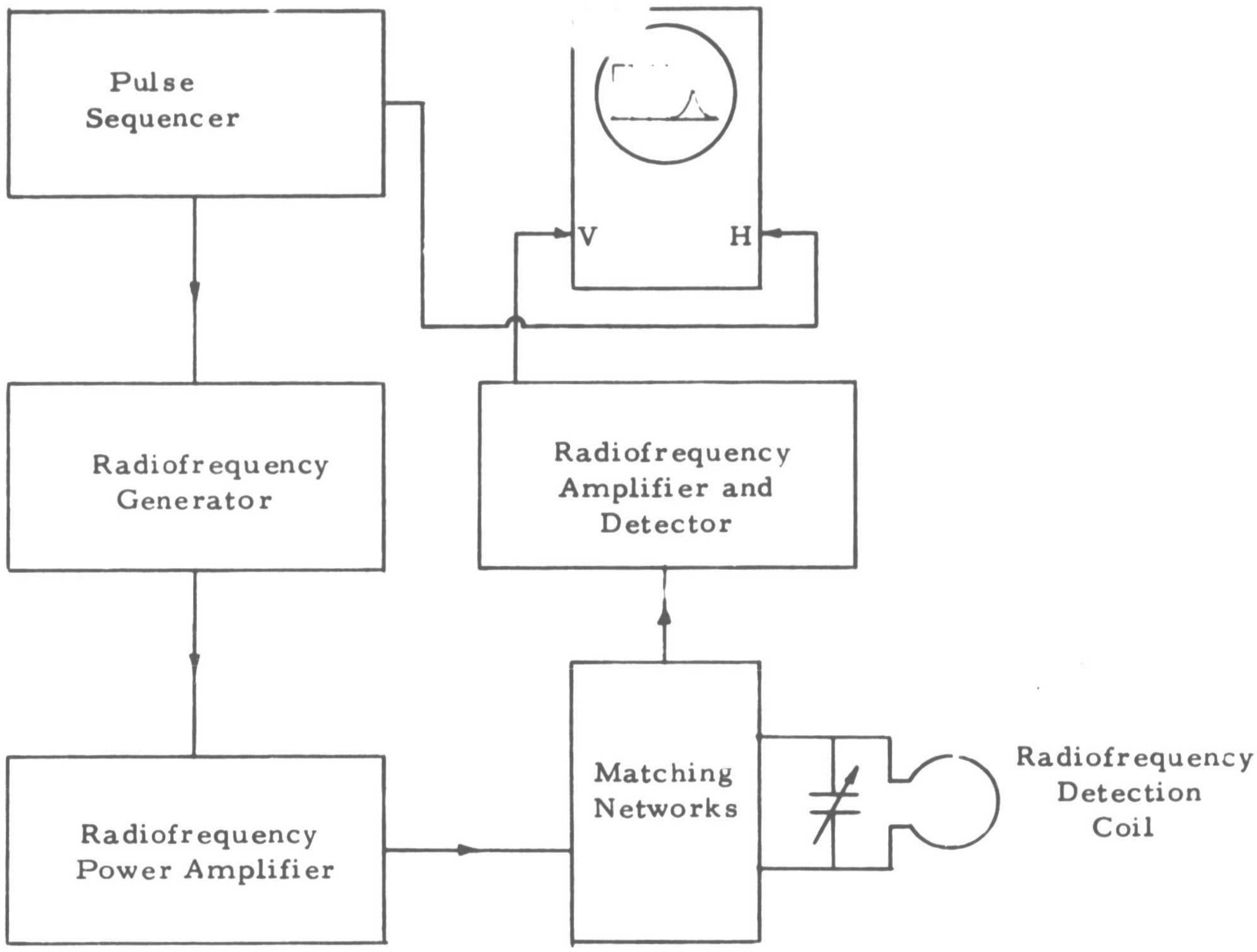

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FIGURE 4. BLOCK DIAGRAM OF THE TRANSIENT ELECTRON MAGNETIC RESONANCE DETECTOR

2. Literature Survey

To aid in assessment of the probability of successfully achieving EMR detection of coal with a transient system and also to aid in determining the system design parameters, a literature survey of the technical and scientific journals was conducted. The computer-assisted literature search spanned appropriate scientific and technical journals and reports from 1964 to the present. Combinations of key words including electron paramagnetic resonance and its variations, transient or relaxation, and spectrometer or coal were examined and printed by the computer. Three-hundred and seventy abstracts fitted the key words of the search. Of these abstracts, 6 contained information pertinent to the use of transient methods for measuring coal. From these references a few other papers published prior to 1965 were located.

While the basic ideas of transient EMR have been experimentally confirmed and reported in the literature, the primary use has been limited to certain cross-relaxation studies. Studies of isolated free radicals such as Na^{+}ions in ammonia solutions have been conducted over a wide range of frequencies from 1 .4 MHz (corresponding to 6.04 Gauss)[1] to the X- and higher microwave regions.[2-3] These radicals have relaxation times in the microsecond range making them accessible to pulsed NMR technology at the lower frequencies. The advanced work is mostly confined to the microwave range and to the electron spin to nuclear spin cross-relaxation studies. However, basic information sought about irradiating power, recovery rates, and spin densities were found.[2] A few other references contained technical information on the detection apparatus. The relaxation rates of the naturally occurring free radicals are very rapid at standard temperatures being on the order of 40 nanoseconds (40×10^{-9} sec.). This affords rapid probing rates but also makes stringent demands upon the equipment. Two further items of interest were found. First, the sensitivity in terms of spin density of the transient method has been found to be excellent[2], and secondly, the requirement of the irradiating magnetic field being greater than the natural resonant range of the sample is not as rigid if longer pulse lengths are used.[2] This does lead to some signal deterioration, however. Thus, while transient EMR had been previously reported in the literature, most of the studies have been concerned with electrons having much longer relaxation times than those typical of coal. In addition, most of the work has been carried out in the microwave frequency range where the required rapid recovery of the apparatus following the transmitter burst is more readily achieved.

3. System Analysis

Modeling analysis calculations were performed for a coal detecting EMR system to determine the radiofrequency power required for optimum performance, the detector bandwidth requirements and the sensitivity of the system in terms of spin density, and to determine the variation in sensitivity as a function of sensor-to-sample distance. One of the prime requirements in the design of a transient EMR system is the determination of the width of the pulse burst to be transmitted and (for the spin-echo mode) the pulse-to-pulse spacing. These requirements are set by the EMR response time constants in the material to be detected. These, in turn, are controlled by the spin-spin relaxation time T_2 which is characteristic of the material to be studied.

Another system design requirement which must be considered is the repetition rate to be utilized. It is desirable from considerations of minimum detection time, maximum signal-to-noise ratio for this to be as high as possible. The maximum rate that can be effectively utilized, however, is set by the spin-lattice relaxation time T_1 which is also characteristic of the particular material. In EMR, T_1 is slightly larger than T_2 but calculations to determine the system specification will be of sufficient accuracy if T_1 is assumed to be equal to T_2.

The time constant T_2 is inversely proportional to the linewidth (in equivalent frequency) of the EMR response. Information from the literature and that from studies conducted at SwRI shows that the linewidths for coals range from 8 Gauss for subbituminous types to as narrow as 1 Gauss for anthracite. The corresponding values of T_2 for these two extremes are 14×10^{-9} and 114×10^{-9} seconds, respectively. The soft coal measured earlier in this program showed typical linewidth on the order of 5 to 6 Gauss which corresponds to T_2 values in the range of 19 to 23 nanoseconds.

For maximum EMR response, the burst of transmitter excitation energy and the spacing between bursts must be short compared to T_2. In practice this requirement can be relaxed somewhat, but if time periods are much greater than T_2, the amplitude of the EMR echo response is seriously degraded. As another consideration, for maximum EMR response, the product of the RF pulse width τ and the intensity of the RF magnetic field H_1 should be equal to a value that will cause the spin axis of any free electron exposed to the energetic burst to precess through an angle 90^o relative to the fixed magnetic field, H_o. For EMR the product τH_1 for the so called "90^o pulse" is 88×10^{-9}. Thus, if the pulse width is 22×10^{-9} seconds (22 nanoseconds) the RF magnetic field intensity must be 4 Gauss (peak) if the EMR response amplitude is to be maximized. If the product τH_1 is less than that required for a 90^o pulse, the amplitude of EMR response decreases as a function of $\sin\theta$ where θ is $(\tau H_1/88)(90^o)$. For example, if the τH_1 product is 44 then the effective precessional angle produced by the pulse is 45^o and the amplitude of the EMR response is 0.707 of what would be obtained if a 90^o pulse were used. These factors were considered in the design of the experimental system.

The EMR detection circuits are gated to allow signal samples to be collected at the peak of the EMR echo response. Subsequent samples are integrated to produce the final output. Consequently, the detected signal-to-noise ratio is improved as the number of samples which are collected within a specified operation period is increased. To maximize this feature, the repetition rate should be made as high as possible within the limitations imposed by T_1 of the material. Since T_1 for coal will be a maximum of about 100 nanoseconds, the pulse (and sample) repetition rate as high as 1 MHz appears useful and even higher repetition rates could prove advantageous.

Using the foregoing relaxation times for coal, the system bandwidth requirements were determined to be on the order of 60 MHz. From considerations of the propagation characteristics of electron magnetic waves in coal as well as the limitations on the size, weight, and power requirements for the magnet, an operating frequency of 400 MHz was selected. With this choice a system Q of approximately 6 was determined as being optimum. This is the maximum Q that should be utilized in the sample coil circuitry. Bandwidths equivalent to the calculated system bandwidths (60 MHz) are required throughout the system where there are limitations affected by this parameter. These components include the transmitter, receiver, and coupling circuits between the transmitter, receiver and sample coil.

The transmitter power required to produce the necessary H_1 field depends upon the range to be covered, and the effective size of the sampling volume. Achievement of the optimum level of 4 Gauss as calculated above would require large amounts of peak transmitter power (tens of kilowatts) if distances on the order of several tens of centimeters are to be covered. The exact amount of power required can be determined once the size, configuration and Q of the sample coil are specified. For this purpose, use can be made of the usual formulas for current flowing in loops or straight wire segments. To produce a field of 4 Gauss at a distance of 25 cm from a 5-cm-diameter coil having a Q of 6 requires a transmitter output peak pulse power on the order of 250 kW but an average power of only 250 watts. Generation of such large peak power and controlling it to be effectively turned on and off in the nanosecond time regime is a very difficult undertaking. The approach utilized in the program was to provide a transmitter output of much more modest levels and accept the lower sensitivity which resulted from this limitation.

The amplitude of the EMR signal to be expected from coal as a function of distance away from the sample coil was also determined. Based on an effective coal detection resolution (as determined by the gradient in the magnetic field) of 1.2 cm (0.5-in.) and a coil 5-cm (2-in.) in diameter, the calculated EMR signal amplitude is as plotted in Figure 5. As may be seen, the signal level ranges from 2.5 mV for coal centered at a distance of 1-in. (2.5 cm) from the sample coil down to 200 μV for coal at a distance of 10-in. (25 cm) from the sample coil. Thus, adequate system sensitivity to detect and measure the thickness of coal over similar (0 to 10-in.) distance ranges should be obtained provided the optimum radiofrequency field intensity is maintained. Such optimum field conditions were assumed in the calculations. On the basis of this analysis and considerations, the possibility of the transient method being suitable for EMR detection of coal over the distance ranges appeared to be excellent. The primary problem appearing to be that of obtaining sufficiently rapid recovery characteristics to permit detection of the EMR signal within a few nanoseconds after the transmitter bursts. An experimental model based on these considerations was constructed and evaluated.

4. Experimental Systems

The transient EMR systems developed during this program were based on the block diagram shown in Figure 4. A number of variations in the design details were evolved during the course of the work in attempts to overcome the problems and limitations which were encountered. These variations are described in Appendix A.

The radiofrequency generator produced either one or two pulse bursts of 400 MHz signal (each of 25-40 nanoseconds duration and spacing) which was amplified by the radiofrequency amplifiers to a level of 10 watts

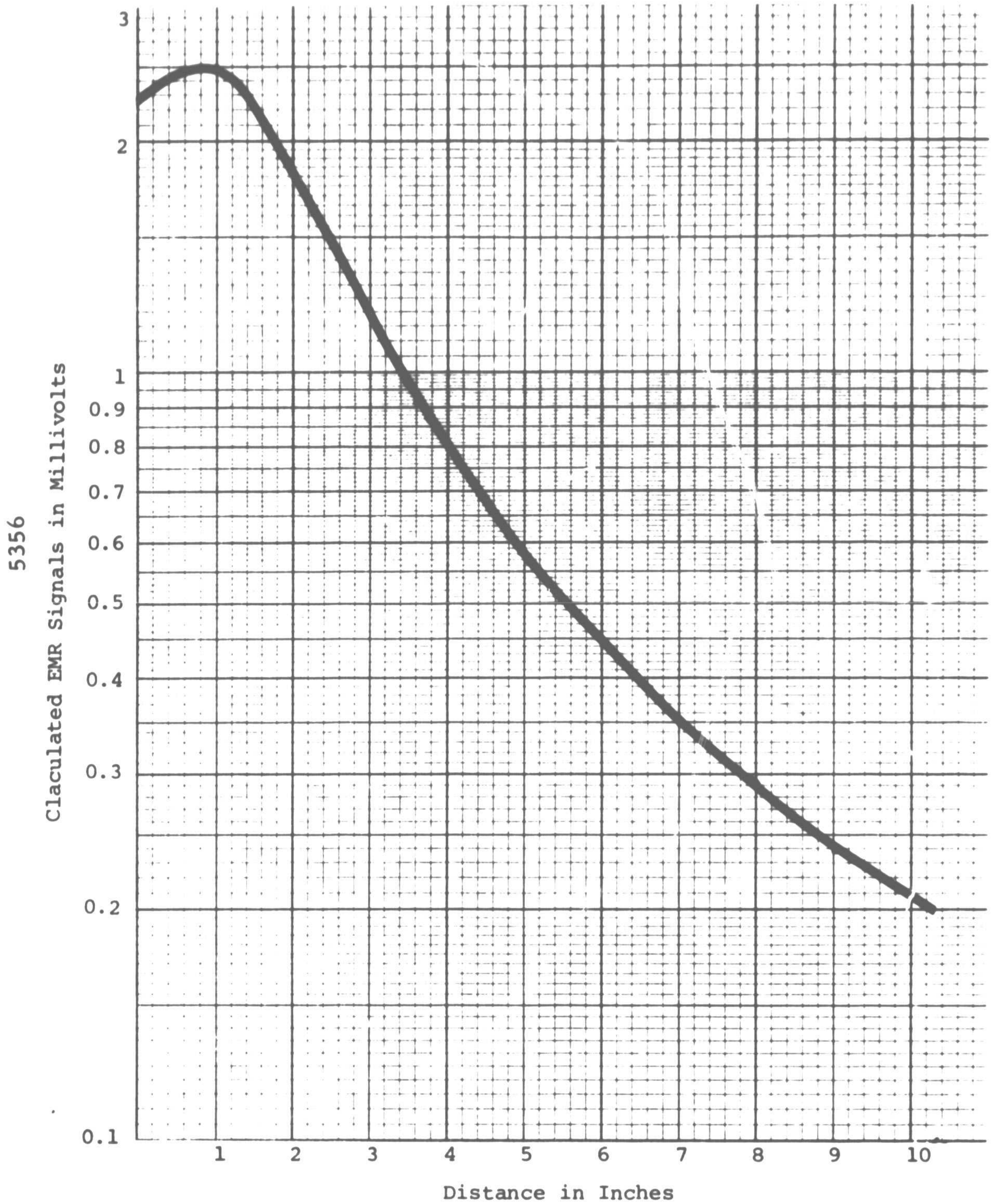

FIGURE 5. CALCULATED ELECTRON MAGNETIC RESONANCE SIGNAL AS A FUNCTION OF DISTANCE FROM THE RADIOFREQUENCY COIL.

peak and applied through a matching network to the sample coil. This coil was located in close proximity to the coal or other material being studied. The output from the matching network was applied to the receiver which boosted the signal amplitude and provided a detected output to an oscilloscope or recorder. The pulse sequencer controls the generator and timing of the pulses used to control the transmitter output as well as the sampling and processing of the signal in the receiver.

A block diagram of the complete transient ESR system as finally developed is shown in Appendix A (Figure A-3). Detailed circuit diagrams are also included in Appendix A. This system was used to demonstrate the detection of transient EMR signals in the laboratory using small samples of diphenylpicralhydrazil (DPPH) in the sample coil. The previous work had shown the amplitude of the EMR response from an equal quantity of coal to be 200 to 300 times weaker than that of DPPH and the linewidth to be greater by a factor of about 3 to 4. These two characteristics made DPPH considerably easier to detect than coal but use of this material was convenient in that it allowed the signal to be obtained under marginal conditions and used as an aid in adjusting the apparatus for optimum performance. These results are still considered to be very significant in that it was the first time that transient EMR detection had been demonstrated with any materials at such low frequencies (400 MHz). However, after a considerable effort to optimize the results, the performance of this system could still not be made adequate for the intended application. The major limitation which restricted further improvement was that of obtaining adequate separation of the desired EMR signal from the pulsed transmitter signal. This resulted in the EMR signal being mixed with the residual transmitter signal and greatly limited the available sensitivity. Small changes in the tuning of the sample coil and variations in the position of material in proximity to the sample coil greatly affected the phase and amplitude of this residual transmitter signal. Means for minimizing this effect were investigated and incorporated in the model, but since further improvements did not appear to be forthcoming, an alternate transient approach used in a self-detecting pulsed oscillator was evaluated. Details of the circuits and evaluation are included in Appendix B.

With the optimized gated oscillator system as shown in Figure B-2, signals could be detected from DPPH at ranges up to about 2-inches from the sensing coil. It was also found possible to detect a usable transient EMR response from powdered coal located within the sensing coil but the response from a block of coal (about 3" x 5" x 1") (7.5 cm x 12.5 cm x 2.5 cm) located adjacent to the coil was very weak.

The foregoing results indicated the need for a very significant improvement in system sensitivity if coal were to be detected at distances up to several inches away from the apparatus. Such capability is essential for coal thickness gauging over similar distances. Except for the possibilities of going to a much higher frequency, the prospects for achieving improved sensitivity with the transient EMR apparatus were not encouraging.

In an effort to provide a better solution to the problem, an alternate means of implementing the EMR detection was investigated for this application. This dual frequency method, as will be described in a following Section (C), produced very encouraging results in initial tests.

5. Experimental Results

As mentioned in the foregoing section, considerable difficulties were encountered in producing a sufficiently clean pulse burst from the radiofrequency transmitters. Figure 6 illustrates some of the results achieved in this regard. In Figure 6 a the output from the intermediate power amplifier is shown. This exposure was made with a high-frequency sampling type scope with the result that while the envelope of the wave is clearly indicated, the individual cycles are not seen because of the lack of synchronization. However, the envelope exhibits a very clear characteristic of the type generally desired. For normal purposes, this would be more than adequate but for detection of the transient EMR response which must occur within a few tens of nanoseconds after the end of the pulse burst, the hangover signal is still significant and may be readily seen if the gain of the oscilloscope is increased to many times that utilized for Figure 6 a. These low-level signals which follow the main bursts are insignificant for most purposes but are frequently many times the amplitude of the transient EMR signal even with a relatively clean wave shape such as that shown in the picture. Figure 6b and Figure 6c show output signals obtained from the radiofrequency power amplifier when driven by the wave shape such as in Figure 6 a from the intermediate power stage. These pictures were made with a normal high-frequency oscilloscope and the wave form of the individual cycles is readily apparent as well as is the shape of the envelope. Figure 6 b was made with a very short pulse input typically on the order of 10 nanoseconds. The major part of the output burst is also of a similar duration. However, the rounded edges on both the leading and trailing edges may be seen, and more importantly, the hang-on signal having a nominal frequency of 160 MHz which follows this burst is also readily apparent. This signal caused severe interference to the detection of EMR signals. Figure 6c shows the output under similar conditions except that the input pulse burst is longer, and consequently, the output pulse obtained from the power amplifier is significantly greater in length. The spurious output following the end of the transmitter burst, however, is still apparent and still of very large amplitude. Considerable efforts were directed toward overcoming this problem but a completely satisfactory solution was never developed. The residual signal is apparently characteristic of the modular amplifier that was employed and results from internal resonances in that device. A filter with sufficient selectivity to reject these components restricted the bandwidth and caused additional problems in ringing at other frequencies.

Figure 7 shows transient EMR detector signals. In Figure 7a, the upper trace is the output of the video amplifier following the double balanced mixer. This shows the characteristic response that was obtained with no sample in the sample coil. The wave shape is due to internal limiting and saturation resulting from the effects of the overloading transmitter bursts appearing at the input. The lower trace on Figure 7 a shows the double balanced

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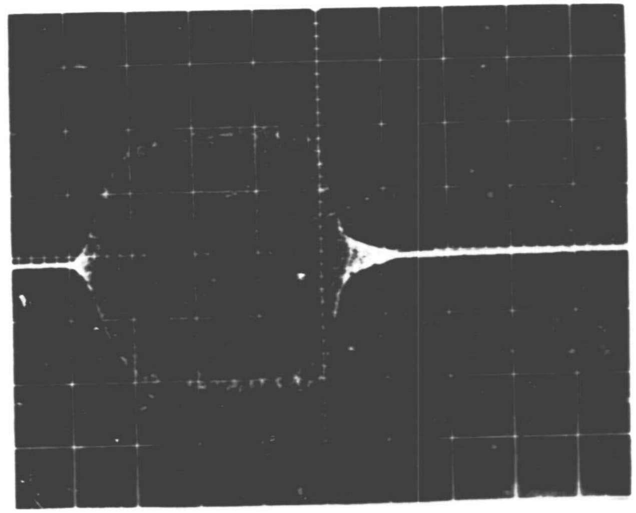
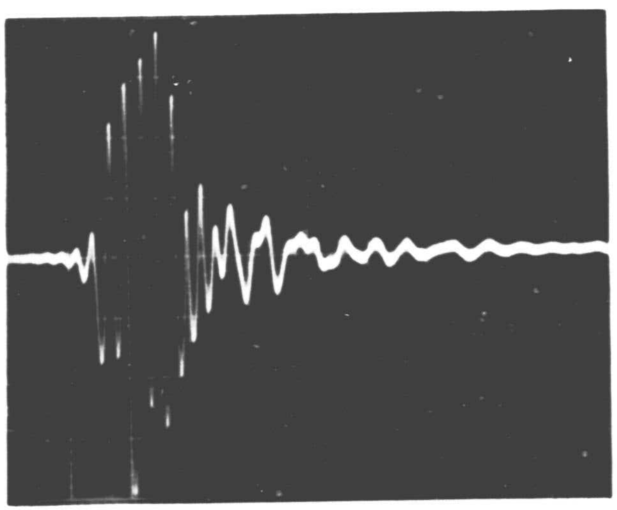
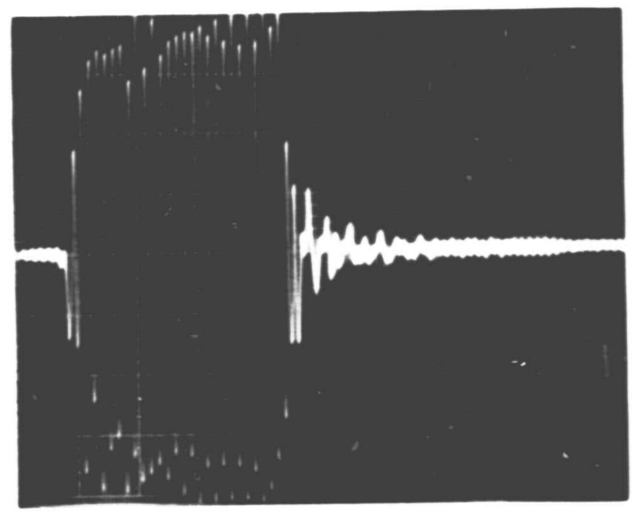


a. Intermediate power amplifier output pulse Vert = 0.1V/cm

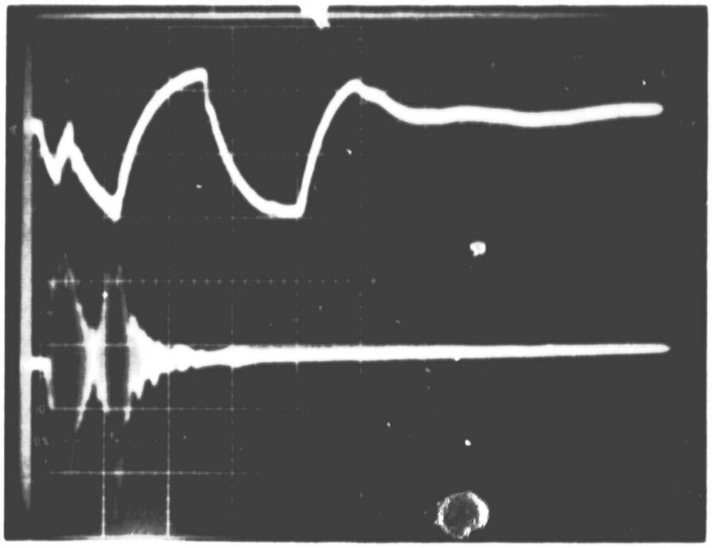


b. Power amplifier output with short pulse Vert = 5V/cm

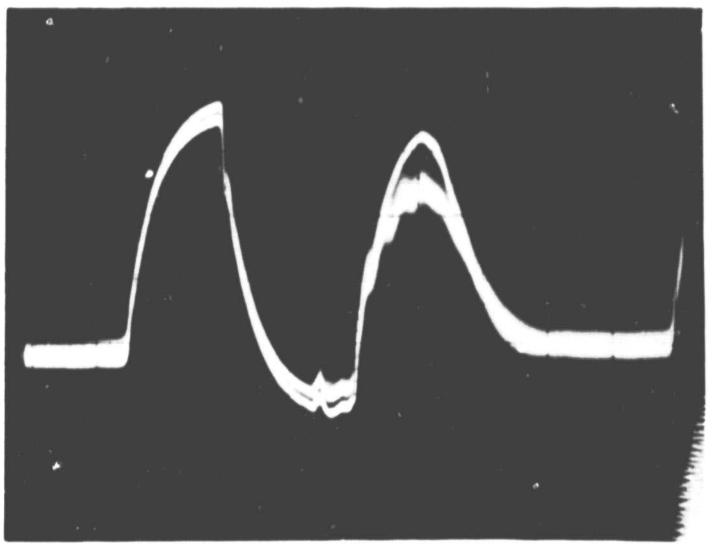


c. Power amplifier output with longer pulse Vert = 5V/cm

FIGURE 6. TRANSIENT TRANSMITTER OUTPUT SIGNALS



a. Upper trace - Video amplifier output
Lower trace - Double balanced modulator input



b. Video amplifier output for two magnetic field intensities showing detection of transient EMR response from DPPH

FIGURE 7. TRANSIENT EMR DETECTOR SIGNALS

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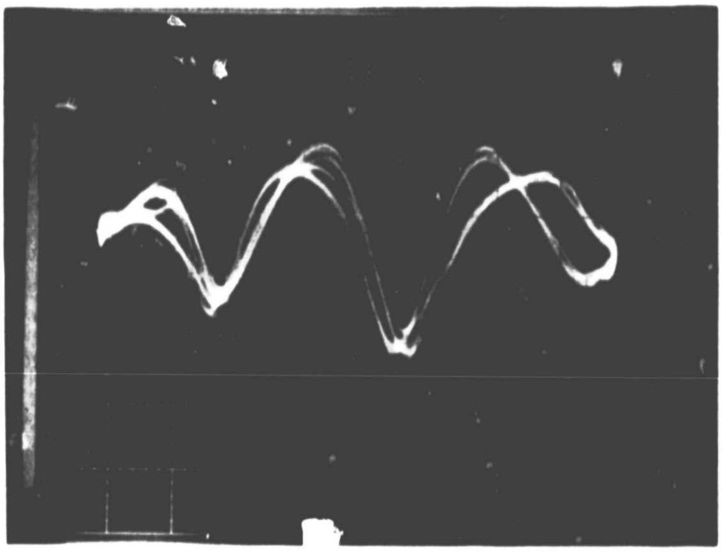

Horizontal - 9 Hz Sinusoidal Sweep
Vertical - 0.2V/cm

FIGURE 8. OUTPUT FROM GATED OSCILLATOR-DETECTOR SHOWING DETECTION OF DPPH BY SWEEPING MAGNETIC FIELD THROUGH RESONANCE

modulator input signal which was obtained from the coupling bridge circuit. The pulse burst shown is the residual transmitter signal caused by imcomplete nulling of the bridge output under the transient conditions. Figure 7b shows two superimposed traces. Each of these was obtained at the output of the video amplifier at different magnetic field levels. One trace, the larger amplitude trace, was made at a magnetic field intensity of 143 Gauss at which point the resonance conditions for electronn in DPPH was established. The smaller amplitude trace was made at a magnetic field intensity of 141 Gauss. The difference between the two traces represents the effect of the transient EMR signal obtained from DPPH superimposed on top of the residual circuit signal that was present with or without a sample. The difference between the two, however, does show a substantial transient EMR response which is well above normal circuit noise. However, in practice it was difficult to use since it was so obscured by being smaller in amplitude than the residual circuit signals.

Figure 8 shows the amplified output from the gated oscillator-detector obtained with a sample of DPPH. For this exposure, the circuit was operated at a quench frequency of 4.2 MHz and the circuit which used a U-310 FET followed by a 2N6550 low-noise amplifier was operating at a frequency of 400 MHz. For this picture, the magnetic field was being swept at a rate of 9 Hz about the nominal resonance level of magnetic field intensity. The larger negative peak is the central resonance of the EMR response while on each side, the smaller peaks are the sidebands spaced at the quench frequency of 4.2 MHz on either side of the EMR resonance. The total magnetic field sweep range in this case was approximately 4 Gauss and was of sinusoidal form. The oscilloscope horizontal was swept in synchronism with this magnetic field sweep. The result that subsequent sweeps are reproduced nearly on top of each other but signals were very good. With this system, the EMR response from DPPH could be detected when the sample was at a distance of 2-in. from the coil. The EMR response from a block of coal (7.5 cm x 12.5 cm x 2.5 cm) located adjacent to the coil could also be detected, but the response in this case was very weak. This was accomplished using a synchronous phase-lock detector as previously described and direct observation on the oscilloscope in real-time was not possible.

C. Dual-Frequency System

1. General

In the development of sensitive magnetic resonance detection apparatus, one of the major problems is to excite the electrons (or nuclei) with a sufficient transmitter power to obtain optimum results while at the same time maintaining a maximum level of sensitivity in the receiver. Since the transmitter signal level is normally many orders of magnitude greater than that of the spin resonance signal to be detected, steps must be taken to prevent the transmitter signal from appearing at the receiver input where overloading would almost certainly occur. In early continuous wave systems this was achieved by operating a detection coil in a balanced bridge circuit such that the transmitter energy appeared at the sample coil but was "balanced" out or "nulled" into a low-level at the receiver input. The bridge, however, allowed the EMR signal from a sample to reach this receiver be acceptable. With these encouraging results the system transmitter was modified to use the gated MECL oscillator and one of the double balance mixers was used as a passive doubler to convert the 200 MHz output from the gated oscillator to 400 MHz. A pulse envelope of acceptable shape characteristics was obtained; however, problems were encountered with the level of the fundamental (200 MHz) and third harmonic component (600 MHz) in the output. Attempts to reduce the amplitude of these spurious components by filtering were not fully effective.

In addition to the above mentioned problem with harmonic content, a troublesome spurious signal was found to be present in the output of the modular 10W power amplifier. This signal persisted for a period of 40 nanoseconds following the second pulse burst and caused severe interference to the EMR detection. The frequency of this unwanted signal was about 160 MHz and it appeared to be generated by one of the (apparently undamped) resonant circuits in the sealed amplifier module. Efforts to correct this problem by filtering and optimization of the operating conditions resulted in a considerable improvement, but were not completely successful.

In the preliminary evaluation of the entire EMR detection system it was found, as had been expected, that the receiver input was overloaded by the transmitter burst. However, it was also discovered that the overload recovery time of the modular integrated circuit amplifiers used in the receiver were excessive and that this characteristic could not be substantially changed by external means. To overcome the problem, the input circuits were revised to use discrete components and a low noise, wide dynamic range E-310 FET in a circuit that offered reduced recovery time and increased freedom from overload. Active gating and damping was also incorporated in the circuit to further improve the receiver, but adequate results could not be obtained. The breadboard system was then modified to the homodyne receiver design. The homodyne offered the advantages of an inherently wide dynamic range and a tolerance for high levels of on-frequency signals. These features reduced the need for a high degree of protection from the transmitter overload and greatly reduced the requirements for complete elimination of leakage from the transmitter between pulse bursts. This receiver with the gated crystal controlled transmitter proved to be a successful combination and allowed transient EMR signals to be detected in diphenylpicralhydrazil (DPPH).

Several means for coupling the transmitter and the receiver to the sample coil were investigated to achieve improved results. Problems were encountered in obtaining adequate efficiency to allow good signal transfer while at the same time obtaining good isolation between the transmitter and the receiver over a wide bandwidth. The best results were obtained through the use of an Anzac wideband power divider type hybrid junction.

A block diagram of the complete transient ESR system as finally developed is shown in Figure A-3. This system used the transmitter of Figure A-2. Further transmitter details are shown in the circuit diagrams of the repetition and 400 MHz generators in Figure A-4 and in the circuit on the 10 watt broad-

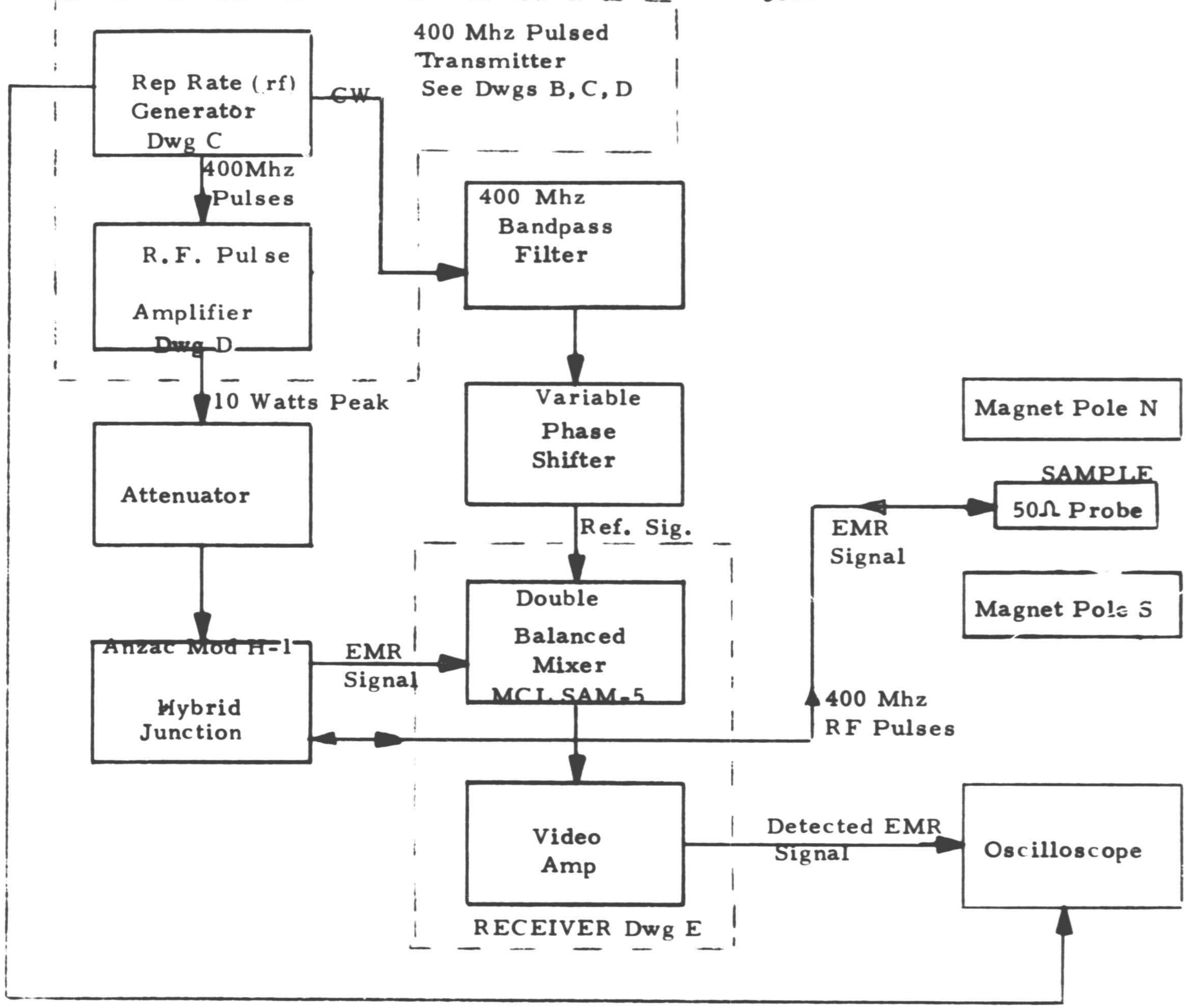

FIGURE A-3. TRANSIENT EMR SYSTEM FOR 400 MHz

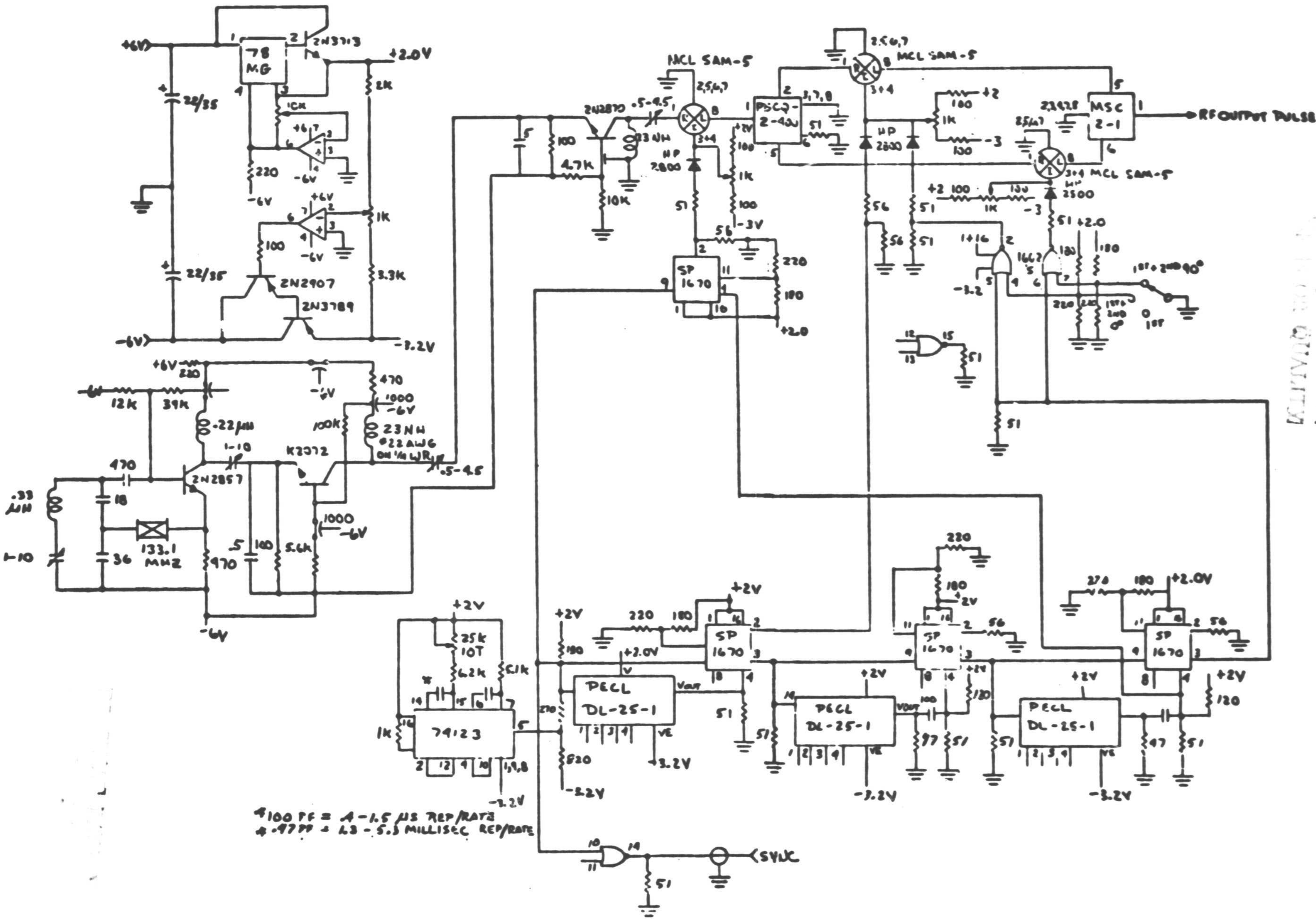

FIGURE A-4. REP RATE AND 400 MHz GENERATOR band 400 MHz RF pulse power amplifier in Figure A-5. The output of the transmitter goes to an Anzac Model H-8 quadrature hybrid junction and from there is connected with an attenuation of approximately 3 dB to the sample probe. A portion of the 400 MHz continuous wave signal from the transmitter is fed through a 400 MHz bandpass filter and a variable phase shifter for use as the reference to the double balanced mixer in the receiver. The receiver circuit diagram, which includes the double balanced mixer as well as the video amplifier, is shown in Figure A-6, and the circuit diagram of the sample coil and other components in the sensing probe are shown in Figure A-7.

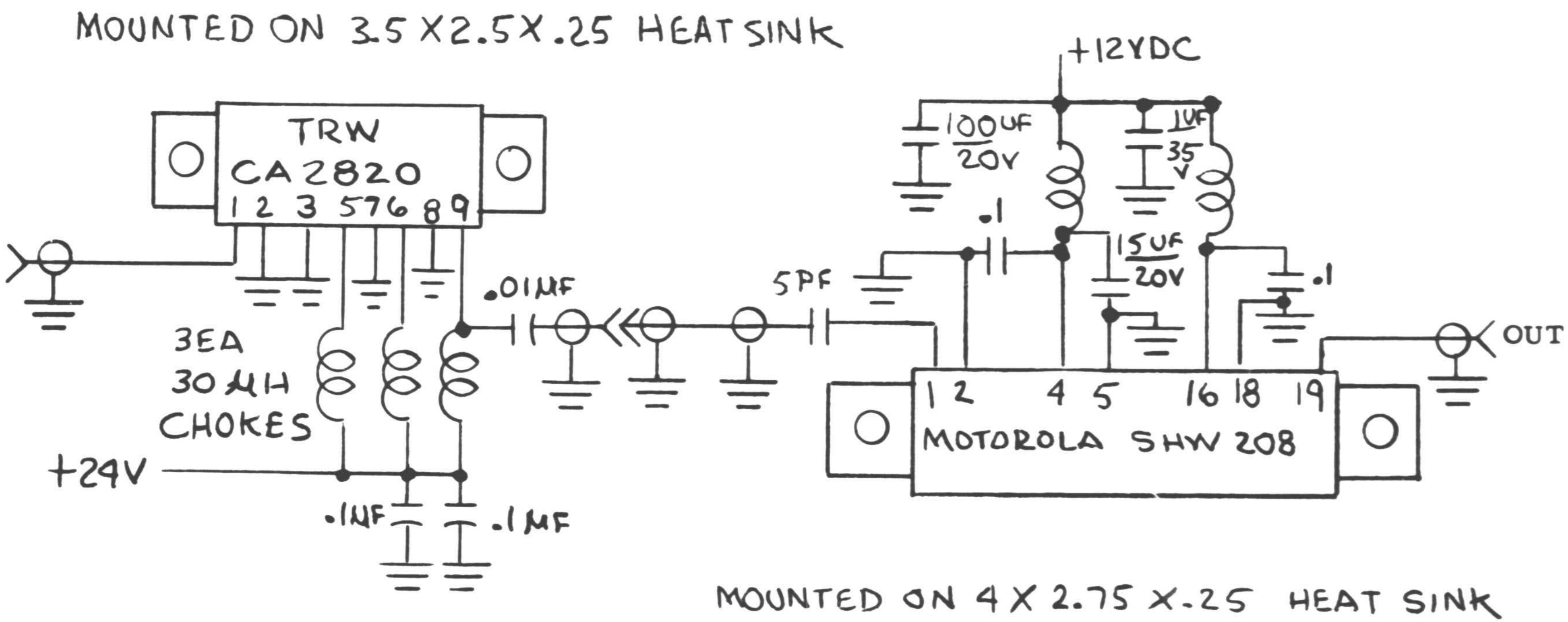

FIGURE A-5. BROADBAND 400 MHz RF PULSE POWER AMPLIFIER

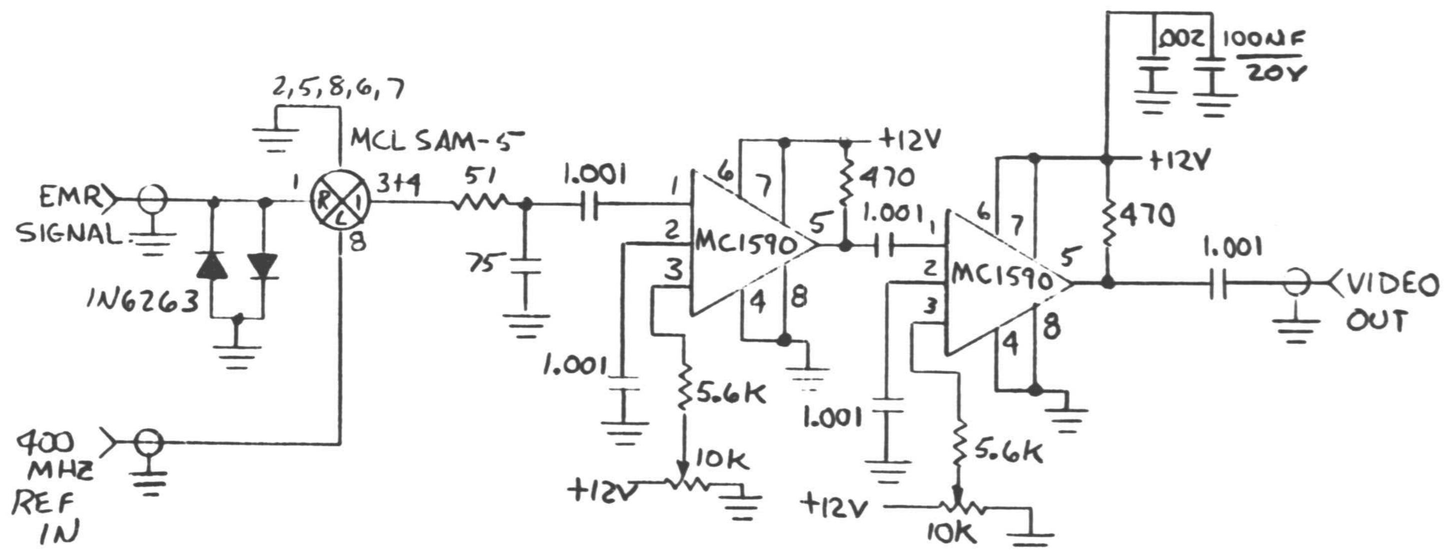

FIGURE A-6. 400 MHz PULSED EMR RECEIVER.

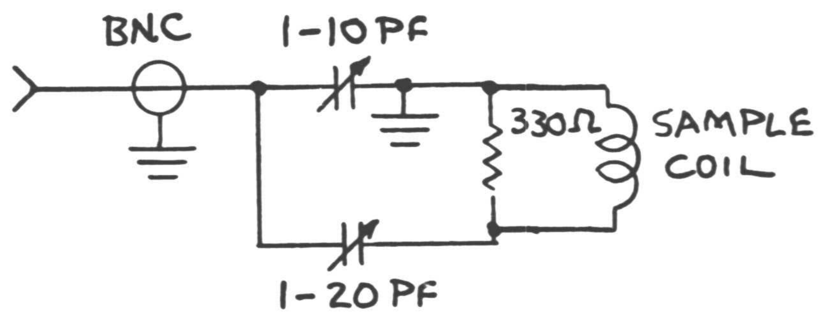

FIGURE A-7. SENSING PROBE.

APPENDIX B

GATED OSCILLATOR-DETECTOR APPARATUS

The gated oscillator-detector appeared to offer the potential of being a readily implemented solution to the recovery time problems. This detection circuit used a single UHF FET transistor and was, in essence, a separately quenched supergenetive detector that had been optimized for EMR applications. The circuit diagram is shown in Figure B-1. The pulse burst generated by the oscillator had rise and fall times of about 5 nanoseconds and the burst length was adjusted to be on the order of 40 nanoseconds. A repetition rate of 1 MHz or higher was found to produce optimum results. Operation of this type detector is based on the effects of the transient (FID) EMR signal intensity with the coil to affect the decay characteristics of the bursts of oscillation. The circuit of the detector is very simple compared to those previously used for the transient EMR and the results were found to be far superior in both inherent stability and usable sensitivity. EMR signal levels on the order of 50 mV were obtained directly from the oscillator-detector when a sample of DPPH was placed in the coil. With the addition of a low noise video amplifier, shown in Figure B-1 on the output of the oscillator-detector it was found possible to detect a sample of DPPH at a distance of nearly 2-in. outside the sample coil. This was achieved with a real-time display of the signal on an oscilloscope. Coal could not be detected directly with the gated oscillator circuit alone even though the several variables that affected performance -- such as the power supply voltage, the oscillator gating voltage, wave shape, pulse rate, and the circuit time constants -- had been optimized using DPPH. To further improve the sensitivity and attempt to obtain signals from coal at short distances away from the sample coil, the gated oscillator-detector was combined with a lock-in amplifier to form the system shown as a block diagram in Figure B-2. By use of this system, which provided modulation of the magnetic field intensity and a synchronous phase-lock detector to process the signal from the EMR system, it was found possible to detect the transient EMR response from a sample of powdered coal located in the sensor coil. The EMR response from a block of coal (about 3-in. x 5-in. x 1-in. or 7.5 cm x 12.5 cm x 2.5 cm) located adjacent to the coil could also be detected, but the response was very weak.

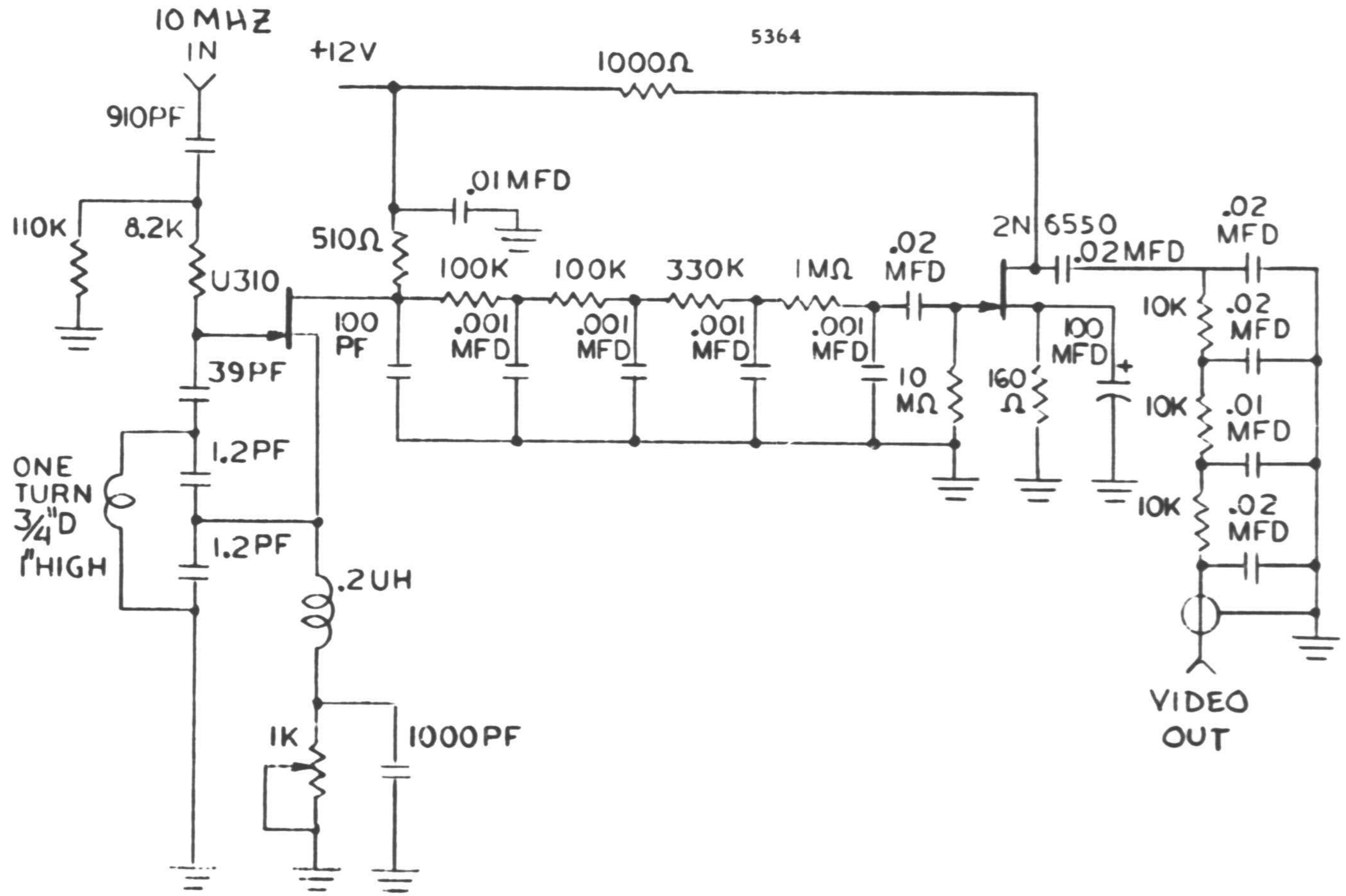

FIGURE B-1. CIRCUIT DIAGRAM OF GATED OSCILLATOR-DETECTOR.

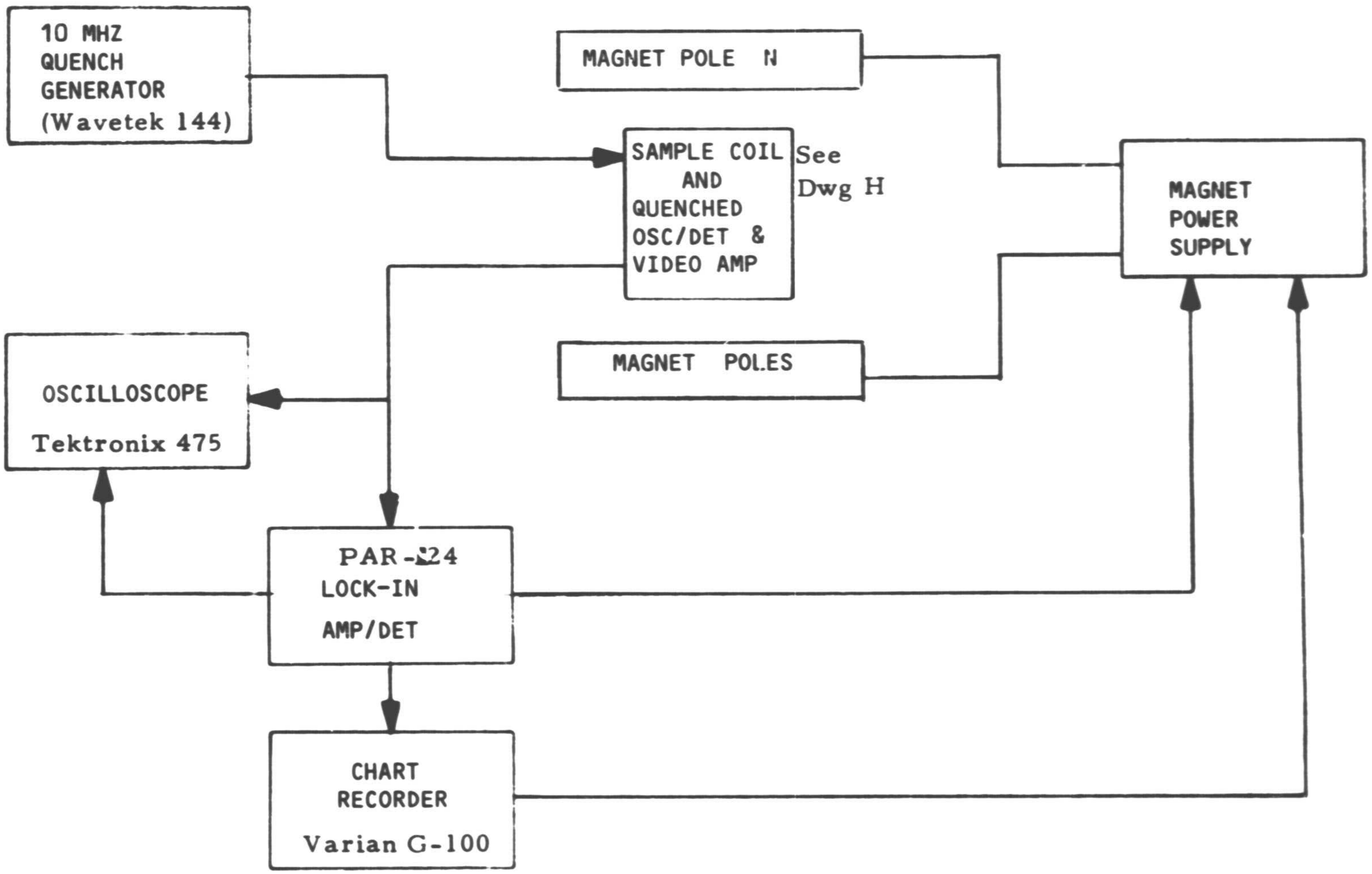

FIGURE B-2. BLOCK DIAGRAM OF GATED OSCILLATOR-DETECTOR TRANSIENT EMR SYSTEM, 400 MHz

APPENDIX C

DUAL FREQUENCY APPARATUS

A block diagram of the dual frequency experimental system developed under Part III of the contract to evaluate the use of EMR for coal thickness gauging is shown in Figure C-1. The system is basically the same as that given in Figure 1 (page 5), but differs in the: (1) frequency of operation; (2) use of an electromagnet of U-shape to provide a measuring field which varies in intensity as a function of distance above the pole faces; (3) use of a common antenna for transmitting and receiving in lieu of separate coils; (4) use of synchronous R.F. detection; and (5) provisions for sweeping the magnetic field intensity to vary the location of the EMR sensing region relative to the plane of the pole faces.

Figure C-2 shows the sensing assembly composed of the magnet, H.F. coils and the UHF antenna. The sensitive detection region is located above the UHF sensing antenna. In this region, the coal or other material being measured is exposed to: (a) a UHF electromagnetic field of 442 MHz generated by the 10 watts of power connected to the dipole antenna; (2) a 6.95 MHz magnetic field produced by 50 watts of power fed to the H.F. coils; and (3) the modulated and/or swept magnetic field produced by varying currents in the coils of the electromagnet. An EMR response from the coal (or other appropriate materials) is produced by that region which is common to the three foregoing fields and in which the magnetic field intensity is proper for resonance at the 442 MHz, the UHF transmitter frequency, or at 435.05 MHz -- the difference frequency between the 442 MHz UHF transmitter frequency and the 6.95 MHz HF transmitter frequency. The EMR signal produced by the coal is detected by the receiver at the frequency of 435.05 MHz. By varying the current in the electromagnet, the sensitive (resonance) region can be produced at selected distances above the pole faces. Thus, by sweeping the current from near zero to the highest allowable value, the sensing region for the experimental system was variable from near the pole faces out to a separation distance of about 8-inches. By knowledge of the magnetic field as a function of current, the thickness of the coal can be determined, unless otherwise limited, by noting the current at which the onset and termination of EMR response occurs. However, with the experimental system, the detection sensitivity limited the range over which a useful EMR signal could be obtained from coal to a distance of about 2-inches. The thickness of a layer of coal less than 2-inches thick could be measured, but with thicker layers the EMR signal decayed into the noise when the sensing region was located at distances greater than 2-inches.

Figure C-3 shows an outline drawing of the electromagnet and Figure C-4 shows the power supply used to excite the magnet. This supply incorporated provisions for modulating the field current at low frequencies (under 20 Hz) and for producing a linear ramp type of sweep.

The radiofrequency and detector electronics portion of the experimental system is shown in Figure C-5. The Duplexer (Decibel Products type DB-4072) is the lower portion of the larger assembly. The duplexer allows to 10 watts of 442 MHz power from the transmitter to be efficiently

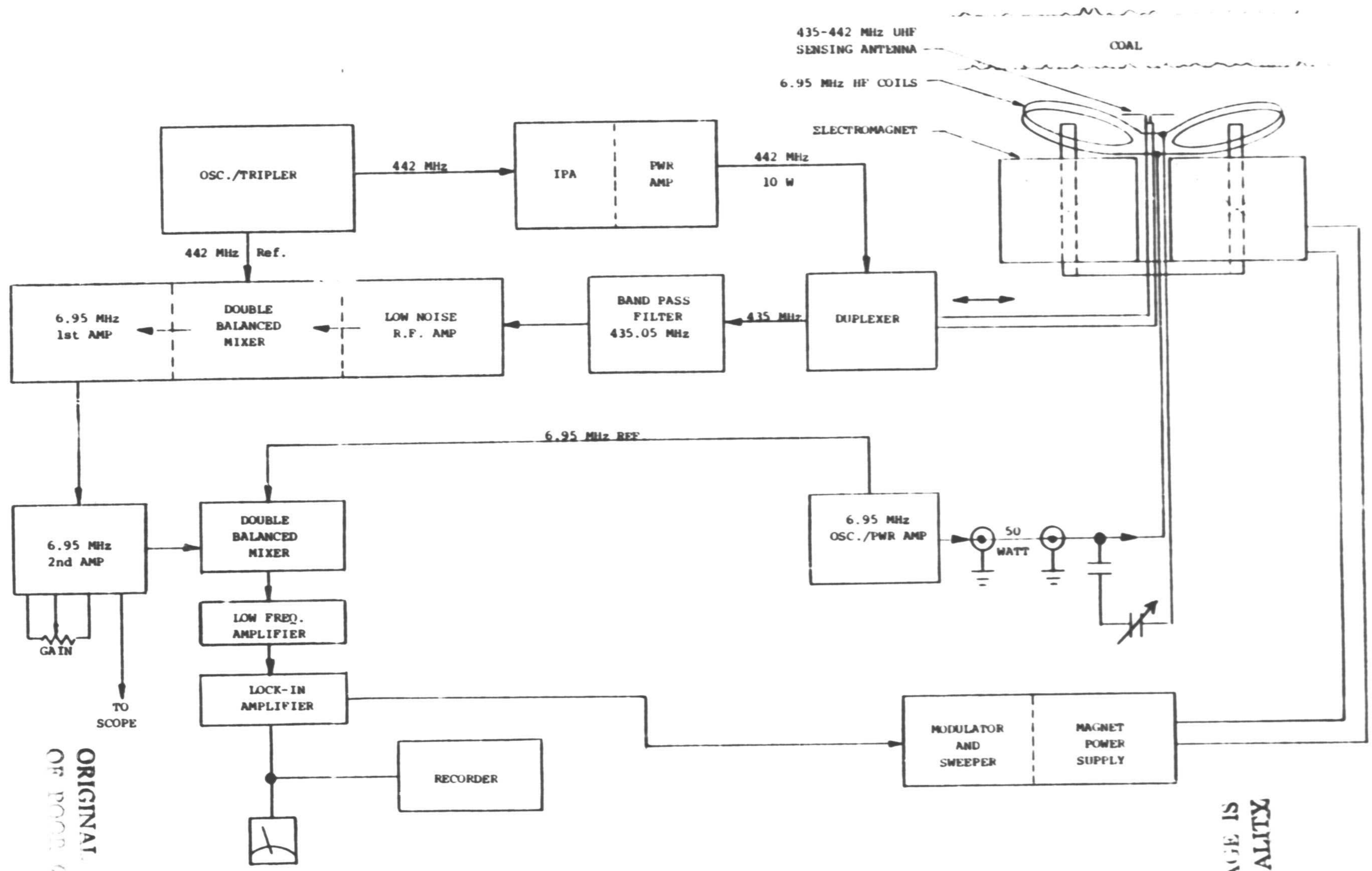

FIGURE C-1. BLOCK DIAGRAM, EXPERIMENTAL EMR.

without great attenuation. This works quite well under laboratory conditions but the balance to achieve a high degree of isolation was very difficult to maintain over long time periods and in the presence of changing environmental conditions or changing samples. It is, therefore, not considered to be readily adaptable to field measurements. The transient instrumentation achieved the desired isolation between transmitter and receiver since the transmitter was turned on for only a short period and the NMR response was received or detected at a time when the transmitter was not producing an output. Thus, the receiver should be designed to have high sensitivity, and, if sufficient protection was provided to prevent damage from the transmitter output, interaction would not normally occur. In the case of the transient EMR system, however, the requirements for recovery times were extremely stringent and obtaining sufficiently clean transmitter outputs free of residual spurious signals posed many serious problems. As a result, the transient approach, while very suited and widely used for NMR detection, did not prove to be practical for the detection of transient EMR signals from coal.

A third detection concept provides the required high isolation between the transmitter and receiver, but does not suffer from the limitations of highly critical adjustment which is characteristic of the balanced bridge method nor from the requirements for high peak powers, clean transmitter signal pulse bursts, and rapid recovery from overload. This method, the dual-frequency concept, had been previously developed at Southwest Research Institute for other applications, and while it is somewhat more complex than the transient apparatus it appeared to offer an ideal solution to the difficulties of detecting EMR response from coal over great distances and in the mining environment. For these reasons this method was considered for the coal thickness gauging application and briefly investigated in Part II of the contract effort.

Since the unanticipated technical problems with the transient method had depleted most of the available funds for Part II of the contract, only a minimum amount of effort was available for use in demonstrating the dual-frequency concept. However, an experimental apparatus was assembled and the performance obtained with this rudimentary system was extremely encouraging. This method is illustrated by Figure 1 (page 5) and in the simplest form requires that the sample be irradiated with two radiofrequency signals which are usually widely separated in frequency. The experimental apparatus at a frequency of 400 MHz was used for one excitation signal and a frequency of 5 MHz was used for the second excitation signal. When the magnetic field is adjusted to the value for resonance, a mixing action occurs in the electrons which causes sidebands to be generated at the sum and difference frequencies. Thus, by tuning the receiver to one of these sideband frequencies, i.e., 405 or 395 MHz, the EMR response can be detected. For other magnetic field intensities and under ideal conditions, no signal component appears at the sum and difference frequencies. Thus, by using a filter ahead of the receiver which provides rejection of the transmitter frequency but passes the sideband frequency, the receiver is isolated from the transmitter. Under these conditions the receiver may be designed to be a normal low noise, continuous wave type receiver of narrow bandwidths which can achieve maximum sensitivity. It should be mentioned that this mixing action occurs when the magnetic field intensity is equal to that for electron resonance at 400 MHz, at 5 MHz, or also at the sum and difference frequencies. However, this multiple response condition should offer no serious problems for using the method for coal thickness gauging.

2. System Analysis

In the basic system the output from the 400 MHz transmitter is applied to a sample coil which is oriented perpendicular to the magnetic field H_o as would normally be the case for continuous wave detection. The output from the 5 MHz transmitter is applied to separate sets of coils which are oriented to produce a field coaxial or parallel with the field H_o. Under these conditions the 5 MHz signal causes the magnetic field to be swept over a range at a 5 MHz rate. This, in essence, frequency modulates the ESR response and results in the sideband generation. The level of the 5 MHz signal required for optimum results can be determined on the basis of FM theory which shows a maximum sideband amplitude when β, the modulation index, equals 1.7 (β is equal to the frequency deviation divided by the modulation frequency). For the modulation frequency of 5 MHz, the optimum peak value of the sinusoidal modulation field amplitude would then be 8.5 MHz. Since the relationship between the electron magnetic resonance frequency and the magnetic field is given by $\gamma = 2.8 \times 10^{-6}$, the modulation of the magnetic field should have a peak value of 8.5/2.8 or approximately 3 Gauss. Since the modulation coils may have a relatively high Q, the amount of power required to produce such field intensities is quite modest. The power requirement for the UHF transmitter at 400 MHz may be determined on the basis of the saturation power density of the electron resonance and is typically, on the size device being considered, on the order of a few watts. Lower power in either the case of the 5 MHz modulation transmitter field or the 400 MHz carrier field results in reduced sensitivity but does not preclude the occurrence of the effect.

The choice of the modulation frequency is arbitrary but somewhat restricted. The use of as high modulation frequency as possible is desirable to ease the filtering requirements to provide sufficient isolation between the transmitter and the receiver. The use of a high frequency is also desirable for some applications where studies of line shapes is important to provide a better separation between the magnetic field intensities where resonance occurs at f_o and at sideband frequencies. For the detection of EMR response in coal and for the thickness gauging application, however, this is not an important consideration. The use of higher frequencies and higher transmitter powers to produce the required modulation field intensities sets a limitation on the maximum that should be utilized. The choice used in the experimental model of 5 MHz is a tradeoff between these two factors and appears to be a near optimum choice.

The power utilized in the 400 MHz transmitter and the experimental model ranged from 1 watt to a maximum of approximately 10 watts. At the 10 watt level the resonances in the DPPH and coal samples, placed in the sample coil, were tending to saturate and little improvement in results was obtained at 10 watts over that which was available with power levels of approximately 3 watts. As the separation distance between the sample coil and the material being measured is increased, advantages to using higher power may become more apparent.

In the ideal situation, mixing between the 400 MHz frequency and the 5 MHz frequency only occurs in the sample material when exposed to magnetic fields of the proper intensities to cause resonance in the electrons. In practice, however, mixing between the two signals can occur in any nonlinear material that might be present in the fields of both coils with the result that a continuous sideband signal may appear at the receiver input. The occurrence of this condition in the iron of the magnet and in other materials has been observed as has the production of the undesired mixing effect in nonlinear components in the transmitter output stages. For this reason some precautions are necessary in the construction of the apparatus to minimize the possibility of both frequencies appearing in undesired regions simultaneously. However, by use of an additional modulation of the magnetic field, the effects of the nonlinear mixing in non-EMR resonant materials can be eliminated. This is shown in Figure 1 and is accomplished by modulating the field at a frequency of 18 Hz. This causes the EMR response to be modulated at 18 Hz and this component is available at the output of the selected receiver. The sideband energy that is caused by nonlinear mixing in non-resonant materials does not cause an 18 Hz component to be present and, by arranging a lock-in amplifier which is sensitive to only the 18 Hz component of the receiver output, the effects of the nonlinear mixing may be rejected and the sole response produced by the EMR activity.

3. Demonstration System

A demonstration system was assembled for evaluation of the dual-frequency concept in the laboratory. This system made use of the apparatus that was available and the performance could undoubtedly be greatly improved by optimum design of the various components. This experimental system utilized the transmitter that had been developed for the transient cases and was previously described in Section II.B.4. It was modified for this application, however, to produce a continuous wave output and power levels up to 10 watts were available. The output could be reduced to lower levels with attenuators. The 5 MHz transmitter made use of a commercially available tunable oscillator to provide an output frequency of 5 MHz. This was connected through a broadband linear RF power amplifier which was set to produce an output power of 6 watts. The receiver was composed of a crystal-controlled frequency converter tuned to 405 MHz. The output of this converter was connected to a Collins R388 communications receiver which was tuned to receive the sideband frequencies. The audio output from the receiver was connected to the input of a lock-in amplifier tuned to 18 Hz. The 18 Hz oscillator in the lock-in amplifier was connected to the magnet power supply to cause the modulation of the magnetic field superimposed on the main magnet field current which produced the resonant field H_O. This modulation was set to provide a field sweep at 18 Hz of less than the linewidth of the material to be detected and was typically on the order of 1 Gauss peak-to-peak.

The magnet used for the laboratory studies provided a volume 5-in.-wide by 8-in.-deep by 8-in.-high in which the field intensity was homogeneous to within 1%. The pair of coils used to provide the 5 MHz modulation were 4-in. in diameter and were tuned to resonance at 5 MHz and loaded to give a matched input impedance of 50 Ohms. The UHF sensor coil was the same as that previously described and shown in Figure 12. This coil is 3/4-in. in diameter. Sample material to be studied was placed in the magnetic field and within the region modulated by the 5 MHz coils but was spaced away from the UHF transmitter coil at selected distances.

The receiver coil, with a design similar to that of the UHF coil, was 2-in. in diameter and similarly loaded to be matched to a 50 Ohm line. The receiver coil was connected to a filter which rejected 400 MHz by approximately 40 dB but passed 405 MHz with only about 2 dB of insertion loss. The design of this filter was based on the concept commonly employed as a duplexer in communication systems where the transmitter and receiver operate at different but closely spaced frequencies and are connected to the same antenna. This filter rejected the 400 MHz transmitter component but allowed the EMR signal at 405 MHz to pass to the input of the selective 405 MHz receiver.

4. Results with Demonstration System

The demonstration dual-frequency system exhibited extremely encouraging results. It was readily possible to detect the response from a sample of DPPH located within a few inches of the UHF coil even when the receiver coil was separated from the magnet assembly by distances of several feet. Thus, the radiated EMR signal from the sample was being detected by the receiver coil over these distances. This detection was readily observed with DPPH samples of approximately 10 grams at separation distances from the UHF coil of up to about 6-in. The EMR signal produced from a 10 gram sample of coal placed near the UHF coil could be detected with the receiver coil up to 10-in. away.

In the initial dual-frequency system the 18 Hz modulation was not utilized and the receiver S-meter was used as an indicator. Under these conditions the sideband was tuned in by the receiver, and was seen to appear and disappear as the field intensity of the electromagnet was varied through resonance. Some instability and the effects of nonlinear mixing were observed when operating in this manner, however. By use of the lock-in amplifier and the 18 Hz modulation, the instability and the effects of the nonlinear mixing were reduced to insignificant levels. In this case, as the magnetic field is tuned through resonance the output indicator on the lock-in amplifier swings from one extreme to the other as it traces out the shape of the EMR response. The shape is similar to those shown for the EMR samples studied in Part I of the contract. The stability under these conditions was very good. On the basis of these findings, the use of the dual-frequency method as the basis for the coal thickness gauge appeared worthy of further development.

5. Experimental System

An experimental EMR system suitable for evaluation of the coal thickness gauging capability was developed under Part III of the contract. This system is described in detail in Appendix C.

6. Results with Experimental System

Numerous tests were conducted during the development of the experimental system to determine that the expected level of performance of the various subsystems was being attained and to optimize these major components. These tests included such fundamental determinations of the power outputs from the 442 and 6.95 MHz transmitters (10 and 50 watts, respectively), the receiver noise figure (2.5 dB) and the intensity of the magnetic field in the space above the pole faces. This is plotted in Figure 9. In addition, several UHF antenna configurations were evaluated to determine the optimum design for achieving the maximum detection range. These structures investigated included a 3-inch diameter circular coil, a full-wave (at 442 MHz) rectangular loop, a half-wave dipole formed into a non-shorted circular loop as well as the linear half-wave dipole which produced the best results and was adapted for the final design. Several coil sizes of both rectangular and circular cross-sections were investigated for use in generating the 6.95 MHz field. The design finally adopted uses three turns of heavy teflon insulated wire enclosed in an unshorted, 11-inch diameter, loop of copper tubing which acts as a Faraday shield.

Tests were conducted to establish the optimum power required for the high frequency (6.95 MHz) field and for the UHF (442 MHz) field. Increases above 50 watts at 6.95 MHz produced insignificant improvements in the detection sensitivity; however, increases above the 10-watt level in the 442 MHz field would result in improved sensitivity, but, for safety reasons, this was not considered advisable. Further tests were conducted to determine the optimum frequency and amplitude for the magnetic field modulation.

Initial tests of the system produced very erratic results. This was found to be due to spurious coupling between the various subsystems and was corrected by extensive shielding and RF filtering of all connections into and out of the assemblies and sub-assemblies.

With the final system, tests were conducted to show the level of performance which could be achieved. Many preliminary tests for optimization purposes were conducted with DPPH which provides a more intense EMR signal than coal. However, tests were also conducted using blocks of coal approximately 3" thick by 10" square. This block of coal could be detected with a 2:1 signal-to-noise ratio (using a 1-second integration time) when placed above the sensing antenna (and magnetic pole faces) at distances up to 2-inches. This distance is the separation between the bottom of the block and the uppermost part of the sensing apparatus. At greater separation distances the EMR signal from the coal rapidly dropped into the noise. Other tests conducted with DPPH showed the capability to detect a change in the position of the lower interface (between the layer of DPPH and air) as small as 0.04 inches.

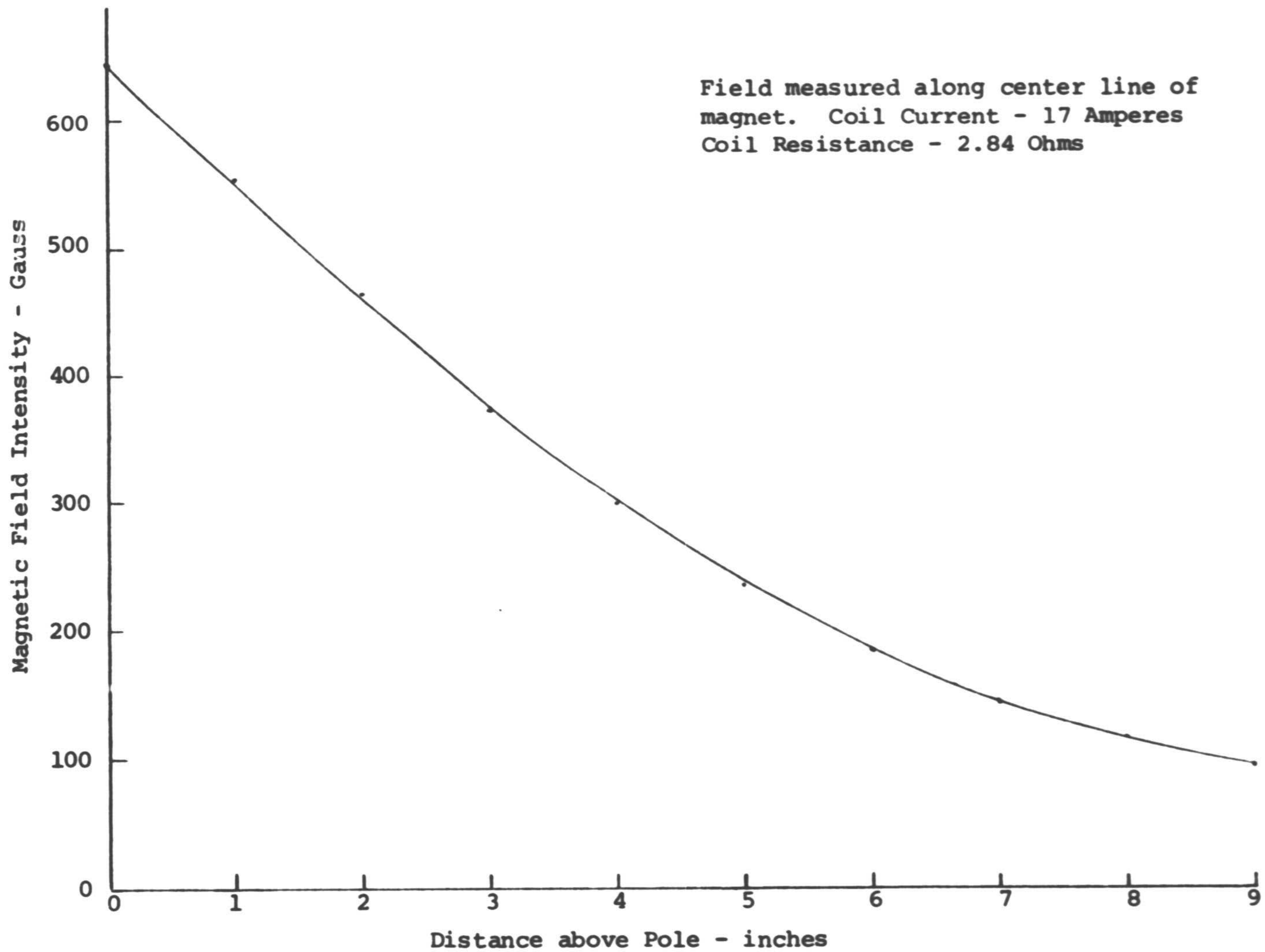

FIGURE 9. FIELD OF U-SHAPED MAGNET.

Efforts were made to determine the causes for the limited detection range and means whereby it could be increased. The performance of each system component was re-examined, but all were found to be operating as expected. To further explore the possibility of obtaining extended detection distances, and consequently greater thickness gauging ranges, tests were conducted with the UHF sensing antenna and the HF modulation coils placed in a large electromagnet of the design as was shown in Figure 1 to allow measurements to be made with the sample in a more homogeneous magnetic field. This magnet provides a field which is of constant intensity, to within 1% over a volume which is 16" high x 26" wide and 20" deep. In this field, the EMR signals from the block of coal could be detected with a 2:1 signal-to-noise ratio at separation distances from the sensing antenna of up to 8-inches. Other than the magnetic field, the system was the same for these tests as for those conducted earlier. This indicates that the system is basically capable of detecting the EMR response from coal at distances of interest for in situ thickness gauging provided a favorable magnetic field is used. This indicates the need to modify the present magnet configuration to achieve such improvements in a fieldable instrument.

III. CONCLUSIONS AND RECOMMENDATIONS

The feasibility of using electron magnetic resonance (EMR) as the basis for gauging the thickness of coal overlaying a rock substrate has been investigated. As a result of this work, it may be concluded:

1. The capability of EMR to distinguish coal from rock (and air) has been established.

2. If properly implemented, EMR is basically suitable for use as a noncontacting means for detecting the front, coal-air, interface as well as the rear, coal-rock, interface of the layer of coal remaining in place after a cut by mining machinery.

3. Three different EMR detection methods have been investigated for use in coal thickness gauging. The balanced bridge continuous-wave method has been demonstrated to have excellent detection sensitivity in laboratory applications, but requires critical adjustments which could be difficult to maintain in a moving environment. The second method, the transient approach, offers the potential of being a sensitive non-critical means for detecting the EMR response from coal; however, the short decay time constants (a few nanoseconds) which characterize the EMR response from coal impose serious recovery time problems in the apparatus which are very difficult to overcome without going to operating frequencies in the upper microwave range where the magnetic field intensity requirements for resonance may be excessive. The third method, the dual frequency approach, offers a better combination of characteristics than the other two. It is relatively noncritical in adjustment, useful at relatively low frequencies and suitable for sensitive detection. However, the coils used for generation of the high intensity radiofrequency field parallel to the D.C. magnetic field introduces some mechanical design complications.

4. The detection of coal at separation distances from the EMR sensor of up to 8-inches has been demonstrated in homogeneous magnetic fields using the dual frequency method.

5. Means for using gradient fields with EMR to allow thickness gauging to be achieved have been developed and the capability to detect both a front and rear coal-air interface have been demonstrated.

6. Detection of coal-air interfaces at separation distances up to 2-inches from the EMR sensor with a resolution of 0.04-inches has been achieved in a gradient field using the dual frequency detection method.

7. Further improvements in the EMR detection apparatus are needed to extend the detection range to distances of 6 to 8 inches or more for mining applications of the coal thickness gauge. Such improvements should be attainable since detection at such ranges has been demonstrated with EMR in homogeneous fields.

It is therefore recommended that the detection apparatus be modified to increase by a factor of 3 to 4 the measurement distance range over which coal thickness gauging can be achieved. Such an improvement should be realized with the following recommended modifications:

1. Alter the magnet design to provide a lower field gradient at the measurement range. This will increase the effective volume of the coal which is sensed and thereby improve the signal-to-noise ratio. Even with this change, the thickness measurement resolution can still be made to be 0.5 inches or better.

2. Increase the magnetic field intensity and the associated EMR frequency to approximately twice that now being used. This will provide an S/N improvement of 4:1 and increase the measurement range by an estimated factor of 2:1.

3. Increase the modulation frequency to be more optimum for coal and proportionately increase the available modulation power.

4. Incorporate more advanced signal processing methods to better extract the desired signal from the noise.

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APPENDIX A

TRANSIENT EMR APPARATUS DEVELOPMENT

A number of variations in the design of the transient EMR apparatus were investigated during the program in order to overcome limitations which were encountered. However, all of these designs were based on the block diagram shown in Figure 4 (page 12).

To obtain good frequency stability, the transmitter frequency was crystal controlled and produced a peak power output of 10 watts. The transmitter pulse width was adjustable over the range of 25 to 40 nanoseconds, and the spacing between the pulse pairs was adjustable over a similar range. A pulse rise and fall time of 3 nanoseconds was set as an additional goal. In the original design the receiver was composed of three stages of low noise hybrid type amplifiers coupled by bandpass circuits to provide the required 60 MHz bandwidth and a noise figure of under 4 dB. Due to overload problems and undesirable transient response characteristics which were encountered, the receiver was modified to a homodyne circuit using no radiofrequency amplification ahead of the double balance mixer. However, the mixer was followed by a low noise video amplifier. The original matching network was a balanced bridge hybrid made from sections of coaxial cable. Because of the narrow bandwidth this was later modified to a resistive bridge and finally, to a broadband hybrid network to improve the operation of the system.

A block diagram of the original transmitter or radiofrequency generator is shown in Figure A-1. The radiofrequency signal begins as a continuously running crystal controlled 133 MHz oscillator. The output of this oscillator is tripled to 400 MHz. In the initial design the 400 MHz output from the tripler was directly connected through a 90^{o} power splitter to two RF gate circuits. The RF gates made use of double balanced mixers especially selected for high RF attenuation. The two output signals provided by the power splitter are at 0^{o} and 90^{o} relative phase angles and both are needed for the pulse echo detection sequence. Each signal is connected to a double balanced mixer gate which is controlled by pulses from the sequencer to generate the bursts of 400 MHz energy. The pulse burst outputs of the two mixers are combined and amplified through a low-power broadband, modular amplifier. The output is then further amplified through a modular power amplifier to an output level of 10 watts peak into a 50-Ohm load. Problems were initially encountered with the leakage between transmitter bursts being of sufficiently high level that the receiver was saturated. To reduce this leakage, an amplifier and the second gated mixer were added between the tripler and the phase splitter. This modified transmitter circuit is shown in Figure A-2. The changes significantly increased the on/off ratio but the need for still further isolation was apparent from the results.

Gated oscillators using an MECL-III NAND gate were investigated as an alternate means for obtaining such improvements. Oscillation could not be obtained with this device at 400 MHz; however, by using a delay line circuit feedback, controllable, nanosecond lengths of oscillation could be obtained at frequencies as high as 280 MHz. The rise time for this gated oscillator was found to be 3 nanoseconds while the fall time was 5 nanoseconds and significant spurious signals following the pulses persisted for only 10 to 15 nanoseconds. The shape and recovery time characteristics also appeared to

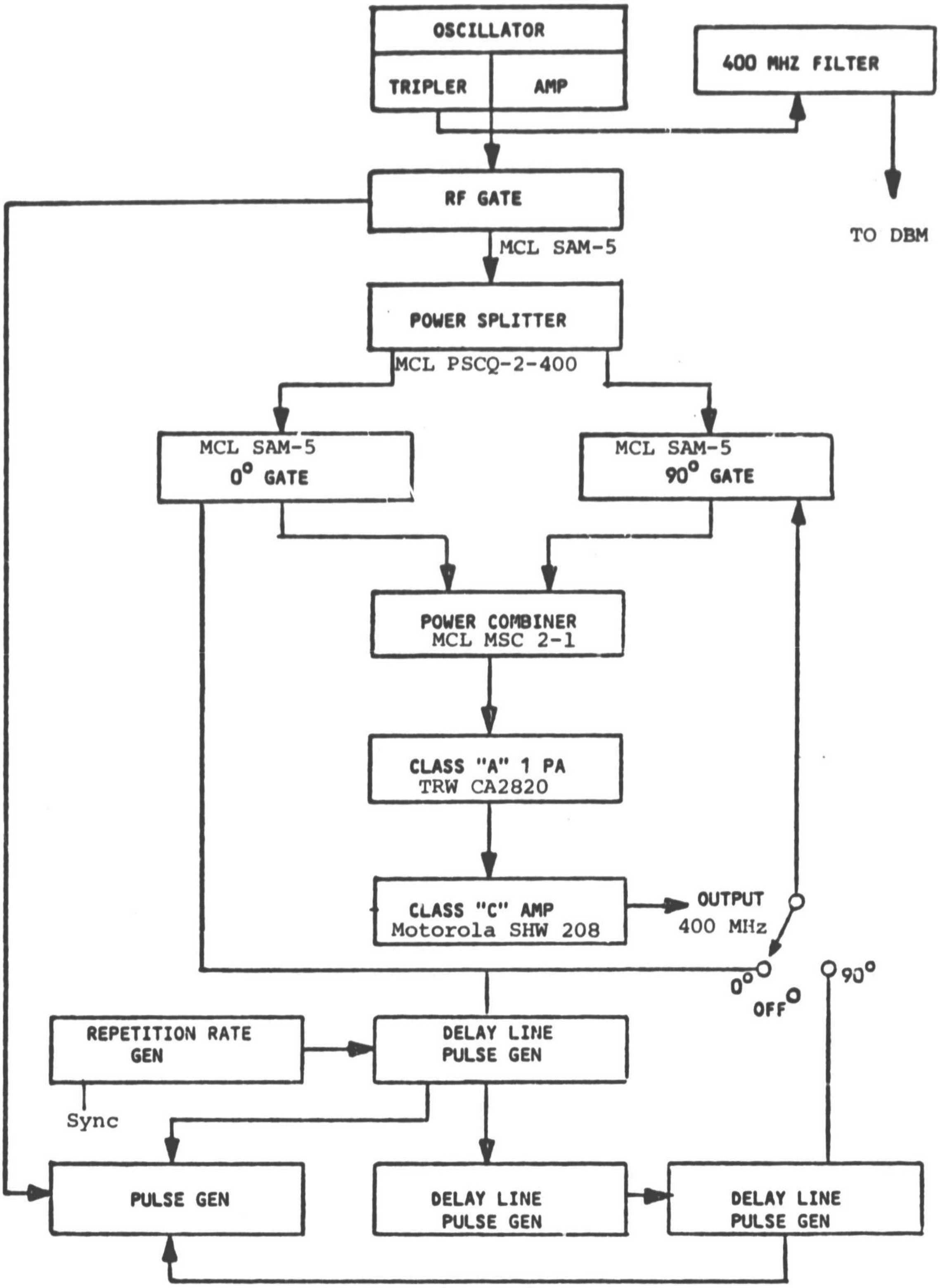

FIGURE A-2. BLOCK DIAGRAM, REVISED PULSED EMR TRANSMITTER

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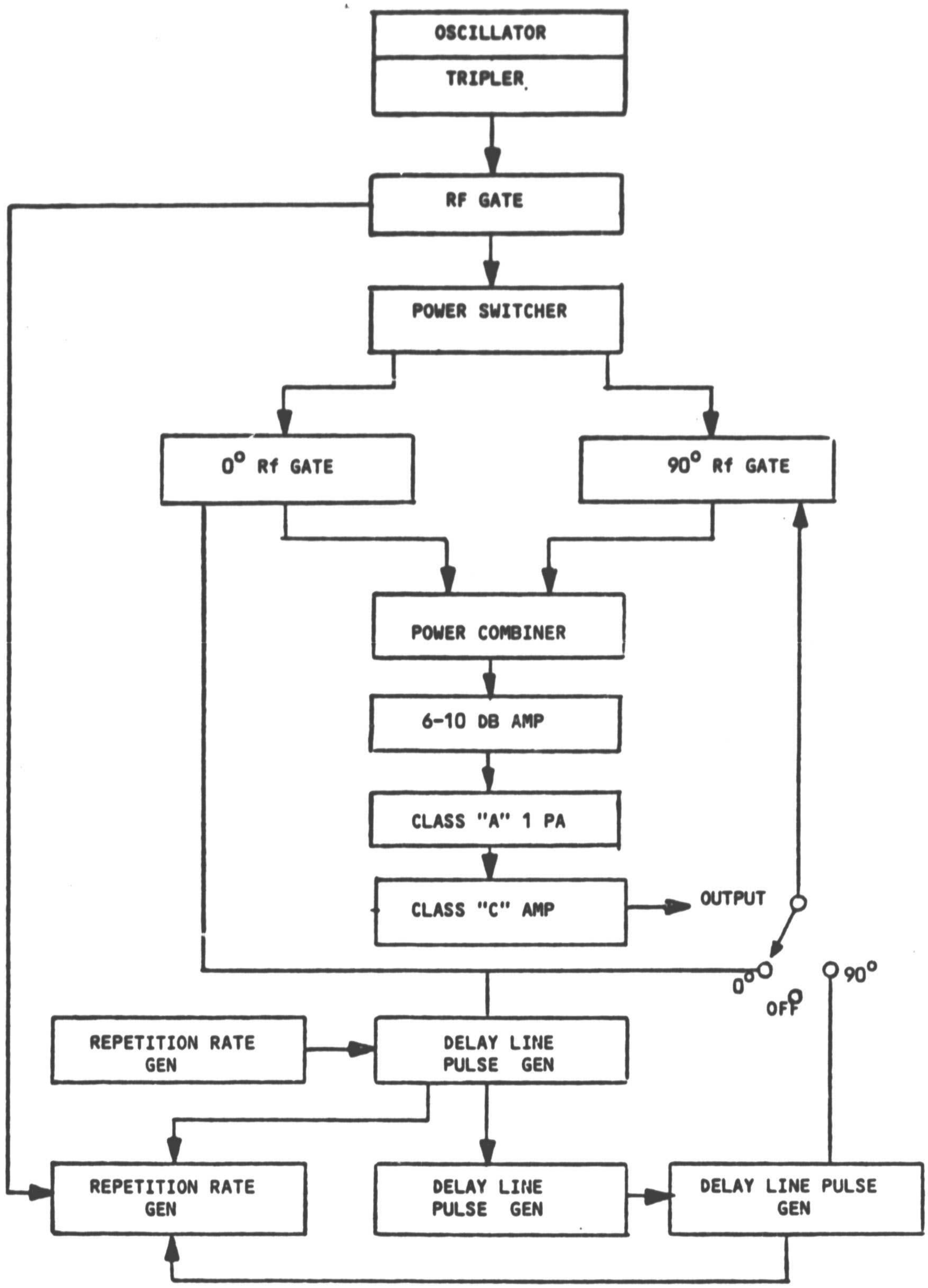

FIGURE A-1. BLOCK DIAGRAM, ORIGINAL PULSED EMR TRANSMITTER

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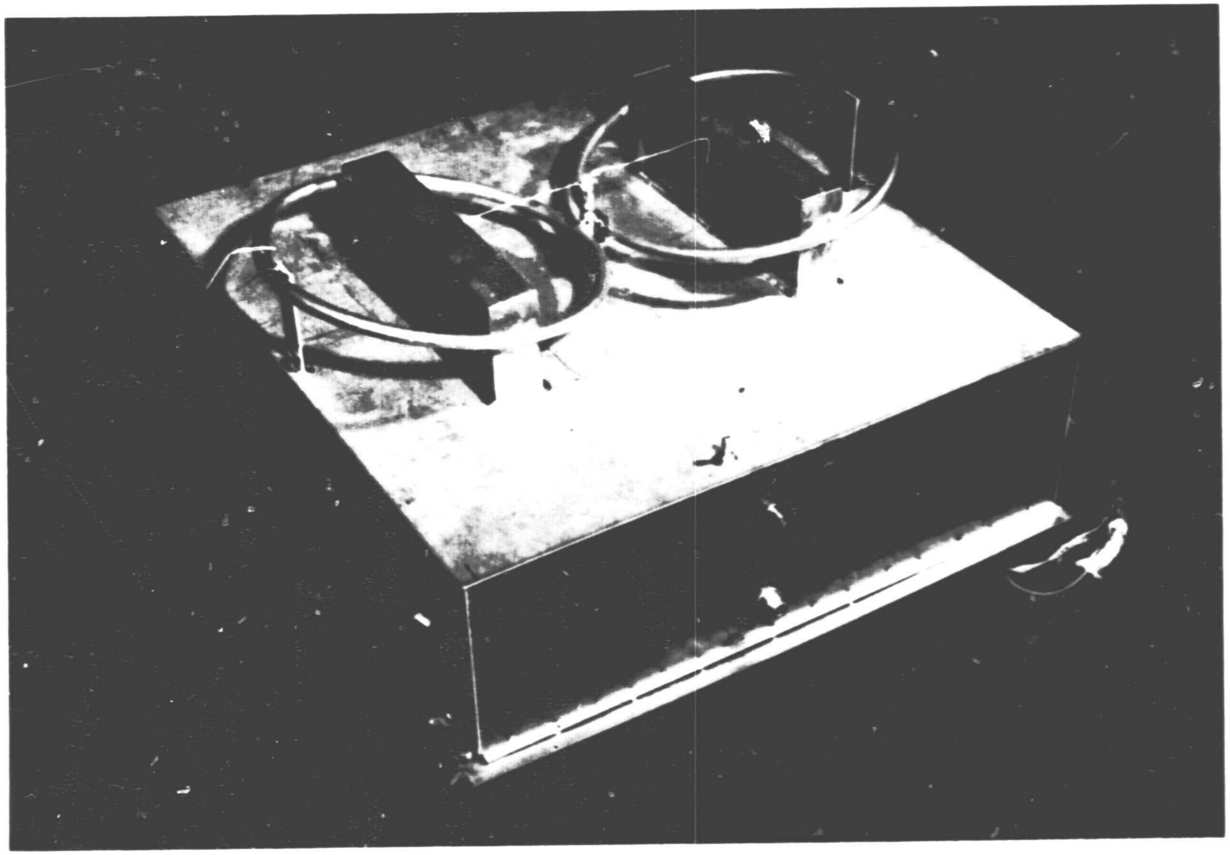

FIGURE C-2. MAGNET, SENSOR ANTENNA AND R.F. FIELD MODULATION COIL ASSEMBLY USED IN EXPERIMENTAL EMR SYSTEM.

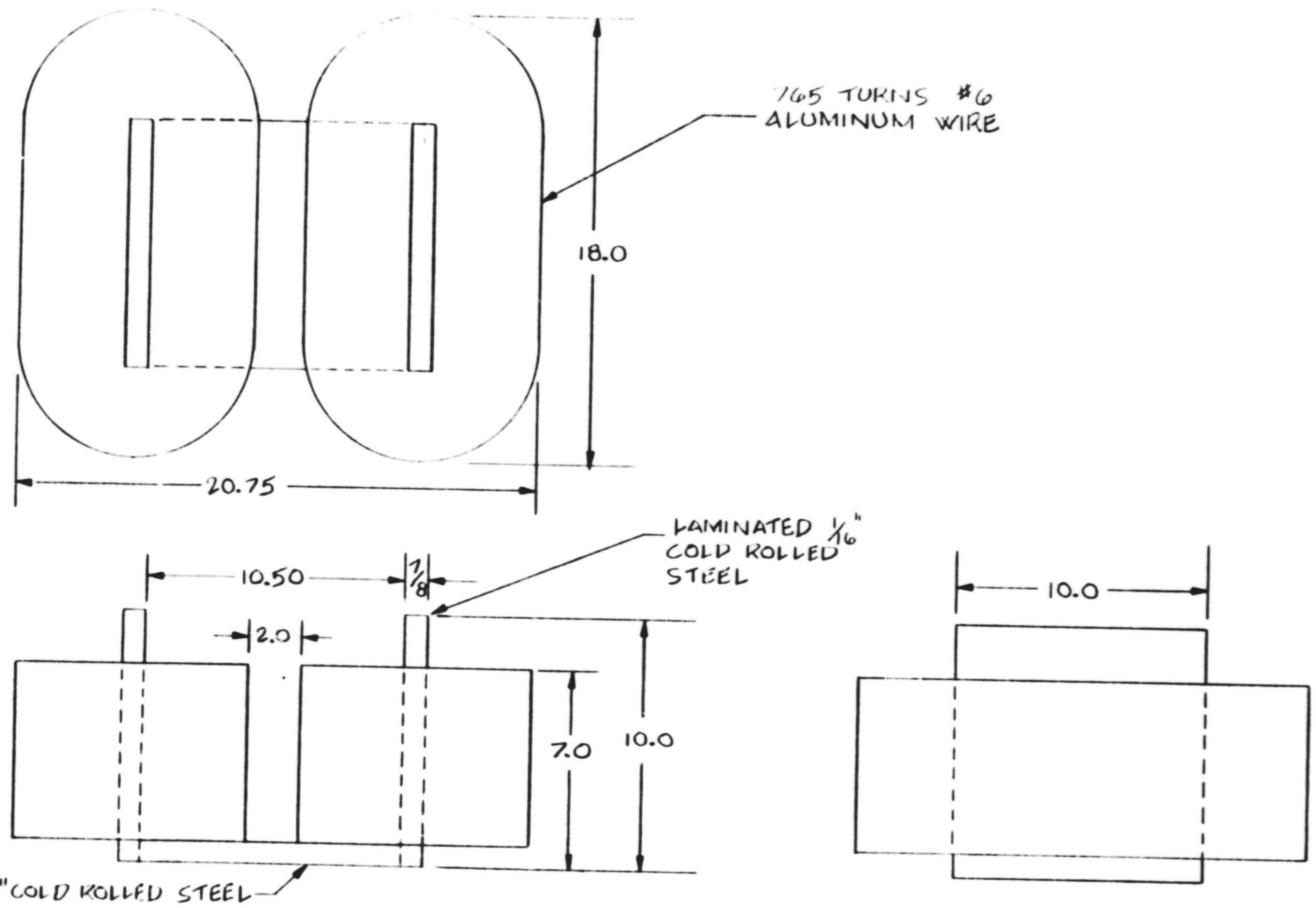

FIGURE C- 3. ELECTROMAGNET DESIGN.

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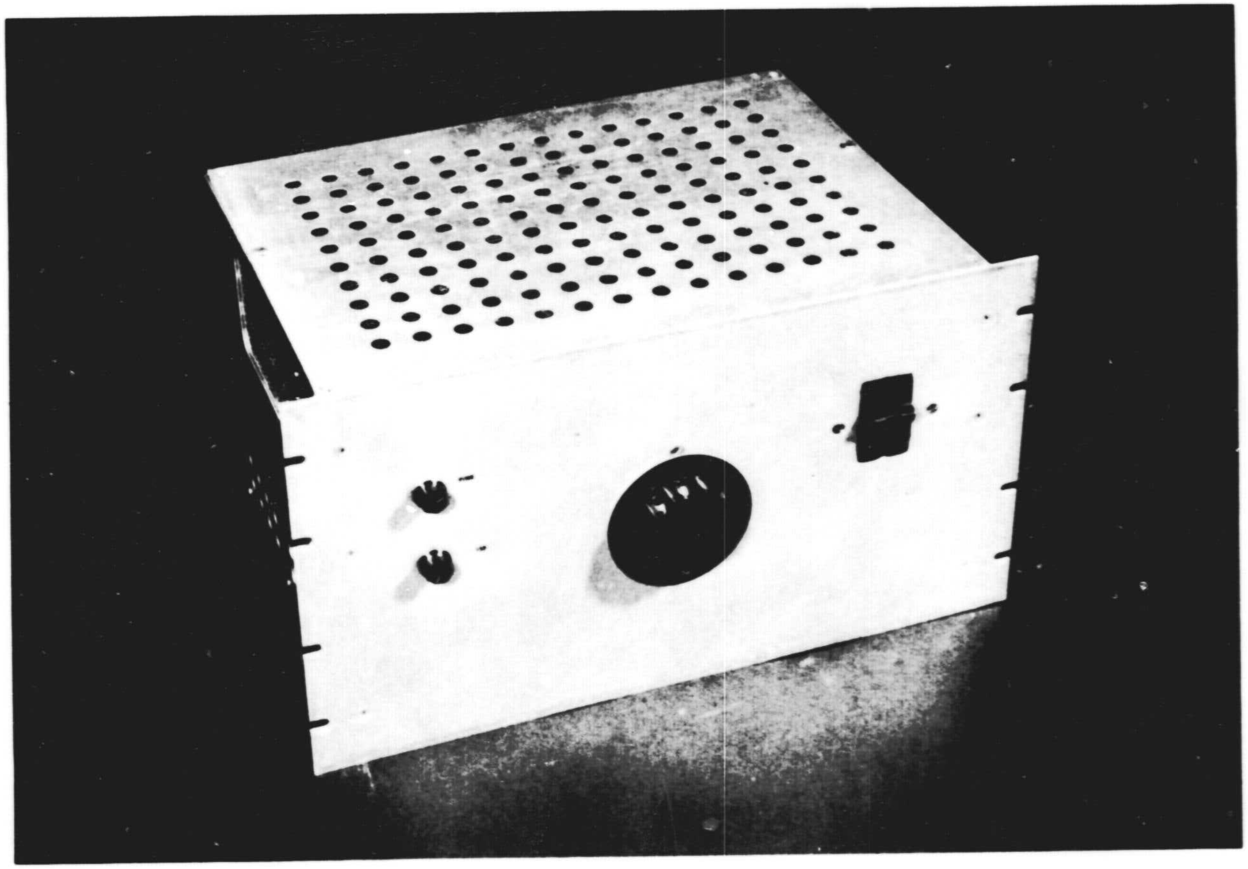

FIGURE C-4. MAGNET POWER SUPPLY, MODULATOR AND FIELD SWEEPER USED WITH EXPERIMENTAL EMR SYSTEM.

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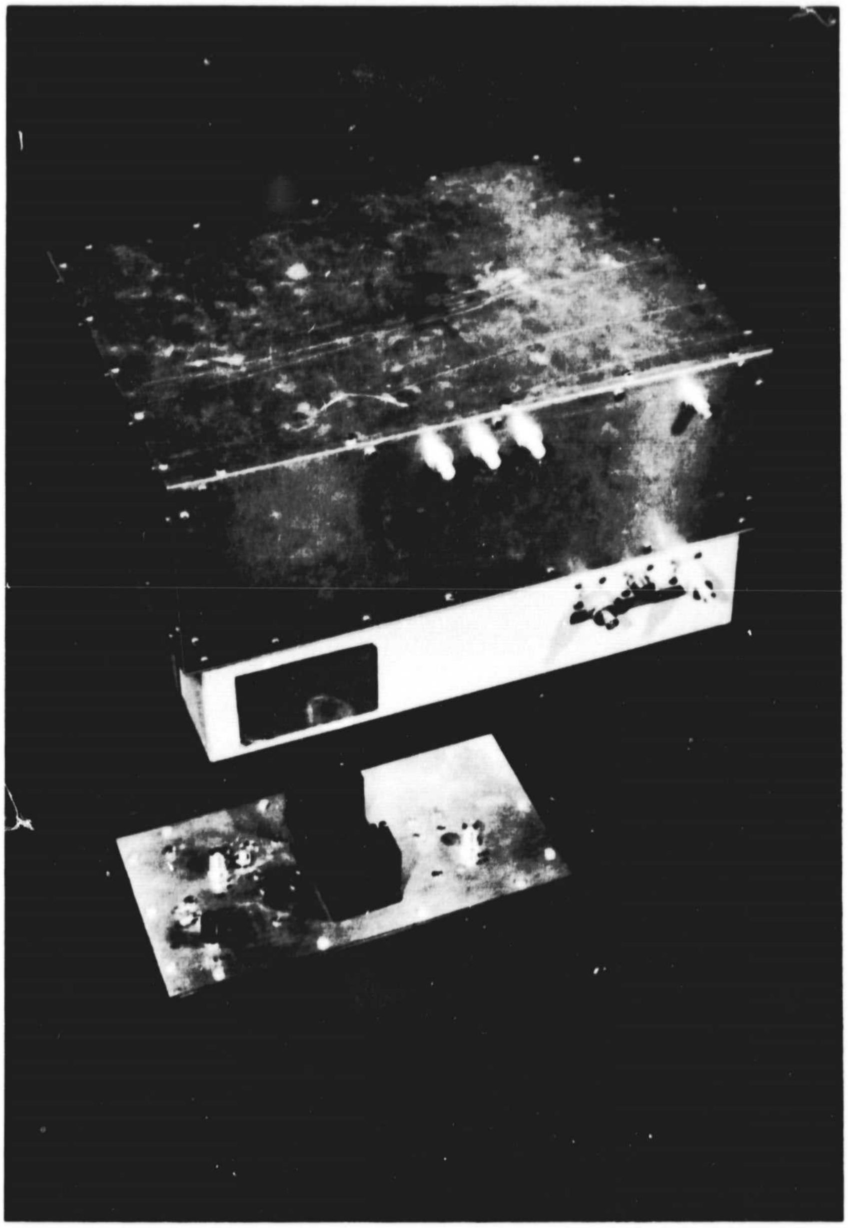

FIGURE C-5. R.F. GENERATORS, DUPLEXER AND DETECTOR PORTIONS OF EXPERIMENTAL EMR SYSTEM.

coupled to the UHF sensing antenna and allows efficient transfer of the 435.05 MHz EMR signal from the antenna to the receiver while at the same time rejecting, by up to 75 dB, direct coupling between the transmitter to the receiver. This causes the 442 MHz transmitter power at the receiver input to be about 75 dB less than that fed to the antenna or a level of -35 dBm. The other parts of the R.F. circuits, see the block diagram, are enclosed in the upper part of the larger assembly except for the 6.95 MHz oscillator-power amplifier.

The 6.95 MHz unit is the smaller assembly in Figure C-5. A circuit diagram of this unit is shown in Figure C-6. The circuit uses a crystal controlled oscillator which produces a low level output. This is amplified through a series of transistor stages to a level (+7 dBm) suitable for use as a double balanced mixer reference. The signal is further amplified by a tuned power transistor in a narrow band circuit. Output levels of up to 50 watts continuous to a nominal 50 ohm load are available from this 6.95 MHz transmitter. This is connected through a coaxial cable up to 20 feet long to the HF coils in the Sensing Assembly. A dual capacitor netowrk times these coils to resonance at 6.95 MHz and provides a nominal input impedance of 50 ohms.

The 435.05 output from the duplexer (EMR signal) is coupled through a narrow bandpass filter (~2 MHz bandwidth) to the input of the low noise (2.5 dB noise figure) dual gate MOSFET RF amplifier in the receiver as shown in the block diagram, Figure C-1, and in the circuit diagram, Figure C-7. The 435.05 MHz output of the amplifier goes to a double balanced mixer (SRA-3) where it is mixed with the 44. MHz reference from the oscillator-tripler to form a synchronous detector having a phase coherent 6.95 MHz output. This output is amplified in two amplifier stages . The bandwidth of this amplifier is about 200 kHz.

Next, the signal is fed to a second tuned amplifier which also uses a type 40673 dual-gate MOSFET as shown in Figure C-8. The output of this stage is coupled to another double balanced mixer (DBM) which uses the reference from the 6.95 MHz oscillator-amplifier to maintain the phase coherent detection. The output of the DBM is the low frequency modulation of the magnetic field. This is amplified in two IC amplifier stages to raise thelevel for direct observation on an oscilloscope or for connection to the input of a lock-in amplifier. The lock-in amplifier produces the reference output used to modulate the magnetic field at a low frequency. The low frequency was normally on the order of 5 Hz and the magnetic field modulation level at the coal being measured was typically 3-gauss peak-to-peak.

The 442 MHz transmitter uses a crystal controlled (147.3 MHz) oscillator followed by a transistor frequency tripler. This is shown in Figure C-6 and the circuit diagram is shown as part of Figure A-4 (Appendix A). The intermediate power amplifier (IPA) and the Power Amplifier are the same as used for the transient EMR work and are shown in Figure A-5 (Appendix A). The power output level is 10 watts (+40 dBm).

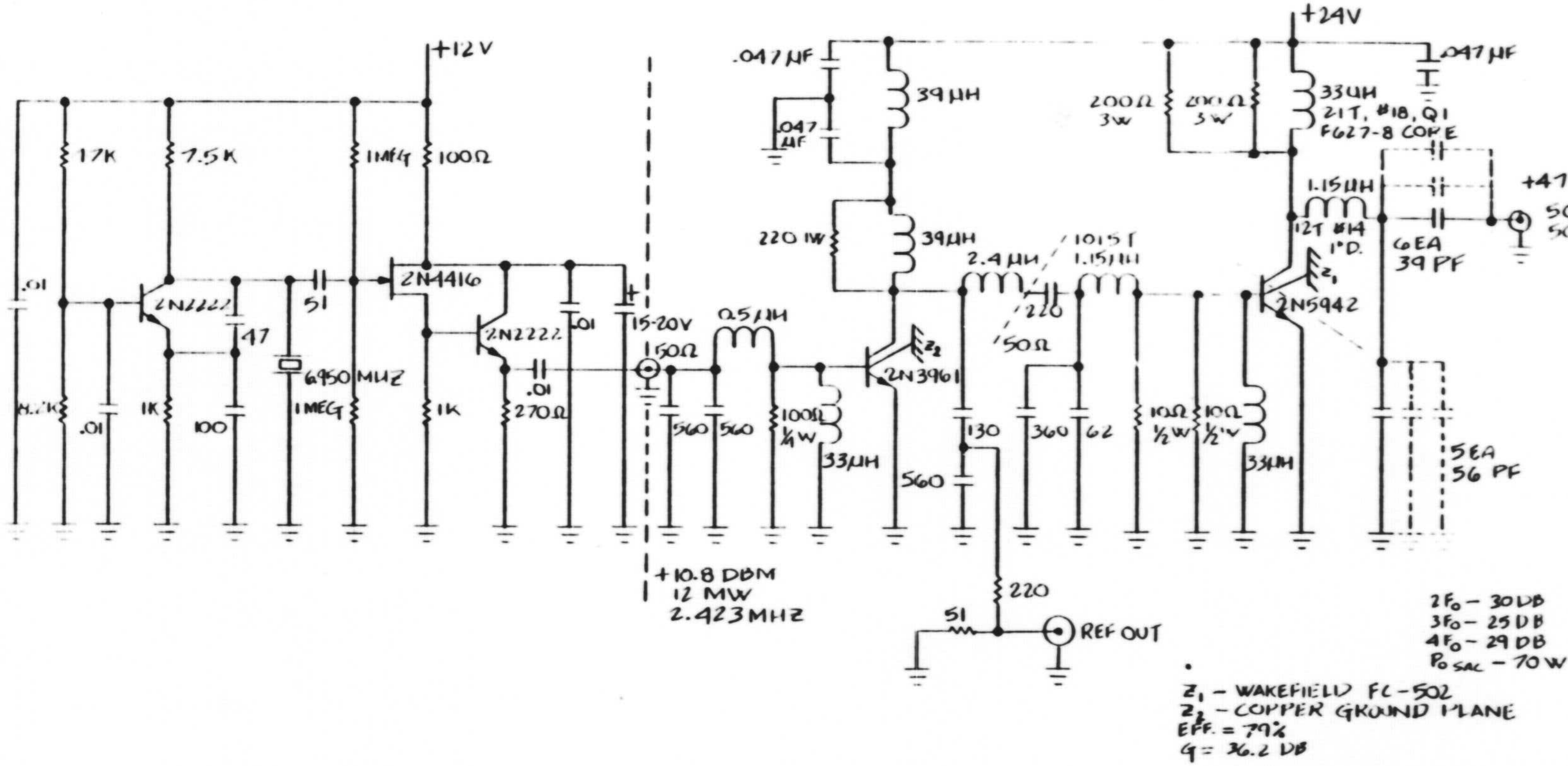

FIGURE C-6. 6.95 MHz OSCILLATOR-AMPLIFIER.

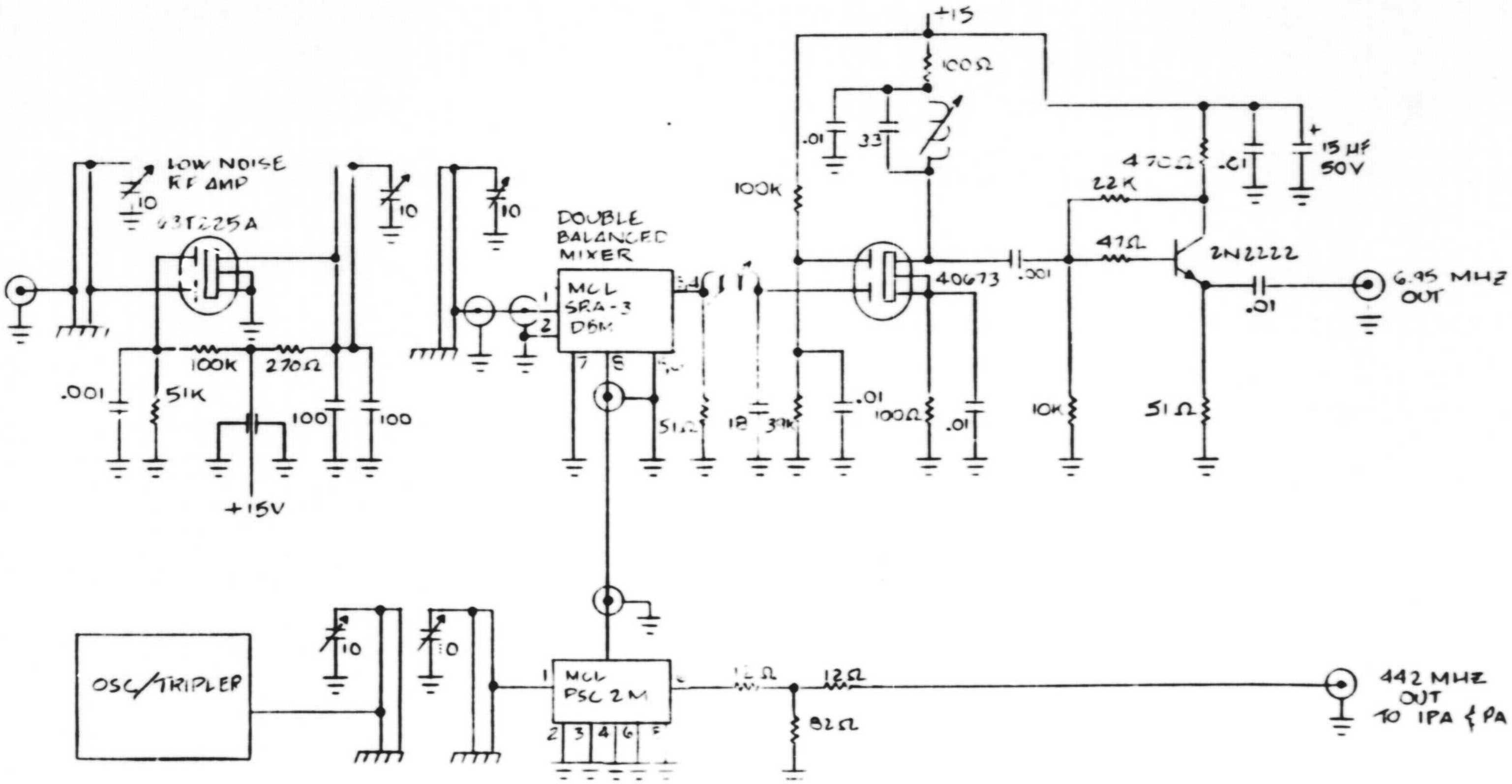

FIGURE C-7. RECEIVER AMP-MIXER AND TRANSMITTER OSCILLATOR/TRIPLER.

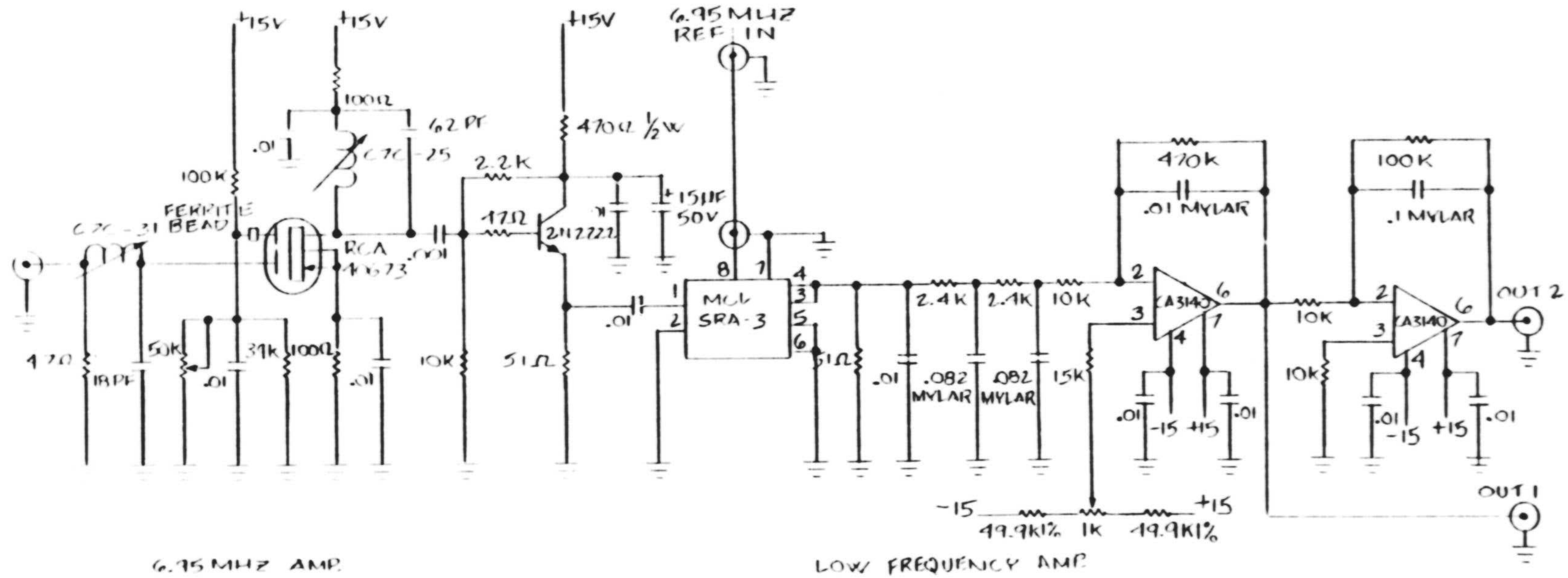

FIGURE C-8. 6.95 MHz AMPLIFIER-DETECTOR AND LOW FREQUENCY AMPLIFIER.