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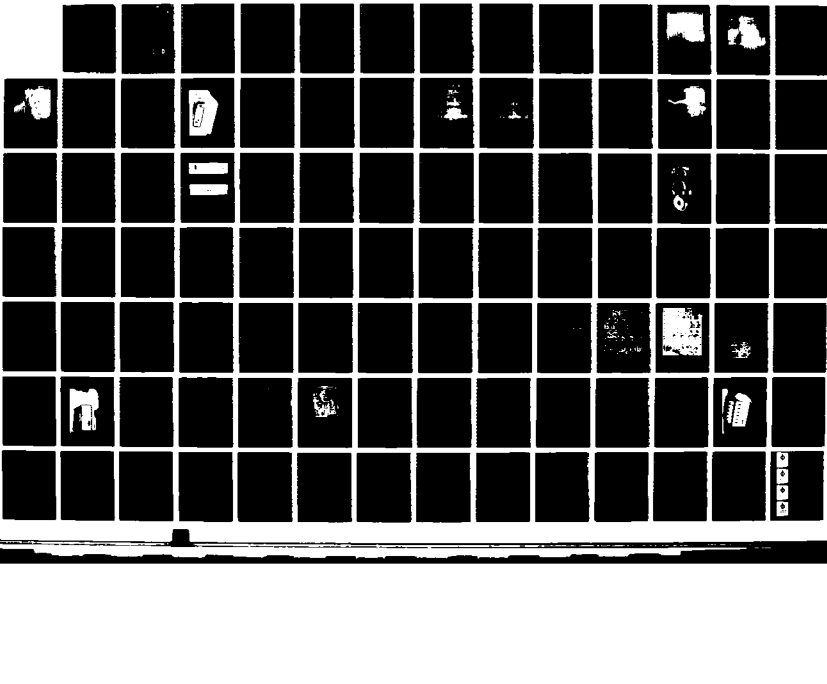

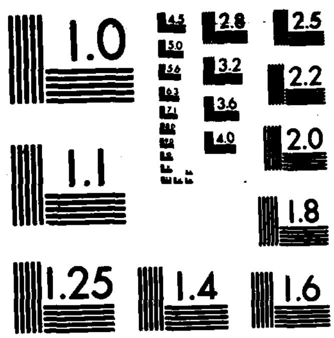

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A NOTCH FILTER INSTRUMENT FOR MEASURING ELF MSK SIGNALS

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This report presents a notch filter technique for measuring extremely low frequency (ELF) signals from the U.S. Navy's ELF Communications System in the presence of other higher-level, low frequency voltages, specifically 60 Hz and harmonics, on public utility systems. The report also describes the design, development, and operation of a special-purpose notch filter instrument that allows the practical realization of this measurement technique.

The instrument, called the Notch Box III, is compact (2.75 x 10 x 9 in.), lightweight (less than 4 lb), and battery operated for complete electrical isolation and portability of its electronic circuitry. It features input buffering and selectable attenuation, input overload warning, a narrow-band 60 Hz notch filter with greater than 80 dB of attenuation, a Chebyshev low-pass filter providing sharp roll-off above 100 Hz, output signal buffering, and battery charge status indication. The Notch Box III can operate 150 hours on a single battery charge. Keywords:

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FOREWORD

This report describes an upgraded special-purpose notch filter instrument, the Notch Box III, designed and built by IIT Research Institute (IITRI) under Contract No. N00039-84-C-0070 in support of the U.S. Navy's Extremely Low Frequency (ELF) Environmental Compatibility Assurance Program. The Notch Box III provides increased flexibility, efficiency, and reliability of operation over earlier versions.

The initial notch filter upgrade was conceived by Mr. J. Gauger. Preliminary design work was done by Messrs. R. Brosh, J. Gauger, and G. Nicholas. Final design was accomplished by Messrs. R. Drexler, J. Gauger, and R. Mizera.

Respectfully submitted,

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A NOTCH FILTER INSTRUMENT FOR MEASURING ELF MSK SIGNALS

1. INTRODUCTION AND BACKGROUND

The U.S. Navy's Extremely Low Frequency (ELF) Communications System provides a method for delivering messages in a reliable, secure manner to submarines operating well below the surfaces of the oceans.[1] Efforts to develop a practical ELF communications system began in the late 1960s. A fully operational facility has been built in the Chequamegon National Forest in northern Wisconsin, and another is being constructed in the Upper Peninsula of Michigan.

A transmitting antenna for ELF signals consists of a very long horizontal insulated cable powered by a transmitter.[2] The antenna current penetrates the earth at the grounded ends of the antenna and launches electromagnetic energy into the earth-ionosphere cavity. This earth return circuit generates a horizontal electric field in the earth parallel to the earth's surface that can induce longitudinal voltages in nearby grounded long conductors. Some common examples of long conductors that are susceptible to ELF-induced interference are:

- commercial power systems with multigrounded neutrals
- telephone systems
- cable television systems
- railroads
- pipelines
- fences.

The mechanisms of ELF earth return current coupling are well understood, and considerable effort has been expended to develop the capability to predict coupled interference.[3-8] In addition, much attention has been directed toward the development of engineering techniques to mitigate interference.[9-12] Both the coupling theory and the interference mitigation techniques have been tested at the Navy's Wisconsin Transmitting Facility (WTF).

Necessary to any successful ELF mitigation effort is the ability to measure the ELF interference. The center frequency of the Navy's ELF Communications System is 76 Hz. This signal must be selected and measured in the presence of other ELF frequencies common to public utilities. Of particular importance is the case of interference on commercial power lines. Here, the

60 Hz system voltages may be three or four orders of magnitude larger, and their harmonics one order of magnitude larger, than the ELF interference voltages.

If the ELF interference is in the form of a single-frequency sinusoid (referred to as continuous wave, or CW), a frequency-selective voltmeter may be used to make the interference measurements. Such a voltmeter can "lock" on a CW signal of a particular frequency and reject other frequencies outside the meter's bandwidth. Special narrow-bandwidth frequency-selective voltmeters were constructed for the Navy and were used along with Hewlett Packard 302A signal wave analyzers for interference mitigation and other measurements at the WTF early in the program. More recently, Hewlett Packard 3581A signal wave analyzers have been used that have a bandwidth selectable from 1 Hz to 300 Hz.

Through August 1976, all interference mitigation measurements were made with CW signals, as this was the predominant testing mode of the WTF up to that time. In September 1976, however, the WTF began transmitting on a 24-hour schedule using a modulated signal. This signal is a type of frequency modulation (FM) called minimum shift keying (MSK), in which the transmitted signal is switched between two frequencies at a given modulation rate. The lower frequency is 72 Hz and the higher frequency is 80 Hz, giving a center or average frequency of 76 Hz.

The measurement of MSK modulated signal in the presence of the 60 Hz power distribution frequency is much less straightforward than for CW signals under the same conditions. The frequency-selective voltmeters mentioned above are not adequate for the following reasons:

- a single, continuous interference frequency is not present for the frequency selective meter to "lock" on
- a wider bandwidth meter must be employed in order to include as much of the frequency spectrum of the MSK signal as possible, but this wider bandwidth will also include the 60 Hz component whose rejection is desired.

To overcome the problem, a notch filter technique was developed for measuring MSK signals in the presence of 60 Hz and its harmonics. A special multiple-frequency notch filter instrument was designed to eliminate 60 Hz, along with its third and fifth harmonics, from the MSK signal. Initially, three such "notch boxes" were fabricated. These instruments were used in conjunction with Hewlett-Packard HP3581A signal wave analyzers, which were normally set for a 30 or 100 Hz bandwidth. Together, these two instruments allowed measurement of the MSK frequency components while excluding the 60 Hz components and other unwanted low frequency signals.

The original notch filter instruments, fabricated nearly 12 years ago, went through one significant performance upgrade. The capabilities of these second-generation instruments, however, were limited by the circuit fabrication technology available at the time of their design. Major constraints were low signal level handling ability and high power consumption. The latter forced the use of bulky, heavy batteries to obtain single-day operation.

To overcome these problems, a third-generation notch filter instrument was conceived that would take advantage of recent advances in integrated circuit technology and improve performance, ease of use, and reliability. Micropower circuitry provided a reduction in power consumption to 1/100th that of the earlier instruments, resulting in an instrument only one-half the size of its predecessor, one-fourth its weight, and able to operate 20 times as long on a single battery charge. Significant improvements were also realized in signal level handling ability, noise performance, and filter response. Several new features were added to assist the instrument user, including additional input voltage ranges, indication of remaining battery capacity, input signal overload warning and disconnect, and options for external power input.

The following sections of this report describe the notch filter measurement technique in more detail, and document the design and development of the improved notch box--the Notch Box III. Section 2 centers on the system design and realization of the upgraded notch filter instrument; Section 3 gives details of the instrument's performance and specifications; and Section 4 deals with instrument operating considerations. Appendixes provide circuit descriptions and layouts, battery charger designs, troubleshooting procedures, and special device characteristics.

2. SYSTEM DESIGN

2.1 MSK Signal Characteristics and Measurement Requirements

As stated previously, MSK is the modulation scheme for the ELF Communications System. MSK is a special form of FM, sometimes referred to as phase continuous frequency shift keying (FSK). The transmitted signal is at one of two discrete frequencies: the higher frequency is called the mark frequency (f_h), and the lower frequency is called the space frequency (f_l). The average of the mark and space frequencies is called the center frequency (f_o). The frequency of change between the mark and space frequency is called the chip or modulation rate (f_c). MSK also requires that the signal change frequency only at the peaks or zero crossings of the sinusoidal wave.

Since MSK is a form of FM, its frequency spectrum is similar to an FM spectrum. The MSK spectrum has its main peak at the center frequency and has declining peaks corresponding to the upper and lower sidebands, with increasing and decreasing frequency, respectively. Figure 1 shows the spectrum analysis of a signal from an IITRI-fabricated MSK Signal Generator.[13] The signal analyzed has space, center, and mark frequencies of 72, 76, and 80 Hz respectively, and a modulation rate of 16 Hz with a pseudo-random pattern. It should be noted that the main spectral peak shown in Figure 1 is about 25 Hz wide, extending to within about 4 Hz of the 60 Hz power line frequency.

This point is further illustrated in Figure 2, which shows the frequency spectrum of the sum of an MSK signal and a 60 Hz signal of approximately the same amplitude. Here it can be seen that the 60 Hz signal completely dominates the first lower sideband of the MSK signal. Thus, the measurement of MSK signals in the presence of the 60 Hz power line frequency poses two seemingly conflicting requirements:

- the bandwidth of the measuring instrument must be limited but relatively wide to include enough of the MSK frequency spectrum to yield an accurate reading
- the bandwidth of the measuring instrument must be narrow with sharp cutoffs to reject 60 Hz signals, which in many cases will be much higher in amplitude than the MSK signal.

The above requirements suggest two possible MSK measurement techniques. The second requirement implies that a sharp cutoff band-pass filter of the proper design might be used to limit the signal passed to the measurement

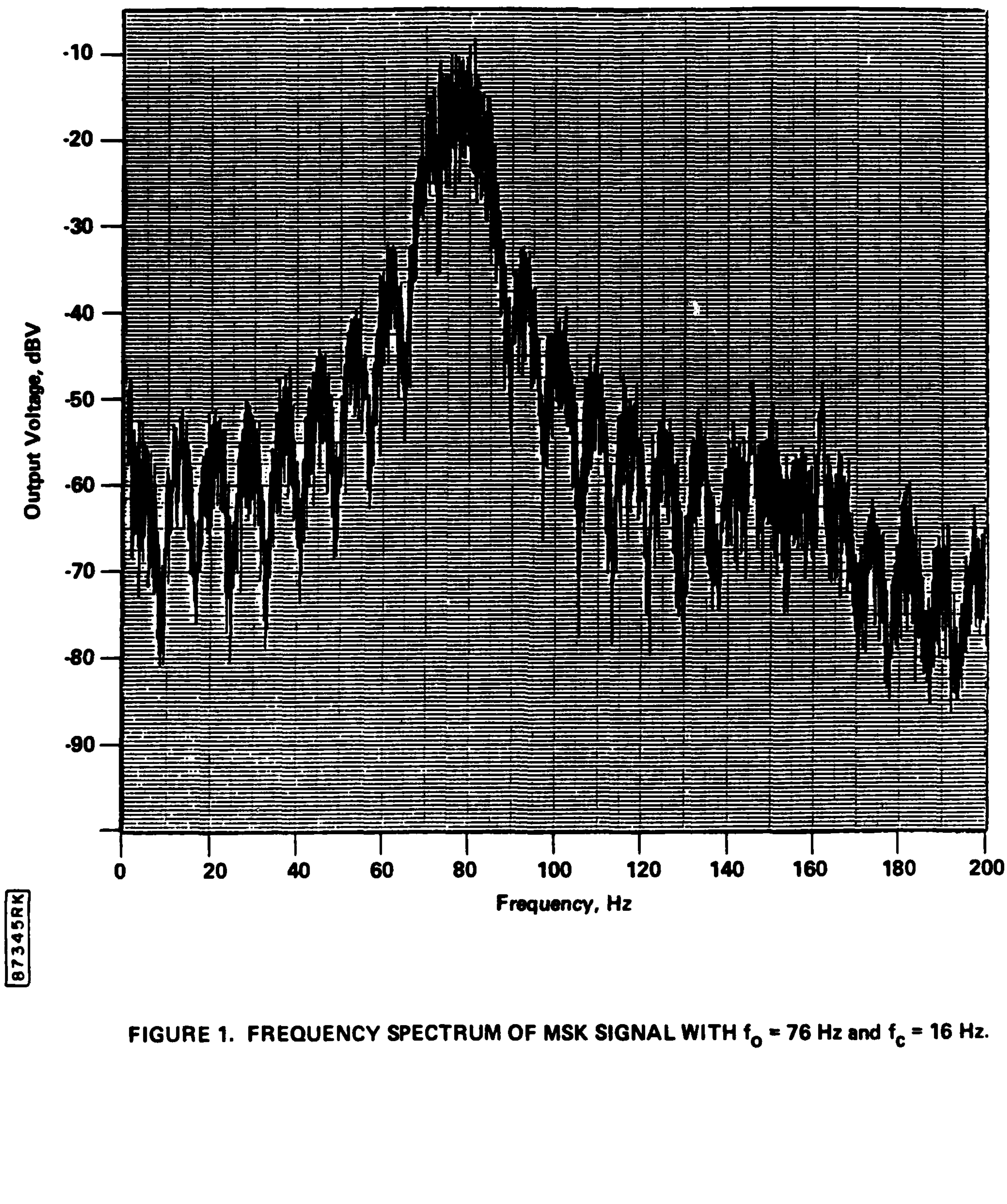

FIGURE 1. FREQUENCY SPECTRUM OF MSK SIGNAL WITH f_o = 76 Hz and f_c = 16 Hz.

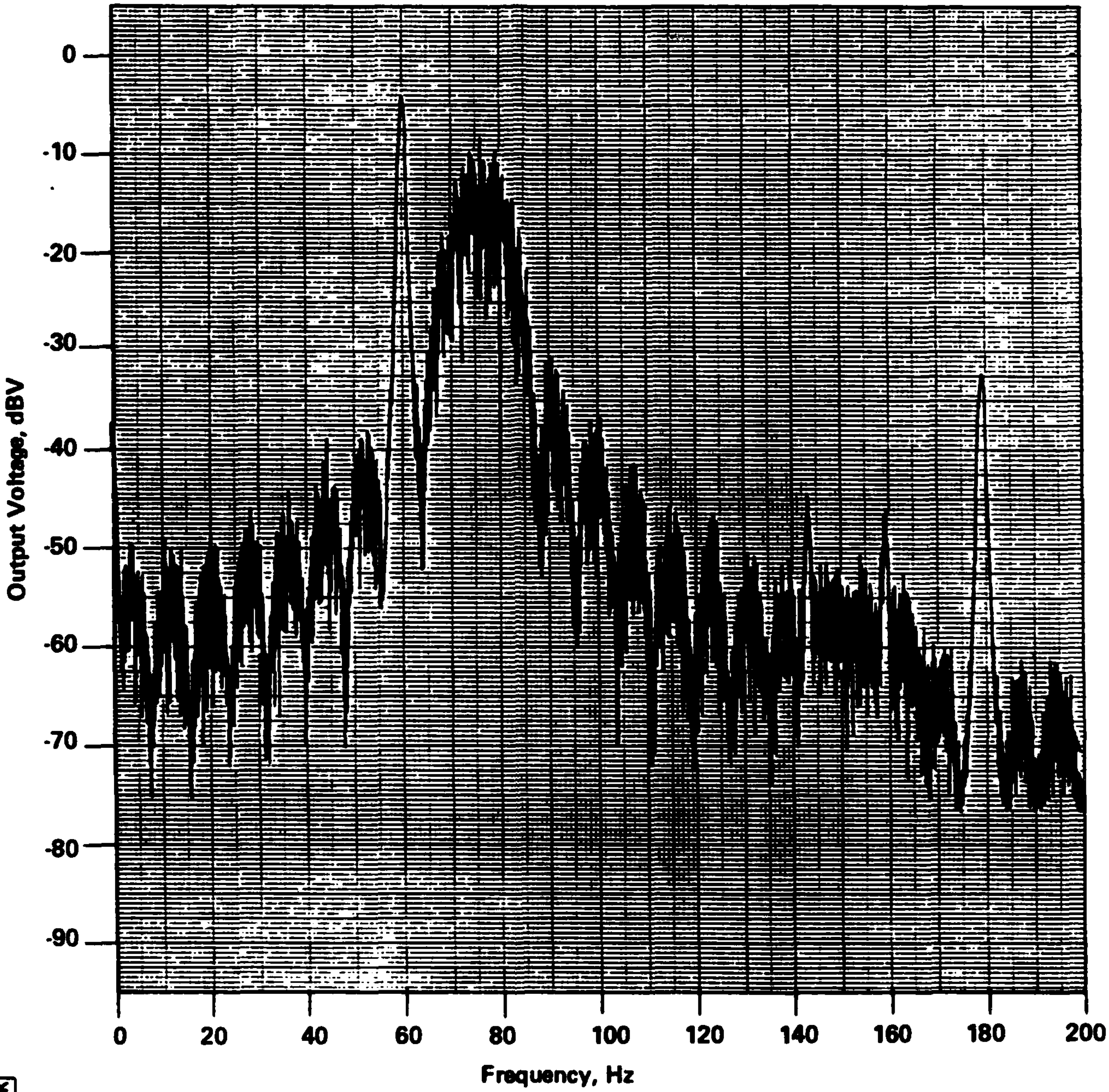

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FIGURE 2. FREQUENCY SPECTRUM OF MSK SIGNAL WITH f_o = 76 Hz AND f_c = 16 Hz, PLUS 60 Hz SIGNAL OF APPROXIMATELY THE SAME AMPLITUDE.

instrument to only those frequencies contained in the main spectral peak of the MSK signal. The primary disadvantage of this approach is that any change in the MSK signal characteristic or an attempt to measure the MSK harmonics would require different band-pass filters.

The use of a wider meter bandwidth, as called for in the first requirement, will give accurate MSK measurements only if 60 Hz signals and harmonics are not present. This implies elimination or subtraction of the unwanted frequency components. Removal of the 60 Hz components can be accomplished with narrow-band, sharp cutoff notch filters centered at 60 Hz and the principal 60 Hz harmonics. This notch filter technique has the advantage of not needing modification if the MSK signal frequencies are changed or if measurement of the first few MSK signal harmonics is required. A sharp roll-off low-pass filter can be substituted for the notch filters at the 60 Hz harmonic frequencies if measurement of MSK harmonic frequencies is not required. These techniques can also aid in measuring CW signals near 60 Hz because they improve the overall dynamic range of the measurement system, allowing the measurement of lower signal levels.

2.2 A Notch Filter Measurement System

The method selected for measuring the MSK signals uses a series of notch and low-pass filters in conjunction with a frequency-selective voltmeter. This technique offers flexibility in terms of the types and frequencies of signals that can be measured and also produces minimum distortion of the MSK frequency spectrum passed to the meter used for the measurements. The latter point is illustrated in Figure 3. This figure shows the spectrum analysis of the same MSK plus 60 Hz signal used to generate Figure 2, after having been passed through a Notch Box III filter instrument. It should be noted that although the first lower sideband is virtually eliminated because it is centered at 60 Hz, the main spectral peak and the first few remaining sidebands of the MSK signal are essentially unchanged.

A block diagram of the notch filter technique for measuring ELF MSK signals is shown in Figure 4. There are three main blocks: an MSK signal source, a notch filter instrument, and a frequency-selective voltmeter. The MSK signal source might be in the form of interference induced on public utilities such as power and telephone lines or on railroads, fences, and

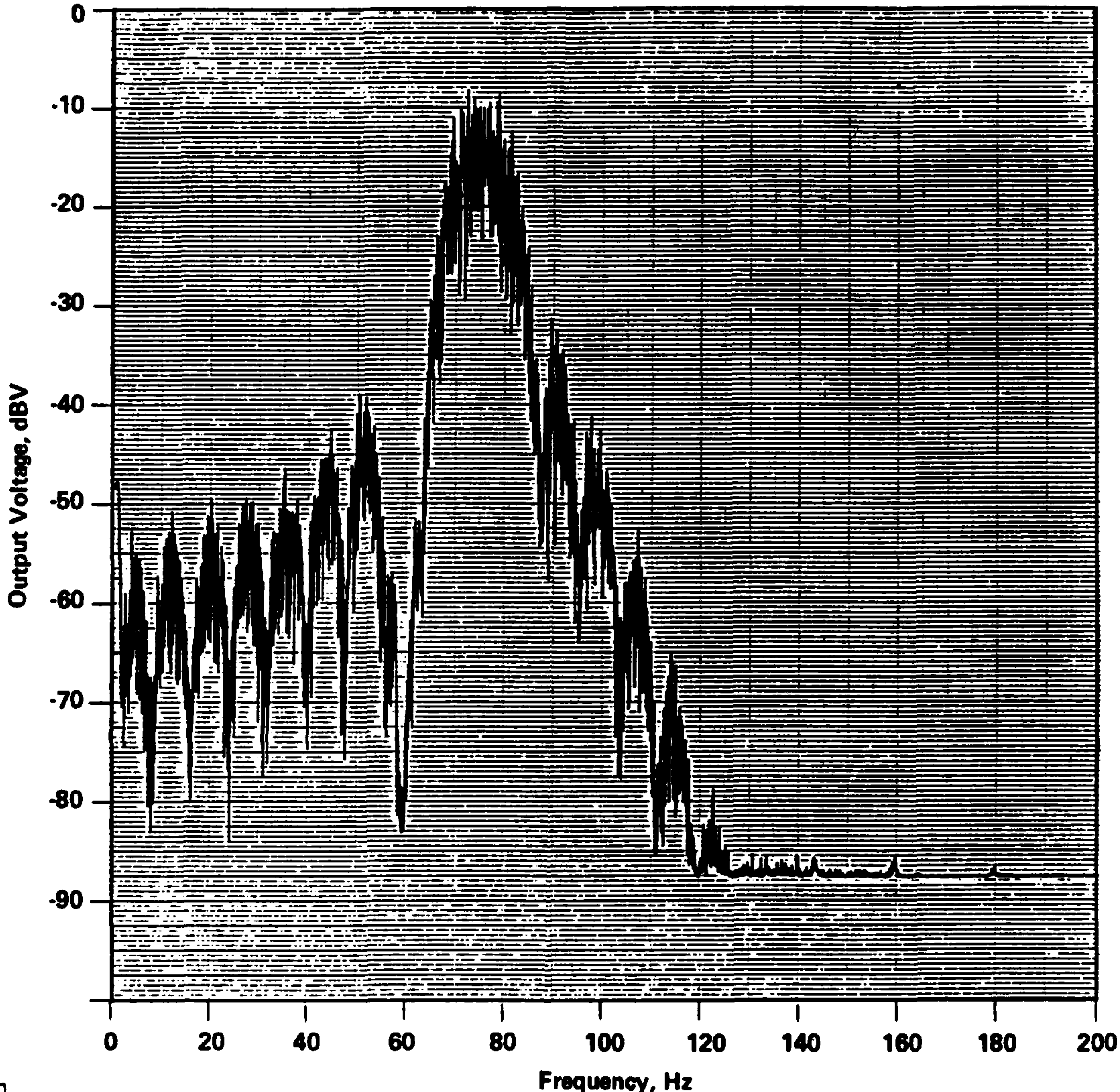

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FIGURE 3. FREQUENCY SPECTRUM OF MSK SIGNAL WITH $f_o = 76$ Hz AND $f_c = 16$ Hz, PLUS 60 Hz SIGNAL OF APPROXIMATELY THE SAME AMPLITUDE AFTER PASSING THROUGH NOTCH BOX.

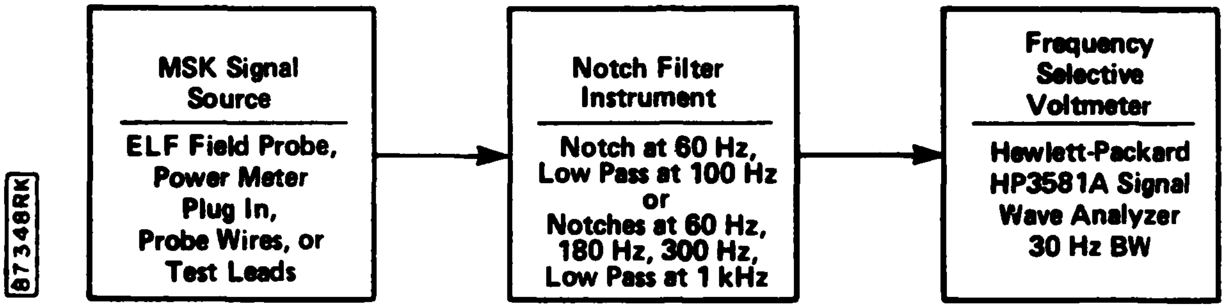

FIGURE 4. BLOCK DIAGRAM OF THE NOTCH FILTER TECHNIQUE FOR MEASURING ELF MSK SIGNALS.

pipelines. Near an ELF Communications System antenna, the MSK signal might be in the form of the electric and magnetic fields generated by the antenna. As such, the input to the notch filter instrument might be from an electric or magnetic field probe, a power meter adapter, a set of ground probe wires, or ordinary test leads.

The notch filter instrument and the frequency-selective voltmeter employed are battery-powered units; this provides portability and electrical isolation. The notch filter instrument contains multiple narrow-band notch filters at 60 Hz and harmonic frequencies or 60 Hz notches only in conjunction with sharp roll-off low-pass filters at 100 Hz, as indicated. The frequency-selective voltmeter is the commercially available Hewlett Packard 3581A signal wave analyzer, which has selectable bandwidths from 1 to 300 Hz. During data measurement, the wave analyzer is tuned to the center frequency of the MSK signal source, but cannot be AFC "locked."

2.3 Notch Filter Instrument

A block diagram of the upgraded notch filter instrument, the Notch Box III, is shown in Figure 5. Figure 6 is a photograph of the Notch Box III. The following paragraphs describe each of the blocks in Figure 5.

The Notch Box III was intended to be used over a wide range of input voltages (0 to 240 V_{rms}) and operate from a small, nominally 12 V battery

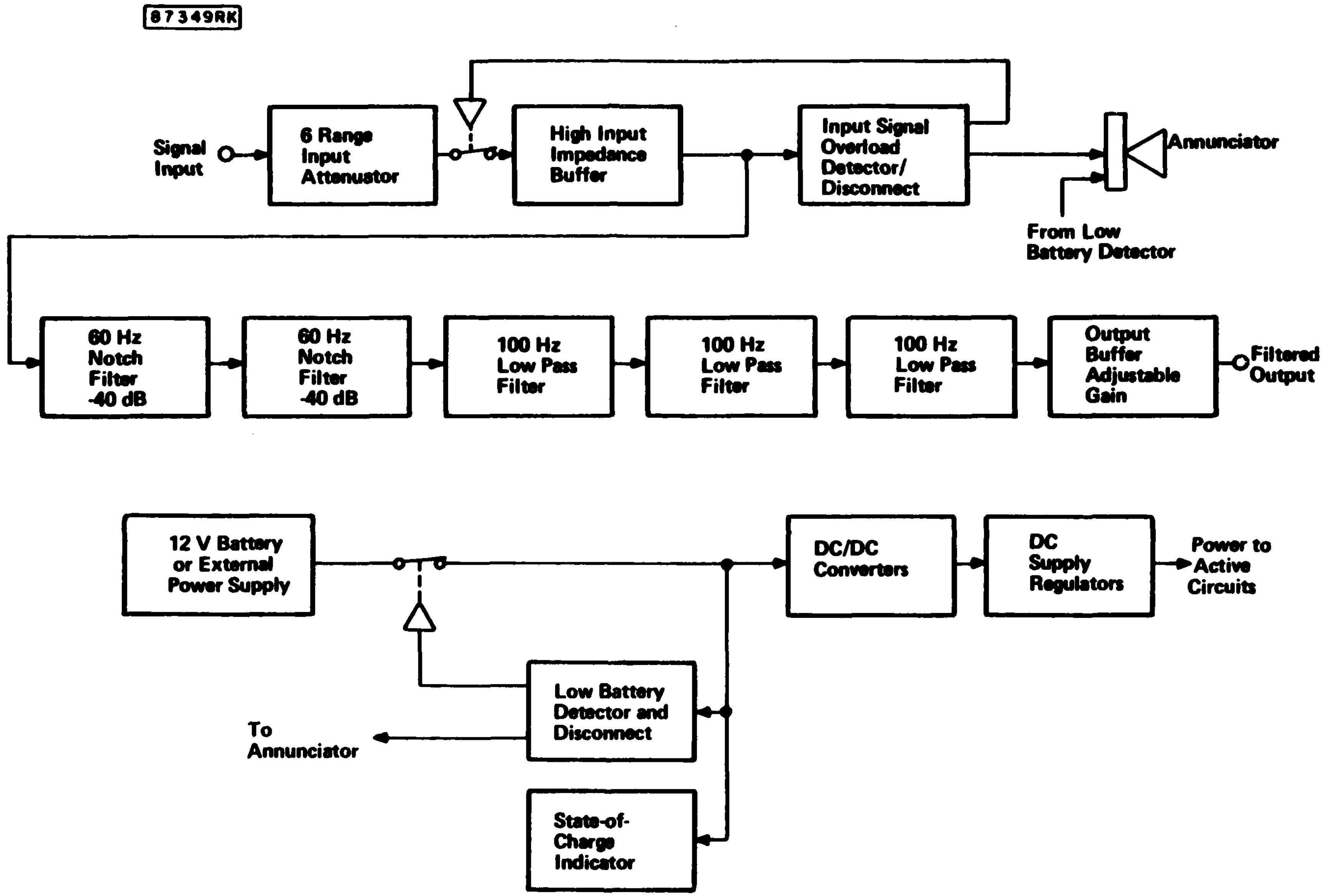

FIGURE 5. NOTCH BOX III BLOCK DIAGRAM.

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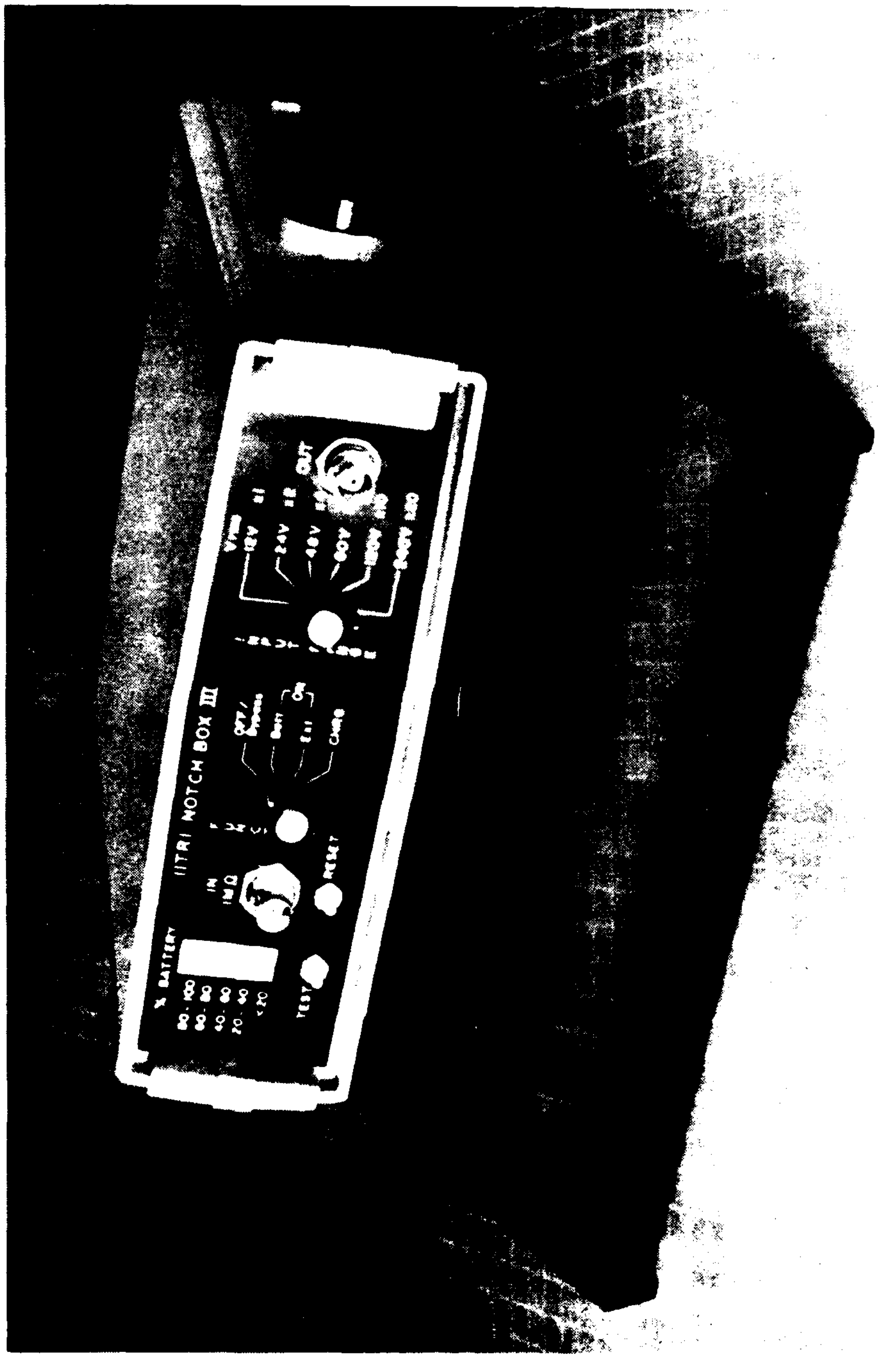


FIGURE 6. PHOTOGRAPH OF NOTCH BOX III.

source. Circuitry had to be devised that could achieve this without compromising accuracy. A notch filter instrument that can meet these requirements was realized by a design that limits the input signal amplitude to a level of 6 V_{rms}, thereby assuring solid linear operation of all circuitry. This was accomplished in the Notch Box III by using an input attenuator to provide six distinct input signal ranges. Minimum attenuation is a factor of two. The signal input is ac-coupled to the attenuator input, where a high input impedance is provided to minimize loading of the MSK signal source.

A high input impedance unity gain buffer amplifier follows the input attenuator. This buffer provides impedance matching to prevent the filter modules from loading the attenuator.

The output of the buffer amplifier is also fed to a micropower voltage detector. The voltage detector senses the peak value of the input signal and disconnects the input to the buffer when the predetermined safety level is exceeded. An annunciator alerts the user to this condition. This overload protection guards against nonlinear operation of the active devices, which can result in increased distortion, the generation of unwanted harmonics, and damage to the active devices.

The filter blocks are realized by using commercially available low power active filter modules. Five modules, placed in series, are used in the Notch Box III--two 60 Hz notch filters and three low-pass filters having corner frequencies at 100 Hz. This combination of filters is used to reject the unwanted 60 Hz, 60 Hz harmonics, and any spurious high frequency noise.

Following the filter series is an adjustable gain output buffer amplifier. This buffer is used to provide: (1) reasonable output signal drive, (2) output short-circuit protection, (3) a low output impedance, (4) a gain to compensate for the minimum input attenuation, and (5) a means of trimming the passband gain. The Notch Box III is normally adjusted for unity gain (0 dB) at a frequency of 76 Hz, the center frequency of the MSK signal. The buffer amplifier directly drives the output.

To allow for a maximum amount of flexibility, the Notch Box III has been designed to operate from a variety of power sources. The standard power source is six internal "AA" size rechargeable lithium batteries. These batteries have sufficient capacity to power the instrument continuously for

150 hr. Should the lithium batteries fail or become unavailable, eight "AA" size non-rechargeable alkaline batteries may be installed instead. An external dc power supply option is also provided via a jack on the rear panel.

Two circuits are used to monitor the battery voltage: a state-of-charge indicator and a low battery detection/disconnect circuit. The state-of-charge indicator circuit employs an LED bar graph to display the remaining battery capacity in 20% increments. The low battery detector triggers the annunciator to sound at 30-second intervals when less than 20% capacity is left, and disconnects the battery pack at the end of its useful capacity to avoid battery damage from deep discharge.

The power source, whether battery or external dc voltage, is fed to a pair of dc/dc converters that step it up to provide two sets of balanced plus/minus supplies. These stepped up voltages are further conditioned by four low-power voltage regulators to obtain the levels required by the active filters and amplifiers.

3. NOTCH BOX III PERFORMANCE

3.1 Transfer Function

The Notch Box III filter modules employ active filter synthesis techniques to achieve multiple-pole realizations with sharp cutoffs and steep skirts. Each notch filter provides a minimum attenuation of 40 dB at 60 Hz, and typically achieves 50 dB. The -3 dB and -50 dB bandwidths of the notch filter modules are 8 Hz and 1 Hz, respectively. The passband response of these filters is given by the manufacturer as ± 0.3 dB (approximately 1%). The low-pass filter modules employed are four-pole Chebyshevs with roll-offs of -24 dB/octave and -3 dB corners at 100 Hz. The passband ripple of these filters is given by the manufacturer as ± 0.25 dB (approximately 1%). All of the above filter modules employ low-power designs that require quiescent currents of only 100 μA and 30 μA, respectively, for each notch and low-pass function.

In addition to the active filter modules, the Notch Box III also has a passive single-pole high-pass filter element formed by the input ac-coupling capacitor and attenuator resistor network. The input combination provides a transfer characteristic with a low frequency -3 dB corner at 4 Hz.

The composite Notch Box III transfer function formed by the above filtering has been plotted in Figure 7. The low frequency corner, 60 Hz notch, and high-pass corner are clearly visible. It should be noted that at least 80 dB of rejection is provided at 60 Hz, 23 dB at 120 Hz, and 80 dB at frequencies of 180 Hz and above. The two usable passbands are from 10 to 50 Hz and from 69 to 90 Hz. This graph was generated using an X-Y recorder driven by an HP3581A signal wave analyzer in the frequency sweep mode with a 1 Hz measurement bandwidth. The corresponding phase response is shown in Figure 8. This phase response was obtained using an HP3575A gain/phase meter in conjunction with the X-Y recorder and the swept frequency output of the HP3581A.

3.2 Signal Port Characteristics

The Notch Box III has two signal ports on the front panel in the form of BNC connectors labeled IN and OUT. The input signal port is designed to accept a wide range of signal levels without being overloaded, block dc

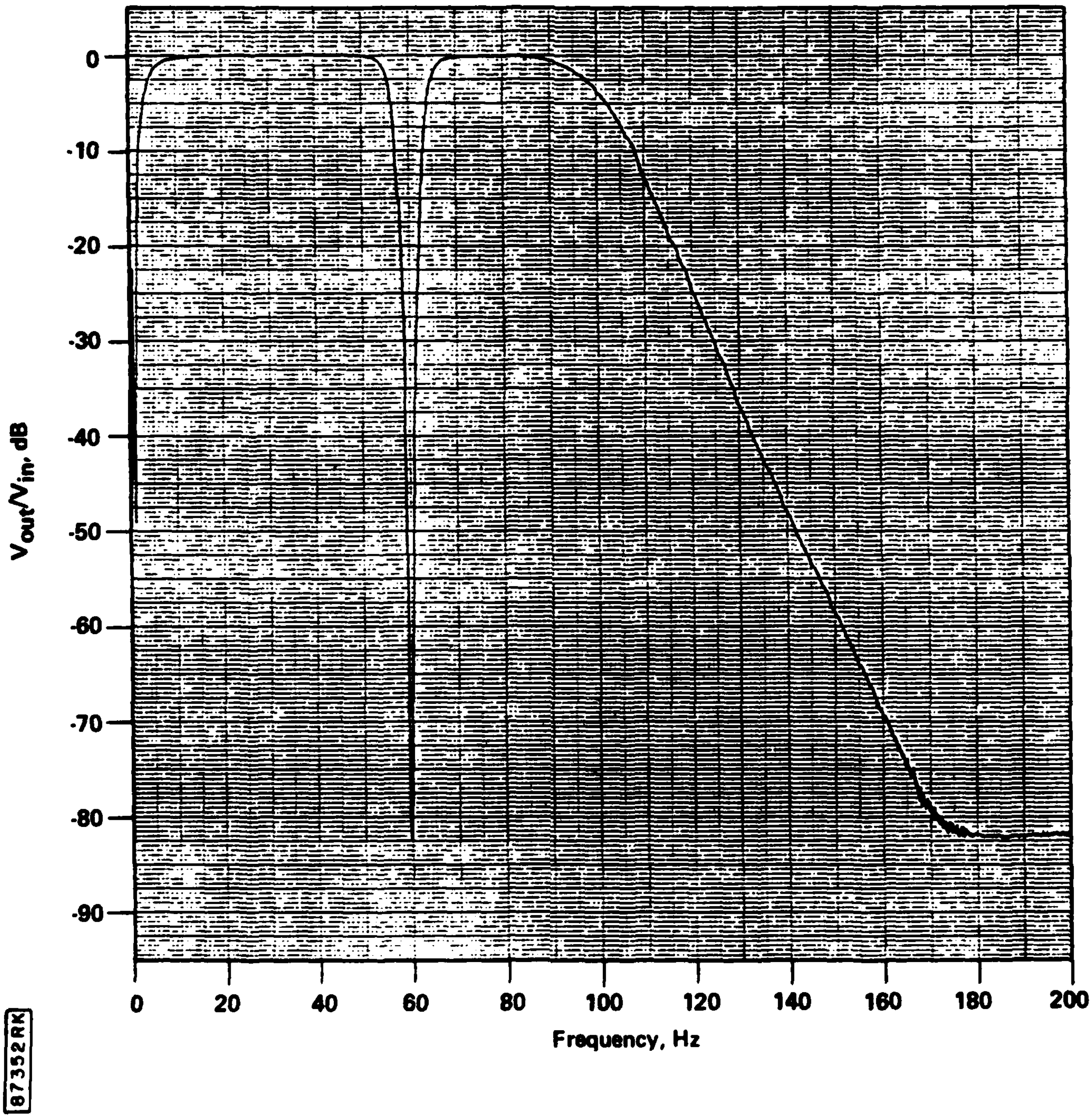


FIGURE 7. NOTCH BOX III TRANSFER FUNCTION, 12 V INPUT RANGE.

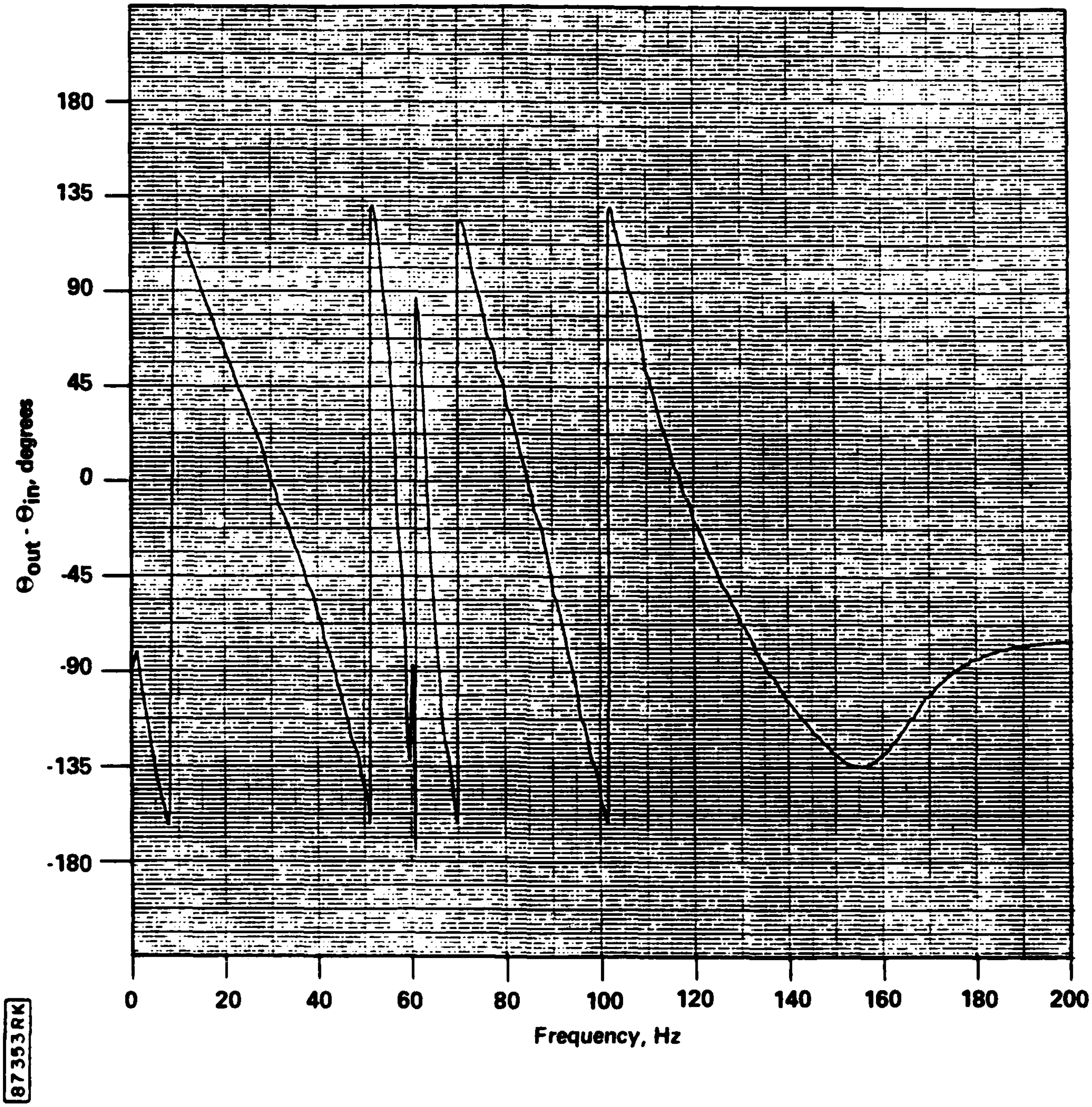


FIGURE 8. NOTCH BOX III PHASE RESPONSE.

voltages, and present a high input impedance to avoid loading the signal source. The output signal port is designed to present a low output impedance and have sufficient power to drive the capacitance of a coaxial output cable without distortion.

3.2.1 Input

Input signal overload can cause two main problems: nonlinear circuit operation and damage to active circuitry. Nonlinear operation will occur when excessive signal levels drive the active circuit elements into saturation or cutoff. The Notch Box III controls the signal level to its active circuitry by using a selectable input attenuator to accommodate six ranges of rms voltage (V_{IN}) at its input jack: 12, 24, 48, 60, 120, and 240 V. Minimum attenuation on the 12 V range is a factor of two. This limits internal signal levels at the filter module inputs (V_{FI}) to a nominal 6 V_{rms}. For values of V_{FI} in excess of 6.5 V_{rms} (9.2 V_{peak}) the filters will begin to generate high levels of input frequency second harmonics. Signal overload is automatically circumvented by a voltage detector circuit set to trigger when V_{FI} = 9 V_{peak}. This circuit disconnects the attenuator output from the buffer amplifier via a magnetic latching relay. However, this requires a finite amount of time, during which high-level overloads or fast transients could damage the buffer amplifier inputs. Low-leakage clamping diodes have been placed at the buffer inputs to prevent damage for input signal transients as high as V_{IN} = 50 kV_{peak}. Input voltages greater than 500 V_{rms} will still exceed the power rating of the input attenuator resistors and may damage the ac-coupling capacitor. A summary of input voltage levels as a function of the input range setting is given in Table 1.

The resistive network of the input attenuator presents a 1 MΩ input impedance to minimize loading of the input signal source. The input is connected to the attenuator network via an ac-coupling capacitor. Together, the input attenuator and ac-coupling capacitor form a single-pole high-pass filter with a corner frequency of 4 Hz. The Notch Box III input connector is switched directly to the output connector by the FUNCTION selector switch when in the OFF/BYPASS position. This facilitates notch box in/out comparative measurements.

TABLE 1. NOTCH BOX III INPUT VOLTAGE LEVELS

	Input Range Setting, V_{rms}*					
	12	24	48	60	120	240
Input Overload Cutoff Voltage, V_{peak}	18	36	72	90	180	360
Input Overload Cutoff Voltage, V_{rms}*	12.8	25.6	51.2	64	128	256
Maximum Input Voltage for Linear Operation, V_{rms}*	13	26	52	65	130	260

* rms levels assume single frequency voltages.

3.2.2 Output

The output port of the Notch Box III is driven directly by an operational amplifier. Thus, the output characteristics of the port are essentially those of the operational amplifier. The output operational amplifier has a low output impedance of 0.1 Ω, and can drive an output voltage swing of 13 V_{rms} into a minimum load impedance of 10 kΩ. The output may be shorted indefinitely without damaging the amplifier. The output stage has an approximate gain of two that compensates for the minimum attenuation of two at the input, providing a nominal passband gain of one (0 dB). Exact adjustment of the passband gain is accomplished via a 15-turn potentiometer. The 0 dB point is usually set at a frequency of 76 Hz, the MSK signal center frequency.

Output noise level is another important parameter of the output port. Some noise is generated in each active circuit within the instrument, with the filter modules being the dominant source. The filters are specified to have a maximum output noise of 50 μV from dc to 50 kHz with their inputs grounded. When connected in cascade, however, the individual module inputs are not grounded, and some noise accumulation will occur from stage to stage. The measured noise will be a function of the type of voltmeter used and the meter's bandwidth.

A frequency spectrum of the Notch Box III output noise from 0 to 200 Hz is presented in Figure 9. This curve was obtained using an X-Y recorder driven by an HP3581A signal wave analyzer in frequency sweep mode with a 30 Hz measurement bandwidth. The noise below 20 Hz is due to the wave analyzer. It

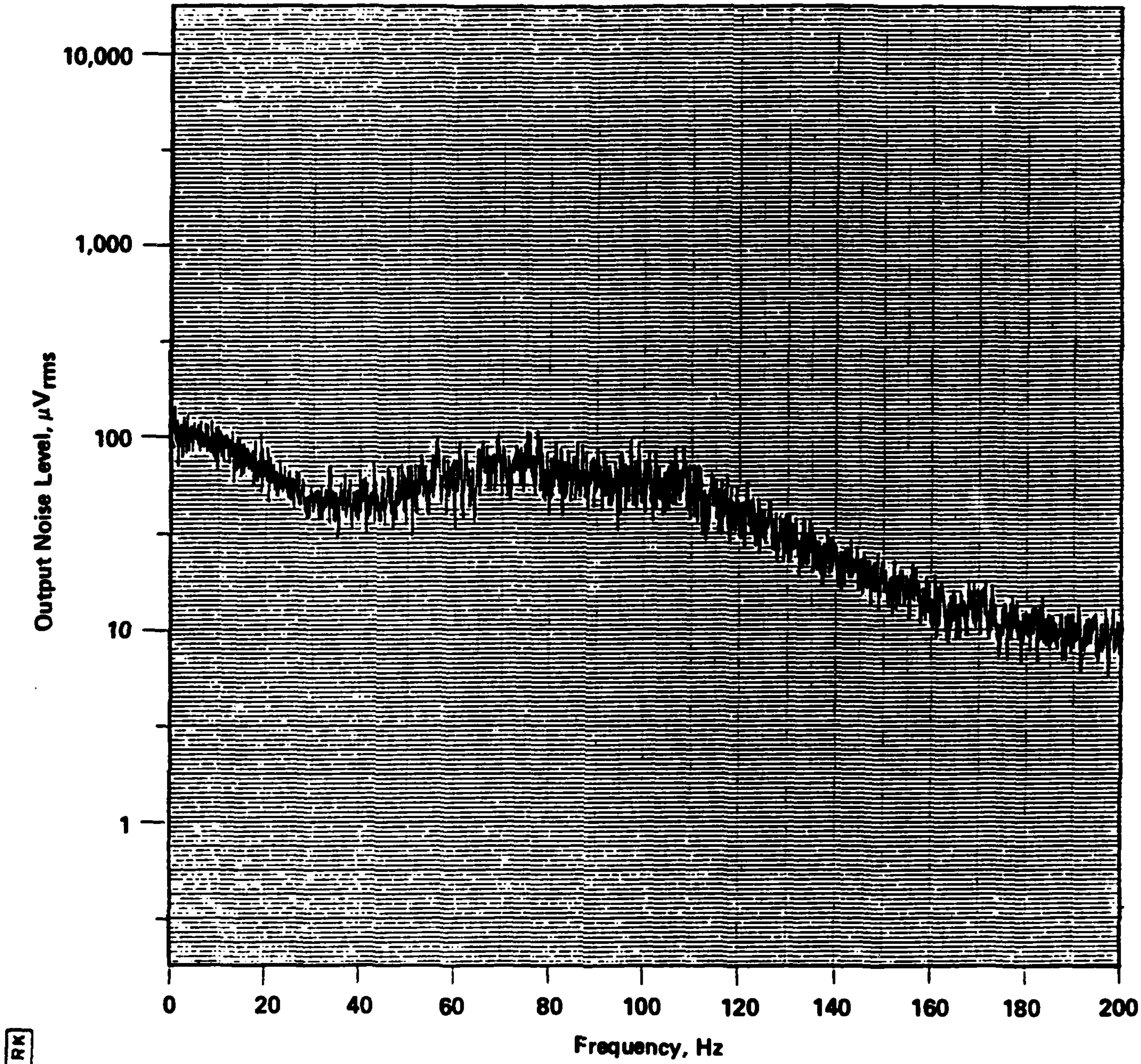


FIGURE 9. NOTCH BOX III OUTPUT NOISE WITH INPUT GROUNDED, 30 HZ METER BANDWIDTH.

should be noted that the maximum noise level is less than 100 μV_{rms} for this bandwidth, and that a noise peak occurs between 50 and 100 Hz. This peak is likely due to phase jitter that occurs in the notch filters, as shown in the phase plot in Figure 8 and the notch filter specification sheet in Appendix E.

Comparative measurements of the Notch Box III output noise have been made using a variety of meters and bandwidths. All measurements were made with the input shorted to ground and the input range on minimum attenuation. Table 2 summarizes these noise measurements. The table shows that the measured output noise is a strong function of the meter bandwidth. Therefore meter bandwidth will dictate the minimum signal that can be measured in the presence of the output noise.

TABLE 2. NOTCH BOX III OUTPUT NOISE LEVELS WITH INPUT GROUNDED

Measurement Instrument	Measurement Bandwidth	Noise Level, μV_{rms} at f = 76 Hz*	Noise Level, μV_{rms} at f = 44 Hz*
HP3581A	3 Hz	50	40
	10 Hz	75	55
	30 Hz	100	80
	100 Hz	110	110
Fluke 8060A	200 kHz	160	
HP403B	1 mHz	420	

*Applies to HP3581A only; 8060A and HP403B measurements are not frequency-specific.

3.3 Measurement Verification

Several tests have been performed to verify the capability of the Notch Box III when used in conjunction with a limited bandwidth meter to accurately measure MSK signals. Measurements of the MSK signal taken with the wideband Fluke 8060A rms digital multimeter and HP403B ac rms voltmeter were used as benchmarks. Comparative readings were also made using a CW signal at the MSK center frequency. A 1 V_{rms} signal amplitude, as set with a Fluke 8060A, was used for all measurements. A summary of the test data is given in Table 3.

The table shows that the HP403B and Fluke 8060A wideband meters read identically for both CW and MSK signals at 76 Hz. It also shows that the

TABLE 3. COMPARATIVE MEASUREMENTS

Measurement Instrument	Measurement Bandwidth	Measured Voltage, V_{rms} 76 Hz CW Notch Box Bypassed	76 Hz CW Notch Box In	76 Hz MSK Notch Box Bypassed	76 Hz MSK Notch Box In
HP3581A	3 Hz	1.00	1.00	0.58	0.58
	10 Hz	1.00	1.00	0.90	0.90
	30 Hz	1.00	1.00	0.98	0.98
	100 Hz	1.00	1.00	1.00	1.00
Fluke 8060A	200 kHz	1.00	1.00	1.00	1.00
HP403B	1 MHz	1.00	1.00	1.00	1.00

Notch Box III has no effect on these wide-band measurements, verifying that the MSK signal is passed through the instrument without significant degradation. Measurements taken with the HP3581A selective bandwidth meter indicate, as expected, that the bandwidth setting has considerable influence on the measured value of MSK signals. This meter read 42% low on the 3 Hz bandwidth setting, 10% low on the 10 Hz bandwidth, and 2% low on the 30 Hz bandwidth. The meter read identically to the wideband meters on the 100 Hz bandwidth setting and for all CW measurements.

As a result of these comparative measurements and the output noise measurements, the use of the Notch Box III with the HP3581A in the 30 or 100 Hz bandwidth setting is recommended for measuring low-level MSK signals in the presence of strong 60 Hz signals. This should provide the highest accuracy with the lowest noise floor. These instruments should be used with shielded cable whenever possible to avoid pickup of any extraneous RF noise that could cause false readings.

3.4 Performance Specifications

Performance specifications for the Notch Box III are summarized in Table 4.

TABLE 4. NOTCH BOX III PERFORMANCE SPECIFICATIONS (page 1 of 2)

Transfer Characteristics	
High-Pass Corner (-3 dB)	4 Hz
60 Hz Notch	
Corners (-3 dB)	56 Hz, 64 Hz
Min. Atten. @ 60 Hz	80 dB
Low-Pass	
Corner (-3 dB)	100 Hz
Min. Atten. @ 120 Hz	23 dB
Min. Atten. ≥180 Hz	80 dB
Passbands	
Low Band	10 Hz to 50 Hz
High Band	69 Hz to 90 Hz
Insertion Gain/Loss	0 ± 1 dB
0 dB Gain Set Point	76 Hz
Input Characteristics	
Input Impedance	1 MΩ, ac-coupled, all ranges
Input Voltage	
Max. Safe	500 V_{rms}
Max. Operating	106% of range setting (rms)
Range/Attenuation	12 V_{rms}/0 dB
	24 V_{rms}/6 dB
	48 V_{rms}/12 dB
	60 V_{rms}/14 dB
	120 V_{rms}/20 dB
	240 V_{rms}/26 dB
Output Characteristics	
Output Impedance	0.1 Ω
Rated Output	13 V_{rms} for R_L ≥ 10 kΩ
Short Circuit Output Current	±15 mA
Output Short Circuit Protection	Continuous to ground
Output Noise (input grounded)	
HP3581A @ 3 Hz BW	40 μV_{rms} @ 44 Hz, 50 μV_{rms} @ 76 Hz
HP3581A @ 10 Hz BW	55 μV_{rms} @ 44 Hz, 75 μV_{rms} @ 76 Hz
HP3581A @ 30 Hz BW	80 μV_{rms} @ 44 Hz, 100 μV_{rms} @ 76 Hz
HP3581A @ 100 Hz BW	110 μV_{rms} @ 44 Hz, 110 μV_{rms} @ 76 Hz
Fluke 8060A (200 kHz BW)	160 μV_{rms}
HP403B (1 MHz BW)	420 μV_{rms}

TABLE 4. NOTCH BOX III PERFORMANCE SPECIFICATIONS (page 2 of 2)

Power Requirements

Quiescent Current	4 mA @ +12 Vdc, 25°C
Lithium Battery Pack	
Nominal Voltage	+14.4 V
Cutoff Voltage	+ 8.0 V
Operating Time (quiescent)	150 hr @ 25°C
Charge Time (full)	12 hr @ 25°C
Alkaline Battery Pack	
Nominal Voltage	+12 V
Cutoff Voltage	+6.9 V
Operating Time (quiescent)	400 hr (est.) @ 25°C
Ext. dc Input Range	+9 to +15 V

Battery Status Indicator

% Battery	Operating Time Remaining at 25°C, hr lithium	alkaline
100-80	150-125	400-250
80-60	125-85	250-75
60-40	85-60	75-35
40-20	60-35	35-10
<20	<35	<10

Temperature and Humidity Range

Specified Operating	0° to 45°C (32° to 113°F), 85% RH, non-condensing
Derated* Operating	-20° to 45°C (-4° to 113°F), 90% RH, non-condensing
Storage	-54° to 55°C (-65° to 131°F), 100% RH, non-condensing

Mechanical

Dimensions (H, W, D)	2.75 x 10 x 9 in.
Weight	
with batteries	4 lb
without batteries	3.65 lb
Case Material	ABS plastic

*At -20°C, output noise doubles, operating time decreases 20% for lithium batteries, 50% for alkaline batteries.

4. NOTCH BOX III OPERATION

4.1 Controls and Features

All Notch Box III controls and input-output jacks are located on the front and rear panels, as illustrated in Figure 10. The following paragraphs describe the controls and jacks, their locations and operation, and related operating features.

4.1.1 Input Jack

Input to the Notch Box III is achieved through a standard female BNC jack, labeled IN, located on the left front panel. The shield of the BNC jack is connected to the aluminum case of the notch box, which forms a continuous shield around the internal circuitry, and to the power supply ground. A 0.05 μF, 1 kV dc capacitor is used to ac-couple the input, which has an impedance of 1 MΩ. The maximum allowable rms input voltage is limited by the input range selector switch described in Section 4.1.7.

4.1.2 Output Jack

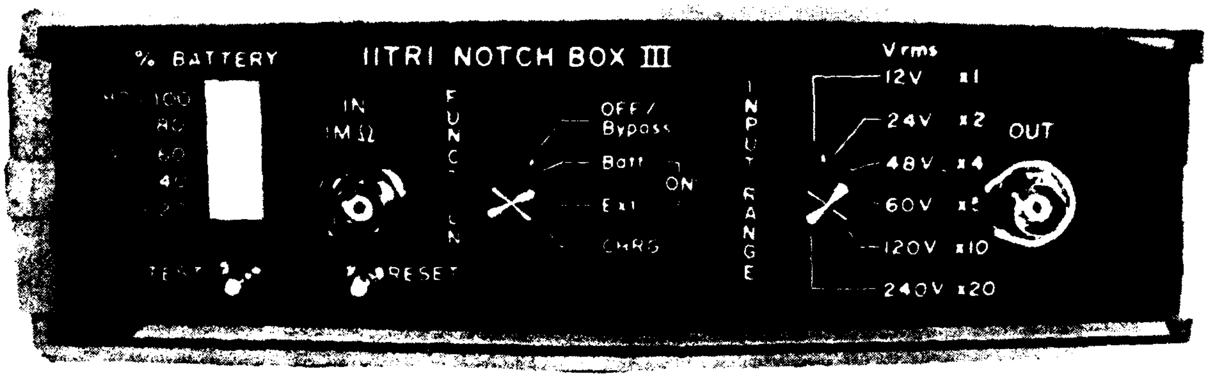
The output of the Notch Box III is accessible via a standard female BNC jack, labeled OUT, located on the right front panel. The shield of the BNC jack is connected to the instrument chassis. The output has a low impedance (0.1 Ω) and is short-circuit protected. A full output voltage of 13 V_{rms} can be driven for load impedances of 10 KΩ or greater.

4.1.3 Charger Input Jack

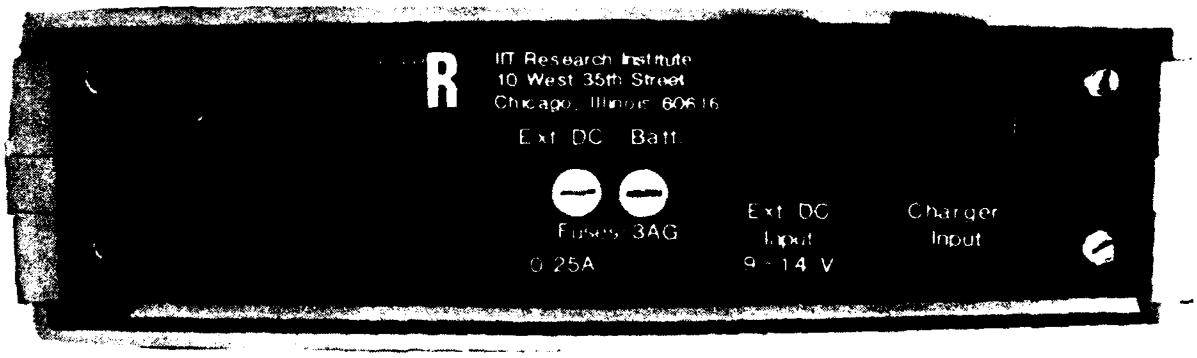
A battery charger input jack, labeled CHARGER INPUT, is located on the rear panel. The socket pins on this polarized jack are connected directly to the internal battery pack when rechargeable lithium batteries are being used and when the FUNCTION switch is in the CHRG. position. Care should be taken not to short the pins. Only the special Notch Box III Battery Charger described in Section 4.3 should be used. Other chargers may damage the lithium batteries. The battery pack is fused at 0.25 A for short-circuit protection.

4.1.4 External DC Power Input Jack

This polarized jack, labeled EXT. DC INPUT, is also on the rear panel. It allows operation from an external dc voltage source between 9 and 15 V. This jack is only enabled when the FUNCTION switch is in the ON-EXT. position.



a. Front panel.



b. Rear panel.

873558 RK

FIGURE 10. PHOTOGRAPHS OF NOTCH BOX III SHOWING (A) FRONT AND (B) REAR PANEL LAYOUT.

This input is fused at 0.25 A and has a series diode for reverse polarity protection.

4.1.5 Function Switch

The rotary switch labeled FUNCTION, located on the front panel, is used to select the mode of operation. Four operating modes are available in the following order:

- **OFF/BYPASS**--All circuitry is off, and the IN jack is connected to the OUT jack. The CHARGER INPUT and EXT. DC INPUT jacks are disabled.
- **ON-BATT.**--All circuitry is powered by the internal battery pack. The instrument is fully operational. The CHARGER INPUT and EXT. DC INPUT jacks are disabled.
- **ON-EXT.**--All circuitry is powered by an external dc supply between 9 and 15 V via the EXT. DC INPUT jack. The instrument is fully operational. The CHARGER INPUT jack is disabled.
- **CHRG.**--All circuitry is off, and all jacks are disabled except for the CHARGER INPUT jack, which is connected directly to the internal battery pack.

4.1.6 Power On Annunciator/Reset

The Notch Box III does not employ a pilot light, but signals that it has been turned on by a twice-per-second sounding of its audio annunciator. The annunciator indicates only that power has been applied to internal circuitry; no internal self-diagnostics are performed. The annunciator will continue to sound until the RESET switch, located on the front panel below the input jack, is depressed.

It should be noted that the reset function will not work if an input signal overload condition exists at turn-on. The power on annunciator may not be triggered if the instrument is quickly cycled through an on-off-on sequence.

4.1.7 Input Range Switch

This front panel rotary switch, labeled INPUT RANGE, allows the user to select the amount of input signal attenuation and, therefore, the maximum allowable ac input voltage. The available voltage ranges and respective attenuation factors are shown in Table 5. These specified rms voltages are the nominal allowable inputs for each range to keep the internal notch box circuitry operating linearly. Input voltages may exceed these values by about 6% before input overload. Related to each input range, and also shown in Table 5, is an output voltage scaling factor that will compensate for the input attenuation. Any voltage measured at the output of the Notch Box III must be multiplied by the appropriate scaling factor for the input range selected to determine its actual value.

TABLE 5. NOTCH BOX III INPUT VOLTAGE RANGES

Input Voltage Range, V_{rms}	Input Attenuation, dB	Output Scaling Factor
12	0	1
24	6	2
48	12	4
60	14	5
120	20	10
240	26	20

4.1.8 Signal Overload Warning/Reset

The Notch Box III is equipped with a peak detector circuit that automatically removes the input signal from the internal active circuitry on conditions of input signal overvoltage. Simultaneously, this circuit activates the audio annunciator to sound twice per second. This function precludes the generation of input signal second harmonic frequencies due to overloading and nonlinear operation of the active filter circuits, and also helps prevent component damage from voltage breakdown. The peak detector is a latching circuit. Therefore the input signal will remain disconnected and the annunciator will continue to sound until the circuit is reinitiated by depressing the RESET switch. Resetting cannot be accomplished until the signal overload condition is removed, either by disconnecting the input cable or by switching to a suitably higher input voltage range. Input signals of an unknown magnitude should be premeasured with a wideband meter prior to connection to the Notch Box III so that an appropriate input range can be selected and possible instrument damage avoided.

4.1.9 Battery Status Display/Test

The Notch Box III will indicate the state of charge of its batteries on the front panel bar graph display when the TEST switch is depressed. Battery status is given as the percentage of capacity remaining in approximate 20% increments. Each increment corresponds to about 30 hours of quiescent (no signal) operating time for the standard lithium battery pack at 25°C. A summary of remaining operating time in hours for the standard rechargeable lithium and optional disposable alkaline cell battery packs, as a function of the battery status indicator level, appears in Table 4. It should be noted that the indicator is not linear for the alkaline cells, because they have a relatively flat voltage-versus-discharge curve.

4.1.10 Low Battery Warning/Shutdown

In addition to displaying battery status, the Notch Box III will sound once every 30 seconds when the battery capacity falls to less than 20%, as a reminder to the user to recharge or replace the battery pack. This warning cannot be overridden, and will cease only when the batteries are charged, the instrument is turned off, or the ON-EXT. function is selected and an external dc supply greater than the low battery trip voltage is used. The low battery detector circuit will automatically shut off the instrument by disconnecting the battery supply when the batteries reach nominal zero percent capacity. This is to prevent permanent damage to the lithium cells from a deep discharge. Note from Table 4 that the user has about 35 hours of operating time between the advent of the low battery annunciator and battery shutdown.

4.2 Operating Considerations

Although the use of the Notch Box III is simple and straightforward in terms of its incorporation as part of a measurement system, there are several important considerations to be kept in mind when this instrument is used. The first and probably the most important consideration is the magnitude of the applied input signal. Even though overvoltage protection has been incorporated into the design of the instrument, inadvertent application of excessively high voltages at the input could cause permanent damage. Thus, care should be exercised when applying any input signal. As stated earlier, if the magnitude of the input signal is not known, the signal should be measured with a wide-band voltmeter to determine the proper input voltage range setting before the signal is applied.

An important consideration from the standpoint of personnel safety is the fact that the Notch Box III chassis is not isolated, but is connected to the shield side of the input and output jacks. This is especially critical if measurements are being made on power circuits. Care should be taken to attach the test leads and cables such that the case is not "hot" with respect to local ground. When making measurements with the Notch Box III, the unit should be treated as a "floating" instrument, and its chassis should be isolated from earth ground. To aid in this isolation, the Notch Box III chassis is almost fully enclosed by a plastic case, with only the front and rear panels exposed. Grounding of the notch box, measurement instrument, or associated cabling can set up ground loops that may cause erroneous readings.

Another consideration is proper care of the batteries to ensure optimum performance. The Notch Box III is supplied with six "AA" size vented lithium batteries and has an option available to change from this configuration to one that uses eight "AA" size alkaline batteries. The lithium batteries should be recharged whenever the battery status indicator shows less than a 20% charge remaining. If these batteries are not recharged promptly, and they remain at a low battery voltage for an extended period of time, permanent degradation of battery life can occur. The optional alkaline batteries are non-rechargeable; once they reach the less-than-20% level, they should be discarded. Care should also be taken not to short the batteries via the charger input, since the batteries have a high short-circuit current capability and arcing is possible. A fast-blowing fuse is directly in series with the batteries to help guard against this danger.

Specific procedures must be followed if one or more lithium batteries are replaced or batteries from different battery packs are intermixed. Lithium battery open-circuit voltage is directly related to its state of charge. All batteries in a series pack must be at the same potential (state of charge) for proper charge-discharge cycling. If they are not, the higher potential batteries will be significantly overcharged on charging cycles, and the lower potential batteries will be deep discharged on use cycles. Both scenarios can damage the batteries. For this reason, before any lithium batteries are reinstalled in a unit, their potentials should be checked. If the potentials are significantly different, the batteries should be individually charged to equipotentials using the single "AA" size lithium battery charger, as described in Appendix C.

A final consideration on Notch Box III operation is the effect of environmental parameters. The most important of these are temperature and moisture. To obtain optimum performance, the Notch Box III should be operated within a temperature range from 0° to 45°C at no more than 85% relative humidity. The instrument can be operated outside these ranges--down to -20°C and up to 90% relative humidity--but with degraded performance. Degradation evidences itself in a factor of two increase in output noise and in a 20% decrease in lithium battery capacity at -20°C. Alkaline battery capacity may be halved at this temperature. If circumstances require that a measurement be taken outside the normal operating temperature range of the instrument, these factors should be considered, and exposure time should be kept as short as possible. As when using any sophisticated electronic equipment in cold weather, care should be exercised to avoid internal moisture condensation when the instrument is returned to warmer environments.

4.3 Battery Charging

The complementary Notch Box III Battery Charger makes it possible to charge the "AA" size vented lithium batteries in series without removing them from the instrument. The charger is designed to connect directly to the Notch Box III via the CHARGER INPUT jack, and is capable of charging the six batteries simultaneously to potentials of approximately 2.4 V each. The charger is described in detail in Appendix B.

To operate the notch box-battery charger combination, the user must take the following steps:

(1) Turn notch box FUNCTION switch to CHRG.

(2) Plug the battery charger ac line cord into a 120 V ac outlet.

(3) Connect the output cable from the battery charger to the CHARGER INPUT jack on the notch box.

(4) Turn battery charger on.

Steps 1 through 3 must precede step 4 to initiate the charging mode, which is indicated by an illuminated yellow CHARGING lamp. If the green CHARGED indicator is illuminated, the charger can be reinitiated by turning it off, then on again after a few seconds. Failure to charge may indicate a malfunction; in such a case, the user should refer to the troubleshooting instructions in Appendix D. The charger is designed to sense the 14.4. V end-of-charge battery pack voltage and disconnect the battery pack to prevent overcharge. The green CHARGED indicator lights when this occurs, and the CHARGING indicator is extinguished.

A state-of-charge indicator identical to that on the Notch Box III is supplied on the battery charger to allow continuous monitoring of the approximate state of charge of the batteries. This indicator remains "on" whenever the batteries are charging. Bringing the batteries from a fully discharged state to a fully charged state takes approximately 12 hours.

4.4 External Power Input and Cables

The Notch Box III can be powered by essentially any dc source between 9 and 15 V via the EXT. DC INPUT jack on the rear panel. The source should be capable of supplying at least 10 mA. Common examples of such sources would include laboratory power supplies, the auxiliary 12 V output on the Notch Box III Battery Charger, 12 V automotive batteries (either directly or via a cigarette lighter socket), and 12 V dry cell lantern batteries. For short periods (i.e., several hours), the Notch Box III may even be powered by a standard 9 V alkaline radio battery. For this scenario, however, the low battery warning will be triggered even with a fresh battery. The external dc input is diode protected for polarity reversal and is fused at 0.25 A.

To aid in using the external dc power supply option, an assortment of accessory cables have been provided to allow flexibility in connecting to different types of dc power sources. This assortment, shown in Figure 11, consists of five pieces:

- Cable 1, a 10 ft cable with a 2-pin male MINI-CON-X connector on one end (to mate with notch box jack) and a dual banana plug on the other.
- Cable 2, a 1 ft cable with a dual banana plug on one end and a cigarette lighter plug on the other.
- Cable 3, a 1 ft cable with a dual banana plug on one end and two Mueller 25-C alligator clips on the other.

- One dual banana splice adaptor.
- One dual banana plug with integral 9 V battery connector.

These five pieces allow for the following cable configurations:

(1) Cable 1 can be used to connect to any supply having dual banana jacks, with standard 0.75 in. spacing.

(2) Cable 1 connected to cable 2 using the banana splice; this allows connection to any standard cigarette lighter jack.

(3) Cable 1 connected to cable 3 using the banana splice; this allows connection to any supply having terminals that will accept alligator clips, such as a car or lantern battery.

(4) Cable 1 connected to the 9 V battery adaptor using the banana splice.

With these four cable configurations, virtually any type of dc power supply having the proper voltage and current ratings can be used to operate the notch box.

4.5 Battery Options

Incorporated into the design of the Notch Box III is the option to substitute "AA" size alkaline batteries for the standard "AA" size vented rechargeable lithium batteries. Alkaline batteries are intended to be used only as a backup for the relatively new lithium chemistry. Located inside the Notch Box III are eight "AA" size battery holders and five slide switches for use in configuring the instrument for the type of battery in use. The battery holders are set in two distinct groups: a group of six and a group of two. The five switches are all oriented in the same direction and have red or white polarity marks to indicate the lithium setting. Table 6 identifies the appropriate battery holders and switch positions for each battery type. The different switch settings determine the number of battery holders in circuit and select the proper low battery thresholds and cutoff levels for each battery type. One of the switches disables the CHARGER INPUT jack when in the alkaline position.

TABLE 6. BATTERY OPTION SETUP

Battery Type	Battery Holders	Switch Setting
"AA" lithium	Group of 6	Dot visible
"AA" alkaline	All 8	Dot not visible

87355A RK

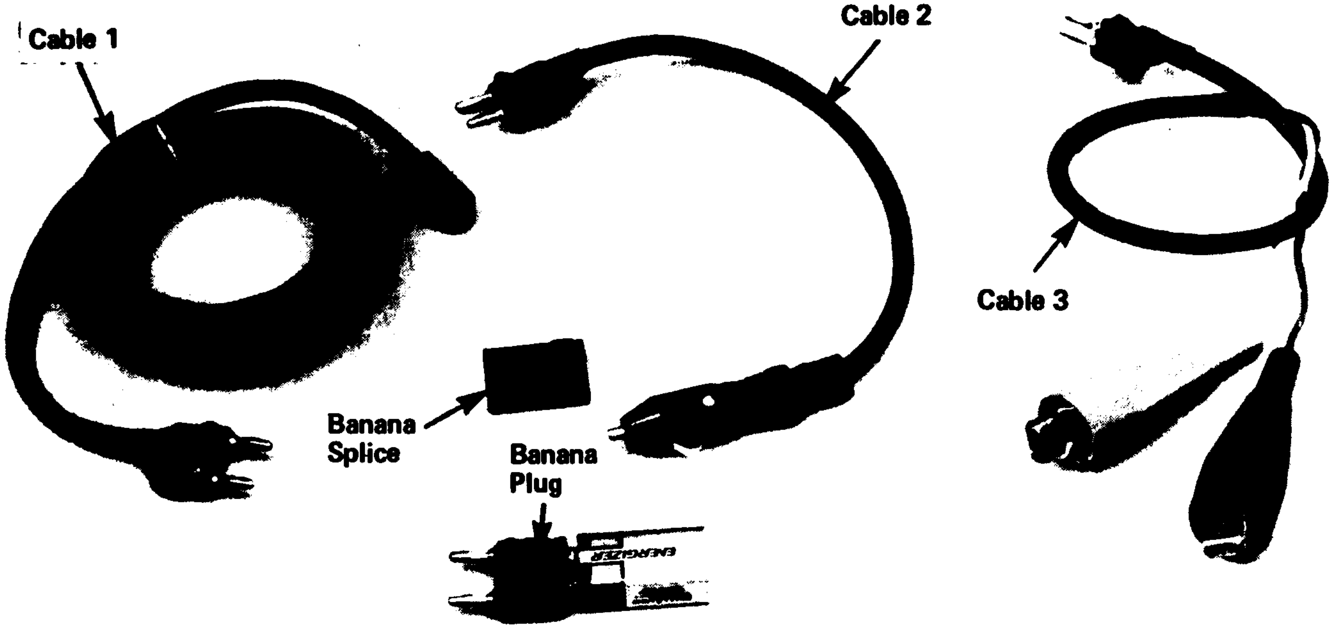


FIGURE 11. NOTCH BOX III ACCESSORY CABLES.

REFERENCES

1. United States Navy, Naval Electronic Systems Command, Seafarer ELF Communications System Final Environmental Impact Statement for Site Selection and Test Operations; Vols. 1-5, 1477 pp., December 1977.

2. Kruger, B., "Seafarer Extremely Low Frequency (ELF) Submarine Command and Control Communications System," Special Communications Project Office, Naval Electronic Systems Command, June 1975.

3. A. R. Valentino and D. W. McLellan, "ELF Earth Return Current Coupling," IEEE Trans. Electromagn. Compat., Vol. EMC-15, pp. 172-176, November 1973.

4. United States Navy, Naval Electronic Systems Command, "Appendix E: Biological and Ecological Information, Seafarer ELF Communications System Draft Environmental Impact Statement for Site Selection and Test Operations," Washington, D.C., February 1977.

5. R. M. Foster, "Mutual Impedance of Ground Wires Lying on the Surface of the Earth," Bell Syst. Tech. J., Vol. 10, p. 408, 1931.

6. J. R. Carson et al., "Wave Propagation in Overhead Wires With Ground Returns," Bell Syst. Tech. J., pp. 539-554, October 5, 1926.

7. E. D. Sunde, Earth Conduction Effects in Transmission Systems. New York: Van Nostrand, 1949.

8. R. O. Carter, "The Mutual Impedance Between Short Earth-Return Circuits," Proc. Inst. Elec. Eng., Part I, Vol. 93, 1946.

9. D. A. Miller and A. R. Valentino, "ELF Earth Return Coupling into Power Systems," IEEE Trans. Electromagn. Compat., Vol. EMC-15, pp. 160-165, November 1973.

10. D. A. Miller et al., "Effects of ELF Interference on Power Systems: Analysis, Field Data, Mitigation Techniques," presented at the IEEE Winter Power Meeting, 1973, Paper C73168-2.

11. D. W. McLellan and D. N. Heirman, "Mitigation of ELF Interference on Telephone Lines," IEEE Trans. Electromagn. Compat., Vol. EMC-15, pp. 166-171, November 1973.

12. A. R. Valentino, M. M. Abromavage, D. W. McLellan, and D. A. Miller, "Project Sanguine Interference Mitigation Research," IEEE Trans. Communications, Vol. COM-22, No. 4, pp. 27-34, April 1974.

13. V. C. Formanek and J. R. Gauger, "Design and Operation of a Minimum Shift Keying (MSK) Generator," IIT Research Institute Technical Report E06249-1, first revision, May 1977.

APPENDIX A
NOTCH BOX III CIRCUIT DESCRIPTIONS

NOTCH BOX III CIRCUIT DESCRIPTIONS

This Appendix describes the circuits used in the Notch Box III. Each circuit is described in terms of individual component use. Design equations used to determine component values are given where useful. A complete schematic of the instrument appears as Figure A-1.

Input Signal Conditioning

Because the Notch Box III was intended to be used with a wide range of input voltages (0 to 240 V) and to operate from a small, nominally 12 V battery source, circuitry had to be devised that could accommodate this without compromising accuracy. Design of an instrument that can meet these requirements is best achieved by keeping the signal amplitude at a level which assures solid linear operation of all circuitry. This is accomplished in the Notch Box III by including six distinct input signal ranges that adjust the input signal amplitude to drive the filtering circuitry in the linear region. Resistors R1 through R7 and switch S2 comprise the input attenuator that does this. Switch S2 allows the user to select the appropriate amount of attenuation for the measurement to be taken. The attenuator effectively reduces the input signal for each range so that nominal voltage to the succeeding circuitry does not exceed 6.0 V_{rms}.

Also included as a part of this input signal conditioning is a capacitor (C1), which provides ac coupling of the input to prevent any dc signals from reaching the active circuitry. One result of including this capacitor is the formation of a high-pass filter by the capacitor input attenuator network. This filter has a -3 dB corner at 4 Hz.

The attenuated signal is delivered to the input buffer amplifier, U1, via relay contact K1-A. This relay contact is the signal overload cutoff switch controlled by the overvoltage detection circuit (see description below). U1 is a low power JFET input operational amplifier configured as a unity gain voltage follower. This provides a buffer between the input attenuator and the following active circuitry. Transient voltage breakdown protection for the buffer amplifier inputs is provided by low-leakage clamping diodes D14 and D15. Together with R1, these diodes will limit the voltage at the amplifier inputs to within one diode drop (0.7 V) of the supply rails for input voltage spikes or transients up to 50 kV.

Filtering

Following the input buffer are the filter modules MOD-1 through MOD-5. MOD-1 and MOD-2 are 60 Hz notch filters that have steep rolloffs and specified minimum attenuations of 40 dB with quiescent current draws of only 100 μA. MOD-3, MOD-4, and MOD-5 are Chebyshev four-pole low-pass filters having -24 dB/octave rolloffs with -3 dB frequencies at 100 Hz while drawing quiescent currents of only 30 μA. The notch filters are arranged in series to provide a minimum of 80 dB of 60 Hz rejection, and the low-pass filters are arranged in series to provide a -72 dB/octave high frequency rolloff, which eliminates 60 Hz harmonics. All filters are special hybrid modules available from Frequency Devices, Inc., Haverhill, Massachusetts. Complete specifications for these filters appear in Appendix E.

Output

Following the filter series is U2, a low power JFET input operational amplifier, set up in an inverting gain configuration. U2 is included in the design to provide: (1) output short circuit protection; (2) a low output impedance; (3) a factor of two gain to offset the factor of two loss in the input attenuator; and (4) a means to trim the passband gain for 0 dB. To accomplish this, R8, R9, and R10 are used to determine the gain of U2 as follows:

$$\text{Voltage Gain} = \frac{-R10}{R8 + R9}$$

R8, a 15-turn potentiometer, is used for gain trimming (normally set for 0 dB at 76 Hz).

Signal Overload Detection/Disconnect

The input buffer amplifier, besides feeding the filter modules, also feeds overvoltage detector circuitry for the signal overload disconnect function. This detector consists of a precision rectifier, which converts the input

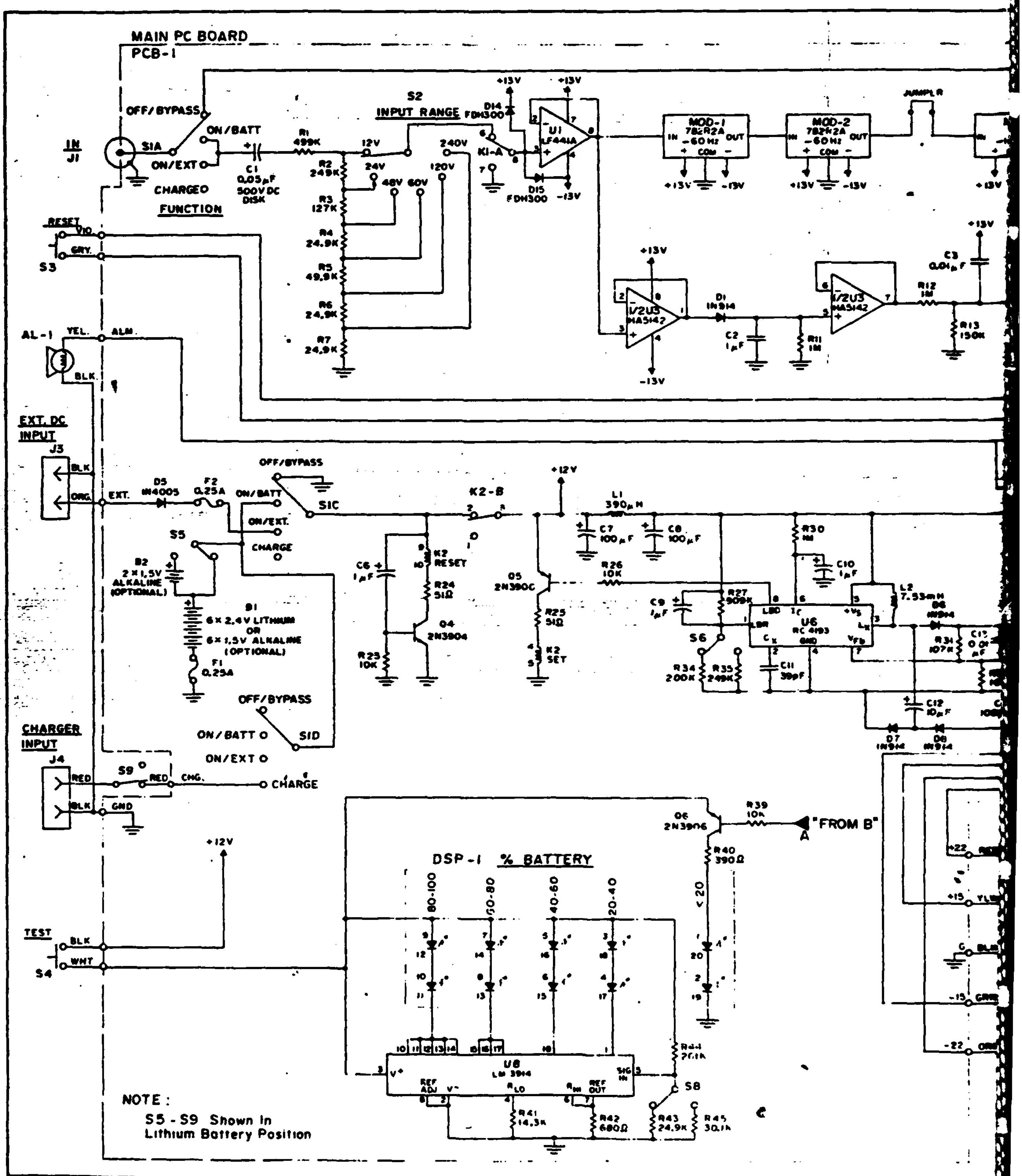


FIGURE A-1. NOTCH BOX III SCHEMAT

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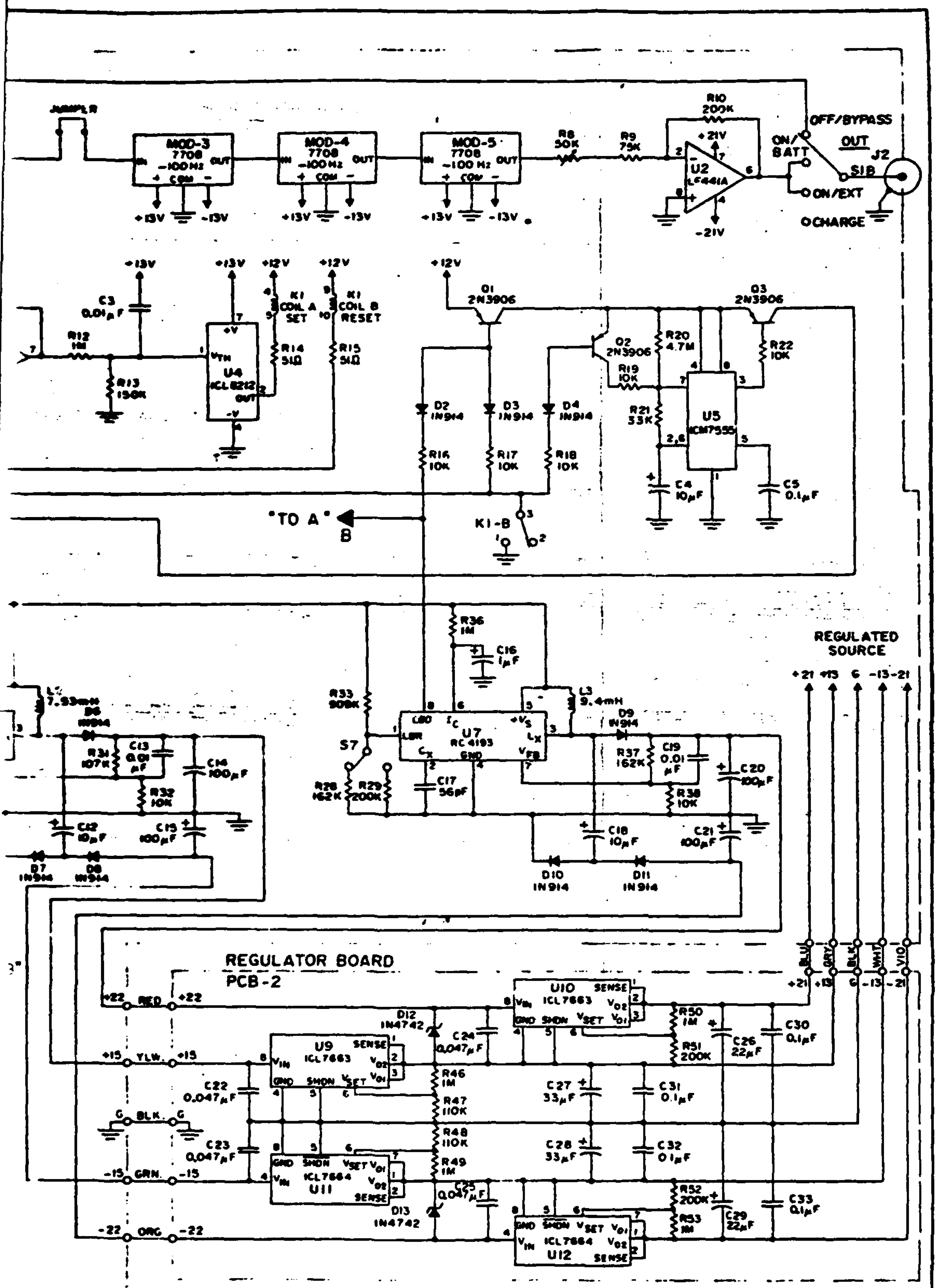

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E06549		
SCALE	DATE DRAWN	NOTCH BOX III SCHEMATIC
NONE	7/1/1986	

. III SCHEMATIC.

2 of 2

signal from ac to dc, followed by a micropower voltage detector that detects the overvoltage state and triggers a latching relay to disconnect the input signal.

The precision rectifier circuit consists of U3, D1, C2, and R11 and operates as follows: To begin, assume that capacitor C2 is discharged. As the signal applied to D1 increases above zero, D1 begins to conduct and the capacitor charges up to the instantaneous value of the input voltage. This continues until the positive peak is reached, at which time the capacitor voltage is equal to the peak voltage. As the signal begins on its downward slope, D1 becomes reverse biased. The capacitor voltage will remain at this peak value, changing only if a load is placed on the capacitor or leakage currents are significant. R11 has been included to act as a load and allow the capacitor voltage to discharge and follow the input signal voltage as it increases or decreases.

The values of R11 and C2 were chosen carefully in order to: (1) keep the time constant of R11·C1 sufficiently large compared to the period of the input signal so that the capacitor discharges almost linearly, and (2) keep the voltage ripple of the rectified signal, which is inversely proportional to the time constant, as small as possible.

The amount of voltage ripple can be determined by equating the amount of charge lost by the capacitor during discharging with the amount of charge gained by the capacitor during charging. These charges can be written as:

$$Q_{lost} = \frac{V_p}{R11} T$$

and

$$Q_{gain} = C1 \cdot V_r$$

where V_p is the peak voltage and T is the period of the input signal. Equating charges gives the ripple voltage as:

$$V_r = \frac{V_p T}{C1 \cdot R11}$$

or:

$$V_r = \frac{V_p}{f \cdot C1 \cdot R11}$$

Given a maximum peak voltage before overvoltage cutoff of 9 V, a maximum voltage ripple of approximately 1% of the peak voltage, and a large time constant compared to the period of the 76 Hz MSK signal, a time constant value of approximately one second results. Using this value results in an actual maximum voltage ripple of approximately 1.2% of the magnitude of the input signal, or 0.1 V.

To prevent the current drawn through D1 from degrading the signal sent to the filter modules, a voltage follower is placed before D1 to act as a buffer. In a similar manner, a voltage follower is placed following R11 to ensure that the maximum load on C1 would be R11. Both of these operational amplifiers are contained in one integrated circuit, U3, an ultra-low power dual operational amplifier.

The dc signal constructed by the precision rectifier is then applied to the input of micropower overvoltage detector U4 via voltage divider R12-R13. U4 is a precision detector that will switch on its open collector output whenever the voltage at its threshold input exceeds 1.15 V.

C3, which is also connected to the threshold input of U4, is included to trigger U4 whenever the notch box is first turned on, providing a "power on" signal to the user. This capacitor has zero net charge at the instant of turn-on, pulling the potential at the threshold input of U4 to 13 V. U4 triggers, and the annunciator sounds as if an overvoltage condition is occurring. The capacitor quickly charges up, and after a few milliseconds acts as an open circuit, allowing the overvoltage circuit to be reset.

The output transistor of U4 is used to activate the "set" coil in latching relay K1. This relay switches contacts K1-A and K1-B, which respectively disconnect the input signal and activate the annunciator. To reset K1, a simple circuit is used that places the "reset" coil of K1 in series with R15, a current limiting resistor, and S3, a momentary switch. The "reset" coil is activated simply by depressing S3.

Annunciator

The annunciator circuitry can be activated by any of three events: (1) overvoltage detection, (2) low battery detection, or (3) notch box turn-on. When overvoltage triggering occurs, relay contact K1-B closes as described above, grounding one end each of R18 and R17. This action then causes D3 and D4 to become forward biased, resulting in turn-on of Q1 and Q2 respectively. Q1 controls power distribution to the annunciator driving circuitry and eliminates quiescent power consumption by this circuitry. Q1 can also be activated by the low battery detector on U7 (see DC/DC Converters, below), which pulls one end of R16 low, thus forward biasing D2 and causing turn-on of Q1. D2, D3, and D4 are included to prevent reverse current flow, which might cause false triggering of the annunciator. Q2 is used as a switch to determine the effective resistance in the upper leg of the network, which determines the frequency of multivibrator U5.

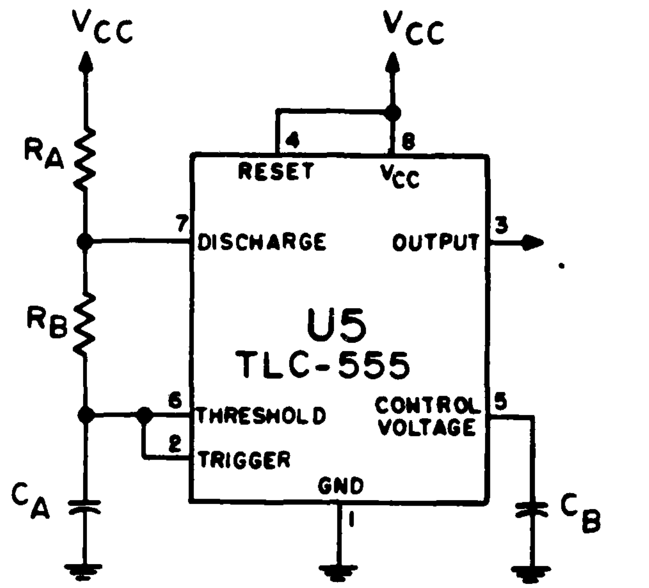
U5 is set up in a standard astable configuration (see Figure A-2a) except for the addition of Q2 and R19 (see Figure A-2b). The resistance R_A of the standard configuration is varied by using Q2 to switch resistor R19 in parallel with R20 as desired, thus allowing a switchable frequency.

The astable multivibrator operates on the principle that capacitor C_A is charged through $R_A + R_B$ until a predetermined threshold is reached. Attainment of that threshold triggers discharging through R_B, resulting in the U5 output changing states. Thus, the frequency and duty cycle of the multivibrator may be set precisely by the ratio of these two resistors. Keeping in mind the fact that the capacitor charges and discharges between 1/3 V_{CC} and 2/3 V_{CC}, the charge and discharge times can be calculated. The charge time is given by:

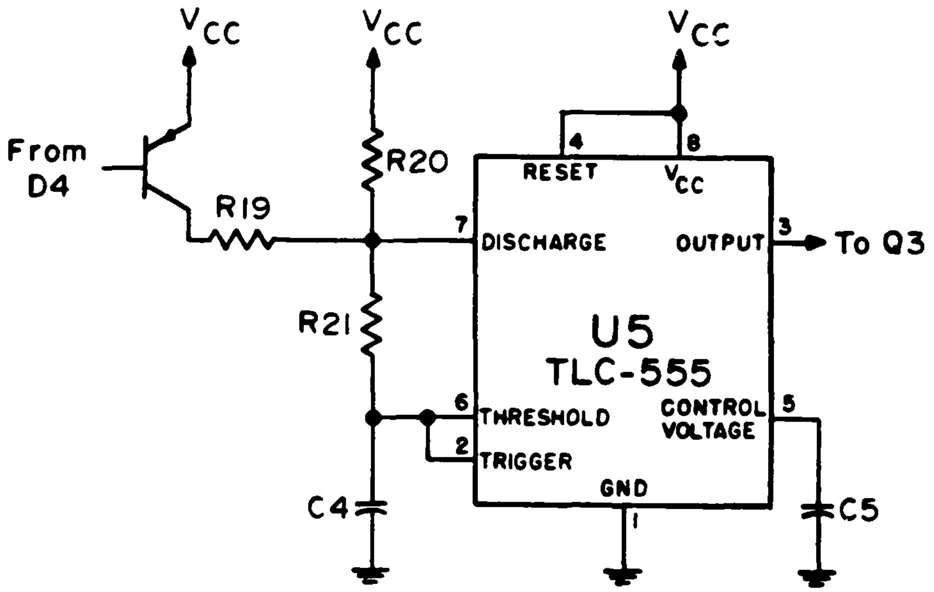
$$t_1 = 0.693\ (R_A + R_B)\ C_A$$

and the discharge time is given by:

$$t_2 = 0.693\ (R_B)\ C_A$$



(a)



(b)

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FIGURE A-2. ASTABLE MULTIVIBRATOR: (a) STANDARD CONFIGURATION; (b) WITH SWITCHABLE FREQUENCY.

Thus, the total period is:

$$T = t_1 + t_2 = 0.693\ (R_A + 2R_B)\ C_A$$

This gives a frequency of oscillation of:

$$f = \frac{1}{T} = \frac{1.44}{(R_A + 2R_B)\ C_A}$$

Table A-1 presents values calculated from the above equations.

TABLE A-1. ASTABLE MULTIVIBRATOR SETUP

Parameter	Triggering Condition: Low Battery	Triggering Condition: Overvoltage
R_A	= R20 = 4.7 MΩ	= R20//R19 = 10 kΩ
R_B	= R21 = 33 kΩ	= R21 = 33 KΩ
C_A	= C4 = 10 μF	= C4 = 10 μF
t_1	32.8 sec	0.30 sec
t_2	0.23 sec	0.23 sec
T	33.03 sec	0.53 sec
f	0.03 Hz	1.89 Hz

In the notch box, R_A is varied to make the period long for low-battery triggering (R_A = R20) and short for overvoltage triggering (R_A = R19(R20)/R19 + R20; or, $R_A \approx$ R19, since R19 << R20). It should be noted that the overvoltage trigger is designed to override the low-battery trigger. This feature takes account of the fact that an overvoltage condition is of more immediate concern. C5 is used to stabilize the internal control voltage of the multivibrator.

The open collector output of U5 is used to control Q3, which switches power to the annunciator. Whenever the output of U5 is high, Q3 and the annunciator are off; when the output is low, they are on. The nominal 3 kHz tone of the annunciator is activated for quarter-second bursts twice per second for turn-on and input overvoltage, and once every 30 seconds for a low battery.

State-of-Charge Indicator

The state-of-charge indicator operates on the principle that as the lithium batteries discharge, their voltage variation is almost linearly proportional to their state of charge. An LM 3914 dot/bar display driver, U8, is used to sense the battery pack voltage and to drive eight of the 10 light emitting diodes (LEDs) on bar graph display DSP-1 to indicate 20% to 100% battery capacity in 20% increments. Resistors R41 through R45 perform voltage scaling and LED brightness control. A circuit diagram of the state-of-charge indicator that employs U8 is shown in Figure A-3.

Switch S8 is used to select resistors to form a voltage divider across which the battery voltage is applied. R44 and R43 are used for lithium batteries; R44 and R45 are used for alkaline batteries. As shown in Figure A-3, the voltage divider output is applied to a series of 10 comparators through an input buffer onboard U8. Each comparator is biased to a different level by a string of 1 kΩ resistors, R41, and a 1.25 V voltage reference. Thus, each comparator will change output states at a different battery voltage level.

R43, R44, and R45 were chosen to enable all comparators at full battery pack voltages, and to limit the current in the divider string to less than 50 μA. Thus:

$$V_{BAT}\ (\text{lith}) = 14.4 = 1.25\ \left(\frac{R43 + R44}{R43}\right)$$

and

$$V_{BAT}\ (\text{alk}) = 12.0 = 1.25\ \left(\frac{R44 + R45}{R45}\right)$$

Similarly, R41 is chosen to disable all comparators at the lithium battery pack 20% capacity voltage, as follows:

$$V_B\ (20\%) \cdot \frac{R43}{R43 + R44} = 1.25 \cdot \frac{R41 + 1\ k\Omega}{R41 + 10\ k\Omega}$$

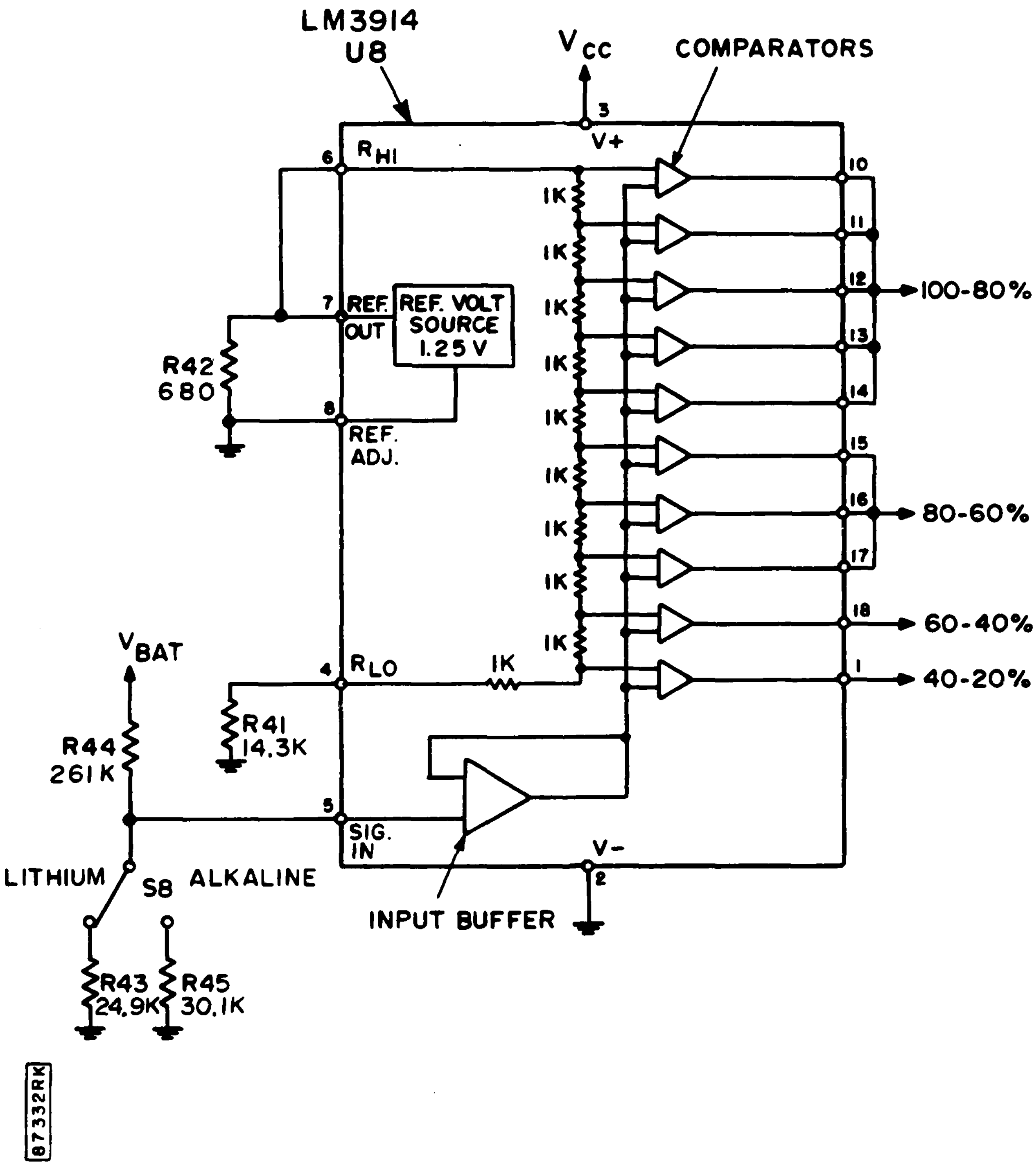

FIGURE A-3. STATE-OF-CHARGE INDICATOR CIRCUIT.

where

$$V_B\ (20\%) = 9\ \text{V (from battery curves)}$$

The LED drive current is determined by R42 as:

$$I_{LED} \doteq \frac{12.5}{R42}$$

The nominal 80%, 60%, and 40% battery capacity voltage trip points of 12.0 V, 10.2 V, and 9.6 V, respectively, were realized by tying together appropriate comparator outputs as shown in Figure A-3.

The remaining two LEDs on the bar graph indicate the 0 to 20% battery capacity level. They are driven by the low battery output of dc/dc converter U7 via Q6, R39, and R40.

Voltage Distribution

The primary objective of the power supply is to take a nominal 9 to 15 V dc input and convert it to regulated ±13 V dc and ±21 V dc voltages. Figure A-4 presents a block diagram of the Notch Box III power supply.

The blocks labeled U6 and U7 are micropower switching regulators (RC 4193) produced by Raytheon Company. The RC 4193 is housed in an eight-lead mini-DIP and is designed especially for battery-operated instruments. It contains a 1.3 V temperature-compensated band gap reference, an adjustable free-running oscillator, a voltage comparator, low battery detection circuitry, and a 150 mA switch transistor with all of the functions necessary to make a complete low power dc/dc converter with dual outputs. The RC 4193 is able to operate over a wide input supply range from 2.4 to 30 V, at a very low quiescent drain of 135 μA. Therefore, U6 and U7 have been designed to convert a nominal 12 V dc input into ±15 V dc and ±23 V dc, respectively.

The blocks labeled U9 through U12 are CMOS programmable micropower voltage regulators produced by Intersil. U9 and U10 (ICL 7663) are positive voltage regulators, and U11 and U12 (ICL 7664) are negative voltage regulators. These are CMOS integrated circuits that contain all the functions of a voltage regulator plus protection circuitry on a single monolithic

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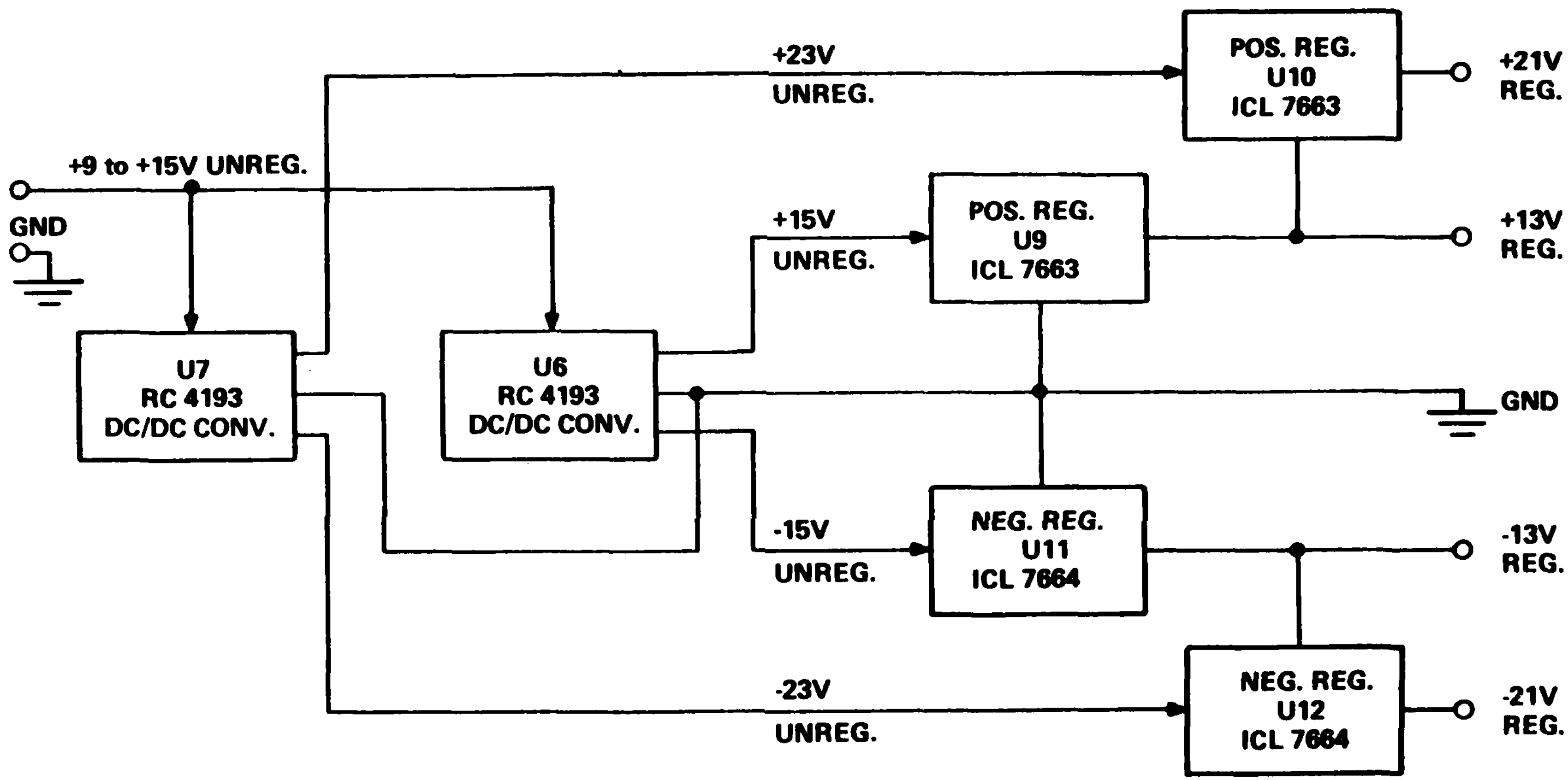

FIGURE A-4. BLOCK DIAGRAM OF NOTCH BOX III POWER SUPPLY.

chip. They are designed to regulate battery voltages in the 5 to 15 V range at maximum load currents of 5 to 30 mA. Initially, this posed a problem in that the maximum input voltage for the regulator chips is 16 V but a regulated ±21 V is needed. To circumvent this limitation, the "ground" references for U10 and U12 are taken at the outputs of U9 and U11. In this stacked configuration a differential of only 10 V appears at the inputs of U10 and U12, and their regulated outputs of ±8 V are added to the ±13 V ouptuts of U9 and U11 to produce the ±21 V outputs.

DC/DC Converters

An in-depth investigation of the dc/dc converter circuitry reveals that when power is first applied, the currents in R30 and R36 supply bias currents to pin 5 (I_C) of the two RC 4193s (see schematic in Figure A-5). These currents are stabilized by unity gain current source amplifiers and then used as bias currents for the 1.3 V band gap references. Very stable bias currents generated by the band gap are mirrored and used to bias the remainder of the chip. As the 4193s are starting up, currents will flow through the pot core inductors and diodes (labeled L2, D6 and L3, D9) to charge the output capacitors C14 and C20 to V_{BAT} - V_D.

At this point, the feedback (pin 7) senses that the output voltages are too low by using voltage dividers consisting of R31 and R32 for U6 and R37 and R38 for U7. The output of the voltage divider is compared to the 1.3 V reference. If the output voltages are too low, the comparator outputs change to a logical zero. The NOR gates then effectively AND the oscillator square waves with the comparator signals; if the comparator outputs are zero and the oscillator outputs are low, the NOR gate outputs are high and the switch transistors will be forced on. When the oscillators go "high" again, the NOR gate outputs go low and the switch transistors will turn off. This turning on and off of the switch transistors controls the storage of energy in the pot core inductors during the on time and the release of that energy into the output capacitors (C14 and C20) during the off time. The oscillators of U6 and U7 run at about 56 kHz and 38 kHz, respectively.

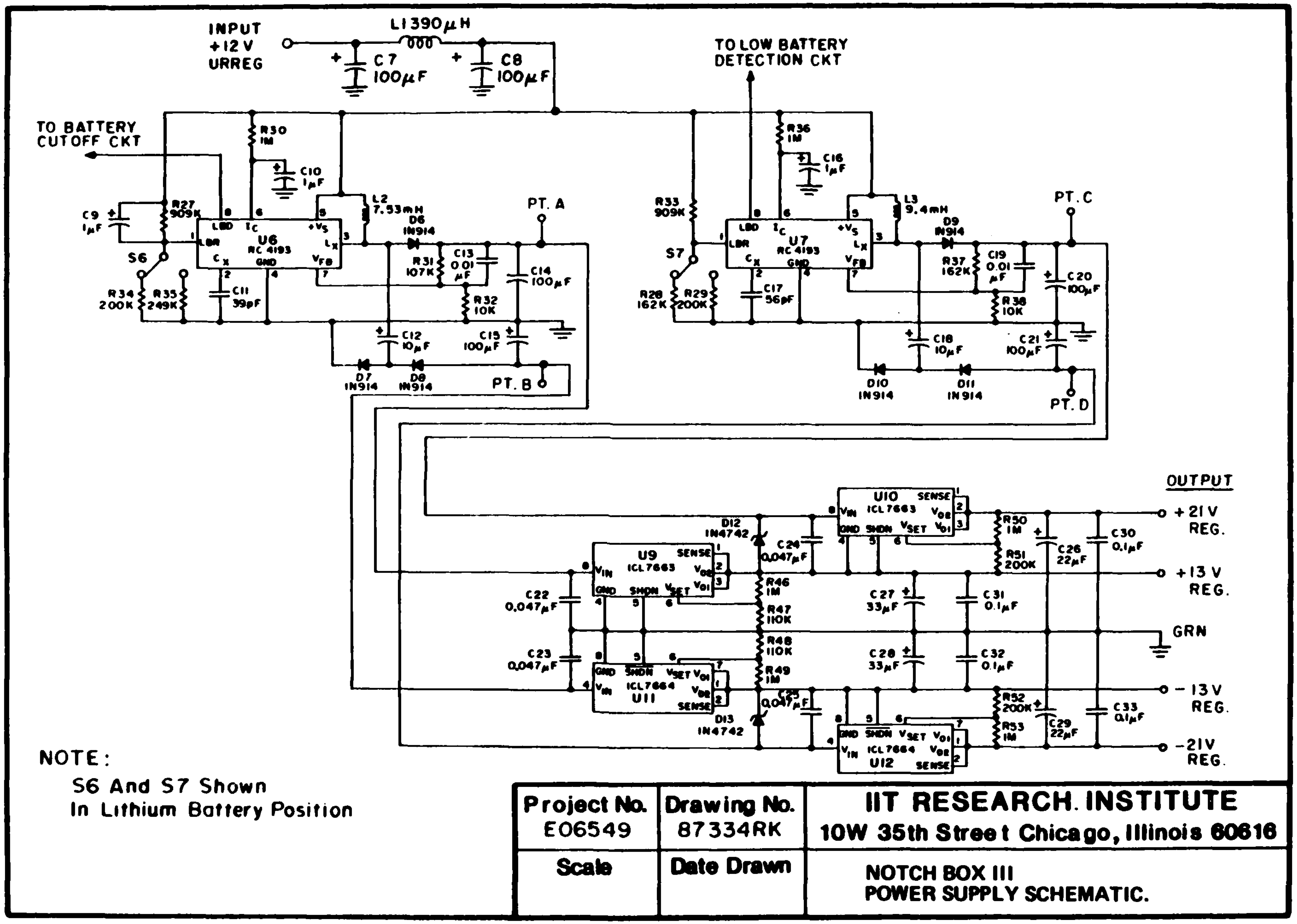

FIGURE A-5. NOTCH BOX III POWER SUPPLY SCHEMATIC.

The comparators will continue to allow the oscillators to turn the switches on and off until enough charge has been delivered to the output capacitors to raise the feedback voltages above 1.3 V.

Thereafter, the feedback system will vary the duration of the on time in response to changes in load currents or battery voltage. If the load currents increase, then the transistors will remain on for a longer portion of the oscillating cycle, thus allowing the currents within L2 and L3 to build up to a higher peak value. The duty cycles of the switch transistors vary in response to changes in load.

Output voltages higher than the input voltages are possible because of the high voltages produced by the rapid changes of current in the inductors L2 and L3. When the switches are opened, the inductor voltages will instantly rise high enough to forward bias the diodes (labeled D6 and D9 on the schematic) to $V_{OUT} + V_D$.

The negative voltages are developed through the 10 μF coupling capacitors C12 and C18 and diodes D7, D8, D10, and D11. When the inductors are discharging into points A and C, shown in Figure A-5, the L_X terminals rise to one diode drop above the voltages at points A and C. During this discharge time, the coupling capacitor C12 charges through D7 (as does C18 through D10), which is forward biased. When the next oscillator cycle starts, the L_X terminals are forced nearly to ground by the internal power transistors, and the more positively charged side of each capacitor is held at close to ground potential. D7 and D10 are then reverse biased, D8 and D11 are forward biased, and the capacitors C12 and C18 discharge into points B and D, respectively. Thus, points B and D are charged to negative voltages (approximately 1 V less than the voltages at points A and C, respectively) with each oscillating cycle.

<u>Regulator Network</u>

As stated earlier, ICL 7663 and ICL 7664 are CMOS integrated circuits that contain all the essentials of a voltage regulator plus protection circuitry on a single monolithic chip. Generally speaking, when working with CMOS devices, two major precautions must be taken: no input pin can be left open-ended, and maximum input voltage values must be rigorously observed. To avoid problems of latchup, voltage must be applied to the supply pin before being applied to any others.

The regulators labeled U9 through U12 accept working inputs of about 1.4 to 16 V. When power is applied, the rate-of-rise of the input may be hundreds of volts per microsecond. This is potentially harmful to the regulators, where internal operating currents are in the nanoampere range. The 0.047 μF capacitors (C22 through C25) on the device side of the switch will limit inputs to a safe level and will prevent input instability. Because of the unique "stacking" of the regulators and their input voltage limits, protection must be provided for U10 and U12 in the event that U9 or U11 should fail. Without this protection, a voltage in excess of 16 V at the input of U10 or U12 would result in destruction of these ICs. To prevent this from occurring, D12 and D13 were added to clamp the inputs of U10 and U12 at a maximum of 12 V.

The resistor divider network consisting of R50 and R51 is used to scale the reference voltage, V_{SET}, for the desired output of +21 V dc using the formula

$$V_{OUT} = (1 + \frac{R50}{R51})\, V_{SET} \qquad \text{where } V_{SET} = 1.3 \text{ V}$$

In similar fashion, R46 and R47 are used to scale V_{SET} for +15 V, R49 and R48 are used to scale V_{SET} for -15 V, and R53 and R52 are used to scale V_{SET} for -21 V. For the ICL 7664, V_{IN-} and V_{SET} are negative, so V_{OUT} will also be negative. Because the leakage current of the V_{SET} terminal is so low, the resistors can be tens of megohms if so desired for minimum additional quiescent drain current. However, at least 1 μA of load current is required to ensure proper operation. The minimum input/output differential in each regulator is obtained using the V_{OUT_1} terminal.

As to output currents for ICL 7663, low currents of less than 5 mA are obtained with the least input/output differential from the V_{OUT_1} terminal. In other words, V_{OUT_2} is connected to V_{OUT_1}. Either output may be used on ICL 7664, with the unused output connected to V_{IN-}.

To prevent a small output-overshoot condition, reservoir capacitors across the loads are chosen so that the regulated output voltages reach 90% of their final value in 20 msec. These capacitors are labeled as C26 through C29 in Figure A-5. Capacitors C30 through C33 are used to filter out high frequency components that may exist.

At the moment power is applied, the RC 4193s are fully on, and the resultant current spike can cause the supply voltage to sag or the inductors to saturate and complicate start-up. A procedure known as "soft start" can cure many of the problems connected with powering up. By adding capacitors C10 and C16 to the start-up circuits, the delay introduced by the RC time constants at start-up allow the output filter capacitors to charge up before the power transistors switch on, reducing instantaneous supply current.

Low-Battery Detectors

The RC 4193 switching regulators U6 and U7 have the capacity to signal a display whenever the battery voltage falls below a programmed level. In this particular application, there are two programmed levels. One level is preset to trigger a low-battery alarm, and the other level is preset to a value that dictates a battery cutoff. These levels are determined by the 1.3 V reference level and by the selection of two external resistors for each desired voltage level. The values of these resistors are calculated according to the following equations:

$$V_{THRESHOLD} = V_{REF} \left(\frac{R27}{R35} + 1\right) \quad \text{for alkaline batteries} \qquad (1)$$

and

$$V_{THRESHOLD} = V_{REF} \left(\frac{R27}{R34} + 1\right) \quad \text{for lithium batteries.} \qquad (2)$$

These equations give the resistor values for the battery cutoff circuitry. To obtain the resistor values for the low battery detection circuitry, one would replace R27/R35 with R33/R29 in Equation 1 and R27/R34 with R33/R28 in Equation 2. The low battery voltage thresholds are set at 8.8 V for lithium batteries and 7.5 V for alkaline batteries. Battery cutoff levels are set at 8.0 and 6.9 V for lithium and alkaline batteries, respectively.

These levels control the pin 8 outputs on U6 and U7, which go "low" when the trip level is reached. The pin 8 output on U7 controls the annunciator, as stated earlier. Pin 8 on U6 indirectly triggers battery cutoff via relay K2 by using R25, R26, and Q5 to switch on the K2 set coil. This "set" action causes contact K2-A to open and disconnect power from all notch box circuitry except the K2 reset circuit.

A capacitor, C9, is included in parallel with R27 to prevent false triggering of the battery cutoff circuit by the initial supply voltage turn-on spike. At turn-on, the capacitor acts as a short circuit and holds the threshold input on U6 at a level equal to the supply voltage, disabling the detector. When the battery voltage stabilizes, after about 0.25 sec, the capacitor acts as an open circuit and allows the circuit to operate normally.

The K2 reset circuit consists of C6, R23, R24, Q4, and the K2 "reset" coil. Activation of this circuit occurs only when the notch box is turned on. At turn-on, C6 is uncharged and acts as an short circuit, allowing application of the battery voltage at the base of Q4, turning it on. When Q4 is on, current is able to flow through the "reset" coil for a period determined by the RC time constant of C6·R23, or 0.01 sec. After this time, C6 becomes fully charged (an open circuit) and Q4 turns off, de-energizing the "reset" coil. The "reset" coil remains latched in this state after power is disconnected from the coil because K2 is a special magnetic latching relay, which requires only a short current pulse to change states, unlike conventional relays requiring constant coil energizing. This feature conserves power that would otherwise be expended with conventional relays.

<u>Line Noise Filtering</u>

A low-pass filter consisting of C7, C8, and L1 is included in the main battery voltage line before the dc/dc converters to prevent current pulses produced by L2 and L3 from feeding noise back onto the voltage source line. This filter is designed to attenuate the 38 and 56 kHz oscillator noise from U6 and U7. The values chosen for L1, C7, and C8 create a high frequency corner at 800 Hz.

Efficiency

The efficiency of the power supply is a primary consideration in a battery-operated instrument such as the notch box. Efficiency and load regulation are improved by using good quality high Q inductors. Ferrite pot cores were employed in the design to fulfill this high Q requirement. Output current capability, as well as efficiency, are severely degraded if the core is allowed to saturate. Therefore, cores were chosen that were permeable enough to handle the magnetic flux produced during maximum current draw.

The inductor values and oscillator frequencies (determined by timing capacitors C11 and C17) are dictated by the battery voltage, output currents, and the low ripple requirement. If either the inductor value or the oscillator frequency is too high, a condition exists where the inductor current will never be high enough to meet the load current, and the output voltage will collapse. On the other hand, if either the inductor value or the oscillator frequency is too low, the high inductor current will cause excessive output voltage ripple, or stress the switching transistor of the RC 4193.

Efficiency was determined by monitoring battery and output voltages and currents. More precisely,

$$EFF = \frac{(V_{OUT})\ (I_{OUT})}{(V_{BAT})\ (I_{IN})} \times 100\%$$

Various combinations of inductor and timing capacitor values were manipulated until the highest possible efficiency was achieved for each dc/dc converter. An average conversion efficiency of about 75% was obtained.

Parts and Layout

A complete parts list for the Notch Box III is given in Table A-2. Printed circuit board layouts and component locations are shown in Figures A-6 through A-10.

TABLE A-2. NOTCH BOX III PARTS LIST (page 1 of 3)

Reference Designation	Description	Manufacturer	Part Number
U1,2	Low Power JFET Op Amp	National	LF441ACH
U3	Micropower Dual Op Amp	Harris	HA2-5142-5
U4	Micropower Voltage Detector	Intersil	ICL8212CTY
U5	CMOS Timer	Texas Instruments	TLC-555CP
U6,7	Switching Regulator	Raytheon	RC4193NB
U8	Linear Dot/Bar Display Driver	National	LM3914N
U9,10	CMOS Positive Voltage Regulator	Intersil	ICL7663BCPA
U11,12	CMOS Negative Voltage Regulator	Intersil	ICL7664ACPA
Mod 1,2	Low Power 60 Hz Notch Filter	Frequency Devices	782R2A
Mod 3,4,5	Low Power Low Pass Filter	Frequency Devices	7708
R1	499 kΩ ±1% Metal Film Resistor, 1/4 W	Dale	CMF-60D
R2	249 kΩ ±1% Metal Film Resistor, 1/4 W	Dale	CMF-60D
R3	127 kΩ ±1% Metal Film Resistor, 1/4 W	Dale	CMF-60D
R4,6,7	24.9 kΩ ±1% Metal Film Resistor, 1/4 W	Dale	CMF-60D
R5	49.9 kΩ ±1% Metal Film Resistor, 1/4 W	Dale	CMF-60D
R8	15 Turn Wire Wound Potentiometer, 50 kΩ	Bourns	3005P-1-503
R9	75 kΩ ±1% Metal Film Resistor, 1/4 W	Dale	CMF-60D
R10	200 kΩ ±1% Metal Film Resistor, 1/4 W	Dale	CMF-60D
R11,30,36	1 MΩ ±5% Carbon Comp. Resistor, 1/4 W	Allen-Bradley	RC07
R12,46,49,50, 53	1 MΩ ±1% Metal Film Resistor, 1/8 W	Dale	CMF-55D
R13	150 kΩ ±1% Metal Film Resistor, 1/8 W	Dale	CMF-55D
R14,15,24,25	51 Ω ±5% Carbon Comp. Resistor, 1/4 W	Allen-Bradley	RC07
R16,17,18,19, 22,23,26,39	10 kΩ ±5% Carbon Comp. Resistor, 1/4 W	Allen-Bradley	RC07
R20	4.7 MΩ ±5% Carbon Comp. Resistor, 1/4 W	Allen-Bradley	RC07
R21	33 kΩ ±5% Carbon Comp. Resistor, 1/4 W	Allen-Bradley	RC07
R27,33	909 kΩ ±1% Metal Film Resistor, 1/8 W	Dale	CMF-55D
R28,37	162 kΩ ±1% Metal Film Resistor, 1/8 W	Dale	CMF-55D
R29,34,51,52	200 kΩ ±1% Metal Film Resistor, 1/8 W	Dale	CMF-55D
R31	107 kΩ ±1% Metal Film Resistor, 1/8 W	Dale	CMF-55D
R32,38	10 kΩ ±1% Metal Film Resistor, 1/8 W	Dale	CMF-55D
R35	249 kΩ ±1% Metal Film Resistor, 1/8 W	Dale	CMF-55D
R40	390 Ω ±5% Carbon Comp. Resistor, 1/4 W	Allen-Bradley	RC07
R41	14.3 kΩ ±1% Metal Film Resistor, 1/8 W	Dale	CMF-55D
R42	680 Ω ±5% Carbon Comp. Resistor, 1/4 W	Allen-Bradley	RC07
R43	24.9 kΩ ±1% Metal Film Resistor, 1/8 W	Dale	CMF-55D
R44	261 kΩ ±1% Metal Film Resistor, 1/8 W	Dale	CMF-55D
R45	30.1 kΩ ±1% Metal Film Resistor, 1/8 W	Dale	CMF-55D
R47,48	110 kΩ ±1% Metal Film Resistor, 1/8 W	Dale	CMF-55D
C1	0.05 μF, 500 VDC Ceramic Disk Capacitor	Sprague	5GA-S50
C2,6,9,10,16	1.0 μF, 50 VDC Tantalum Capacitor	Mallory	M39003-01-2116
C3	0.01 μF, 50 VDC Ceramic Capacitor	Erie	RPE110Z5U103M50V
C4	10.0 μF, 50 VDC Tantalum Capacitor	Mallory	M39003-01-2134
C5,30,31, 32,33	0.1 μF, 50 VDC Ceramic Capacitor	Erie	RPE110Z5U104M50V
C7,8	100 μF, 16 VDC Electrolytic Capacitor	Sprague	510D107M016CD3F
C11	39 pF, 500 VDC Dipped Mica Capacitor	CDE	CD6ED390J03
C13,19	0.01 μF, 100 VDC Ceramic Capacitor	Erie	CK05BX103K
C14,15,20,21	100 μF, 25 VDC Electrolytic Capacitor	Sprague	510D107M025CG3F
C17	56 pF, 500 VDC Dipped Mica Capacitor	CDE	CD6ED560G03
C22,23,24,25	0.047 50 VDC Ceramic Capacitor	Erie	RPE110Z5U473M50V

TABLE A-2. NOTCH BOX III PARTS LIST (page 2 of 3)

Reference Designation	Description	Manufacturer	Part Number
C12,18	10 µF, 25 VDC Solid Tantalum Capacitor	Sprague	196D106X9025KA1
C27,28	33 µF, 20 VDC Solid Tantalum Capacitor	Mallory	THF336K020P1F
C26,29	22 µF, 35 VDC Solid Tantalum Capacitor	Mallory	THF226K035P1F
D1,2,3,4,6,7, 8,9,10,11	Small Signal Silicon Diode	Motorola	1N914
D5	1 A, 600 PIV Silicon Rectifier	Motorola	1N4005
D12,13	12 V, 1 W Zener Diode	Motorola	1N4742
D14,15	Low-leakage silicon diode	Fairchild	FDH300
Q1,2,3,5,6	PNP Silicon Small Signal Transistor	Motorola	2N3906
Q4	NPN Silicon Small Signal Transistor	Motorola	2N3904
L1	390 µH Shielded, Molded Inductor	Dale	IMS-5-390
L2	5.35 mH Pot Core Inductor, consisting of a	Siemens	
	14 x 8mm gapped pot core		B65541-N0315-A028
	14 x 8mm bobbin		B65542-A0000-D001
	14 x 8mm mounting assembly		B65545-B0009-X000
	14 x 8mm adjusting screw		B65549-E0004-X023
L3	220 µH Pot Core Inductor, consisting of a	Siemens	
	11 x 7mm gapped pot core		B65531-L0250-A048
	11 x 7mm bobbin		B65532-A0000-D001
	11 x 7mm mounting assembly		B65535-B0002-X000
DSP-1	10 Segment, 3 Color Bar Graph Display	Hewlett-Packard	HDSP-4832
K1,2	DPDT Miniature Latching Relay with Set, Reset Coils	Teledyne	722D-6
AL1	Continuous, Medium Tone Alarm	Floyd Bell	MC-07-130-5
B1	"AA" Rechargeable Lithium Batteries	Moli Energy Ltd.	--
B1 (Opt)	"AA" Alkaline Battery	Eveready	E91
B2 (Opt)	"AA" Alkaline Battery	Eveready	E91
F1,2	0.25 A, 250 V Fuse	Littlefuse	312.250
Case	Plastic Case with Handle	Pac-Tec	CH-225
Chassis	Aluminum Chassis with Front & Rear Panels	IITRI	--
Card Guide	3 in. Plastic PCB Card Guide	Vector	BR20-13HP
Card Guide	5 in. Plastic PCB Card Guide	Vector	BR20-6HP
Label, Front	Front Panel Label, Anodized Aluminum	IITRI	--
Label, Rear	Rear Panel Label, Anodized Aluminum	IITRI	--
PCB-1	Main Printed Circuit Board, Double-Sided	IITRI/Vendor	--
PCB-2	Regulator Printed Circuit Board, Single-Sided	IITRI/Vendor	--
J1,J2	BNC Panel Jack, Right Angle PCB Mount	National Tel-Tronics	BNC-7159
	Hardware Pkg for above		H9202
J3	Mini-Con-X 2 Cond. Panel Plug	Con-X-All	7282-2PG-323
	Weathertight Cap for above		6295
J4	Mini-Con-X 2 Cond. Panel Jack	Con-X-All	7282-2SG-323

TABLE A-2. NOTCH BOX III PARTS LIST (page 3 of 3)

Reference Designation	Description	Manufacturer	Part Number
S1	4 Pole, 6 Pos. Rotary Switch, PCB Mount, Adj. Stops	Grayhill	71ADF36-02-2-AJN
S2	1 Pole, 6 Pos. Rotary Switch, PCB Mount, Adj. Stops	Grayhill	71ADF36-01-1-AJN
S3,4	SPDT Snap-Action Pushbutton Switch	American Switch	810KMZG
S5,6,7,8,9	SPDT PC Mount Slide Switch	ALCO	MSSA-22

MISCELLANEOUS HARDWARE

Quantity	Description	Manufacturer	Part Number
5	0.5 in. Brass Swage Mount Standoff, 4-40 Thr	Cambion	350-1300-13-07
4	0.125 in. Brass Swage Mount Standoff, 4-40 Thr	Cambion	350-1300-09-07
1	20 Pin Cable Socket with 3 in. Wire	Samtec	CS-20-D-3-7-CP/T
4	8 Pin, 0.20 in. diameter IC Socket	Augat	8059-2G5
2	10 Pin, 0.20 in. diameter IC Socket	Augat	8059-2G9
7	8 Pin DIL IC Socket	Augat	508-AG10D
1	18 Pin DIL IC Socket	Augat	518-AG10D
30	PCB Jack for 0.040 in. diameter Pins	Cambion	450-3286-01-03-00
2	10 Pin Socket Terminal Strips	Augat	510-AG90D-10
8	"AA" Size PCB Mount Battery Holder	Power Dynamics	B-35
2	PCB Mount 3AG Fuse Holders	Littelfuse	345101
2	Knurled Knob	Raytheon	TRA50E21
1	Drawn Aluminum Box 2.25 x 2.25 x 1.0 in. (d x w x h)	Zero	Z36-36-16
9	0.25 in. by 4-40 Machine Screws		
8	0.25 in. by 4-40 Flathead Screws		
12	No. 4 Sheet Metal Screws		
8	No. 4 Star Washers		
8	No. 4 Nuts		

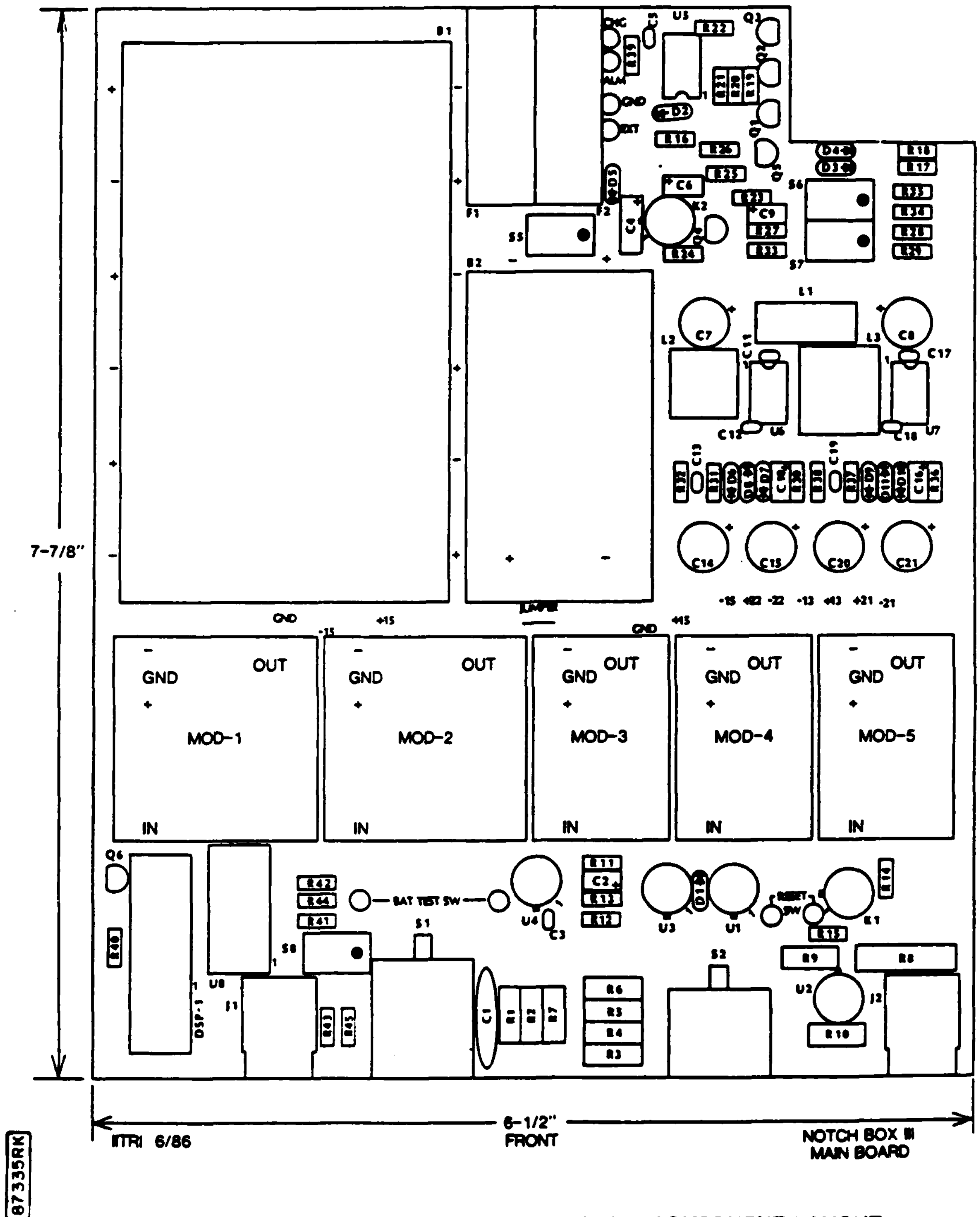

FIGURE A-6. NOTCH BOX III MAIN PC BOARD, COMPONENT LAYOUT.

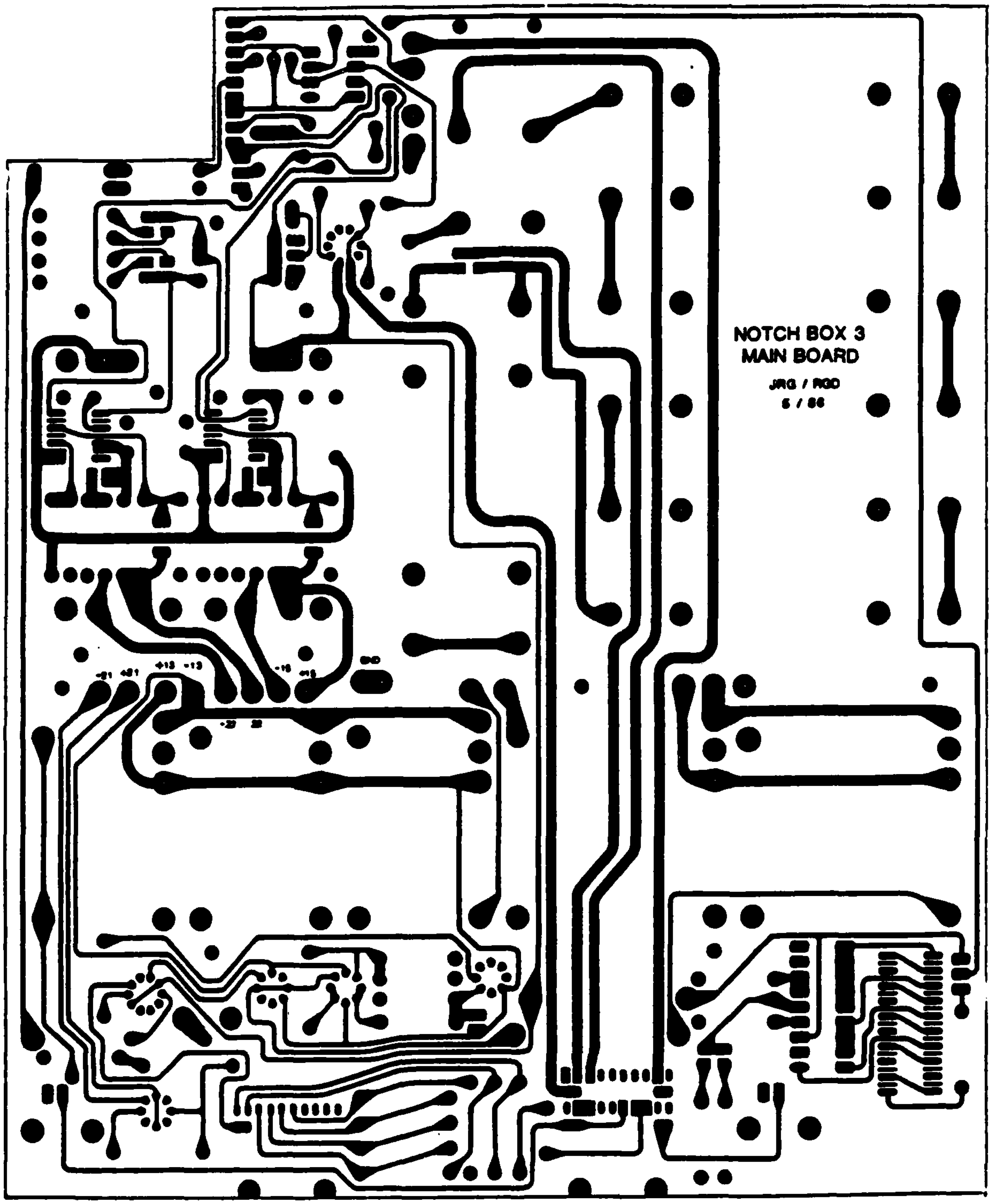

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FIGURE A-7. NOTCH BOX III MAIN PC BOARD, FOIL SIDE.

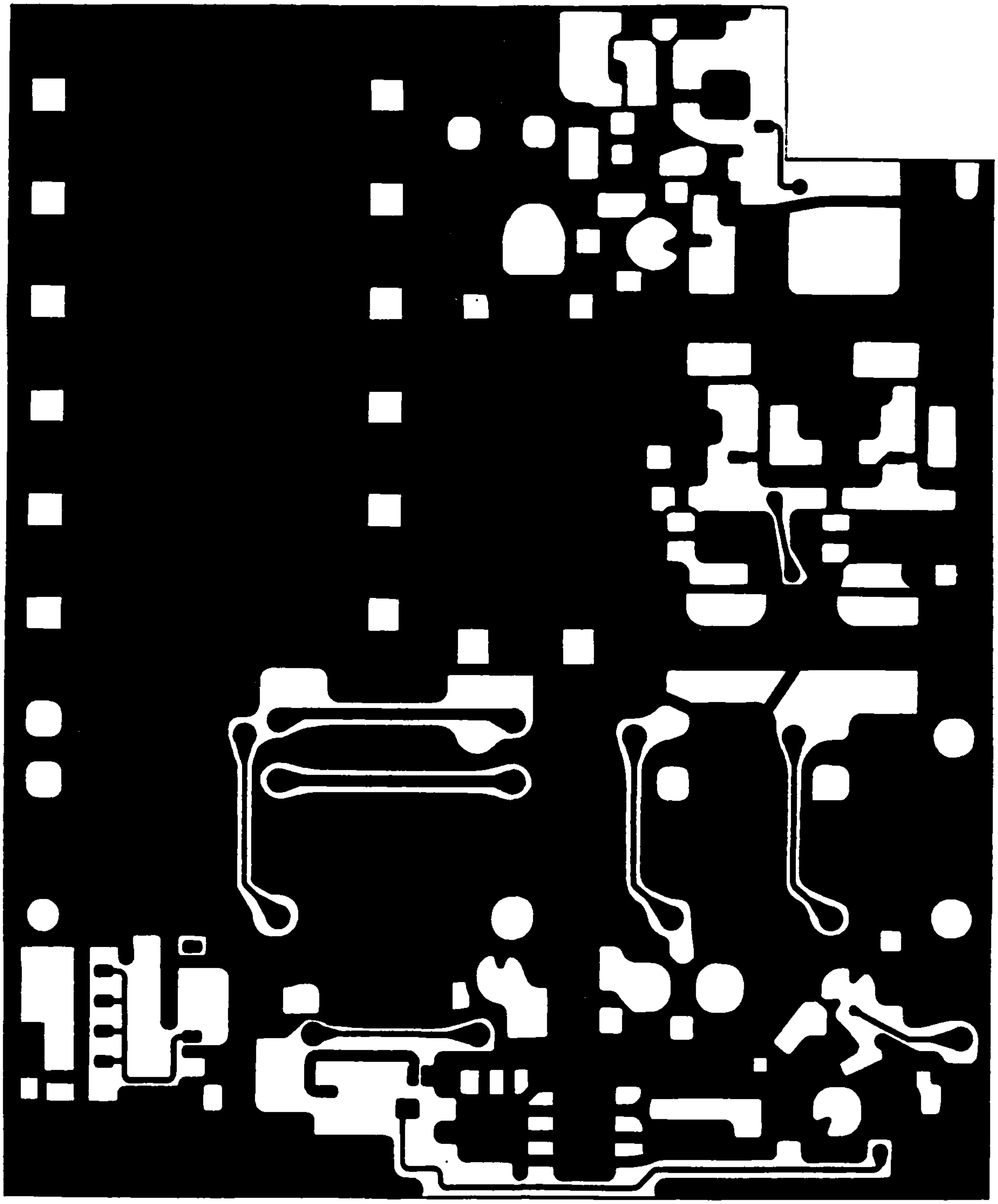

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FIGURE A-8. NOTCH BOX III MAIN PC BOARD, COMPONENT SIDE.

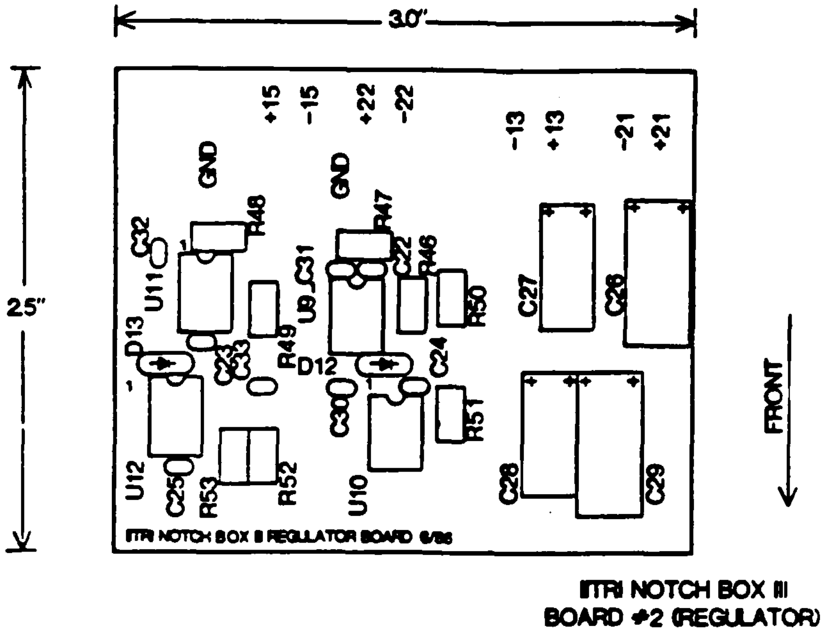

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FIGURE A-9. NOTCH BOX III REGULATOR PC BOARD, COMPONENT LAYOUT.

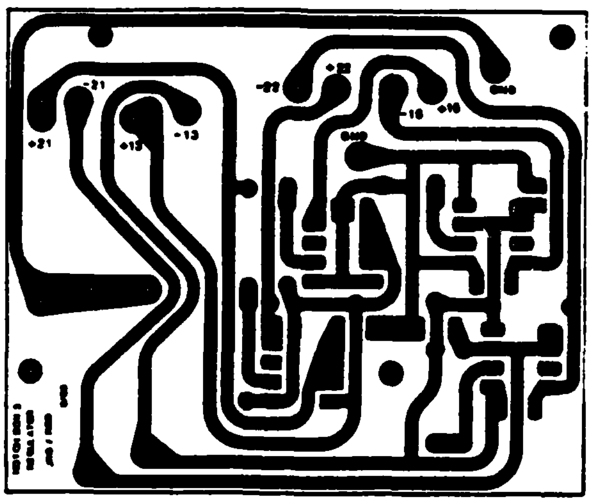

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FIGURE A-10. NOTCH BOX III REGULATOR PC BOARD, FOIL SIDE.

APPENDIX B

NOTCH BOX III BATTERY CHARGER

NOTCH BOX III BATTERY CHARGER

An IITRI-designed Notch Box III Battery Charger complements the notch box. This battery charger serves two functions. First, it allows the user to recharge the lithium batteries used in the notch box without removing them from the instrument. Second, its auxiliary dc output (12 V) can directly power the notch box via its external dc input in laboratory setups.

Figure B-1 is a photograph of the battery charger. The unit is small and portable, and can be used wherever a standard 120 V ac outlet is available. The following sections provide a description of all battery charger controls and indicators, detailed information on its circuits, and instructions on its use.

BATTERY CHARGER CONTROLS AND INDICATORS

Power Switch

This switch, located on the front panel, controls application of the 120 V ac line to the battery charger. When off, the switch also disconnects the charger output via a relay contact. When this switch is turned on, a red LED located next to the switch indicates power application.

Charging Indicators

Two LEDs located on the front panel indicate the operational mode of the battery charger. The yellow CHARGING indicator is illuminated only when charging current is actually flowing and the lithium batteries are being charged at a C/10 rate. When the green CHARGED indicator is illuminated, the charging cycle has been completed and the charger output has been disconnected via a relay contact.

State-of-Charge Indicator

A bar graph display on the front panel allows continuous monitoring of the battery state of charge. The display has five distinct regions that define zones of the remaining battery charge in percentages: 100-80%, 80-60%, 60-40%, 40-20%, and 20-0%. This allows the user to evaluate the state of charge of the batteries at any time.

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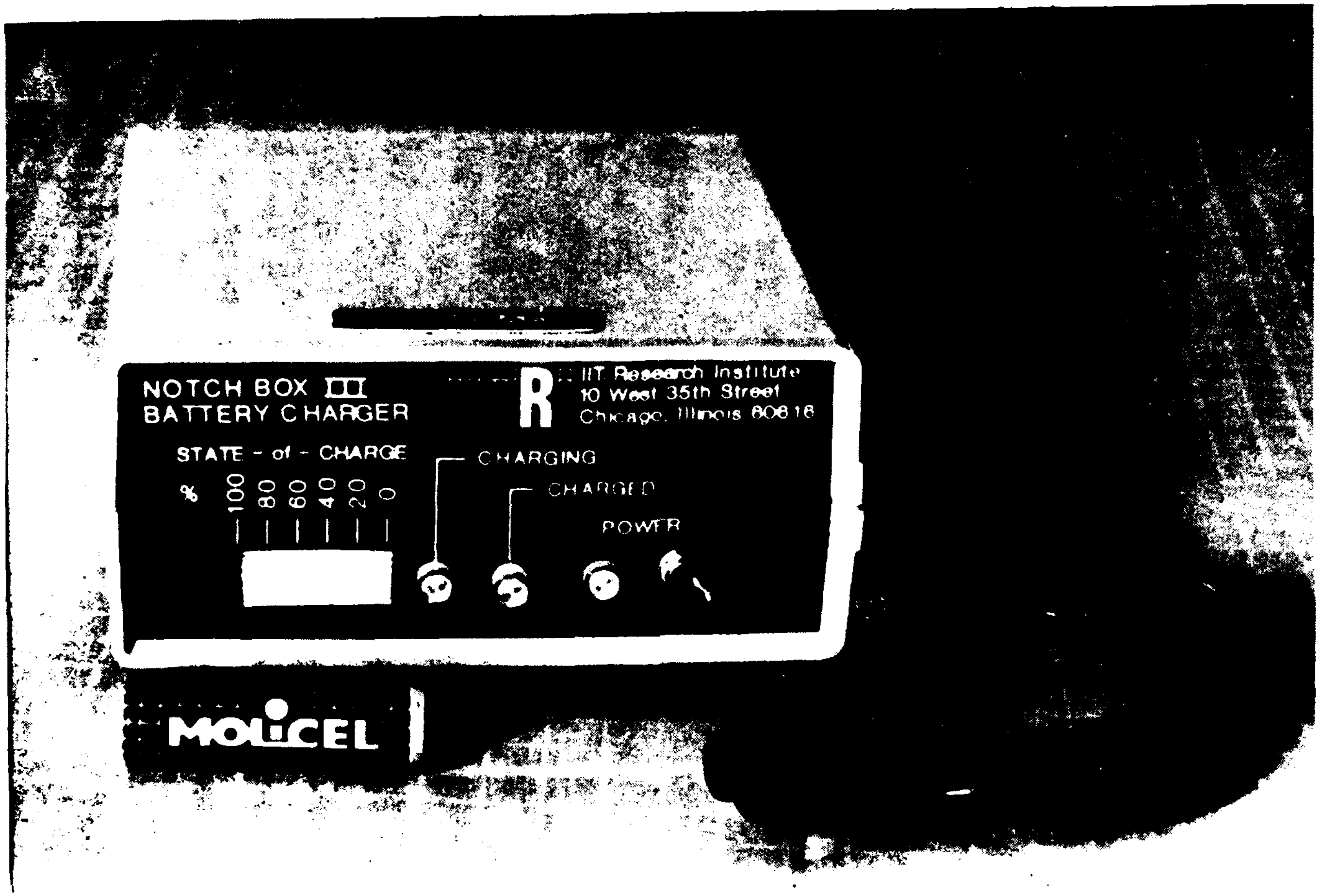

FIGURE B-1. NOTCH BOX III BATTERY CHARGER.

Output Cable

This cable, protruding from the rear of the battery charger, allows direct connection to the battery charger input of the notch box. The cable has a two-pin MINI-CON-X-ALL male plug on its end and is fused inside the battery charger. The fuse can be accessed from the rear panel and has a rating of 0.10 A. Nominal charging current is 60 mA.

12 Volt Supply

Located on the rear panel are two female banana jacks at which a 12 V dc regulated supply may be accessed. This output, in combination with notch box accessory cable 1, makes it possible to operate the notch box via its EXT. DC INPUT.

It should be noted that the battery charger cannot be used to charge a lithium battery pack and simultaneously serve as a 12 V source, because the EXT. DC INPUT and CHARGER INPUT jacks on the Notch Box III are never enabled at the same time.

AC Line Cord

Supplied on the rear panel is a three-conductor line cord with a three-prong plug to mate with any standard 120 V ac socket. The ground conductor of this wire is connected to the chassis ground and the "hot" wire is fused with a 3AG 0.25 A fuse accessible from the rear panel.

CIRCUIT DESCRIPTION

The following paragraphs describe the electrical circuits used in the Notch Box III Battery Charger. Design equations used to determine component values are shown where appropriate. A complete schematic of the battery charger appears as Figure B-2; Table B-1 provides a complete parts list. The layouts of the printed circuit boards used in the notch box battery charger are shown in Figures B-3 and B-4.

Power Supply

Power to drive the battery charger is derived from a 120 V ac 60 Hz source using P1. The ac line voltage is applied across the primary of transformer T1 via line fuse F1 and power switch S1. T1 steps the voltage

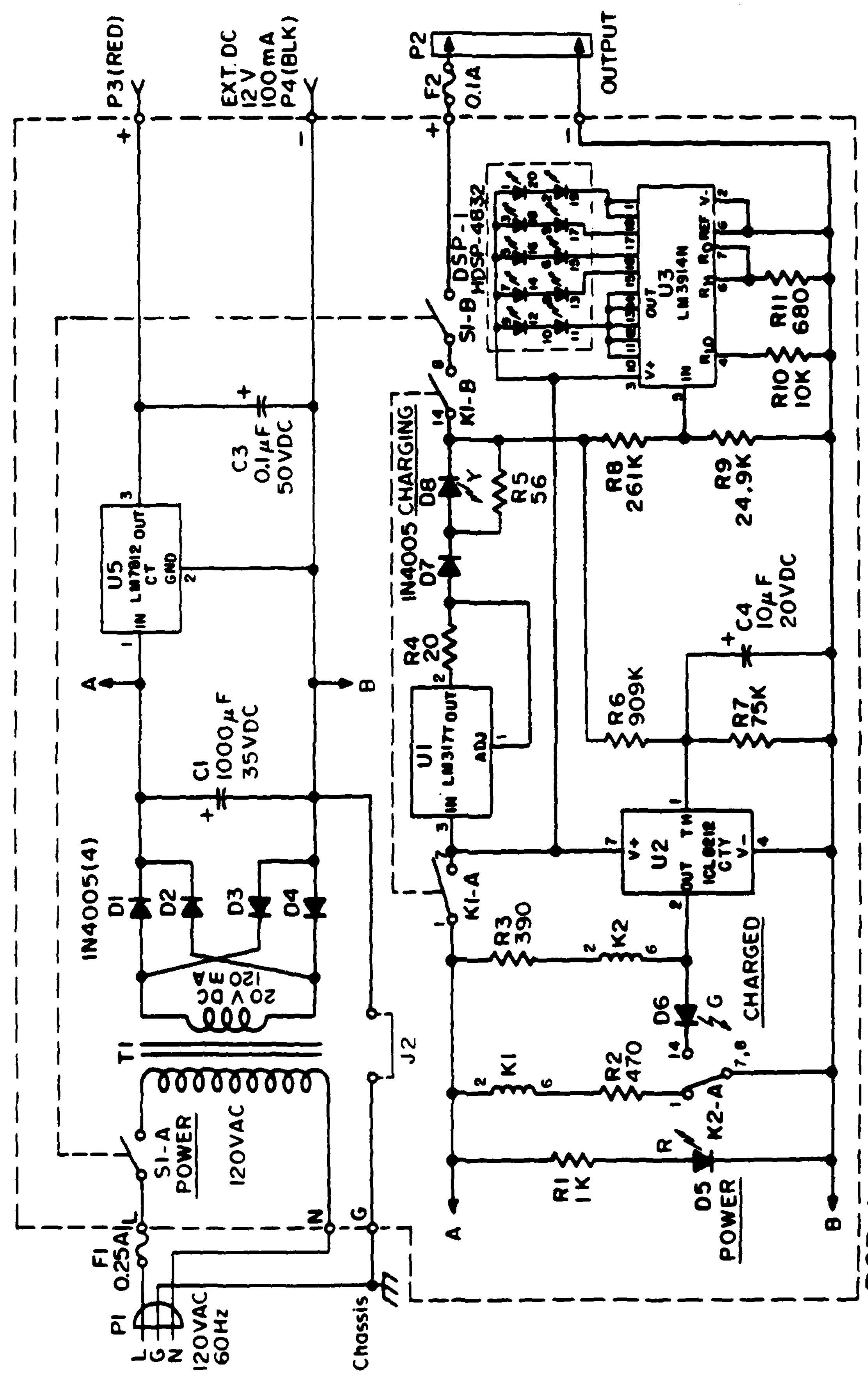

FIGURE B-2. NOTCH BOX III BATTERY CHARGER SCHEMATIC.

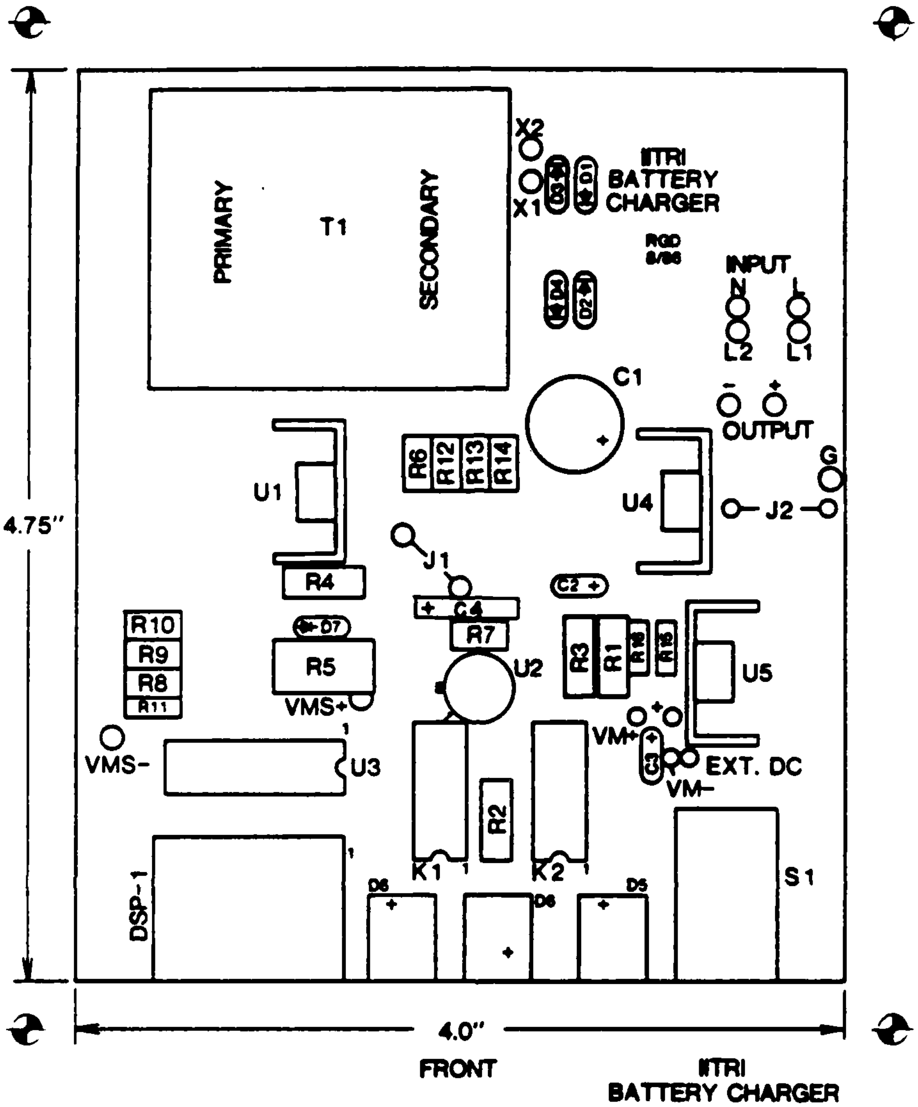

FIGURE B-3. NOTCH BOX III BATTERY CHARGER PC BOARD, COMPONENT LAYOUT.

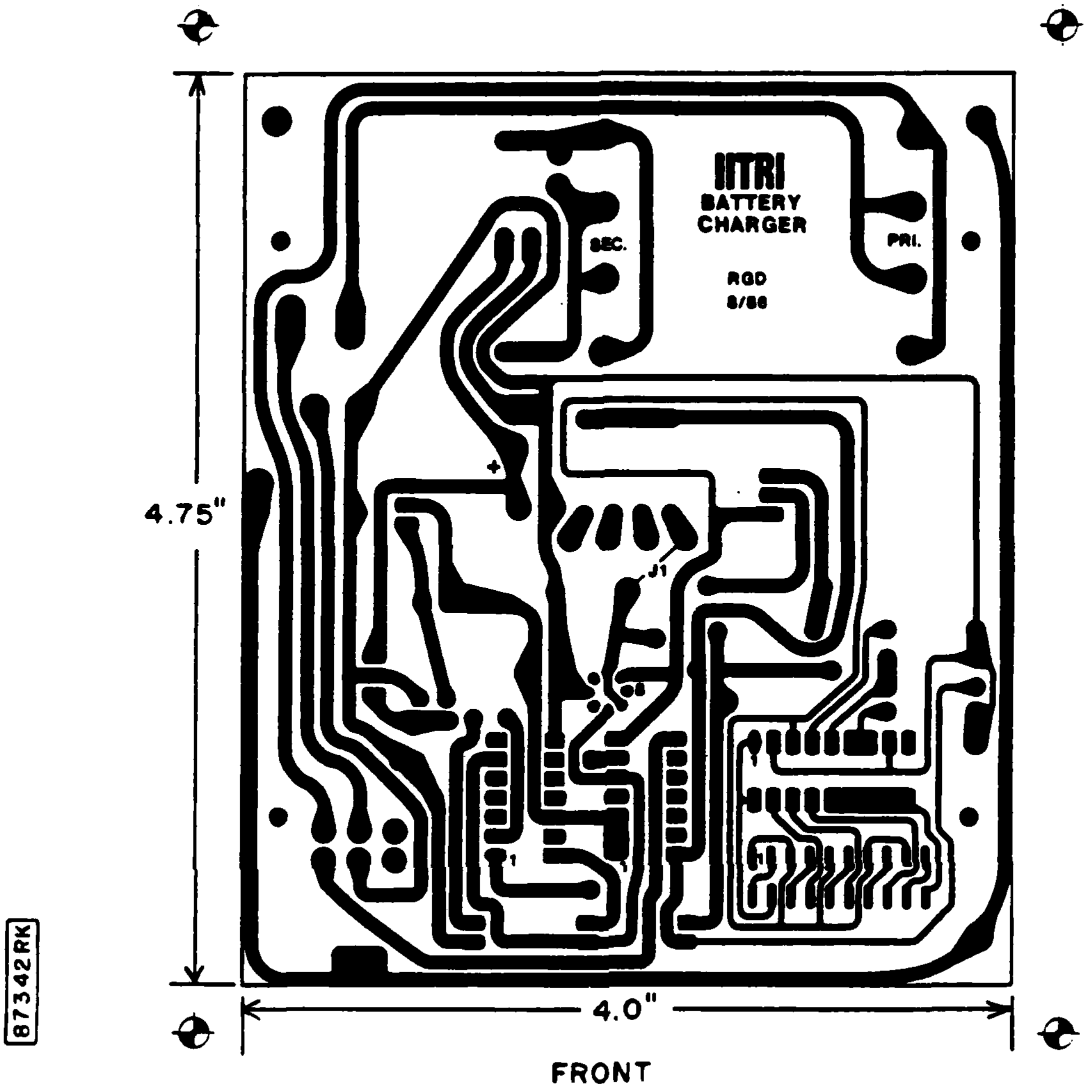

FIGURE B-4. NOTCH BOX III BATTERY CHARGER PC BOARD, FOIL SIDE.

TABLE B-1. NOTCH BOX III BATTERY CHARGER PARTS LISTS (page 1 of 2)

Label	Description	Manufacturer	Part No.
U1	Voltage Regulator	National Semi.	LM317T
U2	Peak Detector	Intersil	ICL8212CTY
U3	Display Driver	National Semi.	LM3914N
U5	12 Volt Reg.	National Semi.	LM7812CT
R1	1.0 kΩ 5% Resistor, 1/4 W	Allen-Bradley	RC20
R2	470 Ω 5% Resistor, 1/4 W	Allen-Bradley	RC20
R3	390 Ω 5% Resistor, 1/4 W	Allen-Bradley	RC20
R4	20 Ω 5% Resistor, 1/4 W	Allen-Bradley	RC07
R5	56 Ω 5% Resistor, 1/4 W	Allen-Bradley	RC07
R6	909 kΩ 1% Resistor	Dale	RN-55D
R7	75 kΩ 1% Resistor	Dale	RN-55D
R8	261 kΩ 1% Resistor	Dale	RN-55D
R9	24.9 kΩ 1% Resistor	Dale	RN-55D
R10	10.0 kΩ 1% Resistor	Dale	RN-55D
R11	680 Ω 5% Resistor, 1/2 W	Allen-Bradley	RC07
C1	1000 μF 35 V Capacitor	Cornell Dubilier	226J102P035XX
C3	0.1 μF 50 V Capacitor	Sprague	104x9050A2
C4	10 μF 20 V Capacitor	Mallory	39003-01-2286
D1,2,3,4,7	Rectifier	Motorola	1N4005
D5	Red LED	Hewlett-Packard	HLMP-3750
D6	Green LED	Hewlett-Packard	HLMP-3950
D8	Yellow LED	Hewlett-Packard	HLMP-3850
DSP-1	Bar Graph Display	Hewlett-Packard	HDSP-4832
K1	DIP Reed Relay (2 Form A)	Sigma	195TE2AE-12G
K2	DIP Reed Relay (1 Form C)	Hamlin	HE721C1210
T1	20 V 120 mA Transformer	Stancor	LB240
S1	DPDT Toggle	American Switch	ST2-1KMA-1Q
P1	SJ Power Cord	Belden	17236B
P2	Plug, 2-Pin	Con-X-All	6282-2PG-323
P3	Banana Jack (Red)	H. H. Smith	1509-102
P4	Banana Jack (Black)	H. H. Smith	1509-103
Socket 1	8 Pin IC Socket	Augat	8059-2G5
Socket 2,3	14 Pin DIL Socket	Augat	514-AG10D
Socket 4	18 Pin DIL Socket	Augat	518-AG10D
Socket 5	20 Pin Wire Wrap Socket	Texas Instruments	C9120-00

TABLE B-1. NOTCH BOX III BATTERY CHARGER PARTS LISTS (page 2 of 2)

Label	Description	Manufacturer	Part No.
Case	Plastic (Gray)	Pac-Tec	CM5-200
F1,F2	Fuse Holder	Littelfuse	345903
1 each	3AG 0.25 A Fuse	Littelfuse	312.250
1 each	3AG 0.10 A Fuse	Littelfuse	312.100
Miscellaneous:			
3 each	LED Holder	P-C-Lite	PCR740
3 each	Clear Round Lens for above holder	P-C-Lite	CLF280CTP
2 each	Heat Sink	EG&G Wakefield	273-AB
2 each	Strain Relief	H.H. Smith	939
1 each	PC Board	IITRI/Vendor	
2 each	Labels (1 front, 1 back) Photofoil	IITRI	
3 each	Mounting Bracket	SPC Tech.	28F1857
3 each	4-40 x 1/4 in. Flathead Screw		
2 each	6-32 x 1/4 in. Machine Screw		
2 each	No. 6 Star Lock Washer		
2 each	No. 6 Nut		

down to 20 V ac, which is then full-wave rectified by D1, D2, D3, and D4, a bridge rectifier. The C1 filters the output of the bridge rectifier, forming a 20 V dc source. To indicate when the power is on, R1 and LED D5 have been placed in series across the 20 V dc source. R1 limits the current through D5 to about 20 mA.

The 20 V dc source also drives U5, a 12 V fixed regulator, which supplies the auxiliary 12 V dc regulated output on the rear panel. C3 provides stability for U5.

Current Source

Adjustable output voltage regulator U1 and resistor R4 form a constant current source used to charge the batteries. The constant current level, I_{set}, is determined by R4 in conjunction with the 1.2 V voltage reference between the output and the adjust pin of U1 as follows:

$$I_{set} = \frac{1.2\ V}{R4}$$

R4 was chosen so that I_{set} is approximately 60 mA, the C/10 rate for the "AA" size lithium batteries. The current regulator and charger output are enabled by relay K1 when the charger is turned on.

Charging and Charged Indicators

D8 is a yellow LED that indicates when charge current is flowing. The R5-D8 parallel combination is in series with the output, allowing the LED to light whenever current is flowing out P2. R5 is placed in parallel to limit the current flow through D8 to 20 mA, thus preventing burnout. The necessary value of R5 for proper current bypassing can be found using:

$$R5 = \frac{2.2\ V}{I_{set} - 20\ mA}$$

D6 is a green LED that indicates when the batteries have reached a fully charged state or when there is no load connected at the output. This LED will light when U2, a micropower voltage detector, senses an output voltage exceeding the threshold determined by the set point resistors R6 and R7, as given by the following formula:

$$V_{threshold} = \frac{R6 + R7}{R7} \times 1.15$$

$V_{threshold}$ is set for the fully charged battery pack voltage level of 14.4 V. Capacitor C4 prevents U2 from false triggering on positive noise voltage spikes.

The open collector output of U2 will change from a high state to a low state when the threshold is reached, energizing relay K2. K2 latches itself on, turns on the CHARGED indicator D6, and de-energizes relay K1. K1 then disconnects the current regulator and the charger output. It should be noted that after U2 has triggered relay K2 to indicate a charged state, the charger can only be reset to the charge mode by turning the battery charger power off, thus de-energizing K2, and then restoring power.

R2 and R3 limit the relay coil operating currents to about 20 mA. Their values can be determined using:

$$R2 = \frac{V_{DC} - V_{K1}}{I_{OP1}}$$

and

$$R3 = \frac{V_{DC} - V_{K2} - 2.2}{I_{OP2}}$$

where V_{DC} is the power supply dc voltage, V_{K1} and V_{K2} are the coil operating voltages, (nominally 12 V), and I_{OP1} and I_{OP2} are the coil operating currents.

State-of-Charge Indicator

The state-of-charge indicator is similar to that of the Notch Box III. Five levels of LED indicators are driven by the bar/dot display driver, U3, rather than four as on the notch box. The resistance values for R8 and R9 were chosen to set the fully charged battery voltage level and minimize current drain, as follows:

$$V_{BAT}\ (100\%) = 14.4\ V = 1.25\ \left(\frac{R8 + R9}{R9}\right)$$

Similarly, R10 sets the fully discharged battery voltage (V_{BAT} [0%] = 8 V) according to the formula:

$$V_{BAT}\ (0\%) \cdot \frac{R9}{R8 + R9} = 1.25 \cdot \frac{R10 + 1\ k\Omega}{R10 + 10\ k\Omega}$$

The LED drive current is determined by R11 as:

$$I_{LED} = \frac{12.5}{R11}$$

The nominal 80%, 60%, 40%, and 20% battery capacity trip points were set at 11.5 V, 10.7 V, 10.0 V, and 9.3 V, respectively, by tying together the appropriate outputs of U3 as shown on the schematic of Figure B-2.

APPENDIX C

"AA" SIZE SINGLE LITHIUM BATTERY CHARGER

"AA" SIZE SINGLE LITHIUM BATTERY CHARGER

To aid in the proper care and operation of the lithium batteries used in the Notch Box III, IITRI designed and fabricated a battery charger capable of charging from one to six "AA" size lithium batteries individually at the same time. This battery charger will bring any six lithium batteries to the same potential so that they may be used together in the notch box. The battery charger brings each battery to a potential of approximately 2.4 V. (All lithium batteries to be used together in a pack must be at nearly the same potential. Otherwise, uneven charging and discharging of the batteries will occur, causing degradation of battery life.)

Figure C-1 is a photograph of the "AA" Size Lithium Battery Charger. The unit is portable, and can be used wherever a standard 120 V ac outlet is available. Operation of the unit is simple: the user inserts the batteries to be charged into the battery holders, plugs the ac line cord into a standard 120 V ac source, and turns the power switch on. The following sections provide a description of all battery charger controls and indicators and detailed information on its circuits.

BATTERY CHARGER CONTROLS AND INDICATORS

Power Switch

This switch, located on the front panel, controls application of the 120 V ac line to the battery charger. When off, the switch also disconnects the charger outputs via relay contacts. When this switch is turned on, a red LED located next to the switch indicates power application.

Charging Indicators

Two LEDs for each of the six batteries are located on the front panel to indicate the charging modes of the batteries. The yellow CHARGING indicators are illuminated only when charging current is actually flowing and the lithium batteries are being charged at a C/10 rate. When the green CHARGING indicators are illuminated, the charging cycle has been completed and the charger outputs have been disconnected via relay contacts.

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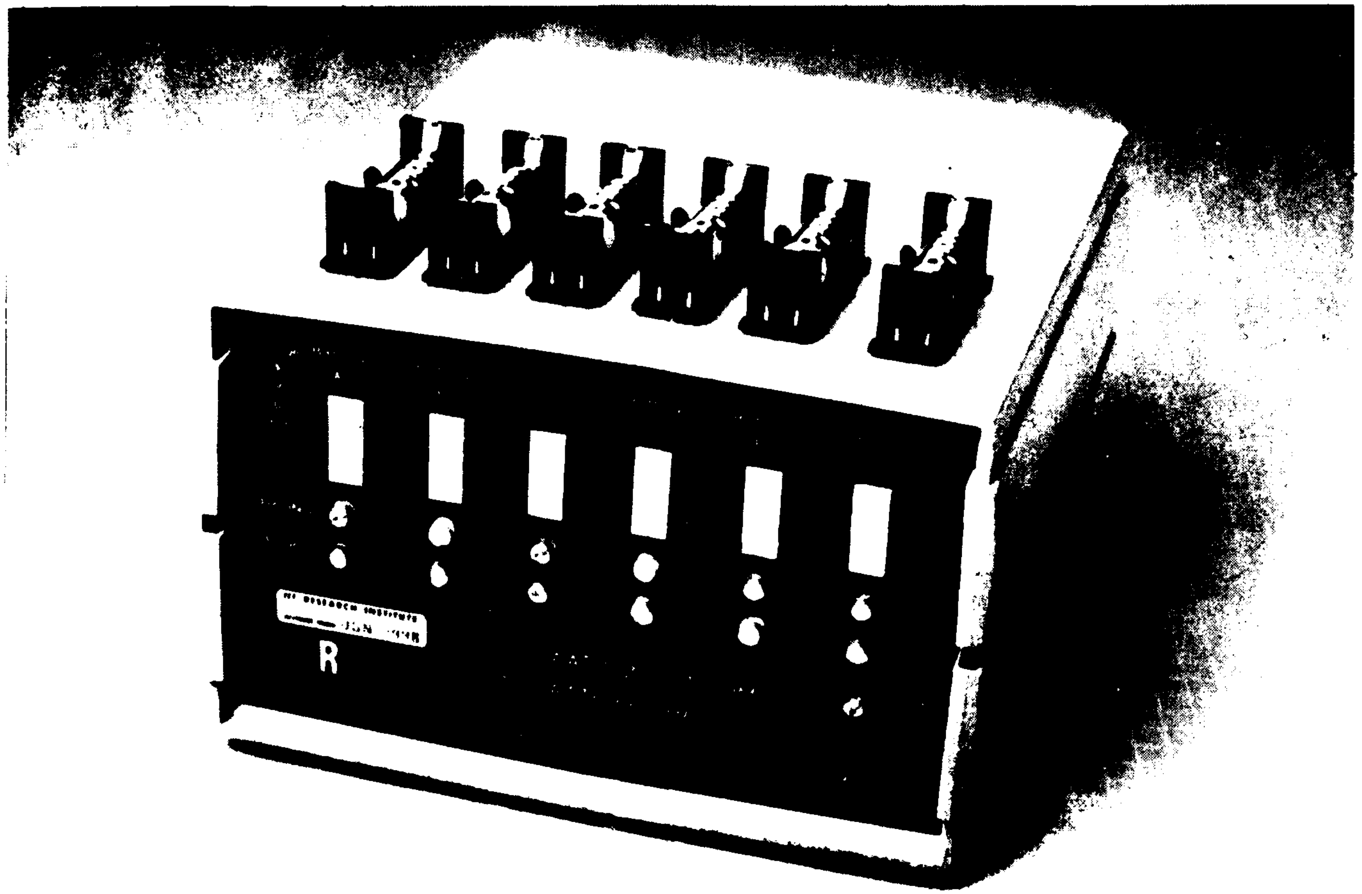


FIGURE C-1. AA-SIZE SINGLE LITHIUM BATTERY CHARGER.

State-of-Charge Indicators

Six bar graph displays on the front panel allow continuous monitoring of the state of charge for each battery. The displays have five distinct regions that define zones of battery charge in percentages: 100-80%, 80-60%, 60-40%, 40-20%, and 20-0%. This allows the user to evaluate the state of the batteries at any time. A letter designation above each bar graph display identifies the battery being monitored.

Battery Holders

Six "AA" size battery holders located on the top of the unit allow quick and easy connection of the batteries. These holders are fused with 0.10 A fuses that can be accessed from the rear panel. The holders are placed directly above their respective displays on the front panel.

AC Line Cord

Supplied on the rear panel is a three-conductor line cord with a three-prong plug to mate with any standard 120 V ac socket. The ground conductor of this wire is connected to the chassis (but not to the circuit ground), and the "hot" wire is fused with a 3AG 0.50 A fuse accessible from the rear panel.

CIRCUIT DESCRIPTION

The circuitry of the single lithium battery charger is contained primarily on six printed circuit boards of two types, referred to as X and Y in the discussion below. Schematics of the X and Y boards are shown in Figures C-2 and C-3, respectively. Table C-1 provides a complete parts list for the charger. Figure C-4 provides an interconnection diagram for the six boards. The PC board layouts are the same as those used in the Notch Box III Battery Charger shown in Figures B-3 and B-4.

Power Supply--X Boards Only

Power to drive the battery charger is derived from a 120 V ac 60 Hz source using P1. The ac line voltage is applied across the primary of the transformers (T1) on the X boards via line fuse F1 and power switch S1 on the "master" X board. T1 steps the voltage down to 12 V ac, which is then full-wave rectified by D1, D2, D3, and D4, a bridge rectifier. The C1 filters the output of the bridge rectifier, forming a 12 V dc source. The 12 V dc source

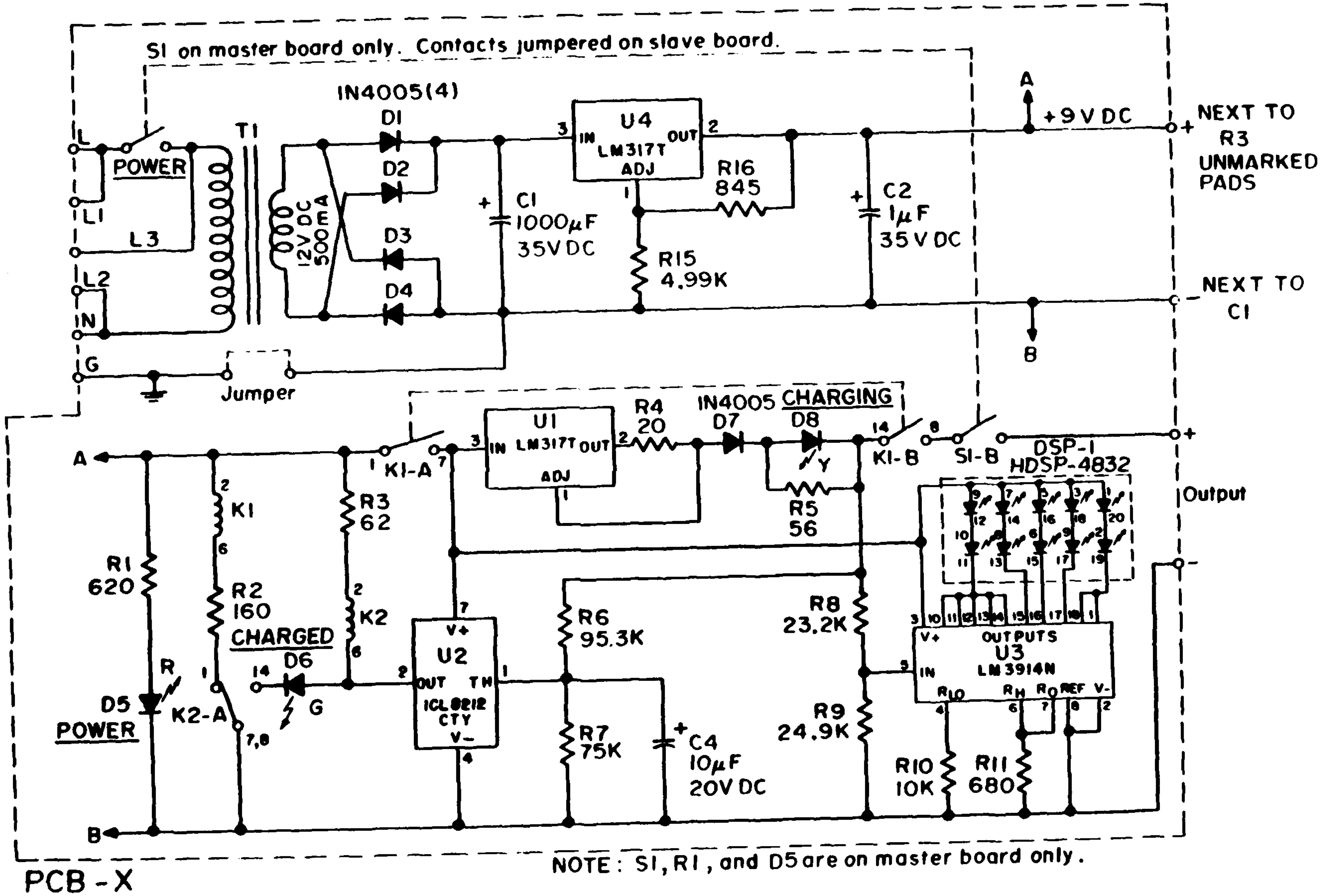


FIGURE C-2. SINGLE LITHIUM BATTERY CHARGER, "X" BOARD SCHEMATIC.

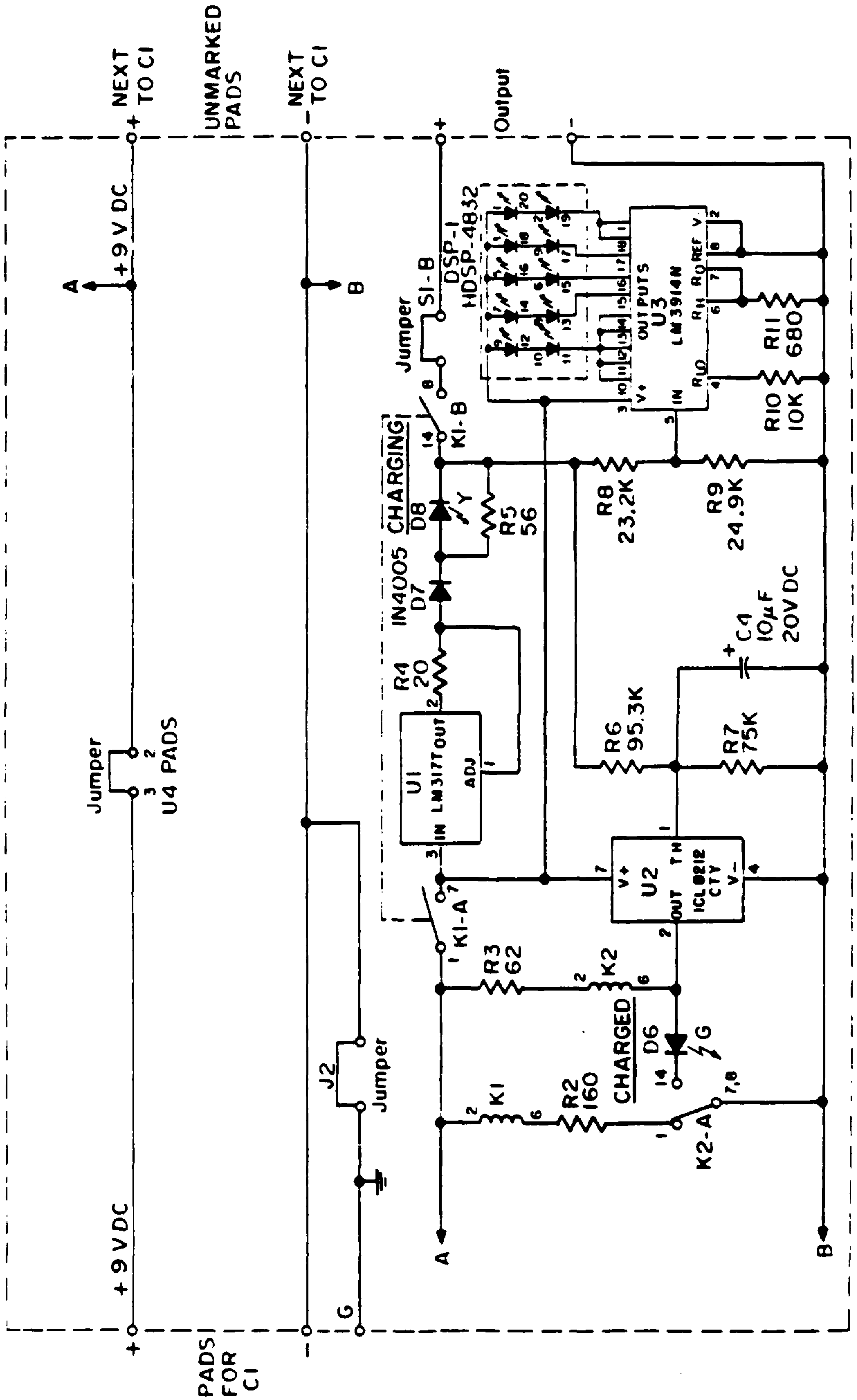


FIGURE C-3. SINGLE LITHIUM BATTERY CHARGER, "Y" BOARD SCHEMATIC.

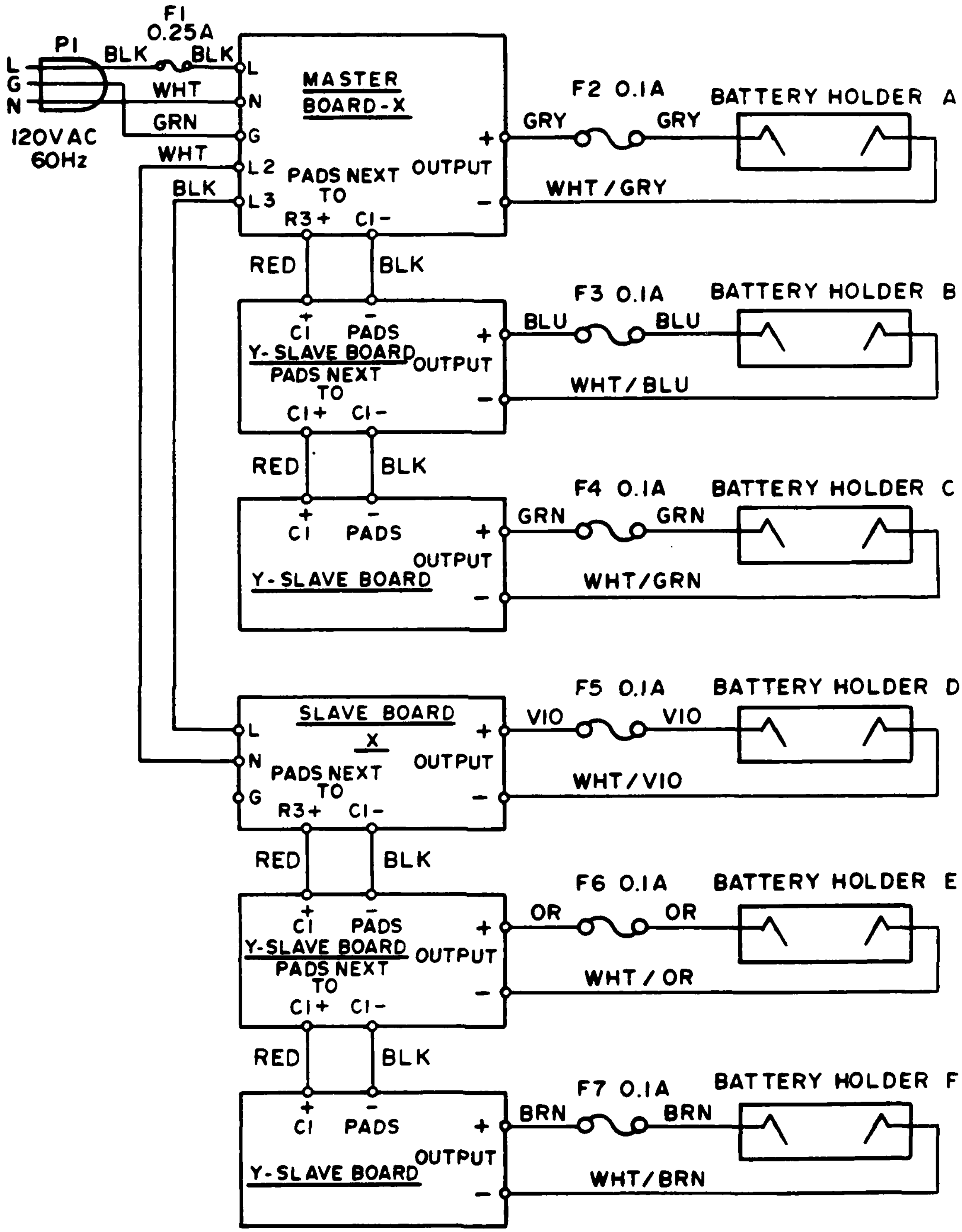


FIGURE C-4. SINGLE LITHIUM BATTERY CHARGER INTERCONNECTION DIAGRAM.

TABLE C-1. SINGLE LITHIUM BATTERY CHARGER PARTS LIST (page 1 of 2)

Label	Location	Description	Manufacturer	Part No.
U1	X, Y	Voltage Regulator	National Semi.	LM317T
U2	X, Y	Peak Detector	Intersil	ICL8212CTY
U3	X, Y	Display Driver	National Semi.	LM3914N
U4	X	Voltage Regulator	National Semi.	LM317T
R1	X	620 kΩ 5% Resistor, 1/4 W	Allen-Bradley	RC20
R2	X, Y	160 Ω 5% Resistor, 1/4 W	Allen-Bradley	RC20
R3	X, Y	62 Ω 5% Resistor, 1/4 W	Allen-Bradley	RC20
R4	X, Y	20 Ω 5% Resistor, 1/2 W	Allen-Bradley	RC07
R5	X, Y	56 Ω 5% Resistor, 1/2 W	Allen-Bradley	RC07
R6	X, Y	95.3 kΩ 1% Resistor	Dale	RN-55D
R7	X, Y	75 kΩ 1% Resistor	Dale	RN-55D
R8	X, Y	23.2 kΩ 1% Resistor	Dale	RN-55D
R9	X, Y	24.9 kΩ 1% Resistor	Dale	RN-55D
R10	X, Y	10.0 kΩ 1% Resistor	Dale	RN-55D
R11	X, Y	680 Ω 5% Resistor, 1/2 W	Allen-Bradley	RC07
R15	X	4.99 kΩ 1% Resistor	Dale	RN-55D
R16	X	845 Ω 1% Resistor	Dale	RN-55D
C1	X	1000 μF 35 V Capacitor	Cornell Dubilier	226J102P035XX
C2	X	1 μF 35 V Capacitor	Mallory	39003-01-2356J
C4	X, Y	10 μF 20 V Capacitor	Mallory	39003-01-2286
D1,2,3,4	X	Rectifier	Motorola	1N4005
D5	X	Red LED	Hewlett-Packard	HLMP-3750
D6	X, Y	Green LED	Hewlett-Packard	HLMP-3950
D7	X, Y	Rectifier	Motorola	1N4005
D8	X, Y	Yellow LED	Hewlett-Packard	HLMP-3850
DSP-1	X, Y	Bar Graph Display	Hewlett-Packard	HDSP-4832
K1	X, Y	DIP Reed Relay, 5 V (2 Form A)	Magnecraft	W171 DIP 25
K2	X, Y	DIP Reed Relay, 5 V (1 Form C)	Hamlin	HE721C0510
T1	X	12 V 500 mA Transformer	Stancor	LB624
S1	X	DPDT Toggle	American Switch	ST2-1KMA-1Q
P1	X	SJ Power Cord, 3 wire	Belden	17236B

TABLE C-1. SINGLE LITHIUM BATTERY CHARGER PARTS LIST (page 2 of 2)

Label	Location	Description	Manufacturer	Part No.
Miscellaneous:				
6 each	Chassis	"AA" Battery Holder	Power Dynamics	B-35
6 each	X, Y	8 Pin IC Socket	Augat	8059-2G5
12 each	X, Y	14 Pin DIL Socket	Augat	514-AG10D
6 each	X, Y	18 Pin DIL Socket	Augat	518-AG10D
6 each	X, Y	20 Pin Wire Wrap Socket	Texas Instruments	C9120-00
13 each	X, Y	LED Holder	P-C-Lite	PCR740
13 each	X, Y	Clear Round Lens for above holder	P-C-Lite	CLF280CTP
8 each	X, Y	Heat Sink	EG&G Wakefield	273-AB
18 each	X, Y	Mounting Bracket	SPC Tech.	28F1857
18 each	Chassis	4-40 x 1/4 in. Flathead Screw		--
Case		Plastic (Gray)	Pac-Tec	CS-500K
7 each	Chassis	Fuse Holder	Littelfuse	345903
F1-	Chassis	3AG 0.50 A Fuse	Littelfuse	312.500
F2-7	Chassis	3AG 0.10 A Fuse	Littlefuse	312.100
1 each	Chassis	Strain Relief	H. H. Smith	939
6 each	Chassis	PC Board	IITRI/Vendor	--
2 each	Chassis	Labels (1 front, 1 back) Photofoil	IITRI	--
6 each	Chassis	6-32 x 1/4 in. Machine Screw		--
6 each	Chassis	No. 6 Star Lock Washer		--
6 each	Chassis	No. 6 Nut		--

is then applied at the input of U4, an adjustable output voltage regulator, which in combination with R15, R16, and C2 forms a 9 V dc regulated supply. This voltage source on each X board is used to supply the current regulator on that board and on two Y boards. To indicate when power is on, R1 and LED D5 have been placed in series across the 9 V dc source on the master X board. R1 limits the LED current to 20 mA.

Current Source--X and Y Boards

An adjustable output voltage regulator U1 and resistor R4 form a constant current source used to charge the battery. The current level, I_{set}, is determined by R4 in conjunction with the 1.2 V voltage reference between the output and the adjust pin of U1 as follows:

$$I_{set} = \frac{1.2\ V}{R4}$$

R4 was chosen so that I_{set} is approximately 60 mA, the C/10 rate for "AA" size lithium batteries. The current regulator and charger output are enabled by relay K1 when the charger is turned on.

Charging and Charged Indicators--X and Y Boards

D8 is a yellow LED that indicates when charge current is flowing. The R5-D8 parallel combination is in series with the output, allowing the LED to light whenever current is flowing out P2. R5 is placed in parallel to limit the current flow through D8 to 20 mA, thus preventing burnout. The necessary value of R5 for proper current bypassing can be found using:

$$R5 = \frac{2.2\ V}{I_{set} - 20\ mA}$$

D6 is a green LED that indicates when the battery has reached a fully charged state or when there is no load connected at the output. This LED will light when U2, a micropower voltage detector, senses an output voltage exceeding the threshold determined by the set point resistors R6 and R7, as given by the following formula:

$$V_{threshold} = \frac{R6 + R7}{R7} \times 1.15$$

$V_{threshold}$ is set for the fully charged battery voltage level of 2.4 V. Capacitor C4 prevents U2 from false triggering on positive noise voltage spikes.

The open collector output of U2 will change from a high state to a low state when the threshold is reached, energizing relay K2. K2 latches itself on, turns on the CHARGED indicator D6, and de-energizes relay K1. K1 then disconnects the current regulator and the charger output. It should be noted that after U2 has triggered relay K2 to indicate a charged state, the charger can only be reset to the charge mode by turning the battery charger power off, thus de-energizing K2, and then restoring power.

R2 and R3 limit the relay coil operating currents to about 20 mA. Their values can be determined using:

$$R2 = \frac{V_{DC} - V_{K1}}{I_{OP1}}$$

and

$$R3 = \frac{V_{DC} - V_{K2} - 2.2}{I_{OP2}}$$

where V_{DC} is the power supply dc voltage, V_{K1} and V_{K2} are the coil operating voltages (nominally 12 V), and I_{OP1} and I_{OP2} are the coil operating currents.

State-of-Charge Indicator, X and Y Boards

The state-of-charge indicator is similar to that of the Notch Box III. Five levels of LED indicators are driven by the bar/dot display driver, U3, rather than four as on the notch box. The resistance values for R8 and R9 were chosen to set the fully charged battery voltage level and minimize current drain, as follows:

$$V_{BAT}\ (100\%) = 2.4\ V = 1.25\ \left(\frac{R8 + R9}{R9}\right)$$

Similarly, R10 sets the fully discharged battery voltage (V_{BAT} [0%] = 1.3 V) according to the formula:

$$V_{BAT}\ (0\%) \cdot \frac{R9}{R8 + R9} = 1.25 \cdot \frac{R10 + 1\ k\Omega}{R10 + 10\ k\Omega}$$

The LED drive current is determined by R11 as:

$$I_{LED} = \frac{12.5}{R11}$$

The nominal 80%, 60%, 40%, and 20% battery capacity trip points were set at 1.92 V, 1.78 V, 1.67 V, and 1.55 V, respectively, by tying together the appropriate outputs of U3 as shown on the schematic of Figure B-2.

APPENDIX D
SIMPLE TROUBLESHOOTING

SIMPLE TROUBLESHOOTING

Flow Charts

The Notch Box III was designed to be a reliable and easy instrument to use. The internal circuitry is defined in blocks so that a user can easily identify any malfunctions as they arise. Figures D-1 and D-2 are troubleshooting flow charts for two of the common problems that may be encountered and the steps to take in order to determine whether they are readily correctable by the user or require a qualified technician for repair.

Passband Unity Gain Frequency

For special measurement scenarios the user may wish to change the passband frequency at which the Notch Box III was adjusted for unity gain. Unity gain is normally set at a frequency of 76 Hz. The output gain is set by adjusting R8. This potentiometer has been made easily accessible so that adjustments can be made quickly when needed. The following steps provide a method by which this can be accomplished.

1. Remove the protective outer plastic case from the chassis to reveal a small hole on the right side panel (as viewed from front of notch box) near the front.
2. Place the chassis on a nonconductive surface. (The plastic case serves as a good stand.)
3. Turn the notch box to the ON BAT. mode with the input range set on 12 V_{rms}.
4. Provide a 1 V_{rms} CW signal of the desired frequency to the input using an ac voltage standard, the Valhalla 2703.
5. Connect a Fluke 8060A rms voltmeter to the output.
6. Insert a small screwdriver in the hole on the chassis and engage it with potentiometer R8.
7. Adjust the resistance of R8 until the rms voltmeter reads exactly the input voltage, 1 V_{rms}.
8. Be sure to indicate on the notch box with a label the 0 dB frequency if it is adjusted to a frequency other than the standard of 76 Hz.

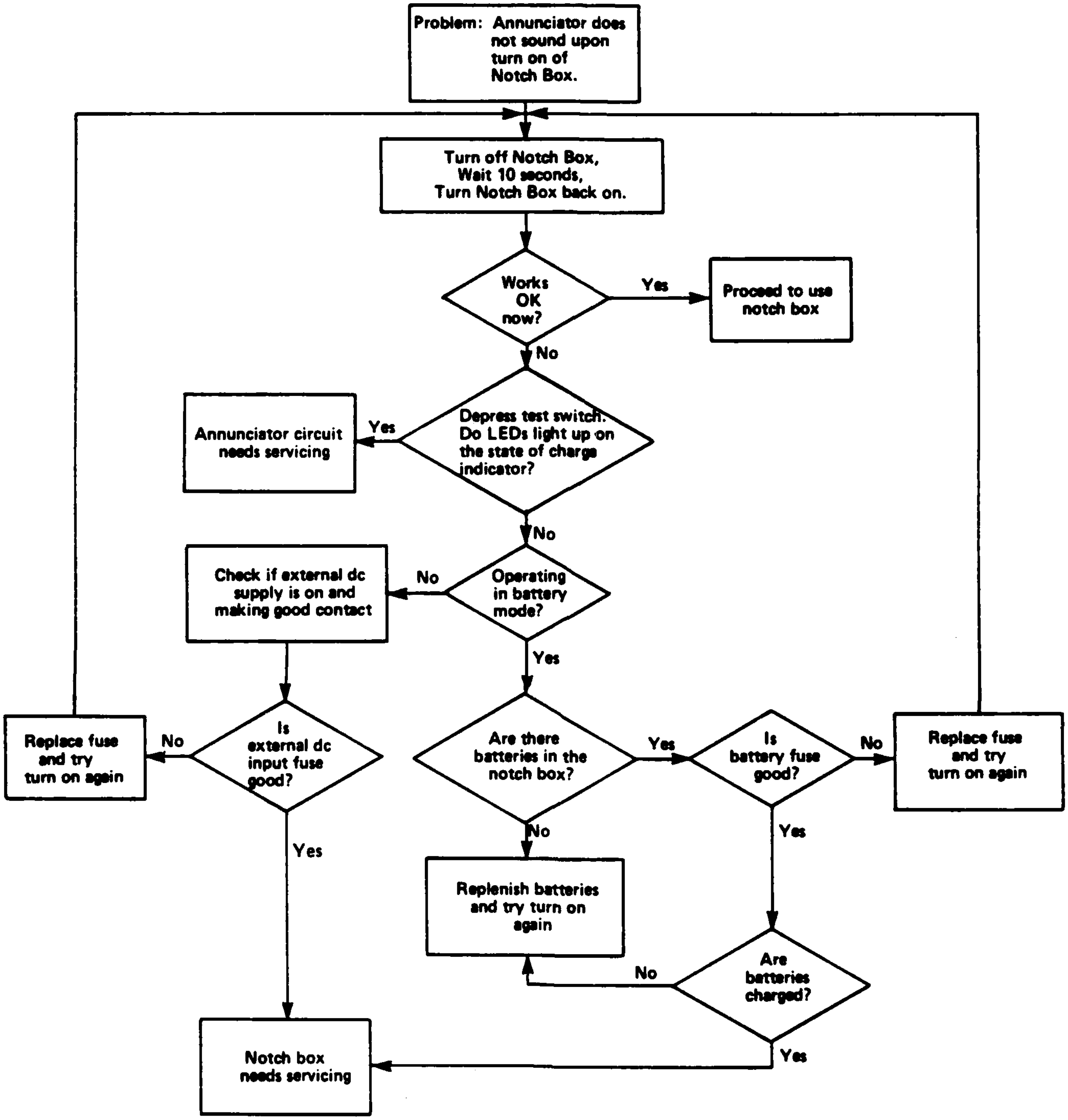


FIGURE D-1. PROBLEM: ANNUNCIATOR DOES NOT SOUND WHEN NOTCH BOX IS TURNED ON.

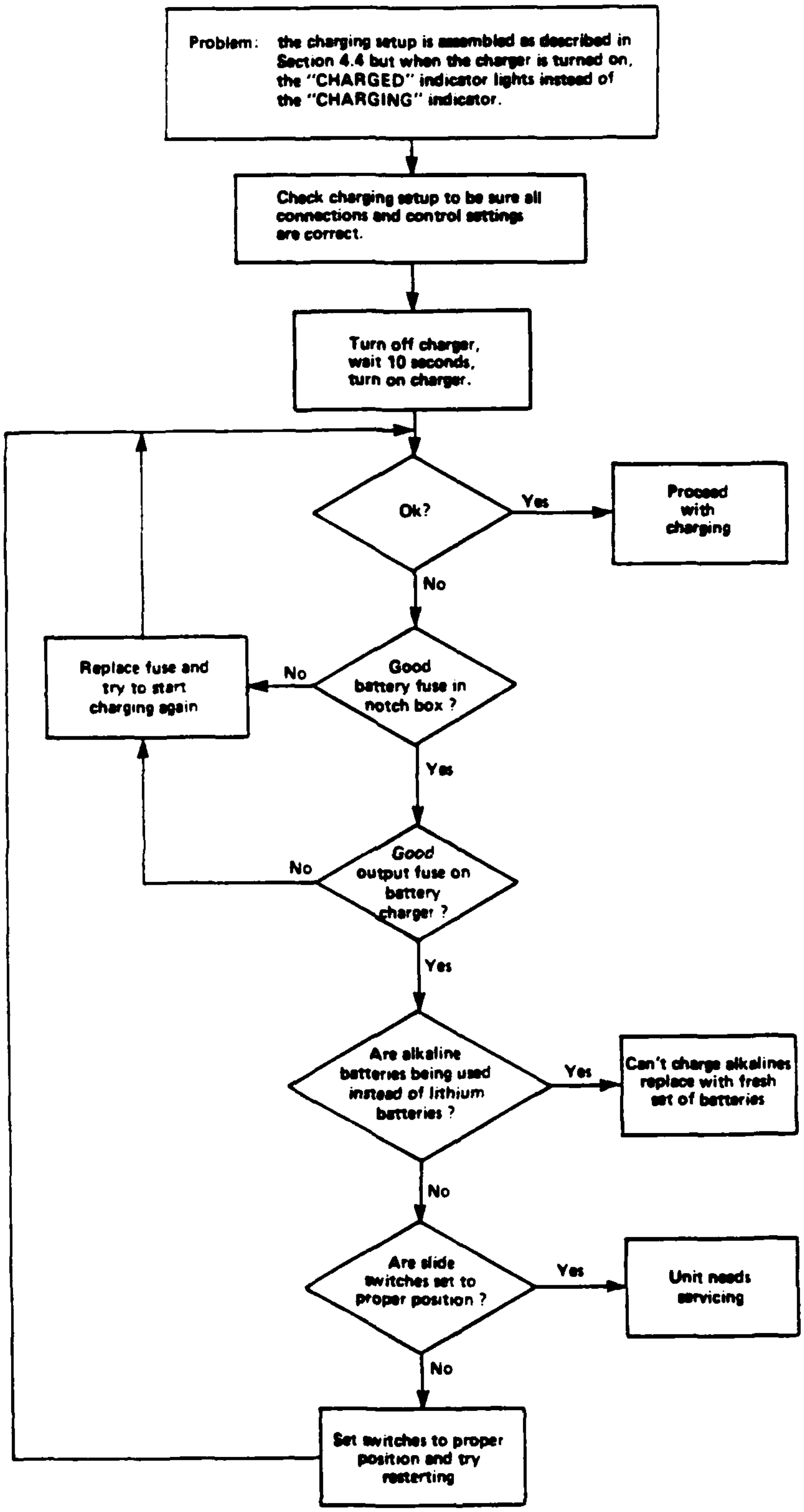


FIGURE D-2. PROBLEM: "CHARGED" INDICATOR LIGHTS WHEN CHARGER IS TURNED ON.

APPENDIX E
SPECIAL DEVICE CHARACTERISTICS

PART NUMBER(S)

782R2A, 782R2B, 782R2C

DESCRIPTION

The 782 2-pole-pair 60Hz notch is a high performance device with a current drain of 100μA. It features a nominal ±0.4Hz 40dB BW and maintains a ±0.25Hz 40dB BW over the operating temperature range of $0^{o}C$ to $70^{o}C$.

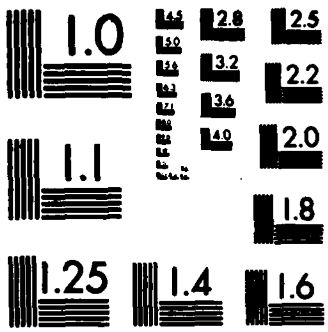
FREQUENCY DEVICES, INC.

25 Locust Street, Haverhill, Mass. 01830

TEL 617-374-0761 TWX 710-347-0314

AD-A193 324 A NOTCH FILTER INSTRUMENT FOR MEASURING ELF (EXTREMELY LOW FREQUENCY) MSK..(U) IIT RESEARCH INST CHICAGO IL R G DREXLER ET AL. JAN 88 IITRI-E06549-34 2/2

UNCLASSIFIED N00039-84-C-0070 F/G 20/3 NL



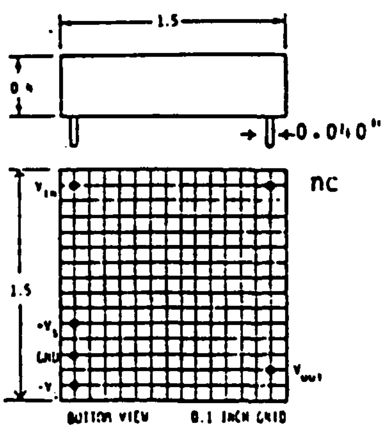
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

SPECIFICATIONS

		782R2A	782R2B	782R2C
Center Frequency (f_0)		60Hz		
Attenuation Characteristics:		See Table 1 for Gain and Φ after theoretical design		
Passband Gain 0 ±0.3dB Inverting		dc and 120Hz	dc and 1000Hz	dc and 10,000Hz
Passband Corners @ 56Hz and 64Hz		3dB Max.		
Stopband Corners				
Typical @ 25°C	60 ±0.3Hz	50dB		
	60 ±0.4Hz	40dB		
Linear Operation: (V_s = ±15Vdc)		±10Vp-p		
Impedance				
Input		200kΩ		
Output		100Ω	20Ω	10Ω
Minimum Load		100kΩ	20kΩ	2kΩ
Temperature Range:				
Operating		0°C to 70°C		
Storage		-45°C to 85°C		
Noise		Typical 50μV RMS, 5Hz to 10kHz BW		
Power Supply:				
Operating Voltage Range		±3 to ±15Vdc		
Quiescent Current		100μA	1mA	10mA
Maximum Safe Supply Voltage		±18Vdc		
Package Data (k-1 case)		1.5" x 1.5" x 0.4"		
		0.040" diameter electro solder plated half hard brass		

NOTE: Values stated are typical for each particular performance parameter.
Specifications are at rated ±15Vdc supply and 25°C operating temperature.

MECHANICAL



Use S1013 Socket.

Pins protrude a minimum of 0.080" from the case. (0.10" typical)

SIZE A	CODE IDENT NO 52339	782R2A, B, C
		SHEET 3 OF 4

820511PM

THEORETICAL PHASE AND GAIN DATA

782R2 A, B, C

FREQUENCY(Hz)	AMP	AMP(dB)	PHASE(deg)
0.0000	1.000	0.000	0.0000
10.0000	1.0000	0.0001	-1.7376
20.0000	1.0001	0.0005	-3.8032
30.0000	1.0001	0.0011	-6.7723
40.0000	1.0001	0.0007	-12.2534
50.0000	0.9940	-0.0523	-28.6440
51.0000	0.9901	-0.0861	-32.4318
52.0000	0.9832	-0.1469	-37.2599
53.0000	0.9702	-0.2625	-43.6120
54.0000	0.9442	-0.4986	-52.2789
55.0000	0.8893	-1.0190	-64.5325
56.0000	0.7729	-2.2376	-82.0972
57.0000	0.5572	-5.0795	-105.8348
58.0000	0.2798	-11.0638	-132.7707
59.0000	0.0693	-23.1856	-157.8731
59.5000	0.0151	-36.4389	-169.2581
59.6000	0.0086	-41.3134	-171.4685
59.7000	0.0036	-48.9318	-173.6632
59.8000	0.0000	-1000.0000	-85.8453
59.9000	0.0021	-53.3976	1.9821
60.0000	0.0028	-50.9133	-0.1840
60.1000	0.0021	-53.4266	-2.3467
60.2000	0.0000	-1000.0000	85.4908
60.3000	0.0035	-49.0187	173.3256
60.4000	0.0085	-41.4293	171.1548
60.5000	0.0148	-36.5838	168.9755
61.0000	0.0670	-23.4752	157.8654
62.0000	0.2627	-11.6106	134.0483
63.0000	0.5174	-5.7239	109.1835
64.0000	0.7258	-2.7832	87.1276
65.0000	0.8500	-1.4112	70.3022
66.0000	0.9151	-0.7711	58.2227
67.0000	0.9489	-0.4557	49.5200
68.0000	0.9673	-0.2889	43.0760
69.0000	0.9779	-0.1945	38.1528
70.0000	0.9843	-0.1378	34.2820
80.0000	0.9975	-0.0218	17.6184
90.0000	0.9987	-0.0116	12.2443
100.0000	0.9990	-0.0088	9.5395
110.0000	0.9991	-0.0075	7.8902
120.0000	0.9992	-0.0068	6.7691

TABLE 1

SIZE	CODE IDENT NO	
A	52339	782R2 A, B, C
		SHEET 4 OF 4

820511PM

PART NUMBER(S)
7708

DESCRIPTION

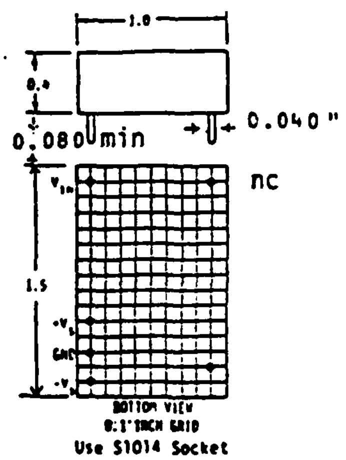
The 7584 is a low power 5 pole 0.5dB Tchebyschev lowpass filter. It is designed with appropriate internal amplitude scaling and output impedance to minimize the effects of amplifier noise, and RF pickup when used in conjunction with a 7585 low power dual notch filter.

PRELIMINARY DRAFT
DATE ______________

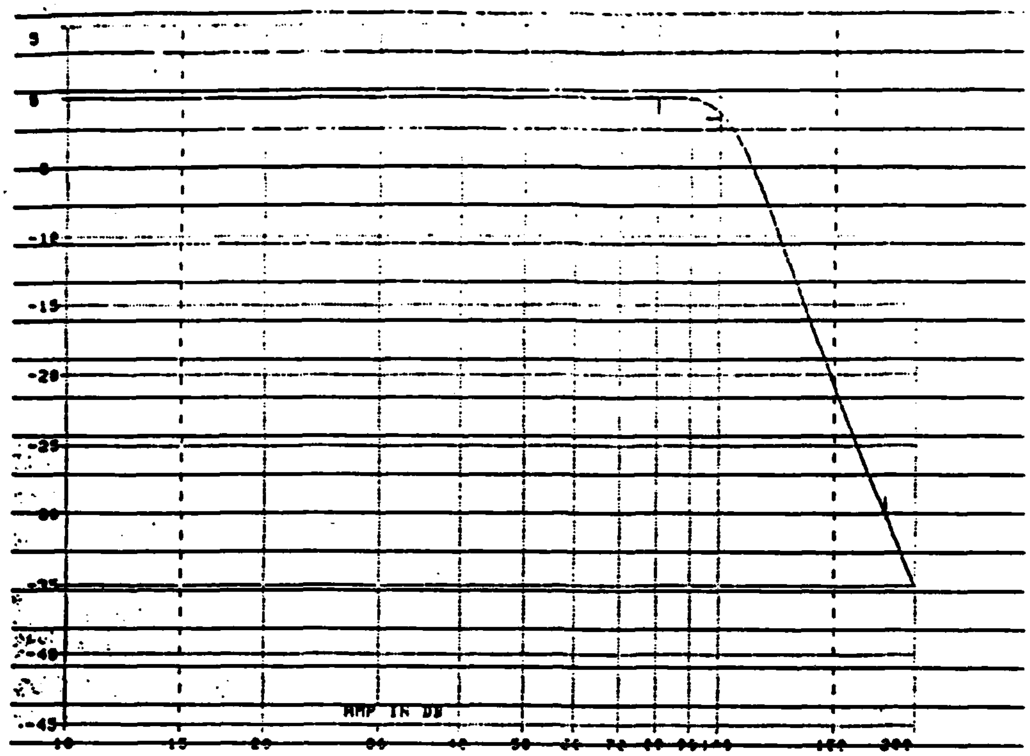
FREQUENCY DEVICES, INC.
25 Locust Street, Haverhill, Mass. 01830
TEL 617-374-0761 TWX 710-347-0314

SPECIFICATIONS

Corner Frequency (-1dB)		100Hz min
Attenuation Characteristics (See Table 1 for theoretical design)		
Insertion Loss (dc)		0 ±0.1dB
Passband Ripple (0Hz-100Hz)		±0.25dB from ideal curve (Table 1)
Attenuation @f_c (100Hz)		≤1dB
Attenuation @1.8f_c (180Hz)		≥30dB
Voltage Swing for Linear Operation (V_s=20Vdc)		±16.5
Impedance		
Input	700kΩ typical	500kΩ minimum
Output	12.5kΩ typical	15kΩ maximum
Load	100k	
Temperature Range		
Operating		0 to +70°C
Storage		-25°C to +85°C
Noise		50μV RMS max (5Hz to 500Hz)
Power Supply		
Operating Voltage		±5V to ±22V
Current (@±20Vdc)		30μA (typ) 45μA (max)
Maximum Safe Supply Voltage		±22V
Size: (N-1 Case)		1"x1.5"x0.4"
Pins		0.040" diameter Electro solder plated half hard brass 0.080" minimum (0.100" typical) protrusion from case



SIZE	CODE IDENT NO	
A	52339	7708
		SHEET 3 OF 4



FREQUENCY(Hz)	AMP	AMP(dB)	PHASE(deg)	DELAY(sec)
0.0000	1.0000	0.0000	0.0000	[illegible]
5.0000	0.9996	-.0016	-10.0752	5.5983E-03
10.0000	[illegible]	[illegible]	[illegible]	[illegible]
15.0000	0.9986	-.0118	-30.2529	5.6163E-03
20.0000	[illegible]	[illegible]	[illegible]	[illegible]
25.0000	0.9977	-.0198	-50.5686	5.6810E-03
30.0000	[illegible]	[illegible]	[illegible]	[illegible]
35.0000	0.9983	-.0151	-71.2503	5.8233E-03
40.0000	[illegible]	[illegible]	[illegible]	[illegible]
45.0000	0.9997	-.0027	-92.5957	6.0474E-03
50.0000	[illegible]	[illegible]	[illegible]	[illegible]
55.0000	0.9998	-.0020	-114.8633	6.3324E-03
60.0000	[illegible]	[illegible]	[illegible]	[illegible]
65.0000	0.9981	-.0164	-138.2815	6.7006E-03
70.0000	[illegible]	[illegible]	[illegible]	[illegible]
75.0000	0.9984	-.0142	-163.4336	7.3585E-03
80.0000	[illegible]	[illegible]	[illegible]	[illegible]
85.0000	0.9989	-.0094	-192.0729	8.7193E-03
90.0000	[illegible]	[illegible]	[illegible]	[illegible]
95.0000	0.9510	-.4366	-227.1591	1.0763E-02
100.0000	[illegible]	[illegible]	[illegible]	[illegible]
105.0000	0.7515	-2.4809	-267.0862	1.0778E-02
110.0000	[illegible]	[illegible]	[illegible]	[illegible]
115.0000	0.4797	-6.3813	-301.0408	7.9078E-03
120.0000	[illegible]	[illegible]	[illegible]	[illegible]
125.0000	0.2873	-10.8328	-324.5697	5.3472E-03
130.0000	[illegible]	[illegible]	[illegible]	[illegible]
135.0000	0.1765	-15.0648	-340.7696	3.7892E-03
140.0000	[illegible]	[illegible]	[illegible]	[illegible]
145.0000	0.1132	-18.9237	-352.5869	2.8580E-03
150.0000	[illegible]	[illegible]	[illegible]	[illegible]
155.0000	0.0756	-22.4326	-361.6867	2.2462E-03
160.0000	[illegible]	[illegible]	[illegible]	[illegible]
165.0000	0.0522	-25.6431	-368.9843	1.8320E-03
170.0000	[illegible]	[illegible]	[illegible]	[illegible]
175.0000	0.0371	-28.6023	-375.0133	1.5325E-03
180.0000	[illegible]	[illegible]	[illegible]	[illegible]
185.0000	0.0271	-31.3487	-380.1065	1.3070E-03
190.0000	[illegible]	[illegible]	[illegible]	[illegible]
195.0000	0.0202	-33.9128	-384.4836	1.1317E-03
200.0000	[illegible]	[illegible]	[illegible]	[illegible]

SIZE	CODE IDENT NO	
A	52339	7708
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