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Intrinsically Safe 5-V, 4-A Rechargeable Power Supply

By John J. Sammarco

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The U.S. Bureau of Mines has developed a regulated, intrinsically safe, rechargeable power supply for portable electronic equipment for underground use. The regulated output is ideal for microprocessor power requirements and is suited for operation in hazardous environments. Two rechargeable, sealed batteries are contained within the power supply. Provisions are made to use an external source of power if these batteries fail. Provisions are also made to charge these internal batteries when needed. The circuit is composed of three main circuits: the main regulator circuit, the input protection circuit, and the output protection circuit. The main regulator circuit provides remote voltage sensing, current sensing, fault monitoring, and internal thermal protection. The input protection circuit checks for excessive input current and low battery conditions. The output protection circuit contains two overvoltage detection devices. Schematics, a parts list, and a calibration procedure are provided to enable readers to fabricate the power supply.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	μF	microfarad
°C	degree Celsius	mA	milliampere
h	hour	s	second
in	inch	V	volt
lb	pound	V dc	volt, direct current
kohm	kilohm	W	watt

INTRINSICALLY SAFE 5-V, 4-A RECHARGEABLE POWER SUPPLY

By John J. Sammarco[1]

ABSTRACT

The U.S. Bureau of Mines has developed a regulated, intrinsically safe, rechargeable power supply for portable electronic equipment for underground use. The regulated output is ideal for microprocessor power requirements and is suited for operation in hazardous environments. Two rechargeable, sealed batteries are contained within the power supply. Provisions are made to use an external source of power if these batteries fail. Provisions are also made to charge these internal batteries when needed. The circuit is composed of three main circuits: the main regulator circuit, the input protection circuit, and the output protection circuit. The main regulator circuit provides remote voltage sensing, current sensing, fault monitoring, and internal thermal protection. The input protection circuit checks for excessive input current and low battery conditions. The output protection circuit contains two overvoltage detection devices.

Schematics, a parts list, and a calibration procedure are provided in this report to enable readers to fabricate the power supply.

[1]Electrical engineer, Pittsburgh Research Center, U.S. Bureau of Mines, Pittsburgh, PA.

INTRODUCTION

NOTE.–With the internal battery, the assembly is regarded as intrinsically safe. If the external source is used, the assembly and its associated equipment must remain in a nonhazardous area (fresh air). Battery charging must always be done in fresh air. Any alteration of the device as described in this report voids intrinsically safe operation and its subsequent approval.

Bureau research results provide advancements in safety and increases in overall mining efficiency through improved technology. This research may result in devices that can readily be used by the mining industry, such as the intrinsically safe, rechargeable power supply (fig. 1) described in this report.

The power supply was designed for portable, electronic equipment used in hazardous environments. For this application, the following criteria are noteworthy: The design must be intrinsically safe (see appendix A); circuit operation should be efficient to maximize battery life; and size and weight should be minimal to enhance portability.

To meet these criteria, the design incorporates multiple and redundant protection circuits to ensure intrinsic safety. Integrated circuits incorporating multiple protection functions were used to minimize circuit count, thus reducing the size and increasing reliability. Components were selected to enable efficient operation to prolong battery life. A means for recharging the batteries exists.

This report describes circuit operation, calibration, and gives parts lists and schematic diagrams for both the power supply and a battery charger.

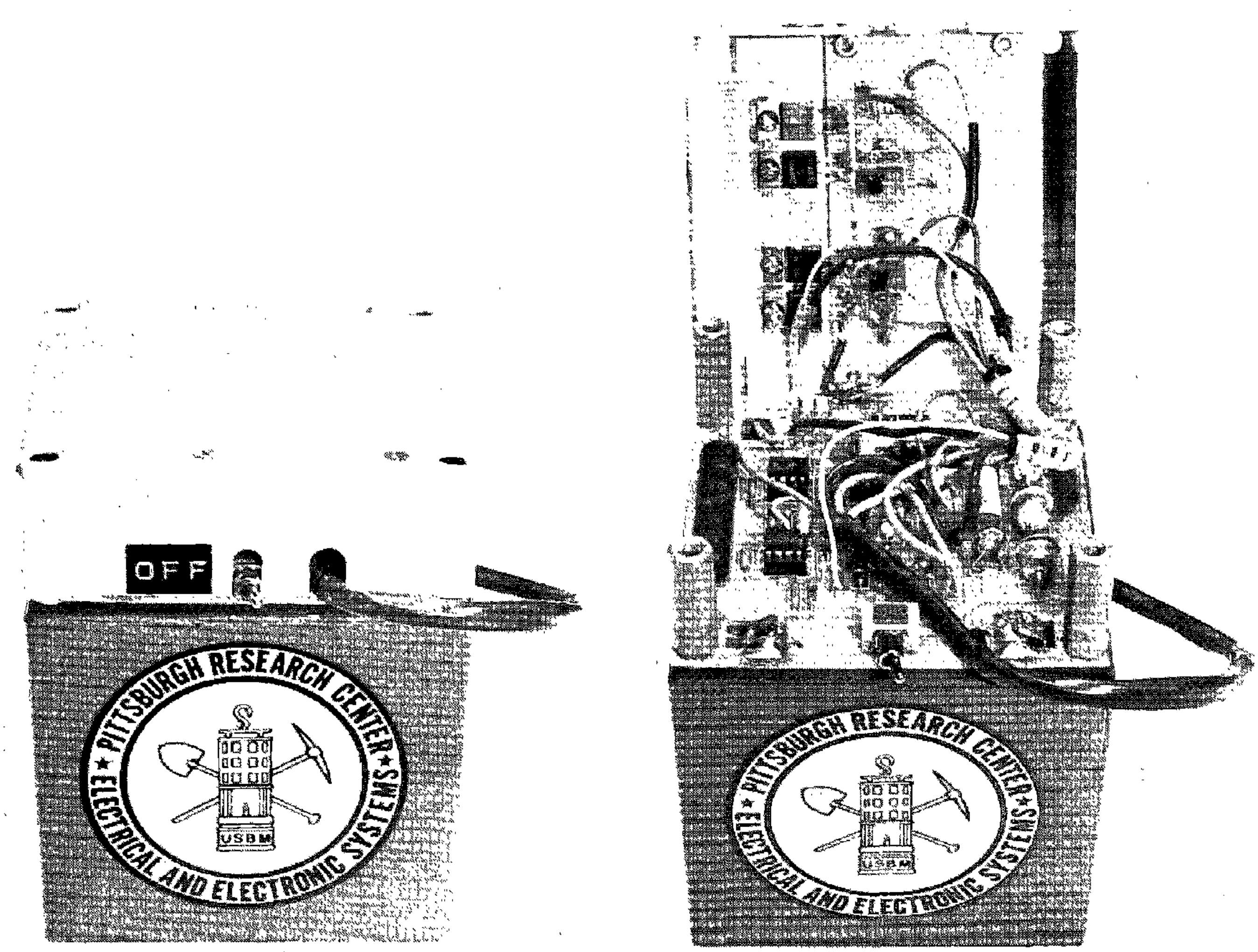

Figure 1.–5-V dc power supply (closed and open).

ACKNOWLEDGMENT

The author wishes to acknowledge John S. Gbruoski, electronics technician, Pittsburgh Research Center, for construction of the device and for assistance during the testing and Mine Safety and Health Administration (MSHA) approval process.

CIRCUIT DESCRIPTION

A block diagram of the power supply is depicted in figure 2. The power supply circuit schematic is depicted in figure 3. This power supply circuit is composed of the main regulator circuit, the input protection circuit, and the output protection circuit. A description of operation for each of these circuits follows.

MAIN REGULATOR CIRCUIT

The functions of the main regulator circuit, shown in figure 4, are to convert the 8-V nominal battery voltage to a 5.0-V output, to provide protection from excessive current, and to provide protection from voltage fault conditions. The main regulator circuit achieves these functions with device U1, a programmable linear voltage regulator. This part was selected because it contains provisions for remote voltage sensing, current sensing, fault monitoring, and internal thermal protection. Additionally, these features, incorporated on one chip, greatly reduce the need for external circuitry and simplifies design.[2]

Linear voltage regulation is achieved by U1 (pin 9) monitoring the output voltage at the remote sensing voltage divider resistors (R6 and R7). The appropriate biasing is supplied to the series pass transistor Q1 to maintain proper output voltage regulation. An increase in output voltage measured by U1 (pin 9) will cause the biasing of Q1 to decrease. Q1 becomes less conductive and the output voltage will decrease to the desired level of output voltage. Various output voltages can be obtained by simply changing the remote sensing voltage. Potentiometer R7 enables changes in the remote sensing voltage divider network so that the output voltage can be adjusted. Once

[2]Fritz, G. Versatile UC1834 Optimizes Linear Regulator Efficiency. Unitrode Corp., Application Note U-95, 1984, pp. 1-12.

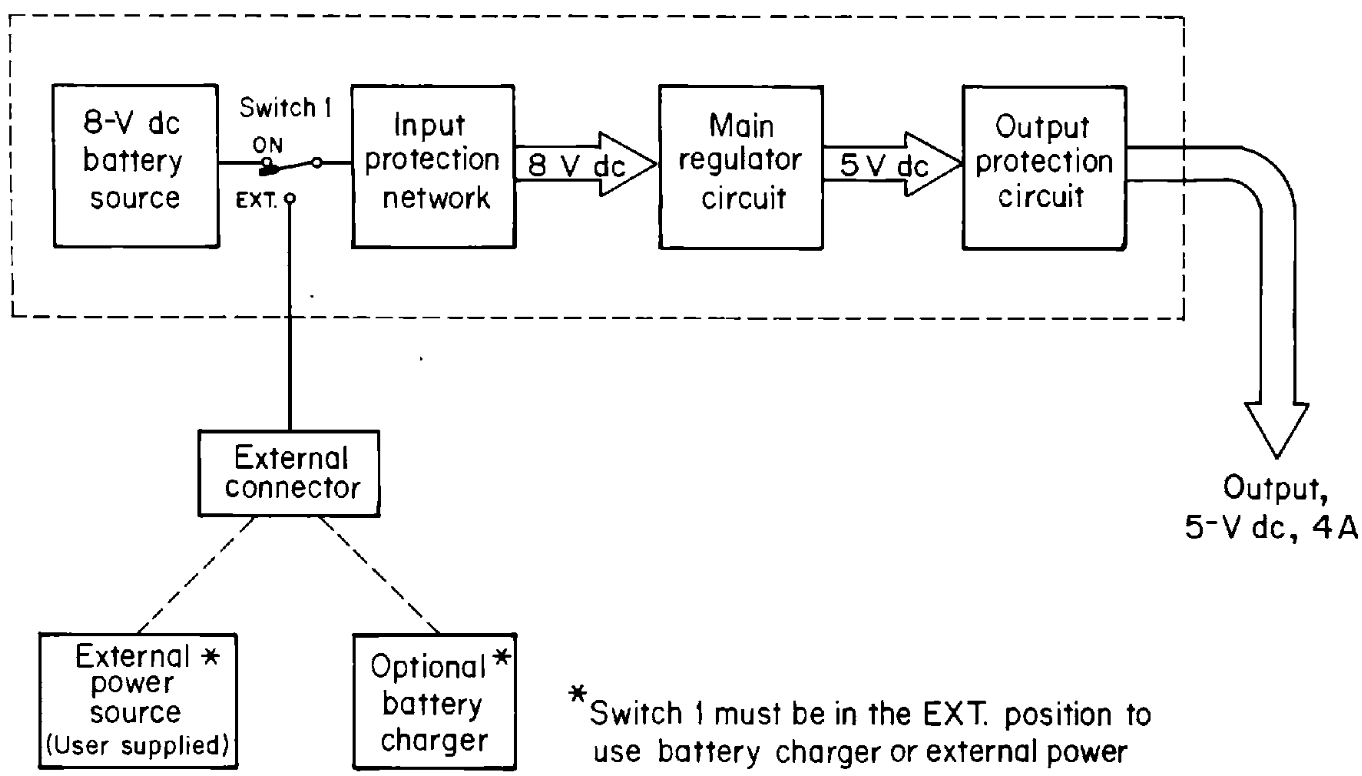

Figure 2.–5-V dc power supply block diagram.

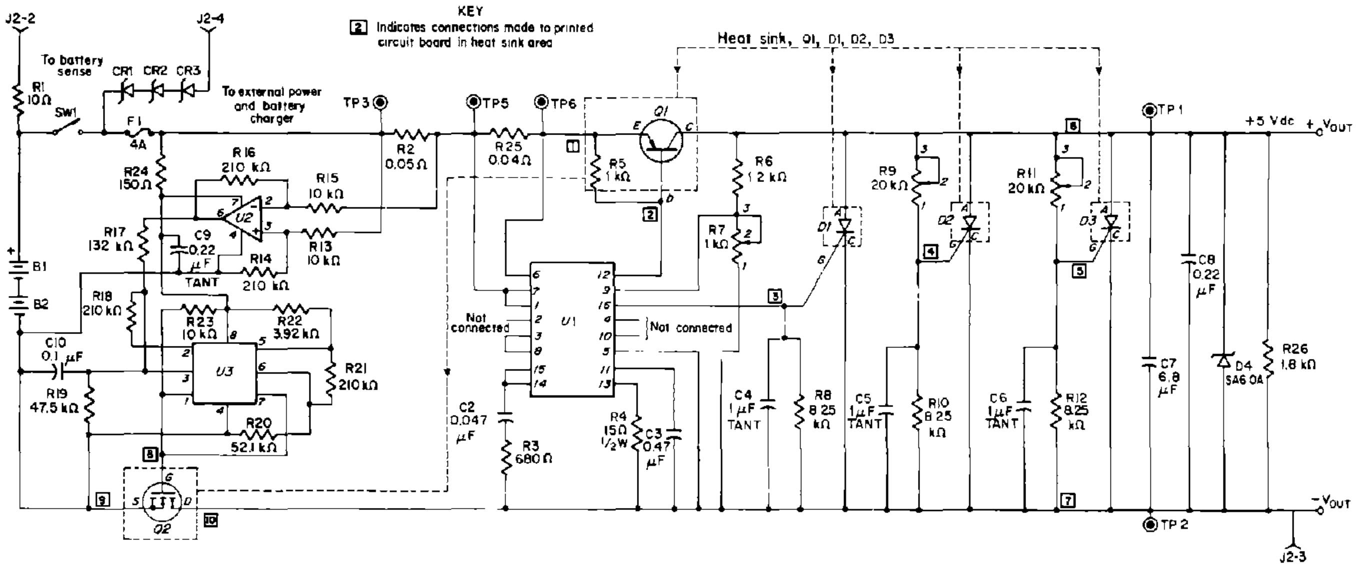

Figure 3.–5-V dc power supply schematic diagram.

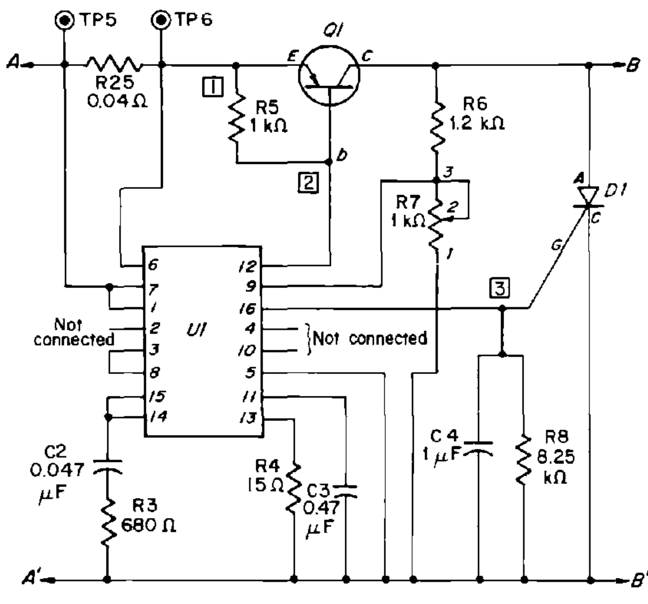

Figure 4.–Main regulator circuit.

the voltage has been adjusted in a laboratory environment, no changes to this adjustment should be made while underground.

Current sensing is used to limit the current into Q1 to protect it from damage and to regulate the maximum output current of the power supply. The input current is sensed by measuring the voltage across R25 with a current sensing amplifier internal to U1. When current becomes excessive the base drive to Q1 is decreased making Q1 less conductive, which limits the output current.

Output voltage fault detection provides protection for two separate voltage fault conditions–overvoltage and undervoltage of the output. The voltage fault detection will tolerate any voltage deviation within ±10% of the nominal output voltage. Any voltage outside this range will be treated as a fault. An overvoltage fault activates a crowbar circuit that switches on a shunt silicon-controlled rectifier (SCR). This effectively places a short circuit across the output causing a large increase in Q1's collector current. Before this current becomes excessive, the current sensing protection of U1 will activate to provide proper protection.

A voltage fault delay line prevents transient voltage conditions from triggering the overvoltage and undervoltage fault protection circuits. This delay is programmable by adding a capacitor from pin 11 to ground. The delay time is about 0.047 s for each microfarad of capacitance.

Finally, a thermal shutdown circuit is incorporated in U1. This circuit will shut down operation of U1 when the internal junction temperatures reach 165° C. This protects U1 from damage because of excessive power dissipation.

INPUT PROTECTION CIRCUIT

The input protection circuit of figure 5 serves two main functions: to provide protection against excessive input current and to detect low battery conditions.

Excessive input current protection is needed to protect the main regulation circuit from damage because of overheating and to limit the output current of the power supply to a safe level. The input current is limited to approximately 4.0 A. This is achieved by sensing the current through R2 and turning Q2 off when excessive current is

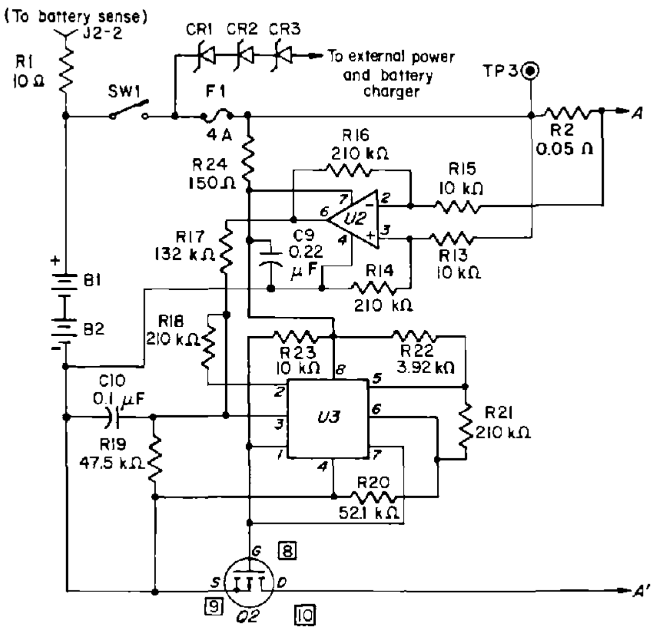

Figure 5.–Input protection circuit.

detected, thus opening the negative connection to the battery. The input current (I) is known by simply measuring the voltage across R2 (E) and applying Ohm's law where E = I * R.

A voltage of 0.2 V will exist across the 0.05-ohm resistance of R2 when 4.0 A of input current is present. This 0.2 V is amplified to about 6.64 V by the differential amplifier circuit of U2. Next, this voltage is sent to the voltage detection circuit of U3. When a 6.64-V or greater voltage is detected by U3, the gate of Q2 is biased to turn off Q2, thus disconnecting power from the battery to the power supply circuit.

The circuit described for current protection is independent and redundant to the current protection circuitry of U1 described in the "Main Regulator Circuit" section. Overcurrent protection is also provided by fuse F1. However, a fuse is not recognized as a protection device when evaluating a circuit for intrinsic safety because the response time of the fuse is not adequate to prevent an ignition in a hazardous environment.

The second function of the input protection circuit is to detect low battery conditions. Operation of the power supply during low battery voltages can deep discharge the batteries, which will shorten their useful life. Two 3.95-V, rechargeable, sealed batteries connected in series are used as the power source. This combination gives a total nominal working voltage of 7.9 V. When a low battery condition of 6.5 V is detected by the circuitry of U3, the metallic oxide semiconductor field-effect transistor Q2 is turned off to disconnect the negative side of the batteries from the power supply circuitry. When the battery voltage increases to 6.6 V, U3 will turn Q2 on, thus restoring battery power to the power supply circuit.

Device U3 is used in the overcurrent detection circuit and the low-battery-detection circuit. This is a dual voltage detector device that operates from any supply voltage in the 1.6- to 16-V range and can monitor voltages greater than 1.3 V. The voltage detection trip points and hysteresis levels are programmed by external resistor networks.[3] U3 is a low-power complementary metallic oxide semiconductor (CMOS) device and typically requires only 3 mA for operation, thus minimizing the current drain on the batteries.

Note that the input circuit also provides the ability to externally sense battery voltage, supply external power, and charge batteries. An external line is designated for sensing battery voltage. This provides easy access for measurement of the battery voltage. A separate line is provided for external power operation or for battery charging. When power switch SW1 is opened (off), the batteries can be bypassed so that external power can be supplied for operation.

The maximum external voltage permitted through this line is 16 V. To charge the batteries, SW1 must be closed and the battery charger must be connected. Information for the battery charger is given in appendix C. The batteries recharge at a constant potential source of 4.96 to 5.10 V dc each, with a charging current of 1.2 A.

CAUTION.–Do not attempt to recharge, replace, or connect batteries while in a hazardous environment. Also, do not attempt to use or connect external power while in a hazardous environment.

OUTPUT PROTECTION CIRCUIT

A separate and redundant overvoltage protection circuit is present at the output as shown in figure 6. Shunt SCR circuits will be activated when an overvoltage condition exists. Two identical shunts are provided. This redundancy provides protection if a failure would occur in one of the shunts. The level at which the SCR's will turn on is determined by resistive divider networks. These trip levels can be adjusted. Potentiometer R9 adjusts the level for SCR D2 and potentiometer R11 adjusts the level for SCR D3.

When a shunt SCR turns on, it effectively makes a short-circuit connection across the output of the power supply. During short-circuit output conditions, a large short-circuit current will flow through the power supply. The power supply will shut down when this current exceeds the levels set by the current protection devices. Once an SCR has tripped, it must be reset by momentarily disconnecting battery supply voltage by toggling power supply switch SW1 to the off position.

[3] Maxim Integrated Products Inc. (Sunnyvale, CA). Maxim Power Supply Circuits Data Book. 1986, pp. 113-123.

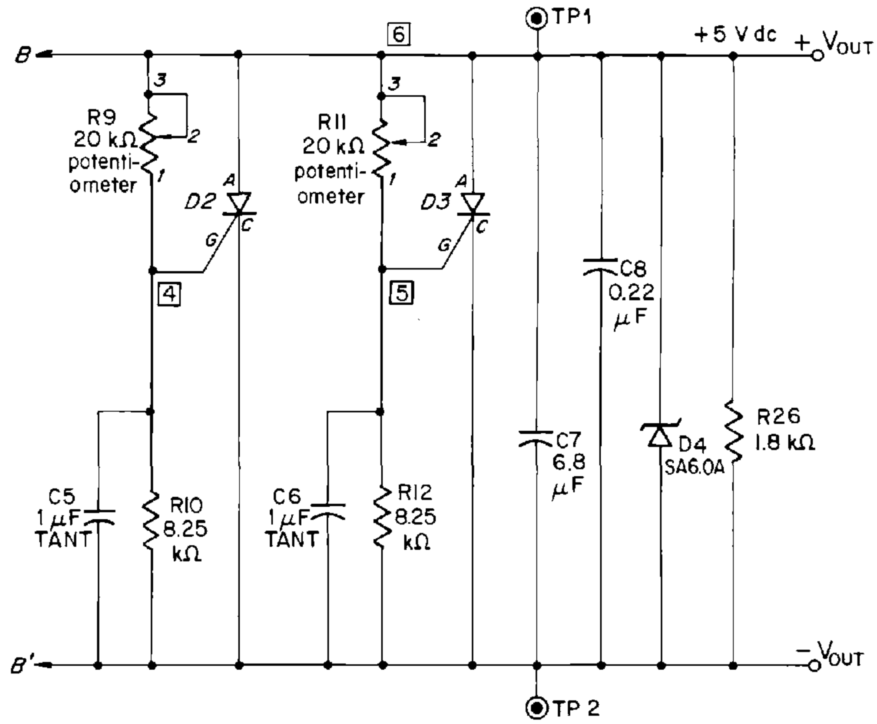

Figure 6.–Output protection circuit.

CIRCUIT CALIBRATION

Once circuit construction is completed, it is necessary to adjust and calibrate the circuit to insure proper operation. All adjustments, after setting, should remain fixed. No adjustments should be made while underground. First the nominal output voltage is adjusted, then the output overvoltage protection trip points are set.

Before the nominal output voltage can be set, it is necessary to temporarily prevent the overvoltage protection circuits of D2 and D3 from tripping. If these trip points are below the nominal output voltage, D2 and/or D3 will turn on and prevent the adjustment of the output voltage. To set the trip points above nominal, adjust R9 and R11 fully clockwise. Next, with battery voltage applied to the circuit, connect a load resistance of 2 ohms (15-W minimum) to the output and adjust R7 until 5 V dc is measured from test points TP1 to TP2.

To set the output overvoltage protection trip points, disconnect the batteries from the circuit and remove U1 and the 2-ohm output load. Connect a variable power supply capable of providing at least 6 V at 1 A to the output of the power supply circuit. This connection should include a 2-ohm, 15-W current limiting resistor in series from the positive terminal of the variable power supply to the positive output terminal of the intrinsically safe power supply. Set the voltage of the variable power supply to 5.3 V dc. Turn R9 counterclockwise until SCR D2 turns on and draws significant current from the variable power supply. Next, increase the voltage to 5.35 V dc and then turn off the variable power supply to reset D2. Turn the power supply on and adjust R11 until D3 turns on. Turn off the variable power supply and disconnect it from the output. Replace U1. This completes the calibration. Table 1 lists the resistors used in the calibration sequences and their adjustment ranges.

Table 1.–Resistor adjustments

Potentiometer	Adjustment	Range, V dc
R7	Allows output voltage to be adjusted.	3.2- 5.5
R9	Varies trip point of rectifier D2 for overvoltage protection.	3.2-12.0
R11	Varies trip point of rectifier D3 for overvoltage protection.	3.2-12.0

LOCAL REGULATION NETWORK

Although the output of the power supply is limited to a nominal output of 5 V, it can be used in a variety of applications requiring multiple voltages by using a local regulation network (note that any additional circuits connected to the power supply must also be evaluated for intrinsic safety). For example, figure 7 depicts a system requiring multiple voltages. By using the 5-V supply as the primary voltage, the other voltages can be derived at each circuit board as needed. For instance, ±15 V can be derived from 5 V using a voltage converter such as the Maxim max680.[4] This is a low-power, CMOS, dc-to-dc converter that comes in an 8-pin, dual in-line package. This chip requires only four external capacitors to complete the circuit design and can operate up to 95% in voltage conversion efficiency.

This approach increases flexibility because the 5-V supply can be used in various applications without redesign. Other desired voltages can be derived as needed.

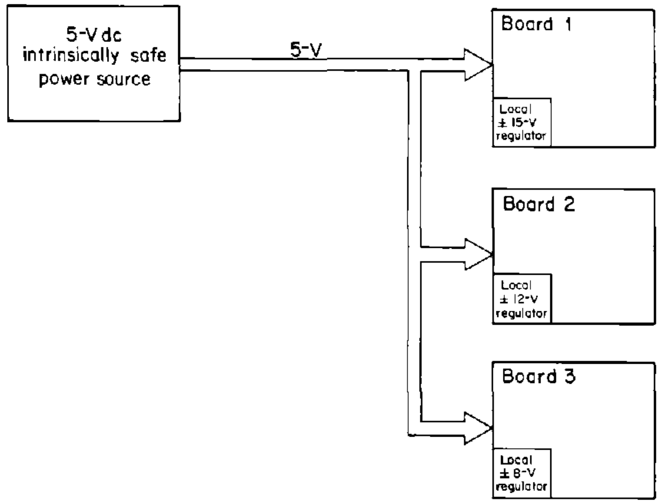

Figure 7.–Local regulation network.

[4]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

SPECIFICATIONS

NOTE.–All specifications pertain to circuit operation at room temperature.

	Min	Max	Nominal
Output:			
Adjustable voltage (V_{in}, 7.9 V dc; load, 1.5 ohms; output voltage values as obtained by varying potentiometer R7) . . . V dc . .	3.2	5.5	5.0
Current (V_{in}, 7.9 V dc; V_{out}, 5.0 V dc) . . . A . .	NAp	NAp	3.3
Input voltage, V dc:			
From battery pack . . .	6.8	8.5	7.9
From external voltage source . . .	6.8	16.0	7.9
		Typical	
Regulation, %:			
Line (V_{in}, 6.8 to 8.4 V dc; load, 1.5 ohms) . . .		0.8	
Load (load current, 0.7 to 2.8 A; V_{in}, 7.9) . . .		2.7	
Miscellaneous:			
Efficiency (V_{in}, 7.9; V_{out}, 5.0; load, 1.5 ohms) . . . % . .		63	
Battery life (V_{out}, 5.5; load, 1.5 ohms; initial V_{in}, 8.44; final V_{in}, 7.04) . . . h . .		1.5	
Maximum power output . . . W . .		22	
Weight (includes battery weight) . . . lb . .		5.5	
Dimensions, in:			
Width . . .		4.0	
Height . . .		4.0	
Length . . .		1.25	

NAp Not applicable.

SUMMARY

An intrinsically safe power supply with a regulated output of 5 V at 4 A has been developed by the U.S. Bureau of Mines. Two rechargeable, sealed batteries are used as the internal power source. External connections are provided to monitor battery voltage, recharge the batteries, and to operate with an external power source connection.

The power supply incorporates detection and protection against excessive voltage and current, excessive circuit junction temperatures, and low battery conditions.

Complete information is supplied on circuit operation and calibration so that this power supply can easily be duplicated for industry use.

APPENDIX A.–INTRINSIC SAFETY

The Code of Federal Regulations[1] defines intrinsic safety as "incapable of releasing enough electrical or thermal energy under normal or abnormal conditions to cause ignition of a flammable mixture of methane or natural gas and air of the most easily ignitable composition."

The power supply has been tested by the Mine Safety and Health Administration (MSHA). Experimental Permit No. 596 has been issued to the Bureau for this device as it is used to power a specific system. **Others wishing to use this power supply must have it certified by MSHA for use in their specific system.**

[1]U.S. Code of Federal Regulations. Title 30–Mineral Resources; Chapter I–Mine Safety and Health Administration, Department of Labor; Subchapter B–Testing, Evaluation, and Approval of Mining Products; Part 18–Electric Motor-Driven Mine Equipment and Accessories; Subpart A–General Provisions, Section 18.2, July 1, 1987.

APPENDIX B.–FABRICATION INFORMATION

This appendix contains a list of parts needed to construct the rechargeable, intrinsically safe power supply described in this report.

Item	Description	Manufacturer	Quantity
Battery: B1, B2	CMF4V10	Eagle Pitcher	2
Capacitor:			
C2	0.047-μF, 50-V dc, monolithic	Mallory	1
C3	0.47-μF, 35-V dc, tantalum	do	1
C4, C5, C6	1-μF, 35-V dc, tantalum	do	3
C7	6.8-μF, 15-V dc, tantalum	do	1
C8, C9	0.22-μF, 50-V dc, tantalum	do	2
C10	0.1-μF, 50-V dc, monolithic	do	1
Diode: CR1, CR2, CR3	1N5823A	Mot	3
Fuse: F1	4-A, 250-V, type ABC, ceramic	Little Fuse	1
Linear regulator:			
U1	UC3834N 16-pin IC	Unitrode	1
U2	LM308N 8-pin IC	National Semiconductor	1
U3	ICL7665CPA 8-pin I	Maxim	1
Rectifier:			
D1, D2, D3	2N6400 SCR's TO-220 (case)	Mot	3
D4	SA6.0A TransZorb	General Semiconductor	1
Resistor:			
R1	10-ohm, WW, 10-W	Dale	1
R2	0.05-ohm, WW, fused, 2-W	IRC	1
R3	680-ohm, 1%, metal film	Dale	1
R4	15-ohm, 5%, WW, 1/2-W	IRC-TRW	1
R5	1-kohm, 1%, metal film	Dale	1
R6	1.2-kohm, 1%, metal film	do	1
R7	1-kohm (25T) #3299W	Bourns	1
R8, R10, R12	8.25-kohm, 1%, metal film	do	3
R9, R11	20-kohm (25T) #3299W	do	2
R13, R15	10-kohm, 5%	IRC	2
R14, R16, R18	210-kohm, 1%, metal film	Dale	3
R17	132-kohm, 1%, metal film	do	1
R19	47.5-kohm, 1%, metal film	do	1
R20	52.1-kohm, 1%, metal film	do	1
R21	210-kohm, 1%, metal film	do	1
R22	3.92-kohm, 1%, metal film	do	1
R23	10-kohm, 5%, 1/4-W	IRC	1
R24	150-ohm, 5%, 1-W	IRC	1
R25	0.04-ohm, WW, 3-W, LPW3-2L	IRC	1
R26	1.8-kohm, 5%, 1/2-W	IRC	1
Switch: SW1	MTM-106D-RA PC-switch SPDT	Alco	1
Transistor:			
Q1	D45VH1	GE	1
Q2	IRF153	GE	1

SCR Silicon-controlled rectifier.
WW Wire wound.

APPENDIX C.–BATTERY CHARGER

The information presented in this appendix is sufficient for construction of the battery charger designed for the Bureau of Mines. This charger is **not** intrinsically safe. Do not attempt to use it in hazardous environments. Battery charging and replacement must be conducted in a safe, fresh air environment. The parts list and schematic diagram (fig. C-1) follow.

Item	Description	Manufacturer	Quantity
Capacitor:			
C11	2,100-μF, 35-V dc	Mallory	1
C12	0.1-μF, 50-V dc	.. do	1
C13	1-μF, 35-V dc	.. do	1
Diode:			
CR12	31DQ03 IR	International Rectifier	1
CR13	80SQ035 IR	.. do	1
Diode bridge: D1	Type KBPC602	General Instrument	1
Linear regulator: U9	UA78GUIC	Fairchild	1
Resistor: R9, R10	RN65C, 39.2-kohm, 1%	Dale	2
Transformer: T1	Type P-8642	Stancor	1

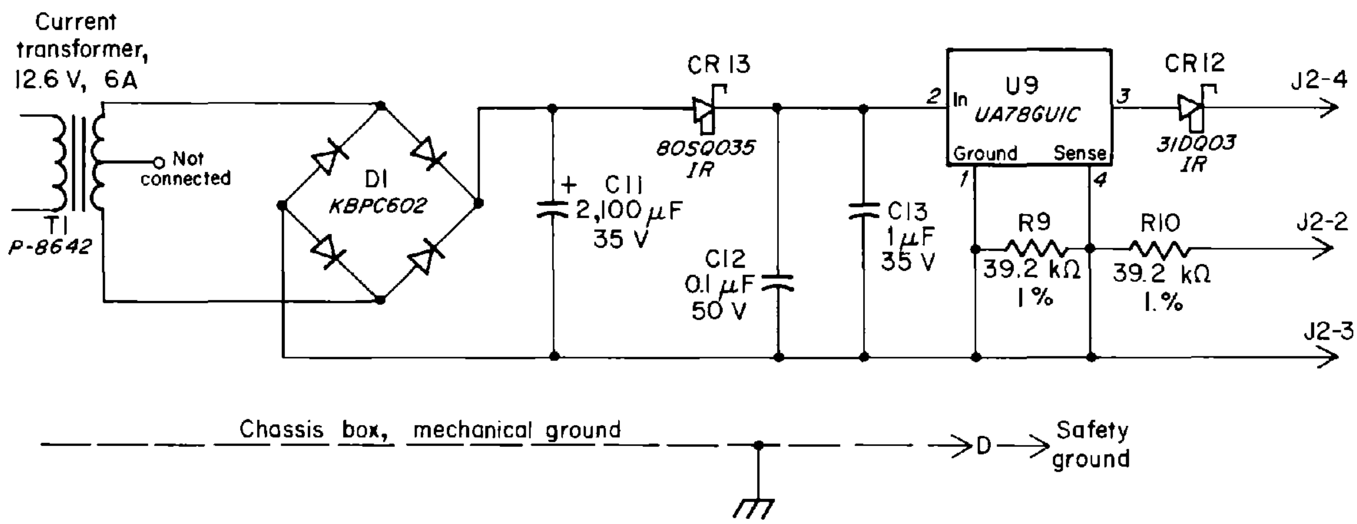

Figure C-1.–Battery charging circuit schematic.

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