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SWITCHING VOLTAGE REGULATOR WITH CURRENT LIMITING AND CONTINUOUS SHORT CIRCUIT PROTECTION FOR (IONS) "ANURADHA"-3SAN21

(The Indian Cosmic Ray Payload on SPACELAB-III)

By

D. P. Devgan and H. S. Mazumdar

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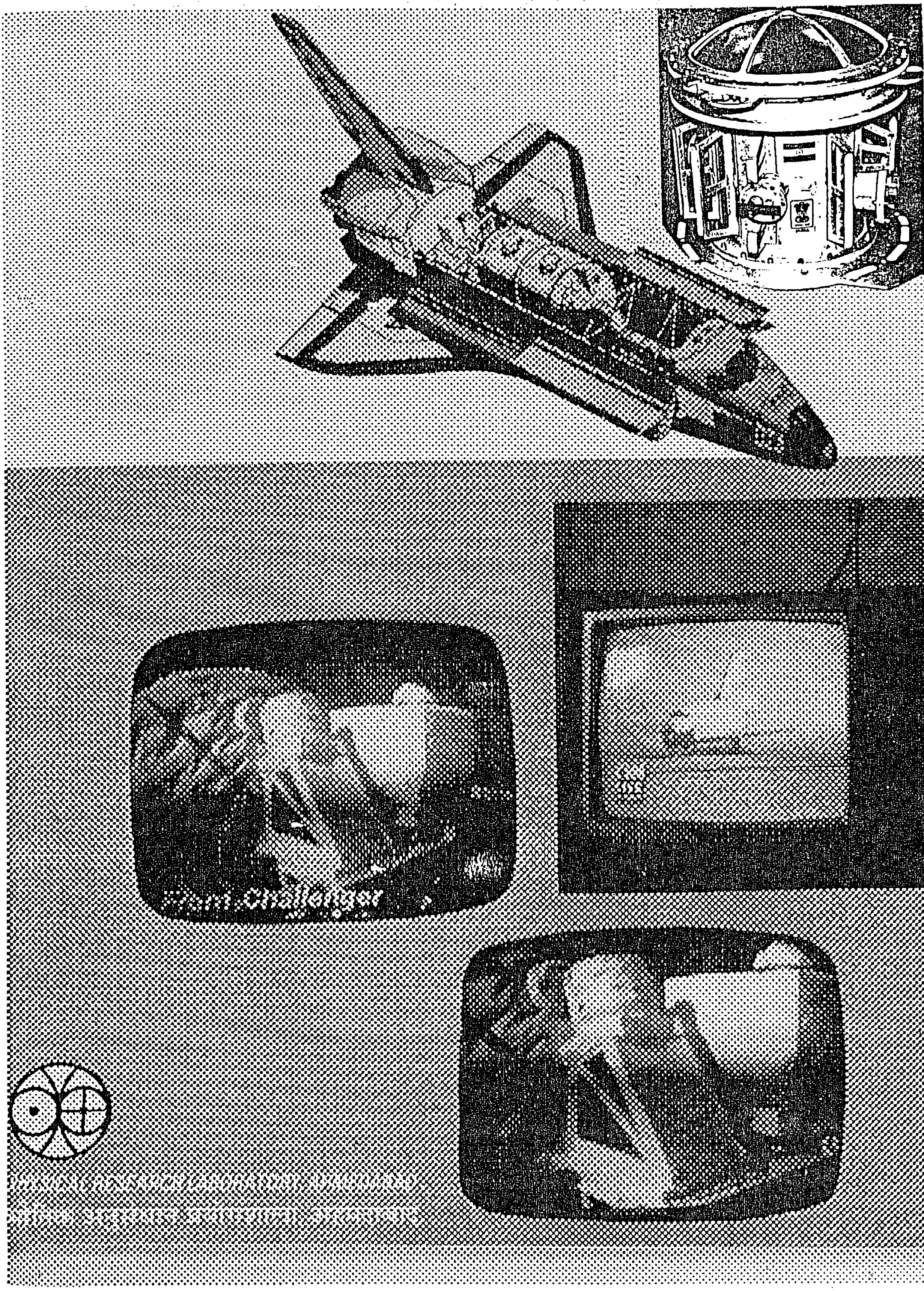
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SWITCHING VOLTAGE REGULATOR WITH CURRENT LIMITING AND CONTINUOUS SHORT CIRCUIT PROTECTION FOR (IONS)"ANURADHA"-3SAN21

The Indian Cosmic Ray Payload on SPACELAB-III

(Conducted on board the
American Space Shuttle Challenger
in the first week of May 1985)

D. P. Devgan and H. S. Mazumdar
Physical Research Laboratory
Ahmedabad-380009 (INDIA)

ABSTRACT:

The power constraints imposed by NASA on the Indian Cosmic Ray Space Lab.-3 experiment (IONS)* "Anuradha", necessitated the design of a power conversion system with higher conversion efficiency for conservation of power, and inbuilt overload and short circuit protection facility. It was decided to design a miniature power supply on a single card which constituted one of the main subsystems of "Anuradha" Cosmic Ray Payload designed by Electronics Laboratory of P.R.L. Ahmedabad, India. The feature that put in a class above other regulated power supplies are higher conversion efficiency (70%) as compared to linears (30% typical) leading to lower dissipation factor, smaller cooling system and giving savings in energy. With higher conversion efficiency achieved as a result of pulse width modulation, the overall result is a highly compact, efficient and reliable state of the art design. It generates +5V regulated DC at 1Amp max. load for logic circuits from +28V ±4V input as the only Power Source available in the Space Lab.

*(IONS) was the name given by NASA to this experiment carried onboard Space Lab.-3.

1.0 INTRODUCTION:

Switching regulators are capable of high efficiency operation where there is large difference between the input and output voltages. The efficiency is, in fact, negligibly affected by the voltage difference since this type of regulator acts as a continuously variable power converter. The features that put it in a class above other regulators are higher conversion efficiency (70%) as compared to linears (30 typical) leading to lower dissipation, small heat sink, giving saving in energy.

Switching regulators are, therefore, useful in battery powered equipments where the required output voltage is considerably lower than the battery voltage. An example of this is a Space Lab/Missile with +28V $\pm$4V battery as its only power source, containing a large number of integrated logic circuits which require a +5V supply. They are useful in space vehicles where conservation of power is extremely important.

A switching regulator with current limiting and continuous short circuit protection facility was designed using monolithic voltage regulator LM 105, voltage comparator LM 111 and few discrete components for (IONS) Cosmic Ray Space Lab. Payload, "Anuradha" whose electronics were designed at Physical Research Laboratory (PRL), Ahmedabad.

The Indian designed Cosmic Ray experiment (IONS) "Anuradha" was successfully conducted onboard the American Space Shuttle Challenger carrying a scientific Laboratory, the Space Lab.-3, which circled round the earth for more than 100 times in the first week of May 1985.

2.0 BASIC OPERATION OF SELF OSCILLATING SWITCHING REGULATOR:

The basic principle by which a switching regulator produces a voltage conversion with high efficiency is explained below:

Fig.1 shows a self oscillating switching regulator. A reference voltage, Vref. equal to the desired output voltage is supplied to the non-inverting input of an operational amplifier. The operational amplifier, in turn, drives the switch transistor Q1. The resistive divider, arranged such that R1>R2, provides a slight amount of positive feed back at high frequency to make the circuit oscillate. At lower frequencies where the attenuation of the LC filter is less than that of the resistive divider, there is net negative feedback to the inverting input of the operational amplifier.

In operation, when the circuit is first turned on, the output voltage is less than the reference voltage and the switch transistor Q1 is turned on. When this happens, current flow through R1 raises the voltage on the non-inverting input of operational amplifier slightly above reference voltage. The circuit will remain switched on until the output rises to this voltage. The amplifier now goes into active region, causing the switch transistor to turn off. At this point, the reference voltage seen by the amplifier is lowered by feedback through R1 and the circuit will stay off until the output voltage drops to this lower voltage. Hence, the output voltage oscillates about the reference voltage. The amplitude of this oscillation (or the output ripple) is nearly equal to the voltage feedback through R1 to R2 and can be made quite small. D1 is a catch diode which provides a continuous path for the inductor current when Q1 turns off. The voltage waveform on the emitter of Q1 will be as shown in the figure. The output of the LC filter will be the average value of switched waveform V1. If the voltage drops across the transistor and diode are neglected, the output voltage will be, Vout = Vin x ton/T and it is independent of the load current. It is obvious from the equation that changes in input voltage can be compensated for by varying the duty cycle of the switched waveform. This is what is done in a switching regulator.

3.0 CIRCUIT DETAILS

Fig.2 demonstrates the use of monolithic voltage regulator LM105 as a self oscillating switching regulator. The circuit generates +5V regulated DC from +28V ±4V unregulated DC input. Feedback to the inverting input of the operational amplifier (Pin 6 of LM105) is obtained through a resistive divider R12 and R13 which can be used to set the output voltage any where in the 4- 20V range. R2 determines the base drive for the PNP switch transistor Q2, which in turn provides enough drive for the series NPN power booster switch transistor Q1. R5 works into the 2K ohm impedance at the reference terminal, producing positive feedback. C7 serves to minimize output ripple by causing the full ripple to appear on the feedback terminal. D1 and D2 are fast recovery catch diodes which provide a continuous path for the inductor current when transistor switch formed by Q1 and Q2 turns off.

During the time transistor switch is turned on (ton), the input voltage is applied to the input of the LC filter (L2 and C8+C9) causing the inductor current to increase and also supply the output current. When transistor switch is turned off(toff), the energy stored in the inductor maintains the current flow to the load through D1 and D2. The LC filter will average the voltage seen at its input and deliver that voltage to the output load i.e. Vout = Vin x ton/T. Therefore, by controlling the duty cycle ton/T, changes in the input voltage can be compensated. If the input voltage increases, the control circuit of LM105 will cause a corresponding reduction in the duty cycle and maintain a constant output voltage. (Pulse width modulation technique).

The transistor switch is always in the saturated state when it is conducting (ton), or otherwise completely non-conducting (toff). The power dissipated in the switch is much lower than that dissipated in a series regulator whose pass transistor is continuously operating in the linear region. The circuit is capable of delivering output currents of 1Amp. and more with only a small heat sink. The current limit can be set by adjusting the sensing resistor R11.

The switching frequency of this regulator has been optimized at about 16KHz at 1Amp. load to keep switching losses minimum. At lower frequencies the core becomes unnecessarily large and at higher frequencies switching losses in Q1, Q2 and Catch diodes become excessive. Q1, Q2 and catch diodes D1, D2 must be fast switching devices to minimize switching losses.

The output ripple of the regulator at the switching frequency is mainly determined by R5. It should be evident from the description of circuit operation that the peak-to-peak output ripple will be nearly equal to the peak-to-peak voltage feedback to pin 5 Of the LM105. Since the resistance looking into pin 5 is approximately 2000 ohms, this voltage will be $\triangle$Vref. = 2000 x Vin/R5. In practice the ripple will be some what larger than this. The peak-to-peak output ripple is reduced to 10 mv p-p by the output filter as shown in the diagram.

When the switch transistors shut off, the current in the inductor will be grater than the load current, so the output voltage will continue to rise above the value required to shut off the regulator. The value of inductor should be large enough so that the current through it does not change drastically during the switching cycle. If it does, the switch transistors Q1, Q2 and catch diodes must be able to handle peak currents which are significantly larger than the load current. The overall efficiency of the regulator over a wide range of input voltages and output currents is better than 70% excluding the efficiency sacrificed in current limiting circuit. With higher conversion efficiency achieved by Pulse Width Modulation, the overall result is a highly compact, efficient and reliable state of the art design.

4.0 CURRENT LIMITING AND CONTINUOUS SHORT CIRCUIT PROTECTION.

Providing short circuit protection is no simple problem, since it is necessary to keep the regulator switching when the output is shorted. Otherwise the dissipation will become excessive even though the current is limited.

The circuit that does this is designed using LM111, an open collector voltage comparator. In this circuit, the current sensing resistor R11 is located in series with the inductor (L2). The value of this resistor is set to about 0.25 ohms to provide current limit action above 1Amp. load. The comparator is suitably biased by R6,R10,R7,R15 and Z2 - a constant voltage diode. R8 and R9 provide fine current limit adjustment. The comparator LM111 senses the over current condition across R11 and turns on its output transistor which supplies current limit signal to pin 7 (shut down) of the regulator's control chip LM105. As a result of this there is a sharp fall in the output voltage and input current. The circuit will continue to oscillate, even with a shorted output, because of positive feedback through R5 and relatively long discharge time constant of C7.

The performance of current limiting scheme is illustrated in Fig.3 and Fig.4. Fig.5 is the photograph of the flight model card. The current limiting characteristics of this circuit are considerably sharp. One disadvantage of this circuit is that the load current flows continuously through the current sense resistor, reducing the efficiency by about 10% at full load but it is a substitution of electrical complexity for achieving sharp current limiting characteristics and continuous short circuit protection.

Soft start was necessary in (IONS) "Anuradha" payload as the isolation DC to DC converter supplying power to the switching voltage regulator had minor starting problem at full load. Initial delay of load current allowed the DC to DC converter to fully stabilize.

Soft start is relatively made simple by connecting a capacitor C-17 to ground from non-inverting biasing point of current limit circuit as shown in the diagram. Initially when the circuit is powered up, the capacitor C-17 forces the output of LM111 to switch low which disables the control IC LM105. As the capacitor charges through R7 and R15, the control IC resumes its normal operation.

C1 and C2 and L1 form the input filter stage to suppress current transients being fed back to the unregulated supply. C8, C9, L3, C10, C11 and C12 form the output filter stage to keep peak-to-peak output ripple less than 10mv. This circuit successfully passed all environmental tests as per NASA specifications at ISAC-Banglore.

The specifications of the circuit of Fig.2 are given in appendix-1 and design procedure in appendix-2.

5.0 CONCLUSIONS:

The switching regulator designed by the authors worked flawlessly and withstood the space environments of Space Lab- III during the Challenger's weeklong flight in operating conditions as well as the launch and landing in non-operating conditions. Prior to the flight and during the post flight analysis the switching regulator continued to be the source of +5V supply to the encoder and other electronics of the payload.

The design could be modified for obtaining any output voltage in the 4V to 20V range by suitable changes in few discrete components and the regulator could be readily used for similar Space and ground applications.

ACKNOWLEDGMENT

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The switching regulator was integrated and tested for its flight worthyness in the cosmic ray payload (IONS) "ANURADHA" at the ISRO Satellite Centre Bangalore through the persistent efforts of Mr.D.V.Subhedar, Mr. Narayan Datt, Dr.S.N.Pradhan, Mr.P.G.Oza and Dr.J.N.Goswami along with the other members of the "ANURADHA" project team. Their efforts are deeply appriciated.

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2)Texas Linear Application Report Series For Switching Regulator.

3) Linear IC Data Book, National Semiconductors, 1979.

APPENDIX - 1

DESIGN SPECIFICATIONS:

Vin	= +28V ±4V
Vout	= +5.0V TO +5.5V
Iout	= 1 Amp (Max.)
Fo	= 16.66 KHz
T	= 60 usec.
ton	= 11.5 usec.
t off	= 48.5 usec.
Output regulation	= 0.1%
Efficiency	= 70%
Output Ripple	= <30 mv (pp)

APPENDIX - 2

DESIGN PROCEDURE :

The following equations outline the design procedure for the switching Regulator of Fig.2 which delivers +5V at maximum current of 1Amp. from +28V $\pm$4V supply. Switching frequency was selected to be about 16KHz with output ripple of <30mv peak to peak.

CALCULATIONS:

Assume nominal Vin = +28V

Fo at 1Amp. load = 16.66KHz

1) $$Vout = Vin \times ton/T = \frac{28V \times 11.5usec}{60usec} = +5.36V$$

2) $$Rf = R5 = \frac{2000 \times Vin}{Ripple} = \frac{2000 \times 28V}{28mV} = 2\ megohm$$

3) $$Vref\ (Ripple) = \frac{2000 \times Vin}{R5} = \frac{2000 \times 28V}{2\ meg\ ohm} = 28mV$$

4) $$L2 = \frac{2.5 \times Vout \times t\ off}{Iout\ (Max)} = 2.5 \times 5.36V \times 48.5\ usec. = 0.649mH$$
or = 0.64 mH

$$No.\ of\ turns\ (L2) = \sqrt{\frac{Req.L}{157.3}} \times 1000 = \sqrt{\frac{0.64mH}{157.3}} \times 1000 = 63.78\ turns$$

5) $$C \text{ (filter cap.)} = \left[\frac{V_{out}}{2 \times L2 \times Ripple}\right]\left[\frac{V_{in}-V_{out}}{F_o \times V_{in}}\right]^2$$

$$= \left[\frac{5.36V}{2 \times 0.64mH \times 28mV}\right]\left[\frac{28V - 5.36V}{16.66KHz \times 28V}\right]^2 = 328.7 \text{ ufd.}$$

6) $$t_{off} = \frac{1}{F_o}\left[1 - \frac{V_{out}}{V_{in}}\right] = \frac{1}{16.66KHz} \times \frac{22.64V}{28V} = 48.53 \text{ usec.}$$

7) $$\text{Output Reg.\%} = \frac{5.360V - 5.355V}{5.36V} \times 100 = 0.093\% \text{ or } 0.10\%$$

8) $$\text{Eff\%} = \frac{5.36V}{28V \times 0.27A} \times 100 = 70.89\%$$

9) $$F_o = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{6.28\sqrt{\underset{mH}{0.64 \times 10^{-3}} \times \underset{ufd}{0.22 \times 10^{-6}}}} = 13.42KHz$$

SELF OSCILLATING SWITCHING REGULATOR

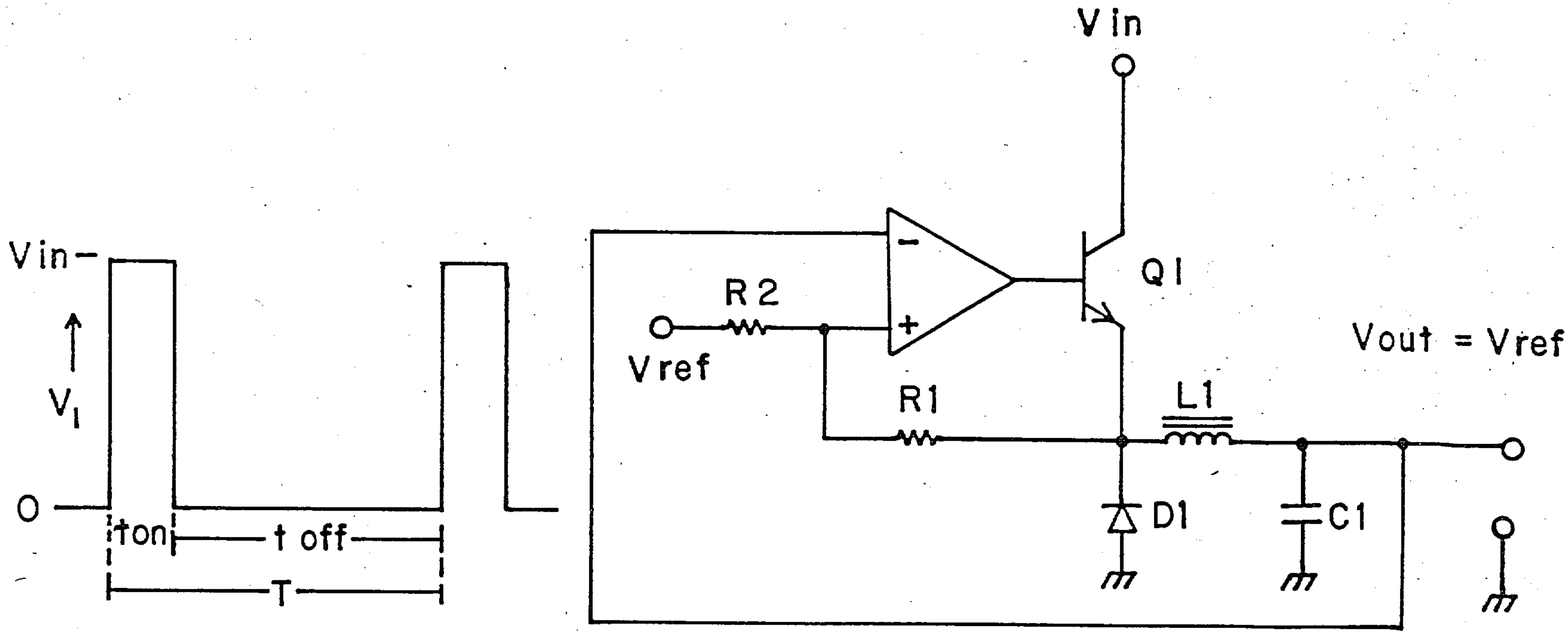

Fig. 1

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Conducted on board the American Space Shuttle Challenger
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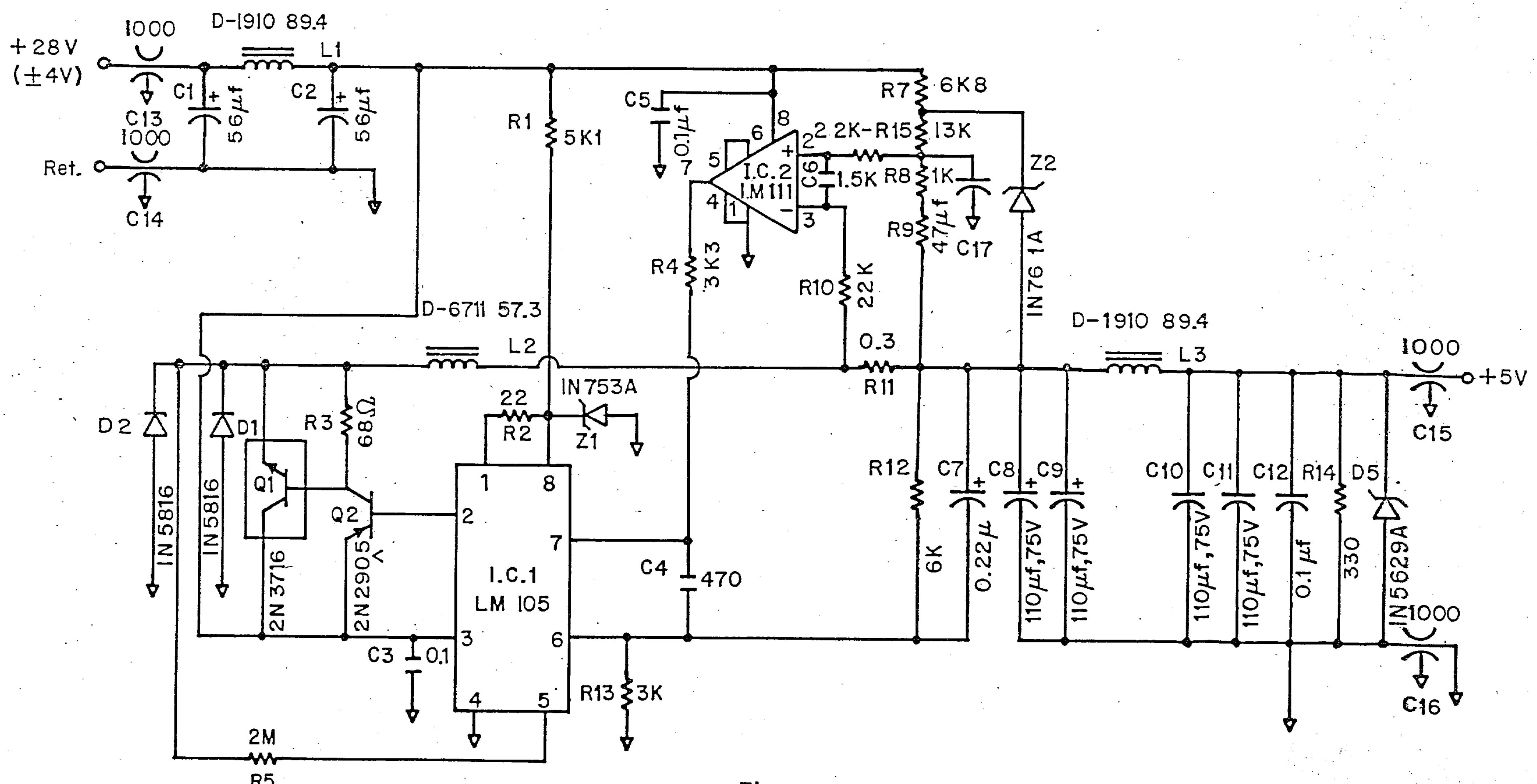


Fig.2

PLOT OF CURRENT LIMITING CHARACTERISTICS
FLIGHT CARD (IONS) "ANURADHA"

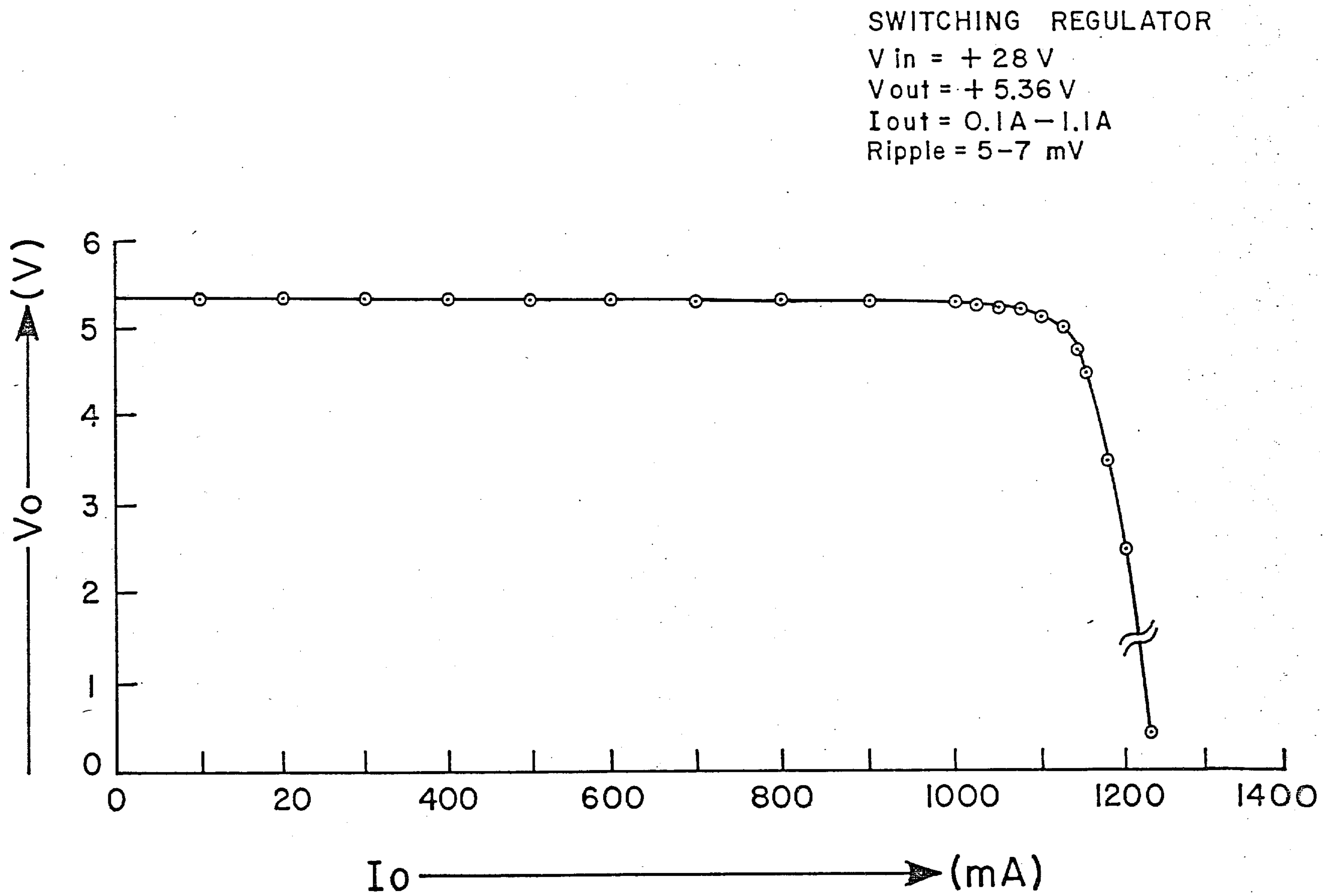


Fig. 3

PLOT OF INPUT CURRENT AS REGULATOR GOES IN TO
CURRENT LIMITING-FLIGHT CARD (IONS) "ANURADHA"

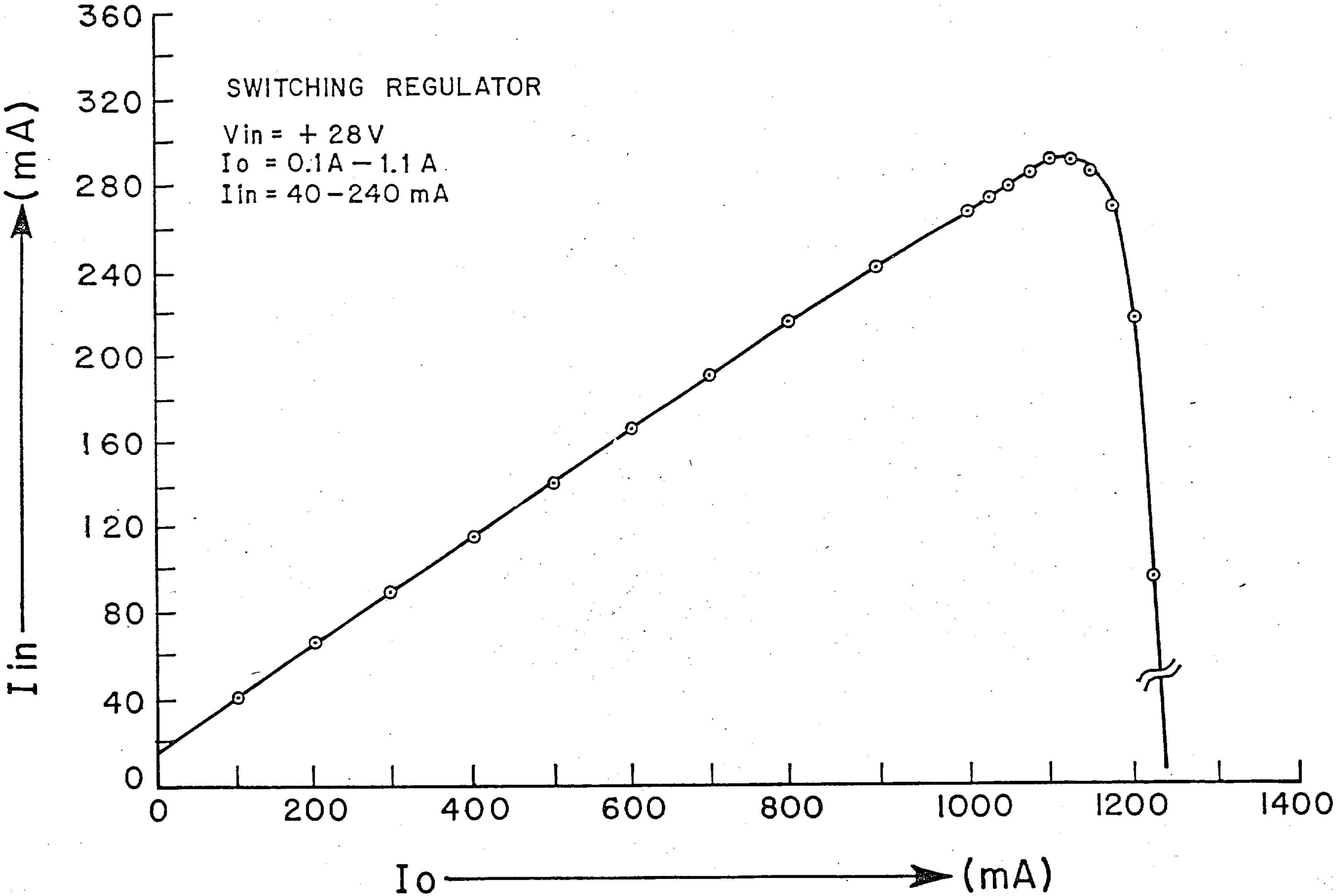


Fig. 4

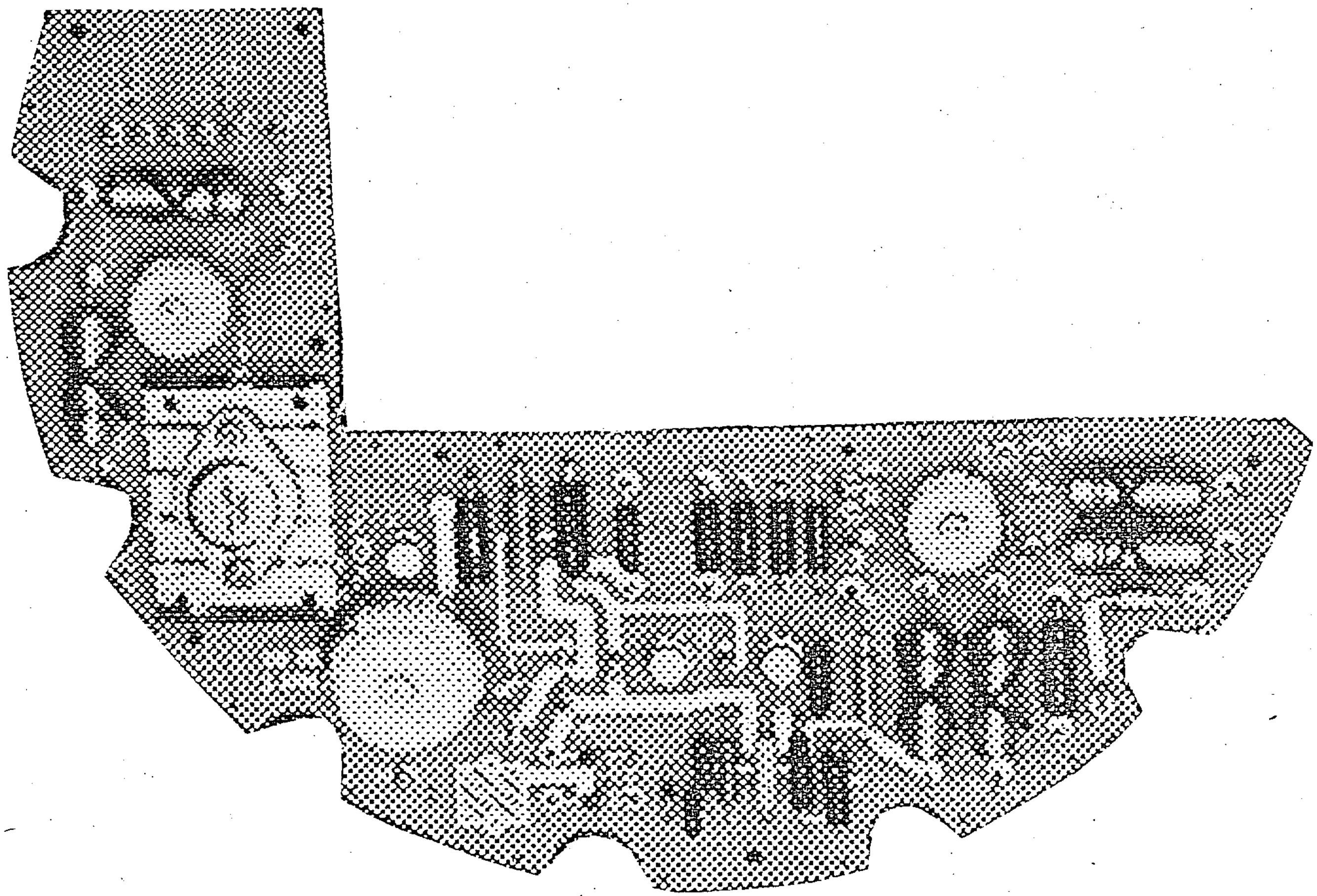
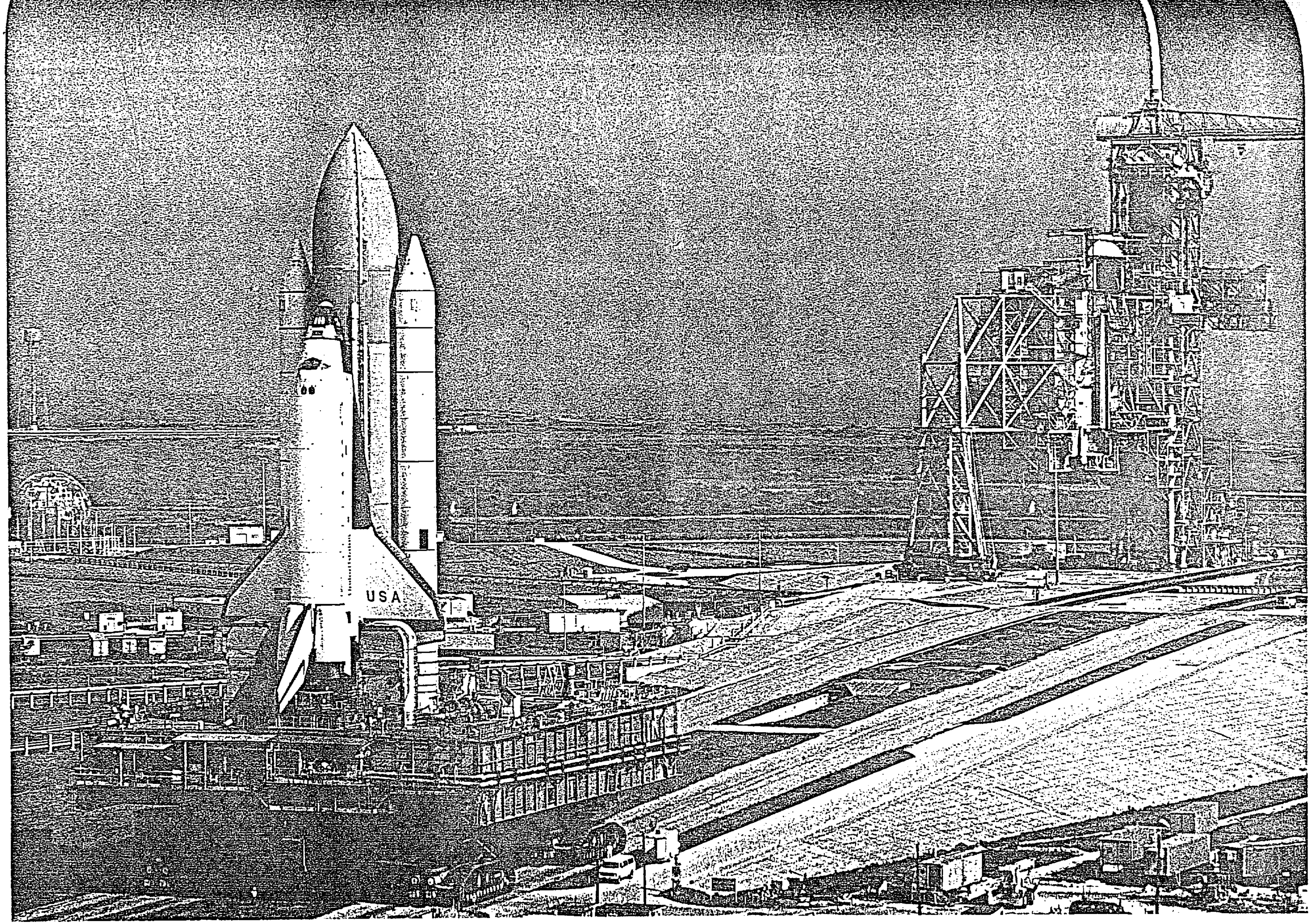


Fig. 5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