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A STUDY OF THE MODIFICATIONS OF NUCLEAR INSTRUMENTATION SYSTEMS FOR JRR-2

April 1978

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In this report a comparative study has been carried out between the original A.M.F. design and the modified design for the nuclear instrumentation systems of the Research Reactor JRR-2, at the Tokai Research Establishment of JAERI.

Due to a fire accident in the control room, in July 1968, the originally designed nuclear instrumentation systems, using conventional vacuum tube circuits, were destroyed and were replaced by the modified design, incorporating solid state linear integrated circuits as basic circuit components.

The results of the reactor instrumentation systems modification at JRR-2 are very encouraging as the operating efficiency of the Reactor registered an improvement of 43%. Moreover the safety aspects have been fully taken care of in the new design and the reactor is well gaurded against all possible instrument failures and human errors.

This report presents the basic theory of operation of the two designs alongwith a comparative safety analysis.

Keywords: Research Reactor JRR-2, Nuclear Instrumentation Systems, Conventional Vacuum Tube Circuits, Modified Design, Solid State Linear Integrated Circuits, Comparative Safety Analysis, Operating Efficiency, Instrument Failures, Human Errors.

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* Senior Engineer, Pakistan Atomic Energy Commission, whose stay at JAERI was sponsored by Japan International Cooperation Agency under Colombo Plan.

JRR－2の改造炉計装の検証

日本原子力研究所東海研究所研究炉管理部
モハメド．アジム*・堀木欧一郎・佐藤　貢

（1978年3月15日受理）

1968年7月のJRR－2制御室火災事故によって，従来の炉計装類が使用できなくなったので，ソリッドステートによる基本回路で構成された改造型炉計装により，制御系の復旧が行なわれた。

その結果，約43％の原子炉運転効率改善を記録することができ，非常に満足すべきものとなった。更に改造型炉計装の設計においては安全対策に充分な配慮を行なったため，起り得る炉計装類の故障，及び，人的誤操作に対し充分に対処し得るものとなった。

この資料は，改造前と改造後の炉計装の設計上の基本原理について述べると共に，安全性解析上の比較を行なっている。

* P.A.E.C. パキスタン原子力委員会

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1. INTRODUCTION

The Japanese Research Reactor No.2 (JRR-2) is owned by the Japan Atomic Energy Research Institute (JAERI) and is located at the Tokai Research Establishment. It was originally designed and installed by an American company, American Machine Foundary (AMF). It is a 10MW (Thermal) heavy water moderated and cooled, tank type of reactor. It first became critical on first October, 1960. Until 1964 it was operated on a non-routine basis for short daily runs. It was from 1964 onwards that the reactor started operating on a regular routine basis, including long continuous operations of 130 hours duration.

The originally A.M.F. designed nuclear instrumentation systems of JRR-2 used standard Honeywell instruments, using conventional vacuum tubes as the basic circuit components. On July 12, 1968 a fire accident occurred in the control room which was caused due to over-heating of a relay coil. In the subsequent fire extinguishing operations, the nuclear instrumentation systems were more or less completely destroyed. After the fire accident it was decided to replace the destroyed instrumentation with newly designed systems using solid state integrated circuits as basic circuit components. The new systems were designed by the Electronics Workshop of JAERI and fabricated by the local industry. The installation of the modified nuclear instrumentation systems was carried out in stages, as shown in Appendix 2.

The replacement of the original A.M.F. designed systems with the modified design resulted in the improvement of the operating efficiency of the reactor, thus exibiting improved reliability of the solid state circuit devices as compared to the conventional type of instrumentation systems, using vacuum tubes.

2. THE A.M.F. DESIGNED NUCLEAR INSTRUMENTATION SYSTEMS

In the original A.M.F. designed nuclear instrumentation systems, the reactor power was monitored and controlled by the following channels.

1. The Linear-N Channel.
2. The Auto-control Channel.
3. The Log-N and Period Channel.
4. The Safety Channels (No.1 and No.2).

A brief theory of operation of the above channels is described in this section.

2.1 THE LINEAR-N CHANNEL

The Linear-N channel is designed to accurately measure the reactor power and display it on a linear scale. Drawing No. CP-AMF-01 shows the signal flow line of this channel. It consists of the following main components,

1. Compensated Ionisation Chamber (CIC).
2. Range Selector Resistance Switch.
3. Electrometer.
4. Linear-N Recorder.

The range of the CIC is between 2.5×10^{2} to 2.5×10^{10}n/cm^{2}-sec. and is mainly designed for the detection of thermal neutrons. The neutron sensitivity is 4×10^{-14} ampere/nv and the gamma sensitivity is 3×10^{-11} ampere/roentgen/hour when operating uncompensated.

The current produced in the CIC is passed through a range selector resistor (one of R1 to R22) selected according to the operating range. The power range is from 2.5 watts to 25 Mwatts with each decade traversed in multiples of 2.5 or 5 or 10. The resistance values for each range are selected to give an output of 100 millivolts to the recorder when the power output is maximum for a particular switch setting. This ensures the movement of the stylus from 0% to 100% on the Linear-N recorder scale.

The voltage drop across the range selector resistor is fed to the head of the Electrometer. This voltage signal is compared with another d.c. voltage from a transmitting slidewire in the Linear-N recorder, which is proportional to the pen position. The resultant error signal is fed to the vibrating capacitor. One plate of the vibrating capacitor is stationary while the other is vibrating according to the line frequency (50Hz). The motion of the movable plate is polarised by means of a permanent magnet, so that the capacity is always maximum during the positive half cycle and minimum during the negative half cycle. Fig. 1 shows the operating principle of the vibrating capacitor.

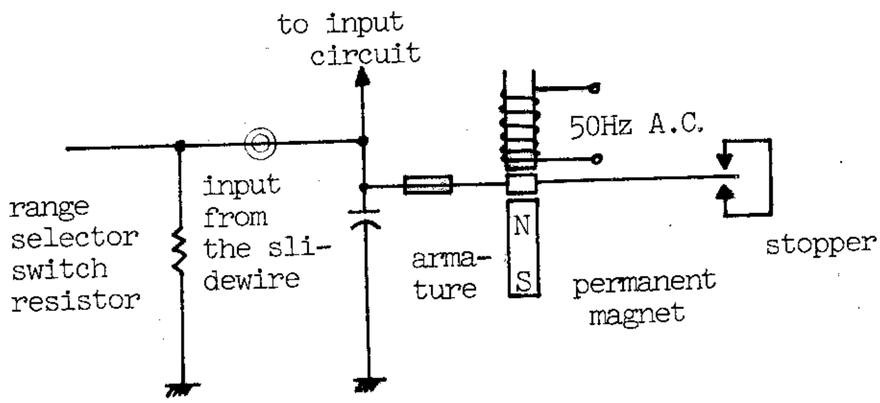


Fig. 1 Operating principle of the vibrating capacitor.

The output from the vibrating capacitor is a d.c. signal with a.c. superimposed, which is fed to the input filter circuit. The input circuit acts as a coupling network between the vibrating capacitor and the voltage pre-amplifier. It provides the neccessary high input impedance to avoid the shunting out the input and also filters the d.c. component out of the signal.

The pre-amplifier amplifies the a.c. output of the conversion stage to a level suitable for operating the cathode follower. This stage is well shielded to avoid pick-up of stray signals at the high input impedance grid level at which it is operating.

The cathode follower provides impedance matching between the electrometer head and the instrument amplifier, and permits transmission of the signal over long distances. The output from the cathode follower is fed to the voltage amplifier through a gain compensation variable resistance. The voltage amplifier multiplies the a.c. output voltage of the cathode follower at D, which is in the order of micro-volts, to a signal which is to the order of several volts at E. The voltage amplifier also filters out components of frequencies other then 50Hz.

The power amplifier is controlled by the voltage at E, and delivers driving power to the balancing motor at F. Both the phase and the magnitude of this driving power are directly controlled by the voltage at the point E.

The balancing motor (Standard Brown Servo-motor) is a brushless, reversible, variable speed induction motor whose direction of rotation is determined by the phase of the driving voltage. One of the windings of the servo-motor is constantly energised by the reference line voltage, while the other winding is energised by the power amplifier with a current whose phase with respect to the line current is dependent upon the direction of unbalance. The slidewire contactor, the pen-carriage assembly and the transmitting slidewire is mechanically coupled to this motor. The motor moves the contactor on the slidewire, when a variable d.c. signal is transmitted through the bridge network to the point of comparison at A. When the voltage drop across the range selector switch and the d.c. signal from the bridge network are equal, a balance is achieved and the motor no longer drives. A rate signal developed by the bridge across the control phase of the motor is fed back to the driver stage inorder to provide damping. This damping is necessary to assure the stability of the electrometer and the recorder system.

2.2 THE AUTO-CONTROL CHANNEL

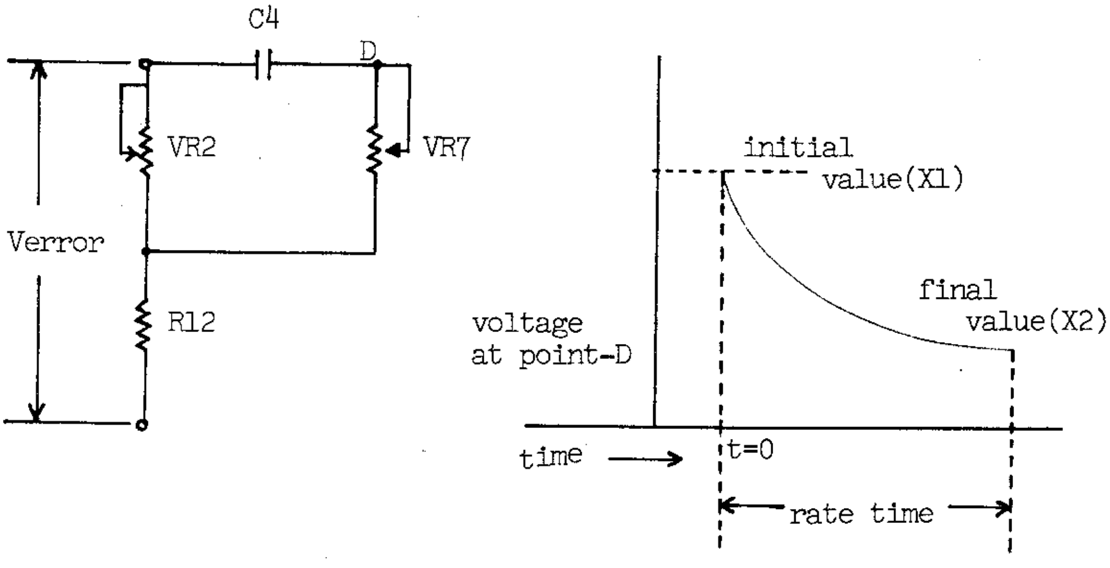
The Auto-control channel is designed to automatically position the regulating rod and maintain the reactor output power at the demand level regardless of disturbances in the reactivity, which may be caused due to temperature changes, fuel burn-up, Xenon and other fission product poisons, and insertion or removal of irradiation materials (samples).

The Auto-control channel consists of the following main components,

1. External error forming bridge network containing a power demand control helipot (10KΩ) in the Linear-N recorder.
2. Reactor controller, consisting of a local error forming bridge network (proportional band and reset networks).
3. Converter type amplifier.
4. Rate network.
5. Servo-motor, containing a rod slidewire for the position feedback (for damping).

The external error forming bridge network consists of a power demand helipot (10KΩ) and a slidewire (10KΩ) in the Linear-N recorder.

The error signal (due to the difference between the actual reactor power and the desired power) appears at point A (Please refer Drawing No. CP-AMF-02) with respect to the reference point B, which is in the local error forming bridge in the reactor controller. This signal is applied to the servo-deviation meter and the servo-permit relay. If the error exceeds ±10% the reactor control is shifted from the auto-mode to manual-mode by the servo-permit relay. In case of a step change in the error signal, the step input error voltage is applied to the rate network consisting of capacitor C4 and a variable resistor VR7, through the gain compensating network formed by VR2 (which is mechanically coupled to the power demand helipot) and R12. The gain compensating network is designed to reduce the gain of the system as the power demand setting is increased. The rate circuit operation is described in terms of the transient response of the output when a sudden change of input voltage is applied. In this case the capacitor C4 appears to be a short circuit, since it cannot charge instantly and the applied voltage appears at point D. But as the resistance VR7 provides a discharge path for C4, the output voltage decays to the potential at point E, and the rate of decay is determined by the setting of resistance VR7. The discharge time of the capacitor C4 is referred as the 'rate time' and is related to the product of VR7 (in MΩ) and C4 (in μF) and can be adjusted from 0.5 second to 11.5 seconds by VR7. The rate circuit is designed to provide increasing rate amplitude with increasing reactor power in order to provide the necessary damping. The rate amplitude is defined as the ratio of the initial value of voltage to the final value and may vary between 2 and 11, depending upon the setting of VR7. Fig. 2 shows the rate network.



$$\text{rate amplitude}=\frac{\text{initial value}}{\text{final value}}=X1/X2$$

Fig. 2 The rate network.

The reset network, comprising of capacitor C3 and variable resistor VR4 also works in the similar way as the rate network and provides a decreasing negative voltage signal at point B, for the damping of the system. The action of the reset network can be analysed by considering a step change in the system error. A step change in voltage is thus applied as a system error between the junction of VR7 and C4 and the bridge reference point B. Neglecting delays in the amplifier and the servo-motor, this step change in voltage at point D appears at point F. For these rapid changes, C3 acts as a short circuit, but charges at a rate determined by the resistance value of VR4. Thus the initial feed-back voltage appears across VR4 and R11, but decays towards zero causing the local error to come to some value other than zero. The rod must then move again to cancel this error. This continuing motion of the rod, as long as there is a system error present, is the reset action. The net voltage, therefore appears at point D, which is coupled to the signal winding of the servo-motor through a chopper and the converter type amplifier. The phase and magnitude of the total error signal controls the speed and the direction of rotation of the servo-motor, which in turn positions the regulating rod.

In operation, a positive power error signal, corrosponding to a negative servo-deviation, requires withdrawal of the regulating rod to add reactivity and thereby increase reactor power. Conversely, a negative power error, corrosponding to a positive servo-deviation, requires insertion of the regulating rod to decrease reactivity and therefore decrease reactor power. As the actual power output approaches the power demand, the power error signal approaches zero.

2.3 THE LOG-N AND PERIOD CHANNEL

The Log-N and Period channel is designed to measure and display the reactor power from 0.001% to 300% (10 watts to 30 Mwatts), over six decades, on a single log scale. It also constantly monitors the rate of rise of reactor power, in terms of reactor period and effectively shuts down the reactor, if this rate of rise of power becomes very sharp and tends to approach a dangerous level. Drawing No. CP-AMF-03 shows the Log-N and Period channel. It consists of the following main components,

1. Compensated Ionization Chamber
2. Log-N and Period Amplifier.
3. A Trip Unit (which is coupled to the Log-N and Period Amplifier).

The signal from the CIC is a d.c. signal which varies over the range of $+5\times10^{-11}$ ampere to $+1.5\times10^{-4}$ ampere. This signal is the input to the Log-N and Period Amplifier.

When the selector switch position is on 'OPERATE', this signal from the CIC is directly coupled through a connector to the plate of Diode V1, thus causing the tube to conduct. As the current through V1 varies a large amount, the voltage drop across the tube varies a much smaller amount. This voltage developed across the diode V1 is proportional to the logarithm of the current passing through it. Over the range from 10^{-11} to 10^{-4} ampere, when the current changes by a factor of ten, the change of voltage is only 0.25 volt. Since the amplifier input impedance for small current inputs is very high (several MΩ) the cathode of V1 has an L-C filter (L3 - C26) to prevent high frequency transients from feeding into the input circuit (caused by reset or other switching operations). The variable resistance R16 sets the cathode reference voltage of the diode V1 for initial calibration. The voltage signal developed across the diode V1 is coupled to the first stage of the two stage d.c. amplifier. The output of the two stage d.c. amplifier is coupled to the grid of a cathode follower amplifier through a R-C filter network to prevent the a.c. noise of 50Hz from being fed to the cathode follower input. The output of the cathode follower is coupled to the Log-N power measuring equipment (Log-N power meter and the Log-N recorder) and to the differentiating network consisting of a capacitor C5 and resistance R28. The cathode follower output is also coupled to the first stage of the two stage amplifier as a negative feedback line for the amplifier stabilization. The output of the differentiating network is coupled to the chopper stabilized amplifier which consists of a 50Hz chopper and a two stage R-C coupled amplifier. The output of this chopper stabilized amplifier is of the reverse polarity with respect to the input signal. If the input rises positively (due to rise in reactor power) the output increases in the negative direction. Thus, in this case the main function of the chopper stabilized amplifier is that of an inverting amplifier. The output of the chopper stabilized amplifier is coupled to the period measuring equipment (Period meter and Period recorder) and the Trip circuit. The output of the chopper-amplifier controls the conduction of two tubes, which contains the relays for fast scram, back-up scram and annunciation. Both tubes has a pi-filter network in the input grids to avoid the a.c. noise from being fed into the trip unit.

The tube V11 has a relay VR5 in its plate circuit. If the reactor power increases sharply the output of the chopper-amplifier will increase negatively, and so the grid bias of V11 will also become more negative. At some point the relay RY5 will be de-energised and contacts 1 and 2 will open, thus energising an external alarm.

Tube V4b has three relays in its plate circuit, namely RY4, RY1 and RY2. As the reactor period becomes shorter, the grid bias of V4b becomes more negative, thus decreasing the plate current. When the plate current decreases to a value at which RY4 is de-energised, contacts 1 & 2 and 5 & 6 open. When contacts 5 & 6 open, an alarm is energised, which provides some time to the reactor operator for corrective action before the reactor shutdown. Contacts 1 & 2 when closed, provide an adjustable drop-out time of relay RY4. When contacts 1 & 2 are open, RY4 will reset automatically if the period increases to approximately 30 seconds. If the reactor period continues to decrease the plate current of V4b decreases further, and a point is reached, when RY1 is de-energised. The point at which RY1 is de-energised is determined by the scram point adjustment resistor R43. With the de-energising of RY1, contacts 1 & 2 and 5 & 6 open (in RY1). With the opening of contacts 1 & 2, the fast scram bank in the safety channel is open circuited, thus resulting in a fast scram. With the opening of contacts 5 & 6 a common scram indication circuit is energised by the +B supply. With the de-energising of relay RY1, the relay RY2 is also simultaneously de-energised, thus opening contacts 5 & 6. With the opening of contacts 5 & 6, the back-up scram bank (in the primary of the magnet power supply) in the safety channel is open, thus interrupting the magnet power supply and resulting in a slow back-up scram. A micro reset button S3 (spring loaded) is provided to reset the relays RY1 and RY2.

2.4 THE SAFETY CHANNELS

Two independent and identical Safety Channels are provided for the redundancy of the safety networks. Each safety channel (Safety # 1 and Safety # 2) measures and displays the reactor power from 0% to 100% (0 to 10 Mwatts) on a single linear scale. The safety channels are designed to provide a reactor reverse at 105% of full power (10.5 Mwatts) and a reactor scram at 110% of full power (11 Mwatts). Drawing No. CP-AMF-04 shows the safety channels. Each Safety channel consists of the following main components,

1. Uncompensated Ionization Chamber (UIC).
2. Single stage D.C. Amplifier.
3. Fast scram actuating circuits.
4. Fast scram safety network (common to both safety channels).
5. Magnet Amplifier (common to both safety channels).

The UIC detects thermal neutrons in the flux range from 2.5×10^{4} to 2.5×10^{10}n/cm^{2}-sec. Ionization currents are produced by thermal neutrons incident on the boron coating enriched to 96% in the B-10 isotope. Neutron sensitivity is 4.4×10^{-4}ampere/nv. The UIC is operated at a minus potential of 300 volts. At this voltage and with an ambient thermal neutron flux of 3×10^{9}nv the UIC generates 130 microamperes. The high voltage electrode is held at -300 volts, while the collector electrode varies between -20 volts to -40 volts depending upon the output current.

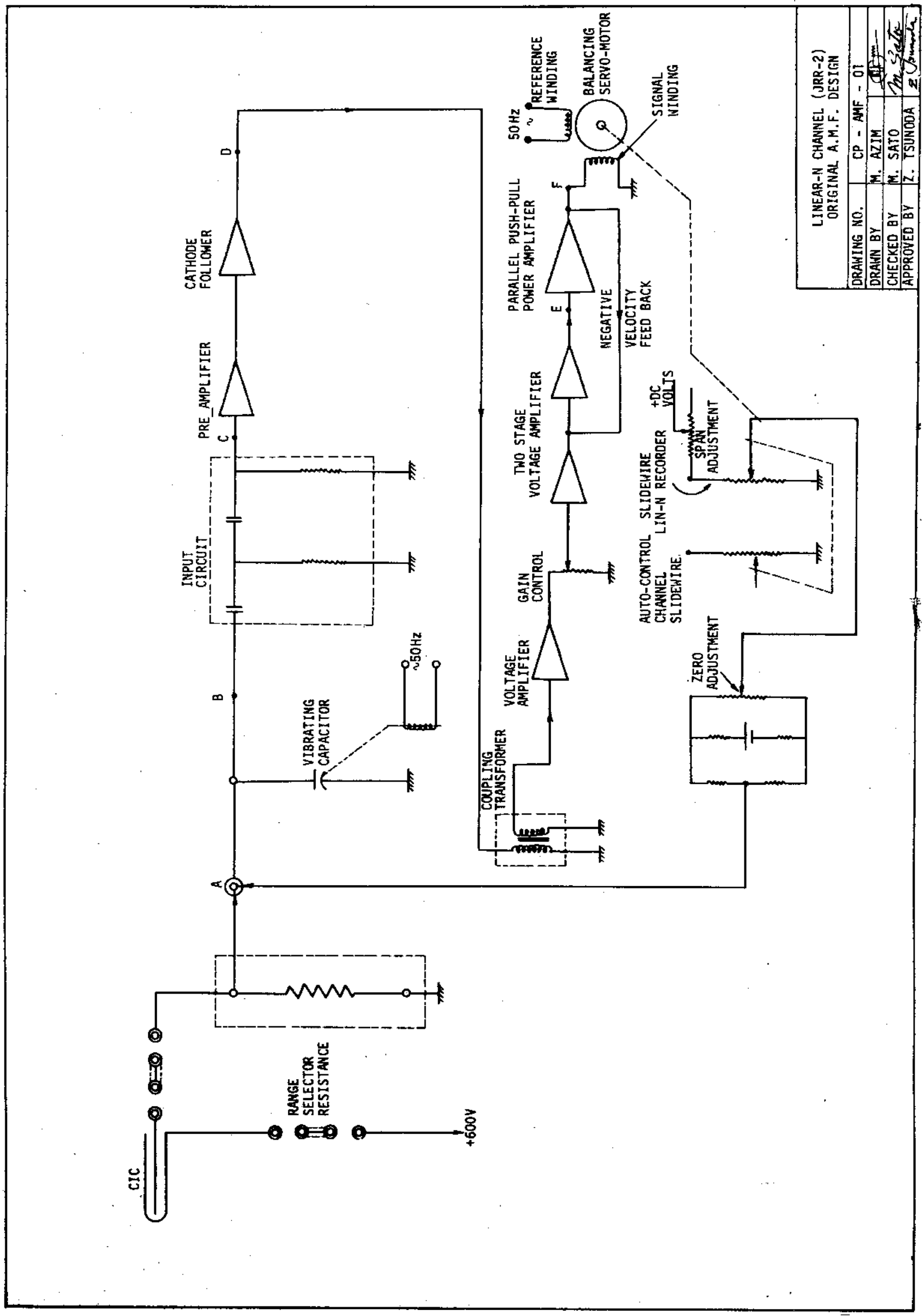
The negative polarity has been chosen so that the voltage developed at the input to the single stage D.C. amplifier increases negatively with the increasing UIC current. As the loss of chamber voltage is an unsafe failure, the high voltage is monitored at the connector of the safety amplifier which supplies high voltage to the chamber. The monitoring relay is connected to ground through the UIC co-axial cable shields. Loss of high voltage to the relay or disconnecting the chamber cables will cause a slow scram. Relays RY13 and RY14 detect the loss of chamber voltage. If the chamber voltage decrease beyond a certain value, relays RY13 and RY14 are de-energised and contacts 1 & 2 open and contacts 6 & 8 make (contacts 6 & 8 not shown in Drawing). With the opening of contacts 1 & 2, slow scram is initiated and with the making of contacts 6 & 8 the relay RY16 is energised resulting in a visible and an audible alarm.

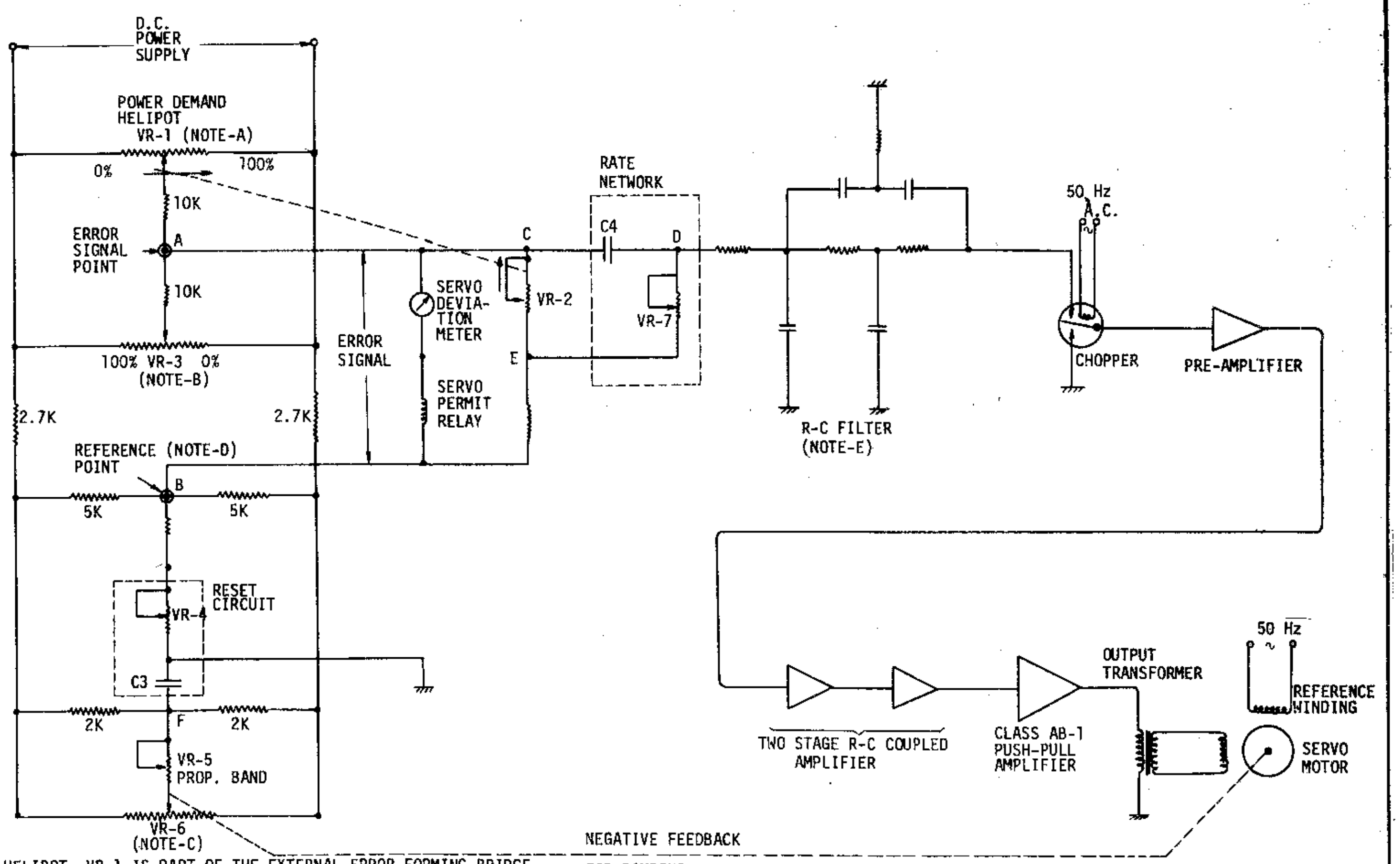
The signal from the UIC is fed to the input of a single stage d.c. amplifier at grid. This input signal increases negatively with the increase in the reactor power (neutron density in the core). In the output of each d.c. amplifier a high speed relay (RY1, RY2, RY3 and RY4) is connected between the plate and the +B supply, which initiate a fast scram signal to the magnet amplifier. When the reactor power reaches 110% of full power, the d.c. amplifier plate current is cut off by the negative signal on the grid. This releases the relay RY1 and contacts 1 & 2 open, which opens the fast scram safety network and the resistance R49 is introduced in the divider network, thus resulting in a high negative potential at the grids of the magnet amplifier tubes (V3 to V6). The plate current of the magnet amplifier tubes is therefore cut off resulting in the release of the control rods and a scram is initiated which is known as a 'FAST SCRAM'. The total time from the scram signal at the grid of the d.c. amplifiers to the interruption of the magnet current is about 5 milliseconds. With the release of the relay RY1, the contacts 5 & 6 open and 6 & 8 make. With the opening of contacts 5 & 6 the back-up scram relay RY5 is de-energised and opens the contacts 3 & 4 (in RY5) in the back-up scram bank, which is incorporated in the primary side of the magnet amplifier power supply, thus resulting in the interruption of the magnet current and a reactor scram. This scram which is initiated by the relay RY5 is known as the 'BACK-UP SCRAM' and the total time from the de-energising of the relay RY5 to the interruption of the magnet current is about 20 milliseconds. With the making of contacts 6 & 8 of RY1 an indicating light is switched on and the relay RY16 is energised, which initiates an alarm signal, thus providing a visible and an audible alarm for the reactor operator. With the opening of contacts 1 & 2 in RY1 (RY2, RY3 and RY4) the relays RY17 and RY18 are de-energised. The de-energising of RY18 gives a signal to the scram monitor, and that of RY17 gives a signal to another safety amplifier, if coupled at point D.

Relays RY9, RY10, RY11 and RY12 are for the detection of the filament failure of the magnet amplifier tubes, and are in series with the filaments. If for example, the filament of V3 is open circuited relay RY 9 is de-energised and contacts 2 & 4 open and 3 & 4 make. This action is such that the contacts 3 & 4 make before 2 & 3 break. This action of RY9 transfer the load of V3 to a dummy resistor R99a, without interrupting the magnet current, and simultaneously a visual indication is switched on, to inform the reactor operator of the failure of the magnet amplifier tube V3. If more than one tube in the magnet amplifier develops an open filament, the magnets will be released, thus resulting in a reactor scram.

The slow scram bank is also incorporated in the primary of the magnet amplifier power supply, in series with the back-up scram bank.

S1a, S1b, S1c and S1d are spring loaded reset buttons for the relays RY1, RY2, RY3 and RY4 respectively.


LINEAR-N CHANNEL (JRR-2)
ORIGINAL A.M.F. DESIGN
DRAWING NO. CP - AMF - 01
DRAWN BY M. AZIM
CHECKED BY M. SATO
APPROVED BY Z. TSUNODA
CIC
RANGE SELECTOR RESISTANCE
+600V
A
B
C
D
E
F
VIBRATING CAPACITOR
~50Hz
INPUT CIRCUIT
PRE_AMPLIFIER
CATHODE FOLLOWER
COUPLING TRANSFORMER
VOLTAGE AMPLIFIER
GAIN CONTROL
TWO STAGE VOLTAGE AMPLIFIER
PARALLEL PUSH-PULL POWER AMPLIFIER
NEGATIVE VELOCITY FEED BACK
50Hz
REFERENCE WINDING
BALANCING SERVO-MOTOR
SIGNAL WINDING
+DC VOLTS
SPAN ADJUSTMENT
SLIDEWIRE LIN-N RECORDER
AUTO-CONTROL CHANNEL SLIDEWIRE
ZERO ADJUSTMENT



NOTES

A:THE POWER DEMAND HELIPOT, VR-1 IS PART OF THE EXTERNAL ERROR FORMING BRIDGE AND IS CONTAINED IN THE POWER DEMAND SET. IT IS MECHANICALLY COUPLED TO VR-2.

B:SLIDEWIRE VR-3 IS CONTAINED IN THE LIN-N RECORDER AND GIVES A SIGNAL WHICH CORROSPONDS TO THE ACTUAL REACTOR POWER.

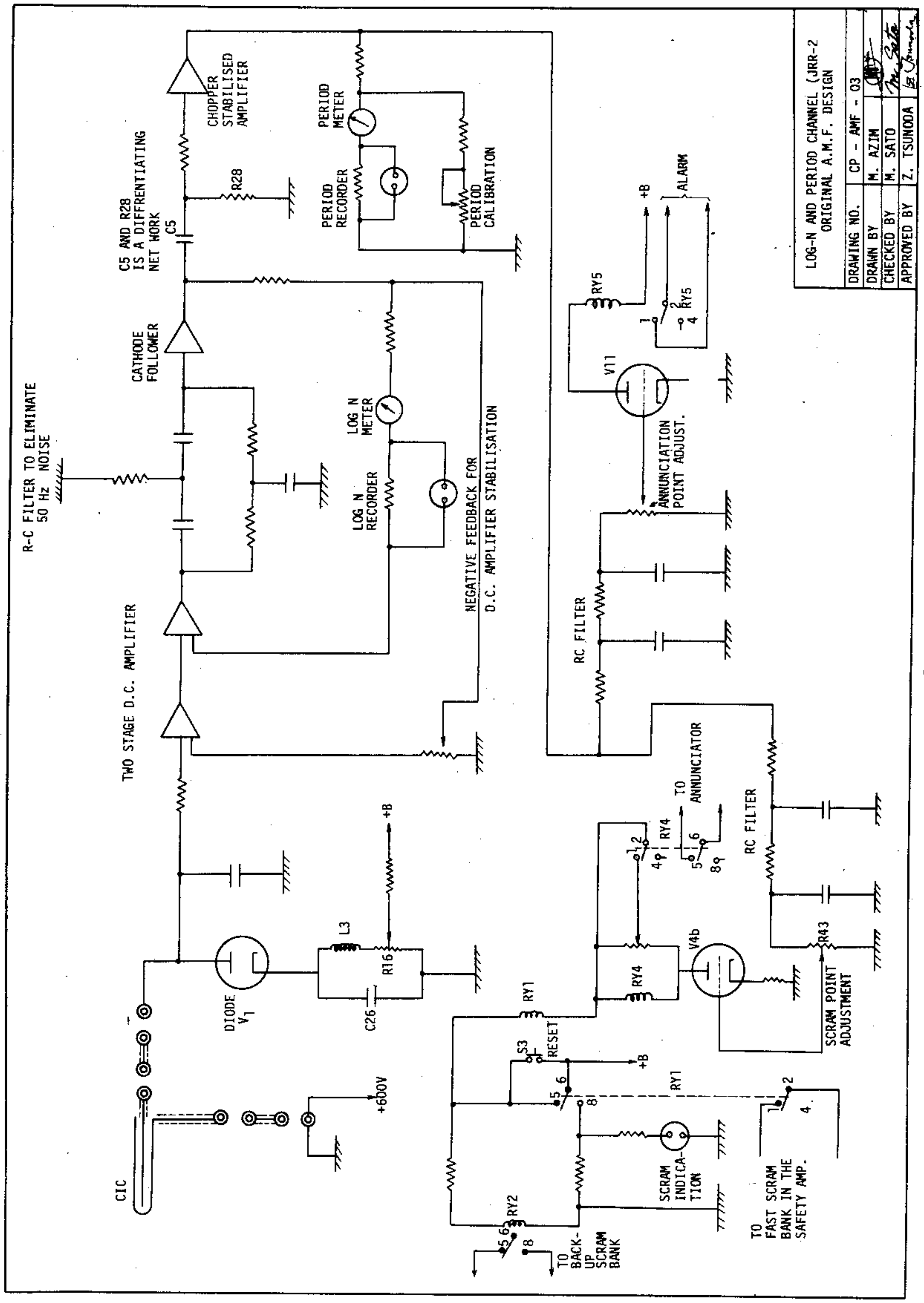
C:SLIDEWIRE VR-6 IS CONTAINED IN THE R-R DRIVE ASSEBMLY AND GIVES A SIGNAL WHICH CORROSPONDS TO THE R-R POSITION. IT PROVIDES A NEGATIVE POSITION FEEDBACK W.R.T. THE SYSTEM ERROR SIGNAL FOR DAMPING OF THE SYSTEM.

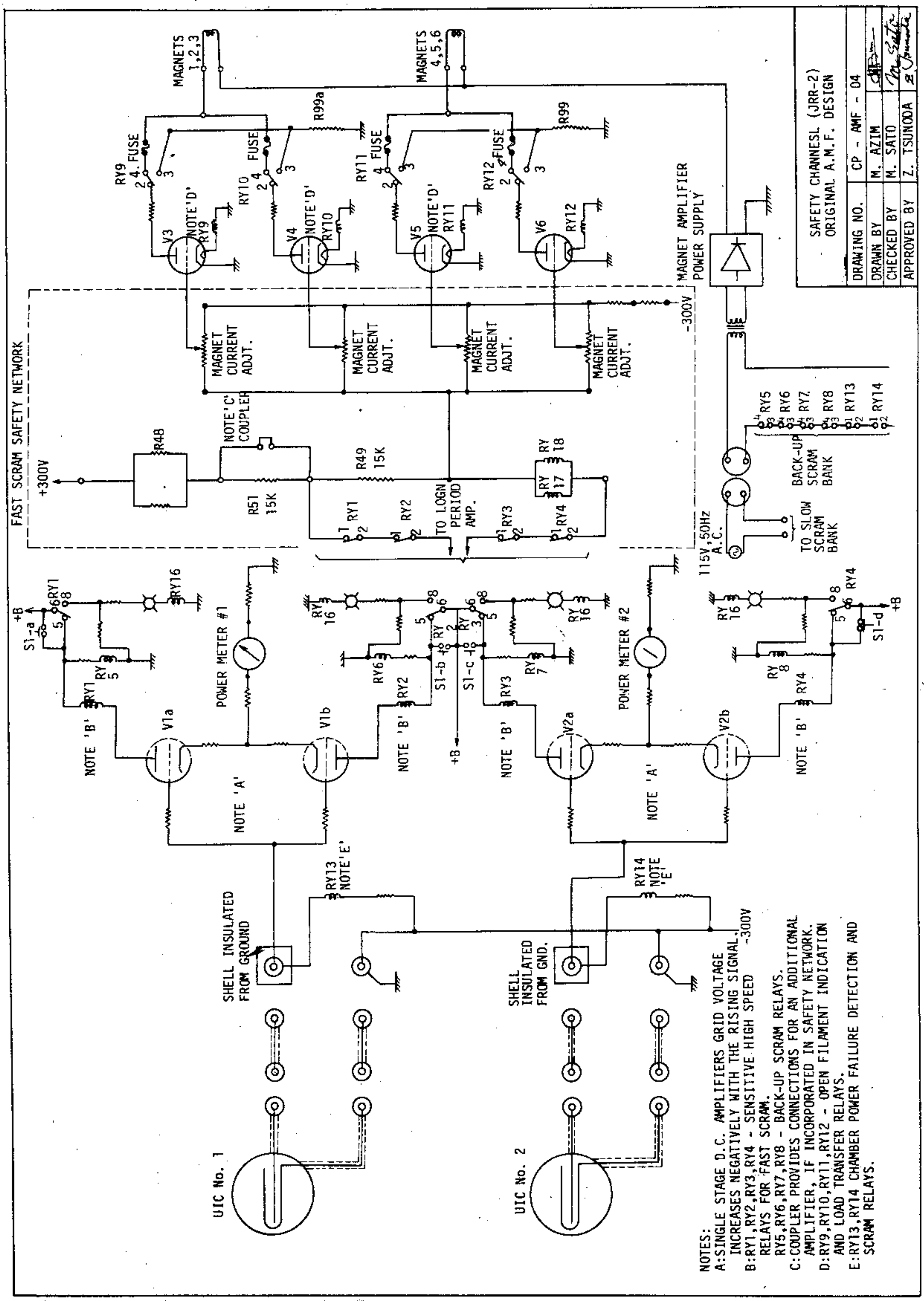
D:POINT B IS A REFERENCE POINT AND ALL SIGNAL VOLTAGES DEVELOPED IN THE BRIDGE ARE MEASURED WITH REFERENCE TO THIS POINT.

E:R-C FILTER ELEMINATES ALL A.C. NOISE FROM THE ERROR SIGNAL BEFORE IT IS FED TO THE CONVERTER TYPE AMPLIFIER.

AUTO-CONTROL CHANNEL (JRR-2)
ORIGINAL A.M.F. DESIGN

DRAWING NO.	CP - AMF - 02	
DRAWN BY	M. AZIM	[signature]
CHECKED BY	M. SATO	[signature]
APPROVED BY	Z. TSUNODA	[signature]


LOG-N AND PERIOD CHANNEL (JRR-2
ORIGINAL A.M.F. DESIGN
DRAWING NO. CP - AMF - 03
DRAWN BY M. AZIM
CHECKED BY M. SATO
APPROVED BY Z. TSUNODA
CHOPPER STABILISED AMPLIFIER
PERIOD METER
PERIOD RECORDER
PERIOD CALIBRATION
C5 AND R28 IS A DIFFERENTIATING NET WORK
C5
R28
CATHODE FOLLOWER
R-C FILTER TO ELIMINATE 50 Hz NOISE
LOG N METER
LOG N RECORDER
NEGATIVE FEEDBACK FOR D.C. AMPLIFIER STABILISATION
TWO STAGE D.C. AMPLIFIER
ALARM
RY5
V11
ANNUNCIATION POINT ADJUST.
RC FILTER
TO ANNUNCIATOR
RY4
V4b
R43
SCRAM POINT ADJUSTMENT
DIODE V1
L3
R16
C26
+B
CIC
+600V
RY1
S3
RESET
SCRAM INDICA-TION
RY2
TO BACK-UP SCRAM BANK
TO FAST SCRAM BANK IN THE SAFETY AMP.


SAFETY CHANNESL (JRR-2)
ORIGINAL A.M.F. DESIGN
DRAWING NO. CP - AMF - 04
DRAWN BY M. AZIM
CHECKED BY M. SATO
APPROVED BY Z. TSUNODA
MAGNETS 1,2,3
MAGNETS 4,5,6
FUSE
R99a
R99
NOTE'D'
MAGNET AMPLIFIER POWER SUPPLY
FAST SCRAM SAFETY NETWORK
MAGNET CURRENT ADJT.
+300V
-300V
R48
NOTE'C' COUPLER
R49 15K
R51 15K
TO LOGN PERIOD AMP.
115V,50Hz A.C.
BACK-UP SCRAM BANK
TO SLOW SCRAM BANK
POWER METER #1
POWER METER #2
NOTE 'A'
NOTE 'B'
NOTE'E'
SHELL INSULATED FROM GROUND
SHELL INSULATED FROM GND.
UIC No. 1
UIC No. 2
NOTES:
A:SINGLE STAGE D.C. AMPLIFIERS GRID VOLTAGE INCREASES NEGATIVELY WITH THE RISING SIGNAL.
B:RY1,RY2,RY3,RY4 - SENSITIVE HIGH SPEED RELAYS FOR FAST SCRAM.
RY5,RY6,RY7,RY8 - BACK-UP SCRAM RELAYS.
C:COUPLER PROVIDES CONNECTIONS FOR AN ADDITIONAL AMPLIFIER, IF INCORPORATED IN SAFETY NETWORK.
D:RY9,RY10,RY11,RY12 - OPEN FILAMENT INDICATION AND LOAD TRANSFER RELAYS.
E:RY13,RY14 CHAMBER POWER FAILURE DETECTION AND SCRAM RELAYS.

3. CHANGE-OVER FROM THE ORIGINAL A.M.F DESIGN TO THE MODIFIED DESIGN

The reactor (JRR-2) operated, using the conventional AMF designed instrumentation systems, from the day of criticality (October 1,1960) until June 1968. It was on the 12th of July 1968 that the overheating of a relay coil caused a fire accident in the control room and in the subsequent fire extinguishing operations that followed, the reactor instrumentation was more or less completely destroyed.

After the fire accident in the control room it was decided to replace the destroyed instrumentation with the newly designed instrumentation systems, incorporating solid state linear integrated circuits as the basic circuit components. This choice was promted by the following obvcous advantages of semi-conductor devices over the conventional vacuum tubes.

1. The semi-conductor circuits generally run at lower internal temperatures then the vacuum tubes and thus exibit improved reliability.
2. As the number of components used in semiconductor circuits are less then the vacuum tube circuits, the chances of instrument failure are less, which leads to improved reliability.
3. Semi-conductor circuits generally exibit better linearity as compared to vacuum tubes.
4. Semi-conductor devices have a wide range of applications as compared to vacuum tubes.
5. Semi-conductor devices have a longer operating life-time than the vacuum tubes, thus resulting in improved reliability and ease of maintenance.
6. Semi-conductor components are less costly than the vacuum tubes and needs little change, thus resulting in higher operational economy.

The modified instrumentation systems using solid state linear integrated circuits were designed by the Electronics Workshop at the Tokai Research Establishment of JAERI, and were fabricated in stages, by the following industries.

1. IKEGAMI - Mito Plant.
2. TOKYO ELECTRIC CO. - Tokyo

From April 1968 the reactor started its routine operations on regular basis under the modified instrumentation systems.

The basic operational theory of the Modified design is described in the next section.

4. THE MODIFIED DESIGN

The modified nuclear instrumentation systems of JRR-2 is based on the standardised 'BIN MODULE SYSTEMS' incorporating solid state linear integrated circuits as the basic circuit components. The reactor power is monitored and controlled by the following instrumentation systems.

1. The Linear and Auto-control Channel.
2. The Log-N and Period Channel.
3. The Safety Channels (No.1 and No.2)
4. The Rod Magnet Amplifier.

The theory of operation of the above systems is described in this section.

4.1 THE LINEAR AND AUTO-CONTROL CHANNEL

The Linear and Auto-control channel measures and displays the reactor power from zero to 25 Mwatts over 22 ranges, on the same linear scale, and automatically controls the power at a desired level. A block representation is shown in Drawing No. CP-MOD-01. This channel consists of the following main components.

1. High Voltage Power Supply.
2. Compensated Ionization Chamber (CIC).
3. Auto Range Selector.
4. Linear-N Amplifier.
5. Three Mode Auto-Controller.
6. Power Amplifier.

4.1.1 HIGH VOLTAGE POWER SUPPLY

The High Voltage Power Supply, supplies stabilized +600 volts D.C. to the high voltage electrode of the CIC and -60 volts to the collector electrode, for gamma compensation. It has a comparator circuit in the output which actuates a scram relay, if the H.V. supply falls beyond a certain predetermined level, thus causing the 'LOW CIC VOLTAGE' slow scram.

4.1.2 COMPENSATED IONIZATION CHAMBER

The Compensated Ionization Chamber is designed to detect thermal neutrons in the flux range from 4.3×10^{2}n/cm^{2}-sec. to 5×10^{10}n/cm^{2}-sec. It has a neutron sensitivity of 2.3×10^{-14}ampere/nv and a gamma sensitivity of 6.4×10^{-12}ampere/R/hour when operating uncompensated. For the power range from zero to 10 Mwatts, it generates a current signal of zero to 90μA.

4.1.3 AUTO-RANGE SELECTOR

The Auto-Range Selector has 22 positions, each with a series resistor and a relay. The desired resistor is automatically switched on, in series with the CIC output current by the series relay. The series relay is operated with the help of a combination of digital circuits, consisting of AND, NAND, OR and NOR gates. The selection of the resistor is determined by the CIC output current. As the CIC current rises with the rise in reactor power, progressively lower values of resistors are switched on in the circuit, so that for each range the voltage output remains constant from zero to 450 millivolts.

4.1.4 LINEAR-N AMPLIFIER

The Linear-N Amplifier (Drawing No. CP-MOD-02) consists of two stages. The voltage signal developed across the auto-range selector resistance is fed to the input stage, consisting of a hybrid IC (K302). This IC has a high input impedance and is enclosed in a specially designed sealed box containing silica-gel, which maintains a constant humidity inside the box, so that the output signal is not affected by the change in humidity. IC-2 is a sign inverting amplifier having a gain of unity. The IC-2 output is fed to the second stage consisting of IC-1, which is also an inverting amplifier having a gain of 9. The output of IC-1 is the output of the Linear-N Amplifier and over one full range, it supplies an output signal of zero to 4 volts D.C. Fig. 3 shows the Linear-N Amplifier characteristics.

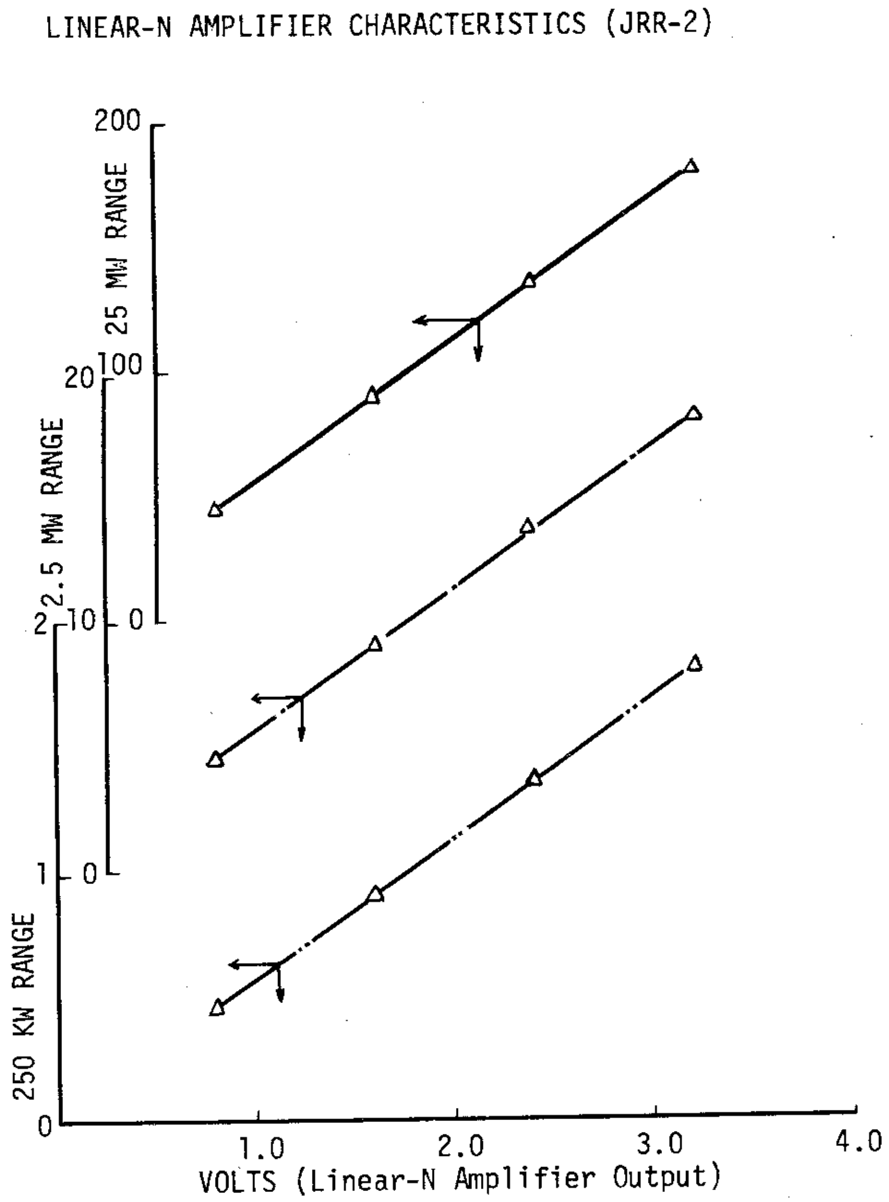


Fig. 3 Linear-N amplifier characteristics

4.1.5 THREE MODE AUTO-CONTROLLER

The Three Mode Auto-controller consists of two main units, namely

i) Three Mode Unit (PC-1).

ii) Servo Deviation Trip Unit (PC-2).

4.1.5(i) Three Mode Unit (PC-1)

Drawing No. CP-MOD-03 shows the three mode unit. This unit compares the Linear-N Amplifier output signal, which represents the actual reactor power, with the reactor power demand signal. The error signal is then amplified, integrated and differentiated so as to provide a Proportional-Integral-Differential (Three mode) signal to the next stage Power Amplifier. The following combinations of the three modes can be selected through a selector switch,

a) Proportional.

b) Proportional-Integral.

c) Proportional-Differential.

d) Proportional-Differential-Integral.

The purpose of integration and differentiation of the error signal is to improve the stability of the system and to provide the necessary damping. It has, however been investigated that only proportional mode of action provides maximum stability and optimum damping for the close loop system of JRR-2.

The Three Mode Unit consists of seven ICs. The output of the Linear-N Amplifier is compared with the reactor power level demand signal at point 'A'. The power demand signal is provided by IC-2, which is a high input impedance voltage follower amplifier, having a demand setting variable resistance in the input. The high input impedance ensures the linearity of the demand signal. IC-4 amplifies the demand signal from IC-2 and displays the desired power level in the output. The error signal from point 'A' is fed to the inverting input of IC-1, which amplifies the error and feeds it to IC-3, the external error meter at 'F' and the servo-deviation trip unit at 'E'. IC-1 has two transistors in the feedback line for transient voltage limitation, so that the output from IC-1 is not affected by the transients. IC-3 is a proportional amplifier having a gain of unity. The proportional output of IC-3 is fed to the integrating and differentiating circuits. IC-6 is an integrating amplifier, which integrates the proportional signal from IC-3 and provides a proportional-integral signal in the output at 'C'. IC-5 is a differential amplifier, which differentiates the proportional output from IC-3 and provides a proportional-differential signal at 'D', through a sign inverting amplifier IC-7.

4.1.5(ii) Servo Deviation Trip Unit (PC-2)

Drawing No. CP-MOD-04 shows the servo deviation trip unit. This unit detects the difference between the actual reactor power and the desired power level (servo deviation). It has two identical circuits for the detection of servo deviation at ±5% and ±10%. If the servo deviation exceeds ±5%, circuit # 1 operates a relay though a switching transistor, which in turn energises an audible and visible alarm circuit to warn the reactor operator. If however the servo deviation goes on increasing and ultimately reaches a value of ±10%, circuit # 2 switches off the transistor Q-2, thus de-energising relay RY-2, which transfers the reactor from automatic mode to manual mode, which is also accompanied by an audible and visible alarm.

The Servo Deviation Trip Unit consists of three ICs, namely, IC-3 (AD741C), IC-4 and IC-5. IC-4 and IC-5 are special high speed comparators (SN7272D), each having two operational amplifiers. IC-4 is for the detection of ±5% servo deviation, whereas IC-5 is for the detection of ±10% servo deviation.

IC-4A detects servo deviation of over +5%, while IC-4B detects servo deviation of over -5%. The bias at the non-inverting input of IC-4A is maintained at a constant potential of +0.225 V, whereas the inverting input of IC-4A is fed by the servo deviation signal from IC-3, which is a non-inverting amplifier, having a gain of unity. If the servo deviation is less than +5%, the bias voltage at point 'A' (non-inverting input of IC-4A) overides the servo deviation input voltage (inverting input of IC-4A) and the output of IC-4A remains at a constant voltage of +1.82 V. As this potential is fed as a bias voltage to the base of Q1, so under these conditions it is conducting, and the relay RY-1 is energised. If, however, the servo deviation exceeds +5%, the servo deviation signal from IC-3 to the inverting input of IC-4A overides the positive bias potential at 'A', and the output of IC-4A drops from +1.82 V to -0.5 V. This change in the output of IC-4A switches off the transistor Q1, as its base is directly coupled to IC-4A output. With the switching off of Q1, relay RY-1 is deenergised. With the de-energising of RY-1, contacts 1 and 2 open and contacts 2 and 3 make. With the making of contacts 2 and 3, an external alarm circuit is energised, which operates a visual and an audible alarm, thus indicating that the servo deviation has exceeded ±5%.

The operation of IC-4B for the detection of -5% servo deviation is identical to the operation of IC-4A, as described above, with only the polarities of the bias voltage and the error signal being reversed. Under normal conditions (for servo deviation less than ±5%) the negative bias at the inverting input at point 'B' of IC-4B is -0.2 V and the output is +2.4 V. If the servo deviation exceeds -5%, the servo deviation signal (IC-3 output) becomes -0.7V, and this signal at the non-inverting input of IC-4B, overides the negative bias of -0.2 V at the inverting input and the output of IC-4B falls from +2.4 V to -0.57 V. This action of IC-4B switches off the transistor Q1, which de-energises relay RY-1, and initiates an audible and visible alarm.

The circuit # 2 is for the detection of ±10% servo deviation. It is similar in design and operation to the circuit # 1, and consists of IC-5. IC-5A is for the detection of servo deviation exceeding + 10%, while IC-5B detects the servo deivation of more than - 10%.

If the servo deivation exceeds + 10%, the servo deviation signal input (from IC-3) at the inverting input of IC-5A will overide the positive bias of +0.335 V at point 'C' and the IC-5A output will fall from +2.43 V to -0.5 V. This drop of potential at the output of IC-5A will switch off the transistor Q2, thus de-energising the relay RY-2. With the de-energising of relay RY-2, contacts 1 and 2 open and contacts 2 and 3 make. With the making of contacts 2 and 3 the reactor is transferred from automatic mode to manual mode, which is accompanied by the audible and visible alarm.

If the servo deviation exceeds - 10%, the negative servo deviation signal from IC-3 to the non-inverting input of IC-5B overides the negative bias potential at the inverting input at point 'D', and the output of IC-5B falls from +2.46 V to -0.5 V, thus switching off the transistor Q2 and de-energising relay RY-2.

The integrated circuits IC-4 and IC-5 have special reset characteristics, so as to avoid unneccessary operation of the relays RY-1 and RY-2 at the critical servo deviation values of ±5% and ±10% respectively.

4.1.6 POWER AMPLIFIER

The Power Amplifier amplifies the d.c. error from the three mode unit, converts it into a proportionate a.c. signal and supplies it to the signal winding of the servo motor, which then rotates in a direction decided by the polarity of the input d.c. error signal and thus tends to cancel the error by placing the regulating rod at the desired level.

Drawing No. CP-MOD-05 shows the Power Amplifier circuit. It consists of six ICs and a'parallel OTL power amplifier' consisting of 6 power transistors. The d.c. error signal from the Three Mode Unit is supplied to the Power Amplifier input at 'A'. The error signal passes through the R-C filter (which eliminates the a.c. noise) before reaching the first stage of amplification by IC-1. IC-1 is a d.c. amplifier with a gain of 10. The output of IC-1 is fed to the chopper amplifier IC-4, which converts the d.c. signal into positive or negative square half cycles (depending upon the polarity of the d.c. input signal) as shown in Fig. 4.

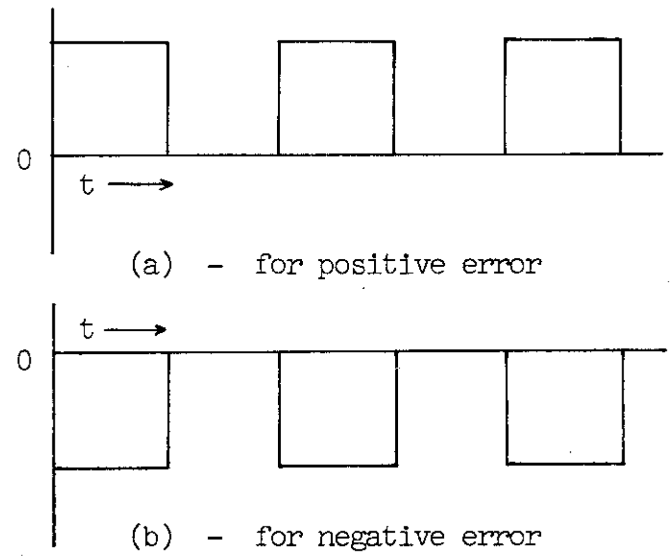


Fig. 4 Chopper amplifier output.

The output of the chopper amplifier is further amplified by IC-5 and passed through capacitors C1 and C2 to eleminate the d.c. component from the signal. The output of IC-5 after passing through C1 and C2 is a square wave. The phase difference between the signals for the negative and positive error inputs from the Three Mode Unit is 180° as shown in Fig. 5.

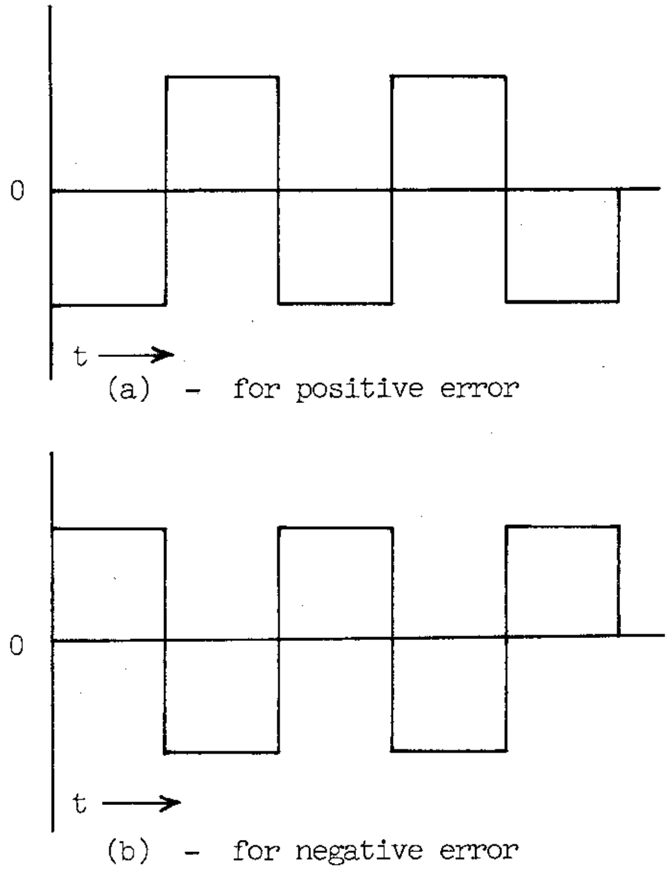


Fig. 5 Square wave Input to IC-6.

The square wave is further amplified by the a.c. amplifier IC-6 and then fed to the active filter circuit comprising of IC-7, R1, R2, C3 and C4. The active filter circuit converts the square wave into a sign wave as shown in Photo. 5. The sine wave output is fed to the a.c. amplifier IC-8 through a coupling transformer (for impedance matching). The IC-8 output is finally fed to the 'parallel OTL power amplifier' consisting of power transistors Q1 to Q6. As the output impedance of the parallel OTL power amplifier is very low (about 16Ω), an output transformer is used between the servo motor and the Power Amplifier for impedance matching. Over current protection to the power transistors is provided by employing a trip relay between the parallel OTL power amplifier and the output transformer. In the case of any transients, the over-current protection relay trips the main power supply and prevents any damage to the power transistors. The phase difference between the signal winding input of the servo motor and the reference winding input is 90° for the positive error and causes the motor to move in one direction. In the case of the negative servo error the phase difference between the signal winding input and the reference winding input is 270° and causes the servo motor to move in the opposite direction. Fig. 6 shows the phase difference between the reference winding signal and the error signal.

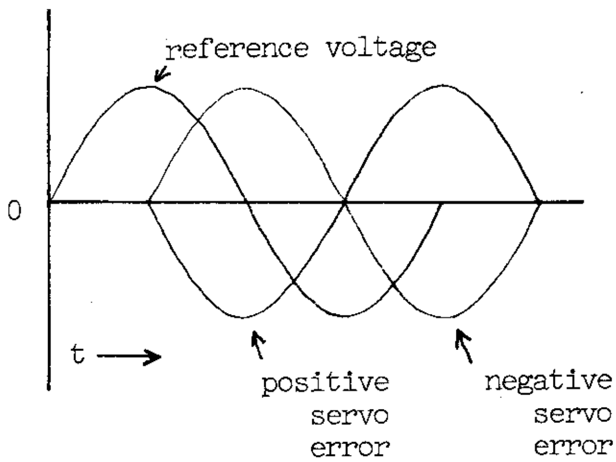


Fig. 6 Phase difference between the reference voltage and the servo-error.

Protection against +12 V and +B failure for the Power Amplifier is provided by transistors Q7, Q8, Q9 and relay RY-1. The relay RY-1 transfer the reactor from automatic mode to manual mode in the case of +12 V and +B failure. Fig. 7 shows the Power Amplifier characteristics.

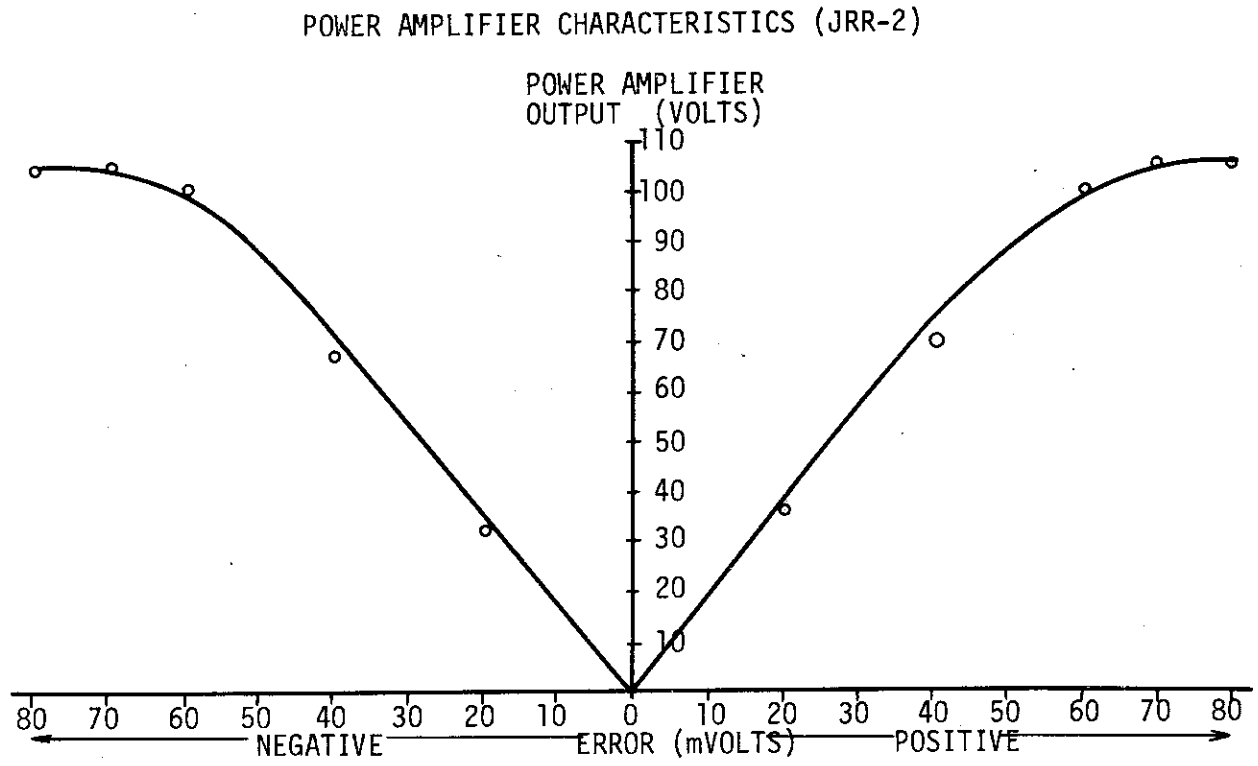
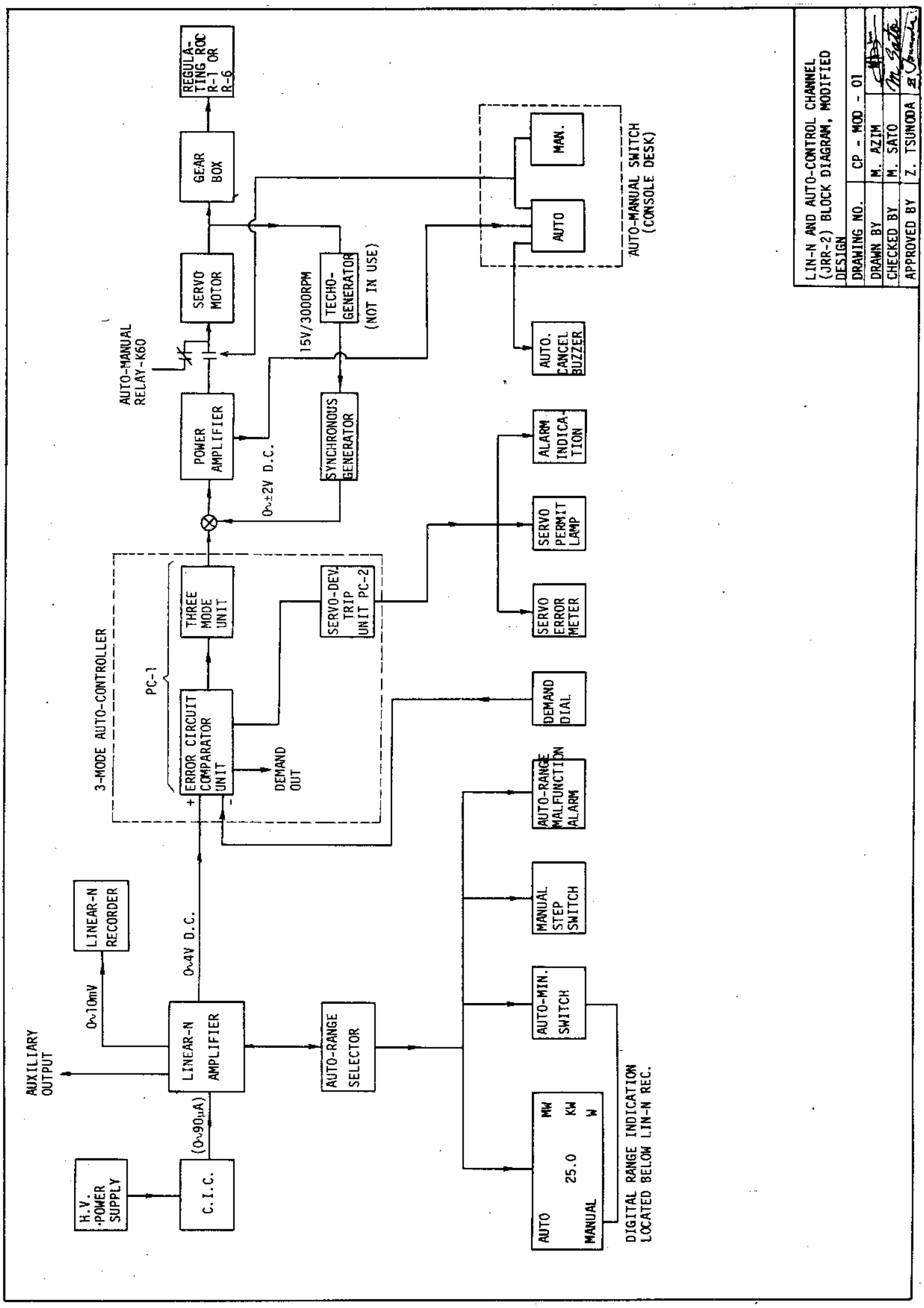
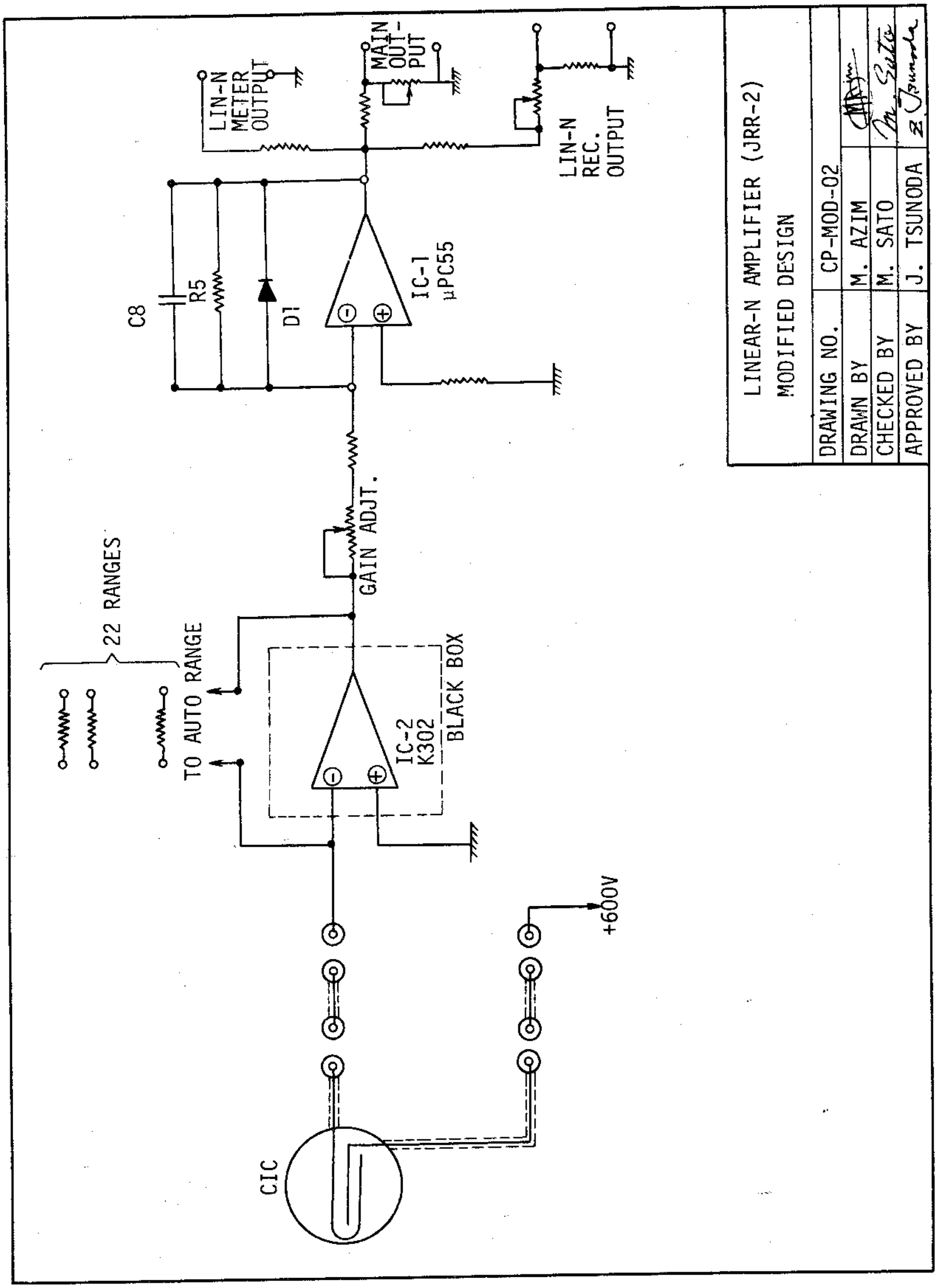
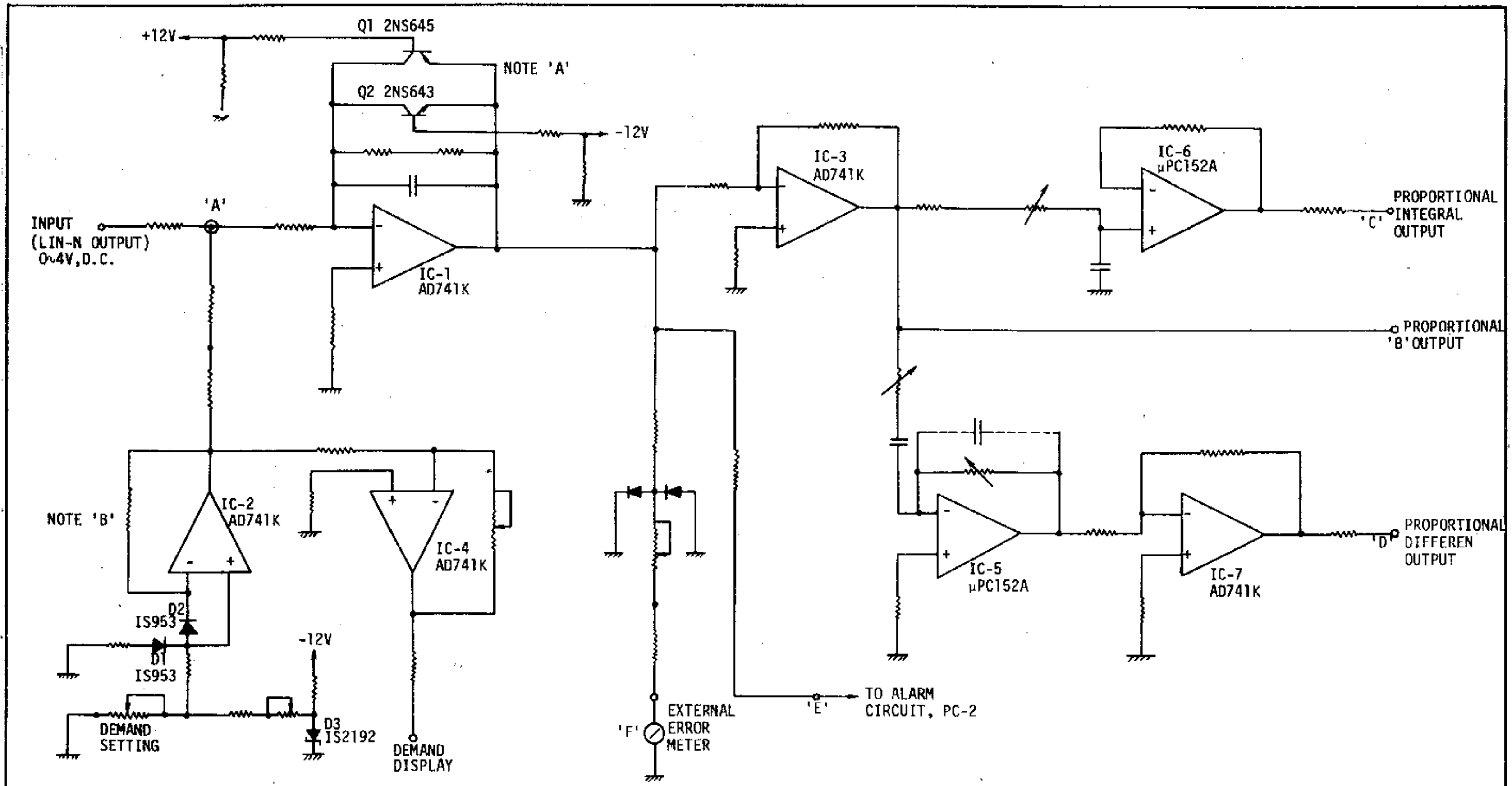


Fig. 7 Power amplifier characteristics


H.V. POWER SUPPLY
C.I.C.
(0∿90μA)
LINEAR-N AMPLIFIER
AUXILIARY OUTPUT
0∿10mV
LINEAR-N RECORDER
0∿4V D.C.
AUTO-RANGE SELECTOR
3-MODE AUTO-CONTROLLER
PC-1
ERROR CIRCUIT COMPARATOR UNIT
DEMAND OUT
THREE MODE UNIT
SERVO-DEV. TRIP UNIT PC-2
0∿±2V D.C.
POWER AMPLIFIER
AUTO-MANUAL RELAY-K60
SERVO MOTOR
15V/3000RPM
TECHO-GENERATOR
(NOT IN USE)
SYNCHRONOUS GENERATOR
GEAR BOX
REGULA-TING ROD R-1 OR R-6
MAN.
AUTO
AUTO-MANUAL SWITCH (CONSOLE DESK)
AUTO. CANCEL BUZZER
ALARM INDICA-TION
SERVO PERMIT LAMP
SERVO ERROR METER
DEMAND DIAL
AUTO-RANGE MALFUNCTION ALARM
MANUAL STEP SWITCH
AUTO-MIN. SWITCH
AUTO
MANUAL
25.0
MW
KW
W
DIGITAL RANGE INDICATION LOCATED BELOW LIN-N REC.
LIN-N AND AUTO-CONTROL CHANNEL (JRR-2) BLOCK DIAGRAM, MODIFIED DESIGN
DRAWING NO.
CP - MOD - 01
DRAWN BY
M. AZIM
CHECKED BY
M. SATO
APPROVED BY
Z. TSUNODA


LIN-N METER OUTPUT
MAIN OUT-PUT
LIN-N REC. OUTPUT
C8
R5
D1
IC-1 μPC55
GAIN ADJT.
22 RANGES
TO AUTO RANGE
IC-2 K302
BLACK BOX
+600V
CIC
LINEAR-N AMPLIFIER (JRR-2)
MODIFIED DESIGN
DRAWING NO. CP-MOD-02
DRAWN BY M. AZIM
CHECKED BY M. SATO
APPROVED BY J. TSUNODA



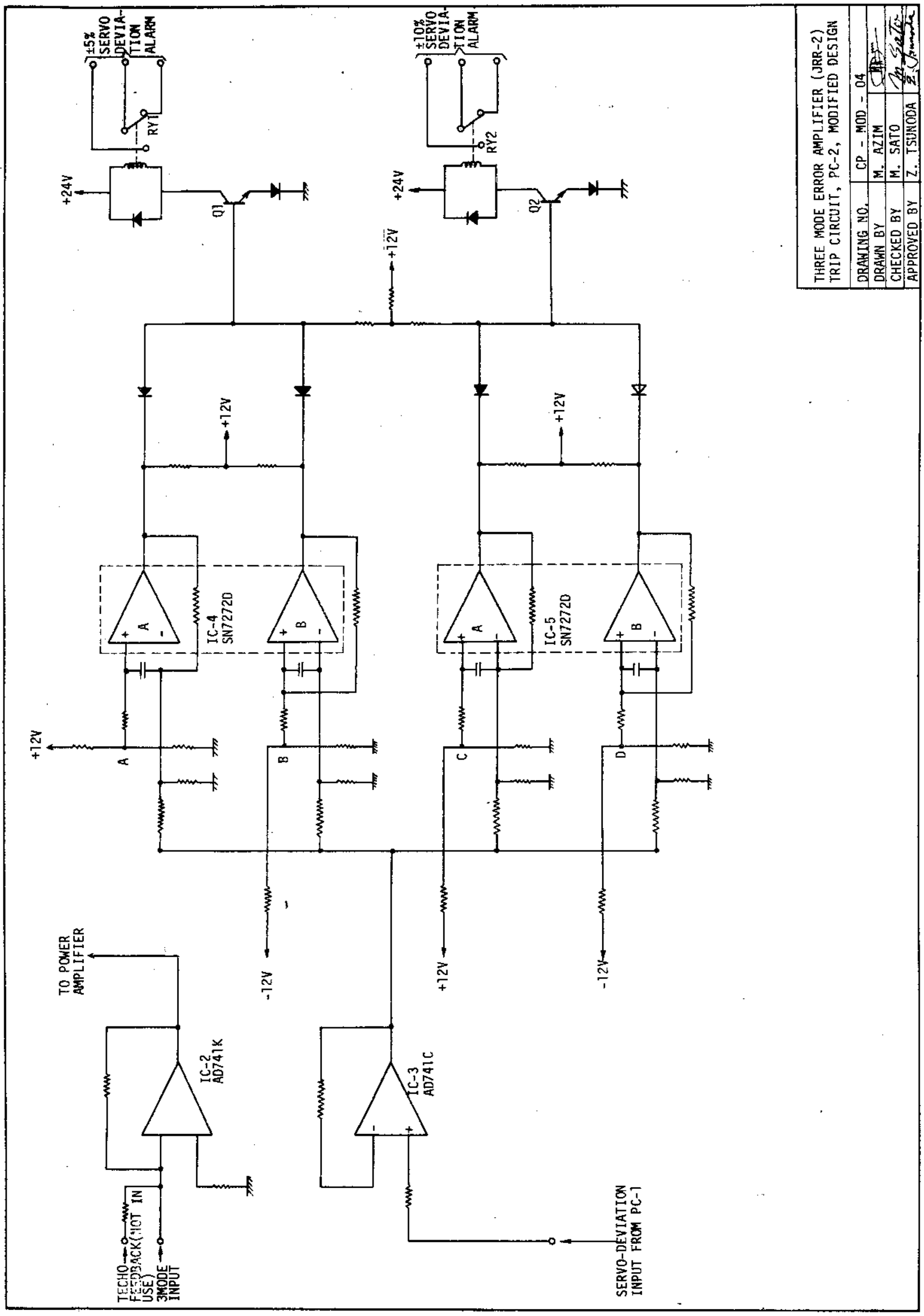
NOTES:

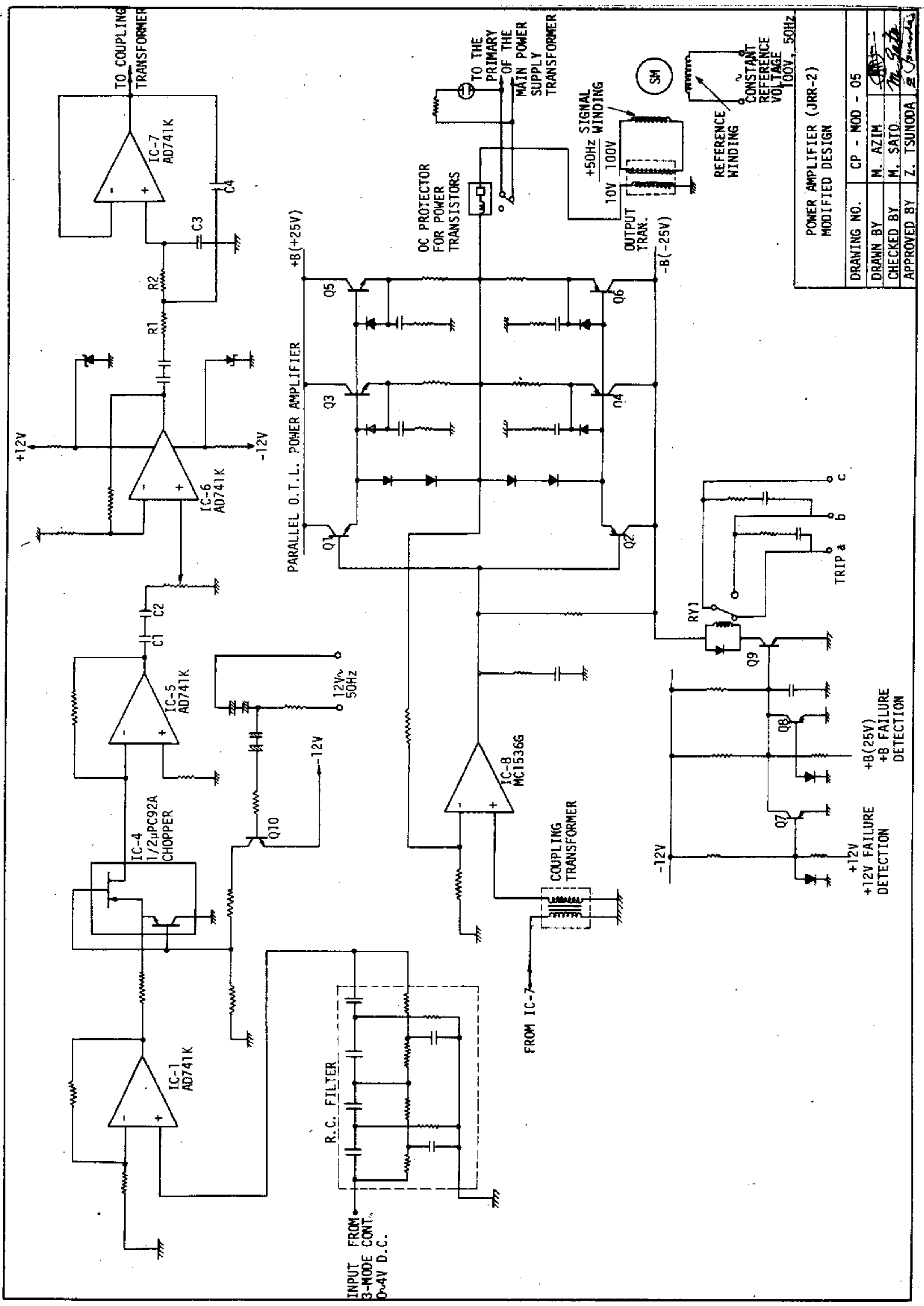
A: IC-1 HAS TWO TRANSISTORS IN THE FEEDBACK LINE FOR VOLTAGE LIMITATION UNDER TRANSIENT CONDITIONS, SO THAT OUTPUT OF IC-1 IS NOT AFFECTED BY THE TRANSIENTS

B: IC-2 IS A VOLTAGE FOLLOWER AMPLIFIER WITH HIGH INPUT IMPEDANCE, TO MAINTAIN LINEARITY OF THE DEMAND SIGNAL.

THREE MODE ERROR AMPLIFIER (JRR-2)
ERROR CIRCUIT, PC-1, MODIFIED DESIGN

DRAWING NO.	CP - MOD - 03	
DRAWN BY	M. AZIM	(signature)
CHECKED BY	M. SATO	M. Sato
APPROVED BY	Z. TSUNODA	Z. Tsunoda


THREE MODE ERROR AMPLIFIER (JRR-2)
TRIP CIRCUIT, PC-2, MODIFIED DESIGN
DRAWING NO. CP - MOD - 04
DRAWN BY M. AZIM
CHECKED BY M. SATO
APPROVED BY Z. TSUNODA
±5% SERVO DEVIA-TION ALARM
±10% SERVO DEVIA-TION ALARM
RY1
RY2
+24V
+24V
Q1
Q2
+12V
+12V
+12V
+12V
IC-4 SN7272D
IC-5 SN7272D
A
B
C
D
-12V
+12V
-12V
TO POWER AMPLIFIER
IC-2 AD741K
IC-3 AD741C
TECHO FEEDBACK(NOT IN USE)
3MODE INPUT
SERVO-DEVIATION INPUT FROM PC-1


TO COUPLING TRANSFORMER
IC-7 AD741K
C3
C4
R1
R2
+12V
-12V
IC-6 AD741K
C1
C2
IC-5 AD741K
12V~ 50Hz
-12V
Q10
IC-4 1/2μPC92A CHOPPER
IC-1 AD741K
R.C. FILTER
INPUT FROM 3-MODE CONT. 0~4V D.C.
PARALLEL O.T.L. POWER AMPLIFIER
+B(+25V)
Q5
Q3
Q1
Q6
Q4
Q2
OC PROTECTOR FOR POWER TRANSISTORS
TO THE PRIMARY OF THE MAIN POWER SUPPLY TRANSFORMER
OUTPUT TRAN.
-B(-25V)
10V
+50Hz 100V
100V
SIGNAL WINDING
SM
REFERENCE WINDING
CONSTANT REFERENCE VOLTAGE 100V, 50Hz
IC-8 MC1536G
COUPLING TRANSFORMER
FROM IC-7
RY1
Q9
TRIP a
b
c
Q8
+B(25V)
+B FAILURE DETECTION
Q7
-12V
+12V
+12V FAILURE DETECTION
POWER AMPLIFIER (JRR-2)
MODIFIED DESIGN
DRAWING NO. CP - MOD - 05
DRAWN BY M. AZIM
CHECKED BY M. SATO
APPROVED BY Z. TSUNODA

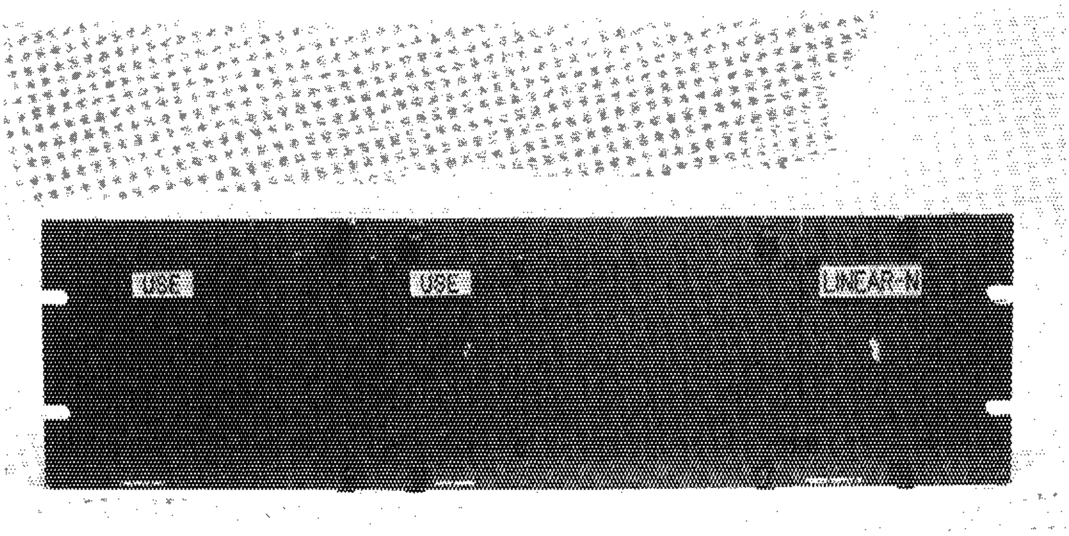


Photo 1. Linear-N module (Front view)

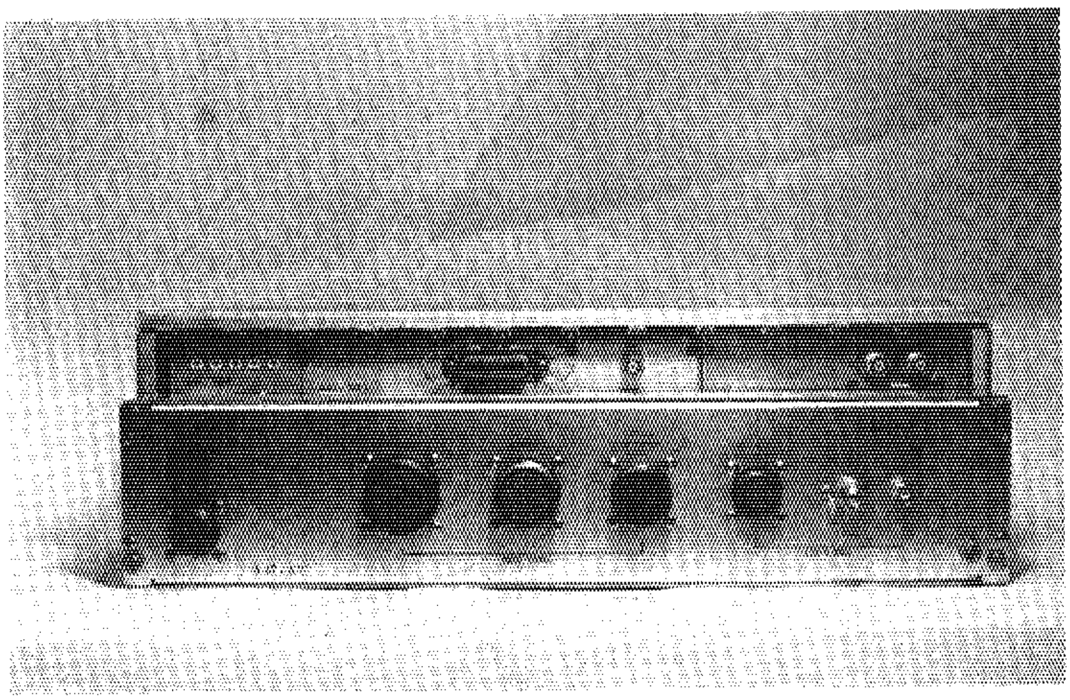


Photo 2. Linear-N module (Rear view)

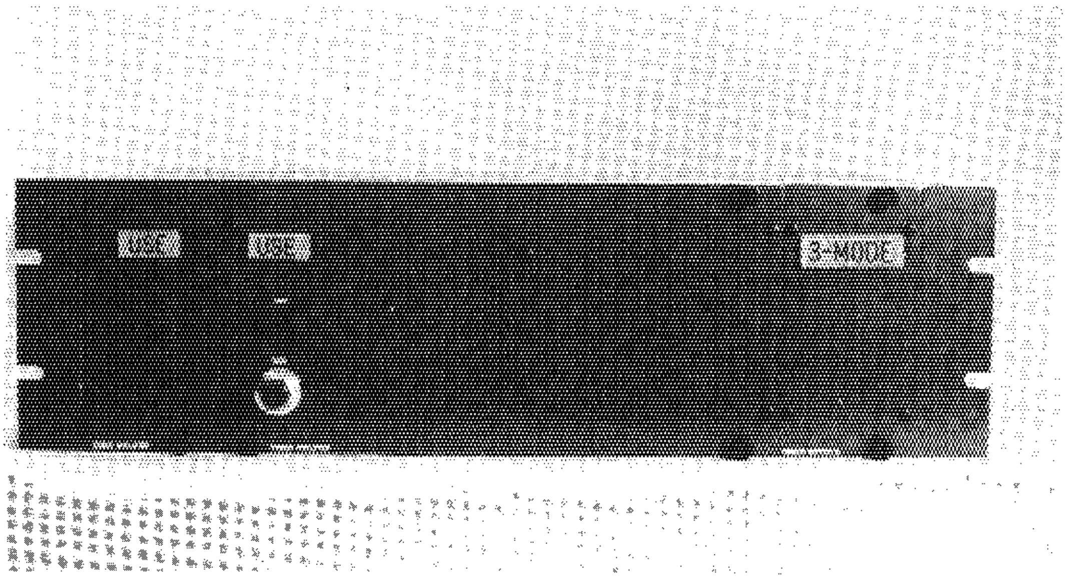


Photo 3. Three mode controller module
(Front view)

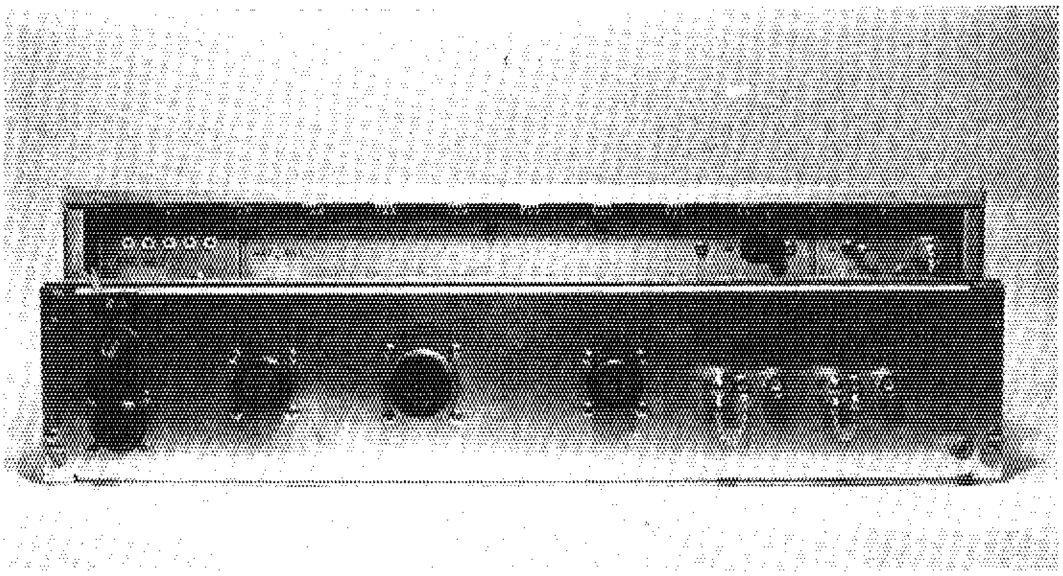


Photo 4. Three mode controller module
(Rear view)

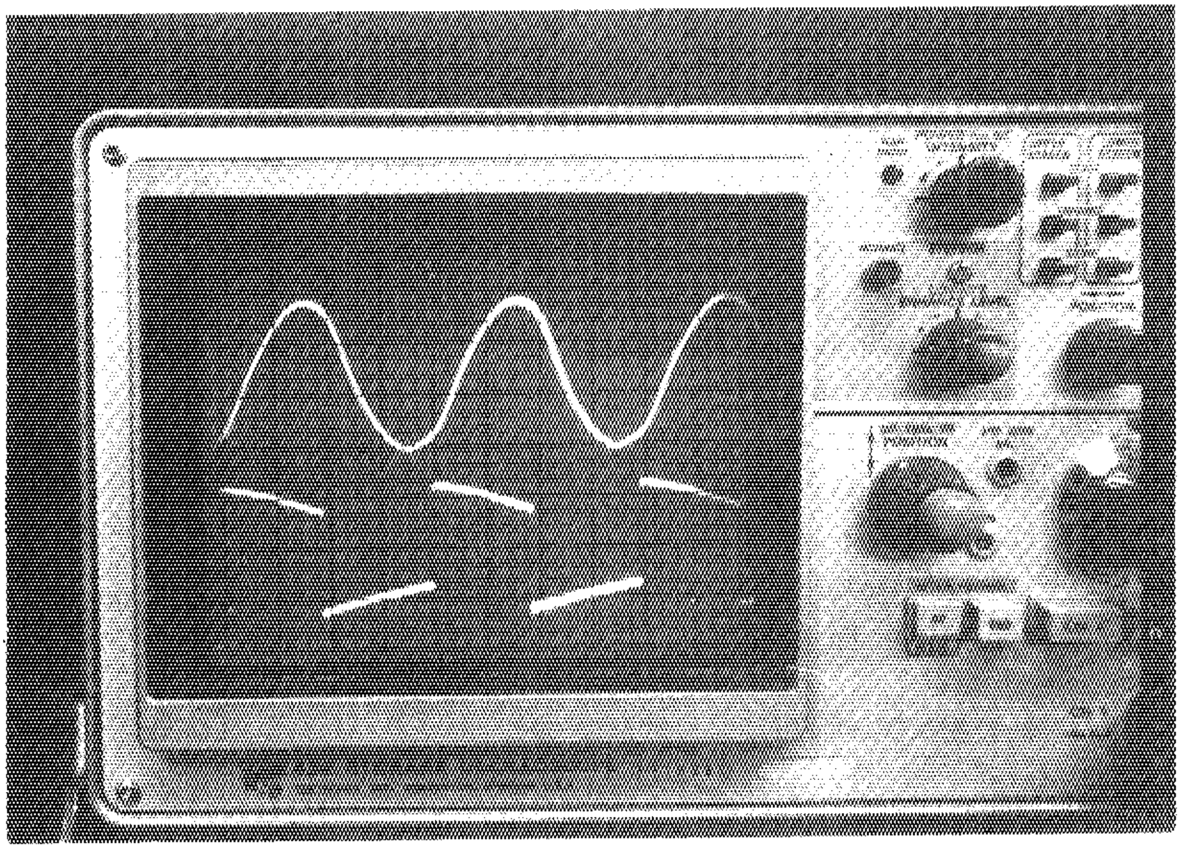


Photo 5. Active filter characteristics

4.2 THE LOG-N AND PERIOD CHANNEL

The Log-N and Period channel measures and displays the reactor power from 0.001 % to 300 % (10 watts to 30 Mwatts) on a single log scale, over six decades. It also constantly monitors the rate of rise of reactor power, in terms of reactor period and effectively shuts down the reactor, if this rate of rise of power becomes very sharp and tends to approach a dangerous level. Drawing No. CP-MOD-06 shows the Log-N and Period Amplifier circuit and Drawing No. CP-MOD-07 shows the Safety Trip circuit. This channel consists of the following main components.

1. High Voltage Power Supply.
2. Compensated Ionization Chamber (CIC).
3. Log-N Amplifier.
4. Period Amplifier.
5. The Trip Unit.

The high voltage power supply and the CIC have already been explained in the Linear-N and Auto-control channel. The rest of the components will now be described.

4.2.1 LOG-N AMPLIFIER

The Log-N amplifier consists of two stages, namely the Log-N stage and the output stage. Fig. 8 shows the Log-N amplifier.

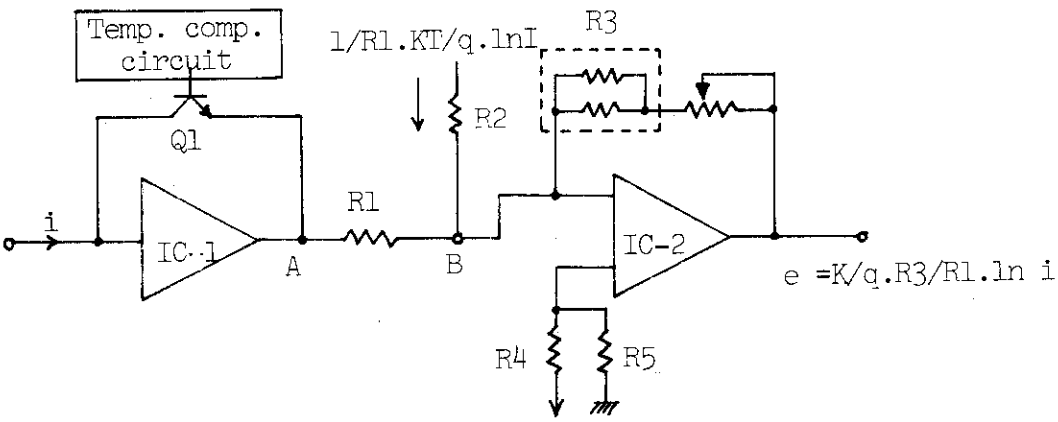


Fig. 8 The Log-N Amplifier.

IC-1 is a special hybrid integrated circuit (K302) with high input impedance and is enclosed in a specially designed sealed box, containing silica gel. Silica gel maintains a constant humidity in the box, so as to make the characteristics of IC-1 independent of any humidity variations. The feedback line of IC-1 has a transistor Q1. The base of Q1 is coupled to a temperature compensation network (temperature compensation amplifier with gain=1) consisting of five transistors, in Darlington coupling, which maintain a constant base bias and maintains the conduction of Q1 independent of any temperature variation inside the sealed box. The output stage consists of IC-2, which is an inverting amplifier with a thermistor R3 in the feedback line. The thermistor R3 is enclosed in the sealed box, along with IC-1. so as to automatically regulate the IC-2 output in case of any temperature variation in the sealed box.

As the transistor Q1 is connected between the feedback line of IC-1, the emitter to base voltage of Q1 (Veb) is directly proportional to the output of IC-1. The current flowing through a transistor is a function of temperature, and for currents less than 10^{-11}ampere, it is determined by the following equation,

$$i = I_o \text{ (exp. } qVeb/KT-1)$$

Where I_o= current at absolute temperature
q = electron charge
K = Boltzmann's constant
T = operating temperature
and Veb = emitter to base voltage

For current values higher than 10^{-11}ampere, the above equation simplifies to,

$$i = I_o \text{ exp. } qVeb/KT$$

Simplifying this equation, we get,

$$i/I_o = \text{exp. } qVeb/KT$$

or $$\ln i - \ln I_o = \frac{q \cdot Veb}{K \cdot T}$$

or $$Veb = \frac{K \cdot T}{q} (\ln i - \ln I_o) \tag{1}$$

As this voltage is proportional to IC-1 output, it appears at point 'A' in Fig. 8. To cancel the effect of the term $- \frac{K \cdot T}{q} \cdot \ln I_o$, a positive bias voltage (equal to $\frac{K \cdot T}{q} \cdot \ln I_o$) is applied at point 'B' through the resistance R2. The input voltage signal for the second stage (i.e. IC-2) is therefore equal to,

$$e_i = \frac{K \cdot T}{q} \ln i \tag{2}$$

IC-2 is an inverting amplifier, with thermistor R3 in the feed-back circuit. As the resistance of R3 is directly proportional to the temperature, the effective feedback resistance of IC-2 can be represented by R3/T, where T is the operating temperature. The IC-2 output signal is therefore equal to

$$e_o = e_i \cdot \frac{R3/T}{R1} \tag{3}$$

substituting the value of e_i from equation-(2), in equation-(3) we get,

$$e_o = \frac{K \cdot R3}{q \cdot R1} \ln i \tag{4}$$

where $\frac{K}{q}$ = a constant

and $\frac{R3}{R1}$ = circuit constant

and i = the current through transistor Q1
= the current from the CIC.

The output voltage of IC-2 is therefore proportional to the logarithm of the CIC output current, which is the basic design criterion of the Log-N and Period channel.

Fig. 9 shows the characteristics of the Log-N amplifier on a semi-log scale.

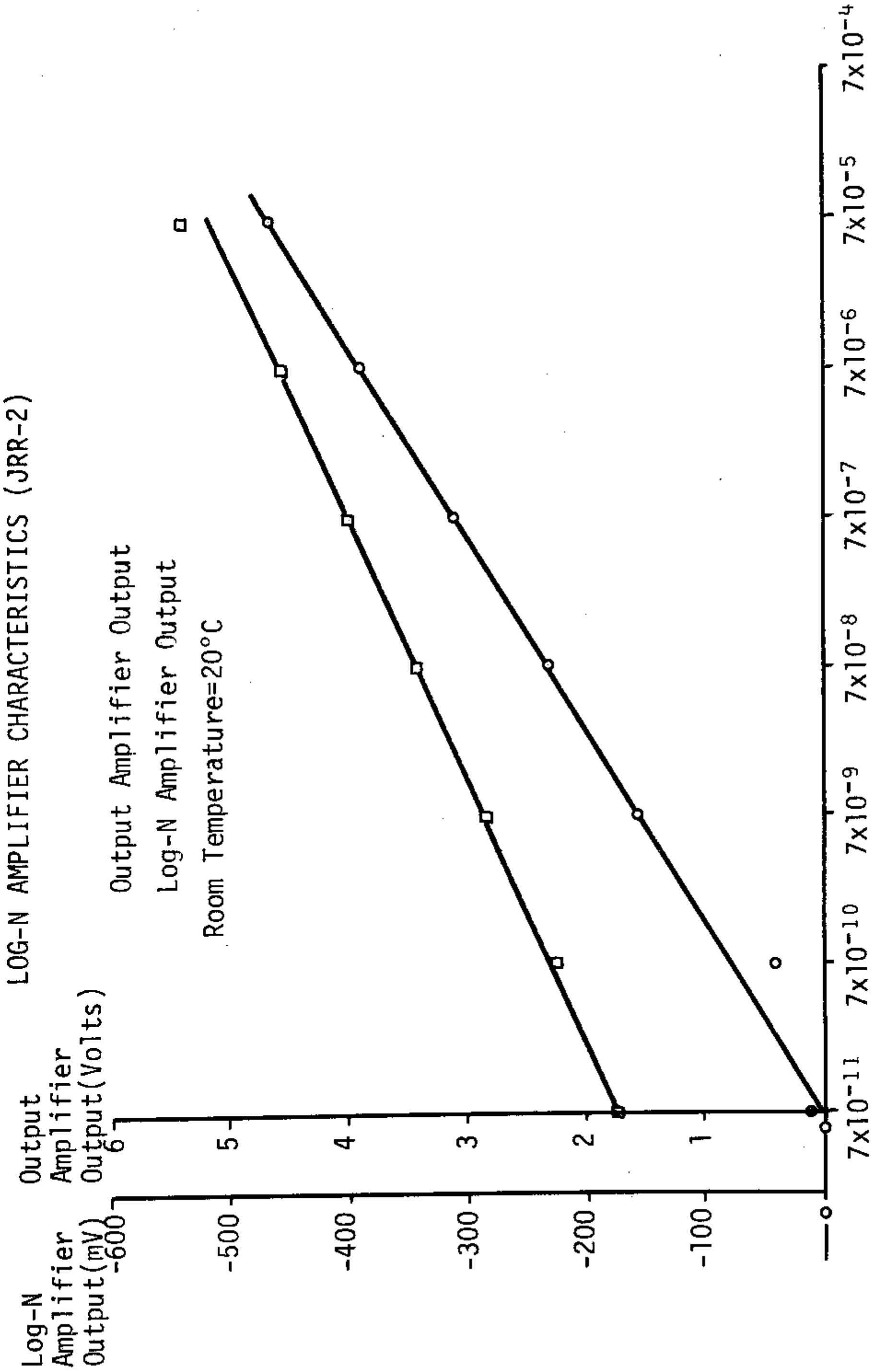


Fig. 9 Log-N amplifier characteristics

4.2.2 PERIOD AMPLIFIER

The Period amplifier differentiates the constantly rising signal from the Log-N amplifier and provides a constant d.c. signal in the output, which is the measure of the reactor period. It consists of two stages, namely the differentiating stage and the output buffer stage. Fig. 10 shows the Period amplifier. IC-3 is a hybrid integrated circuit (K302), which receives the Log-N amplifier output. It is basically a differentiating amplifier with a series capacitor C1 and a feedback resistance R6. In order to eleminate the fluctuations of the output signal, a balancing integral action is also provided by the use of a series resistor R5 and a feedback capacitor C2. As the reactor power rises at a constant rate, the input signal to IC-3 (from the Log-N amplifier) will be a constantly rising d.c. As IC-3 is an inverting differential amplifier, the output is a constant d.c. voltage signal with negative polarity, which appears at point 'A' in Fig. 10. As the rate of rise of power changes, the output of IC-3 will only vary in

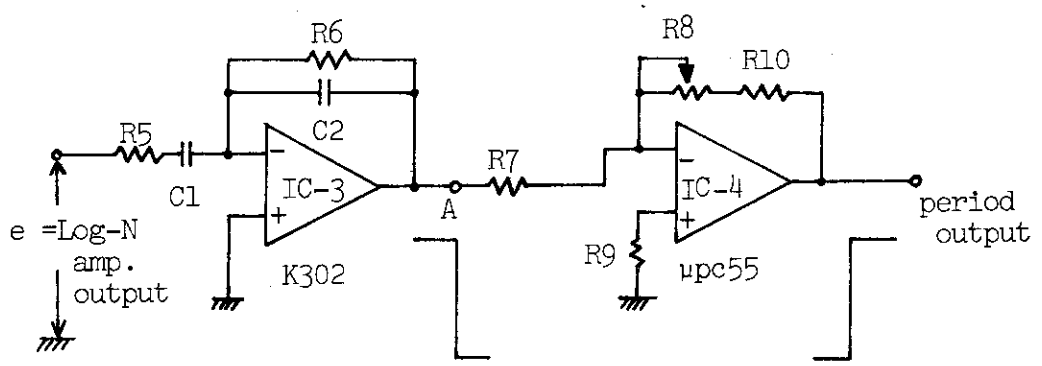


Fig. 10 The period amplifier.

amplitude. The output of IC-3 is fed to the output stage buffer amplifier IC-4, which has a gain of unity. As IC-4 is also an inverting amplifier, its output will be a d.c. voltage signal, and its amplitude represents the rate of rise of reactor power and is expressed as the reactor period in seconds.

The gain adjustment of the Period amplifier is provided by the variable resistance R8, in the feedback line of the output buffer amplifier IC-4. Fig. 11 shows the Period amplifier characteristics.

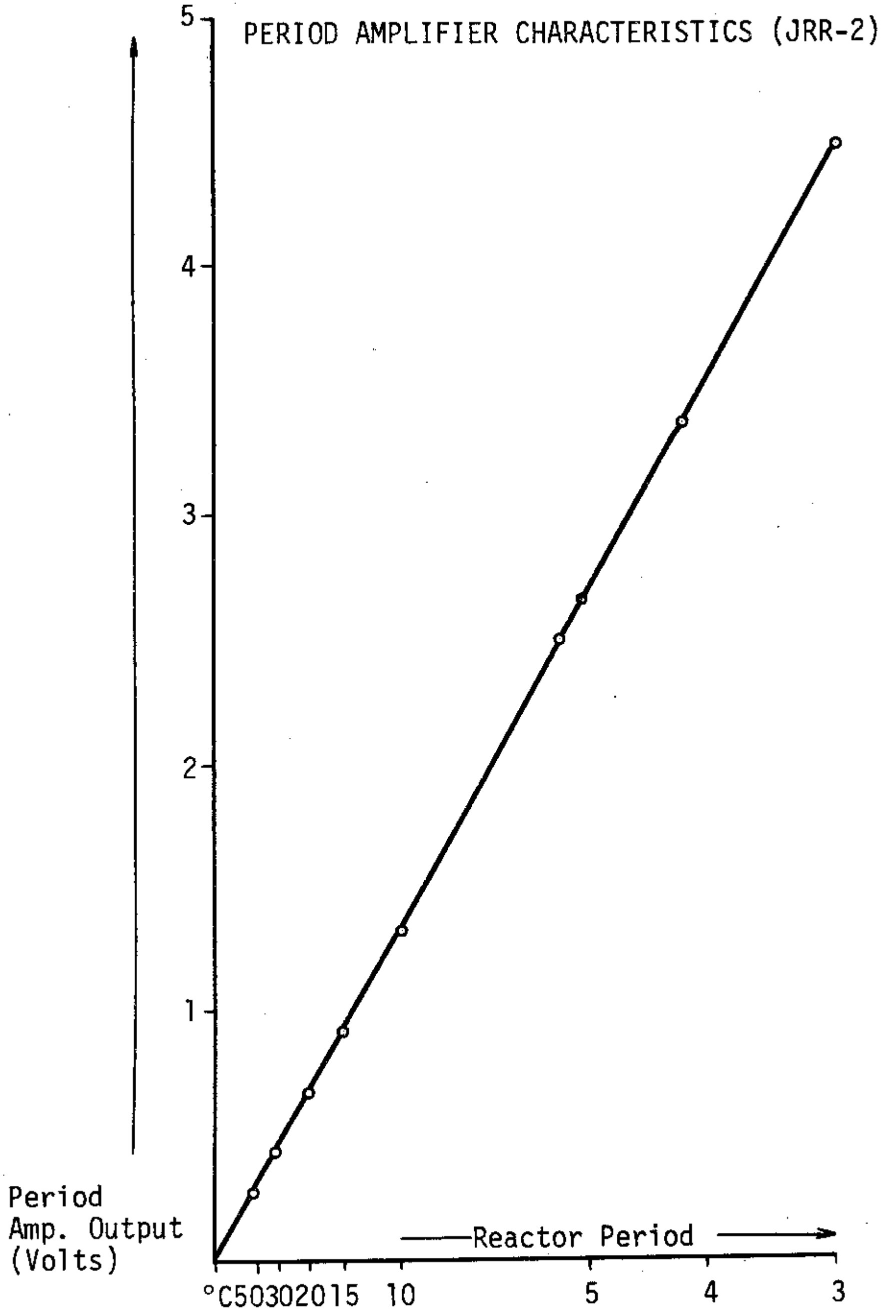


Fig. 11 Period amplifier characteristics

4.2.3 THE TRIP UNIT

The Log-N and Period Trip Unit initiates the necessary safety actions, if the reactor period tends to approach undesirable levels, and thus keeps the rate of rise of reactor power within safe limits. It provides inhibition, reverse and scram at the reactor period of 30 seconds, 10 seconds and 3 seconds respectively. The design of the Trip Unit also incorporates a fail-safe scram network, which initiates a fast scram accompanied by a back-up scram, if the circuit preceeding the Trip Unit, i.e. the Log-N and Period Amplifier fails and a negative signal appears at the input of this unit.

Drawing No. CP-MOD-07 shows the Log-N and Period Trip Unit circuit. It consists of six comparator ICs and thirteen switching transistors. Under normal operating conditions, a constant d.c. signal of + 2 volts appear at the output of the Trip Unit, at point 'A', which is fed to the next stage Rod Magnet Amplifier. The safety actions of the Trip Unit are described as follows.

INHIBITION:

The inhibition of the control rods takes palce if the reactor period reaches a value of 30 seconds. The inhibition circuit consists of IC-4, transistor Q11 and relay RY-3. In this case a signal of +0.44 volt appear at the input of the Trip Unit. As this signal appears at the inverting input of IC-4, it overides the constant positive bias at the non-inverting input and the output of IC-4 changes from +3.16 volts to -0.58 volt. This change of the IC-4 output switches off the transistor Q11, thus the relay RY-3 is de-energised, which causes the inhibition of the control rods. As Q11 is switched off, a positive bias appears at the base of Q12, which is switched on, and in turn switches on Q13. With the switching on of Q13, the lamp L3 is switched on, which provides a visual indication to the reactor operator.

REVERSE:

The reversal of the control rods takes place if the reactor period reaches a value of 10 seconds. The reverse circuit consists of IC-3, transistors Q8, Q9 & Q10 and relay RY-2. In this case a signal of +1.33 volts appear at the input of the Trip Unit. As this signal appears at the inverting input of IC-3, it overides the constant positive bias at the non-inverting input and thus changes the output from +3.23 volts to -0.51 volt. This change of IC-3 output siwtches off the transistor Q8 as its base voltage changes from +0.63 volt to -0.51 volt. The relay RY-2 is thus de-energised and causes the reversal of the control rods. As Q8 is switched off, transistors Q9 and Q10 are switched on, thus switching on the lamp L2, which provides a visual reverse indication to the reactor operator.

SCRAM:

The reactor scram takes place, if the value of the reactor period reaches 3 seconds. The 'FAST SCRAM' and the 'BACK-UP SCRAM' is provided by two independent networks operating in redundancy.

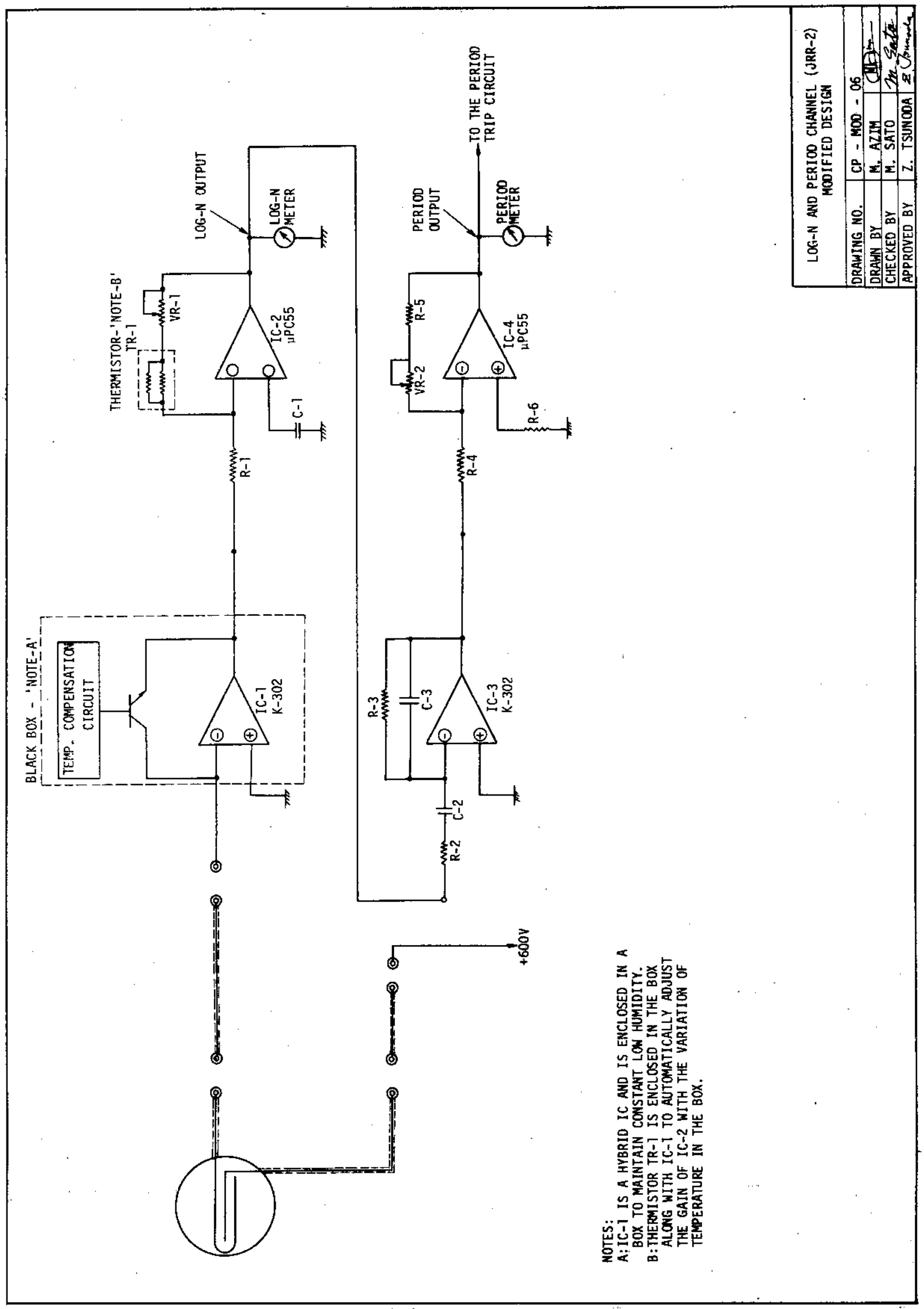
The first scram network consists of IC-2, IC-6 and transistor Q5, while the second scram network consists of IC-5 and transistor Q1.

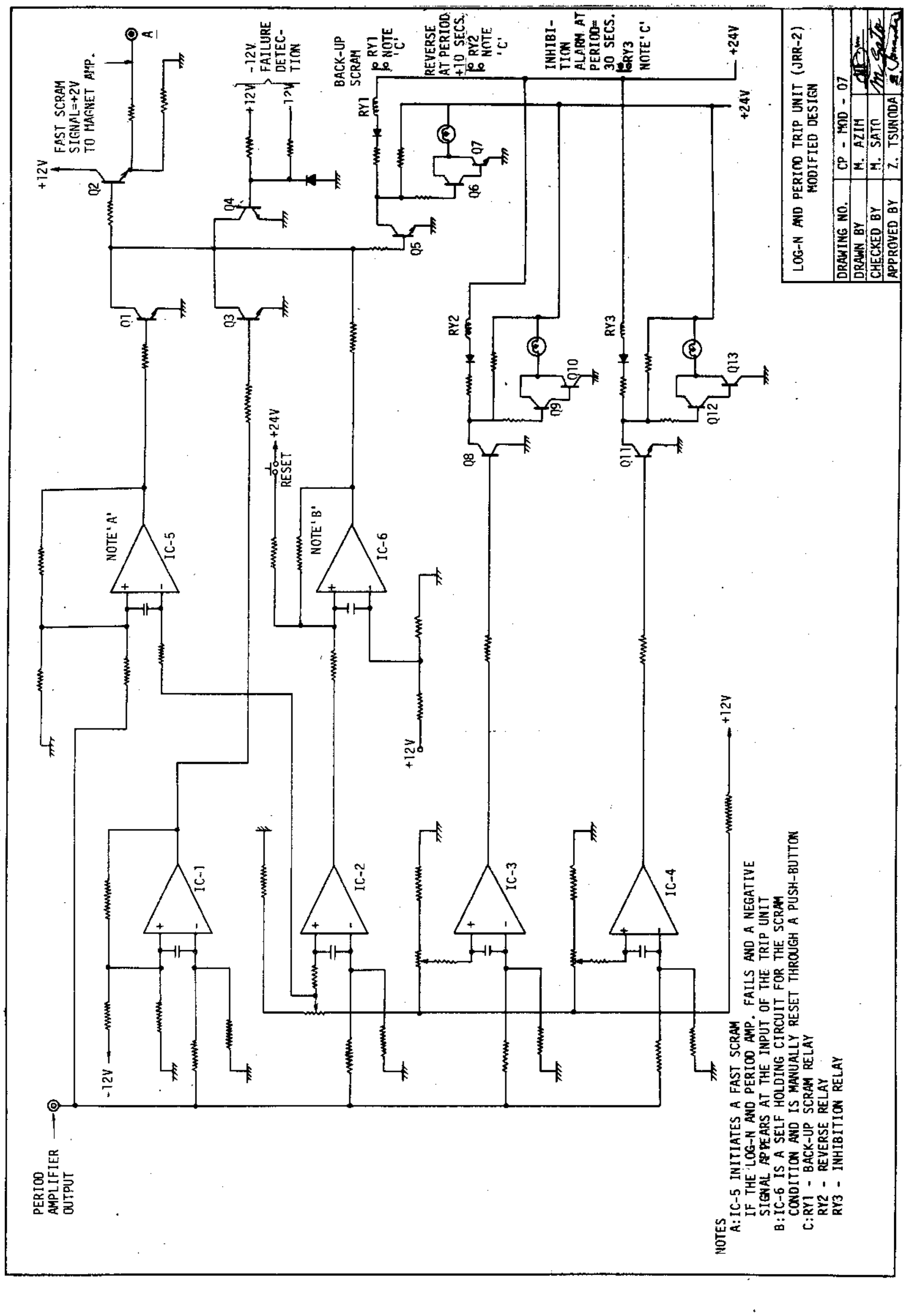
If the reactor period reaches a value of 3 seconds, a signal of +4.47 volts appear at the input of the Trip Unit. As this signal appears at the inverting input of IC-2, it overides the constant positive bias of 2 volts at the non-inverting input and thus changes the IC-2 output from +3.1 volts to -0.54 volt. As the IC-2 output is directly coupled to the non-inverting input of IC-6, the output of IC-6 changes from +3.4 volts to -0.5 volt and thus switches off the transistors Q2 and Q5. Due to the switching off of transistor Q2, the potential at the output 'A' of the Trip Unit falls from + 2 volts to zero, and thus the 'FAST SCRAM' is initiated through the Rod Manget Amplifier. With the switching off of transistor Q5, relay RY-1 is de-energised and causes a 'BACK-UP SCRAM' (as the contacts of relay RY-1 are incorporated in the back-up scram bank). The lamp L1 is also switched on as transistors Q6 and Q7 are switched on, thus providing a visual scram indication. IC-6 is a self-holding circuit and with-holds the scram condition, until it is reset through the reset switch.

As the reactor period reaches the value of 3 seconds, the output of IC-5 changes from -0.55 volt to +3.4 volts, as the trip signal input, at the non-inverting input of IC-5 overides the constant positive bias of 2 volts. This change of IC-5 output switches on the transistor Q1, which causes the base potentials of Q2 and Q5 to drop to zero, thus switching them off. The switching off of Q2 causes a 'FAST SCRAM' and the switching off of Q5 causes a 'BACK-UP SCRAM' through relay RY-1, as described earlier.

IC-1 and transistor Q3 constitute the fail-safe scram network. If a negative signal appears at the Trip Unit input, due to failure in the preceeding stage, it is applied to the inverting input of IC-1, which overides the constant negative bias of 1.16 volts at the non-inverting input, thus causing the output to change from -0.42 to +3.2 volts. This change of IC-1 output switches on the transistor Q3. The switching on of transistor Q3 causes the transistors Q2 and Q5 to be switched off, which results in a 'FAST SCRAM' and a 'BACK-UP SCRAM' as before.

Transistor Q4 is for the detection of -12 V power supply failure. If -12 V power supply fails, a positive bias will be applied to the base of Q4, which will then be switched on. The switching on of Q4 will switch off the transistors Q2 and Q5, as their base potentials will drop to zero, thus a 'FAST SCRAM, and a 'BACK-UP SCRAM' will be initiated as before.


LOG-N AND PERIOD CHANNEL (JRR-2)
MODIFIED DESIGN
DRAWING NO. CP - MOD - 06
DRAWN BY M. AZIM
CHECKED BY M. SATO
APPROVED BY Z. TSUNODA
TO THE PERIOD TRIP CIRCUIT
LOG-N OUTPUT
LOG-N METER
PERIOD OUTPUT
PERIOD METER
THERMISTOR-'NOTE-B'
TR-1
VR-1
IC-2
μPC55
C-1
R-1
R-5
VR-2
IC-4
μPC55
R-6
R-4
BLACK BOX - 'NOTE-A'
TEMP. COMPENSATION CIRCUIT
IC-1
K-302
R-3
C-3
IC-3
K-302
C-2
R-2
+600V
NOTES:
A:IC-1 IS A HYBRID IC AND IS ENCLOSED IN A BOX TO MAINTAIN CONSTANT LOW HUMIDITY.
B:THERMISTOR TR-1 IS ENCLOSED IN THE BOX ALONG WITH IC-1 TO AUTOMATICALLY ADJUST THE GAIN OF IC-2 WITH THE VARIATION OF TEMPERATURE IN THE BOX.


LOG-N AND PERIOD TRIP UNIT (JRR-2)
MODIFIED DESIGN
DRAWING NO. CP - MOD - 07
DRAWN BY M. AZIM
CHECKED BY M. SATO
APPROVED BY Z. TSUNODA
FAST SCRAM SIGNAL=+2V TO MAGNET AMP.
-12V FAILURE DETECTION
BACK-UP SCRAM
REVERSE AT PERIOD +10 SECS.
INHIBITION ALARM AT PERIOD= 30 SECS.
PERIOD AMPLIFIER OUTPUT
RESET
NOTE 'A'
NOTE 'B'
NOTE 'C'
NOTES
A:IC-5 INITIATES A FAST SCRAM IF THE LOG-N AND PERIOD AMP. FAILS AND A NEGATIVE SIGNAL APPEARS AT THE INPUT OF THE TRIP UNIT
B:IC-6 IS A SELF HOLDING CIRCUIT FOR THE SCRAM CONDITION AND IS MANUALLY RESET THROUGH A PUSH-BUTTON
C:RY1 - BACK-UP SCRAM RELAY
RY2 - REVERSE RELAY
RY3 - INHIBITION RELAY

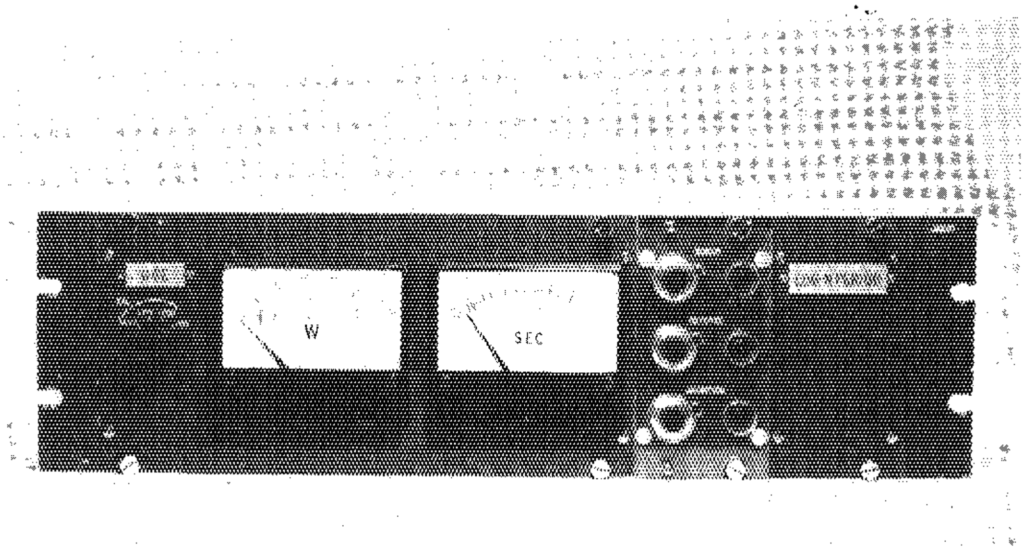


Photo 6. Log-N and period module
(Front view)

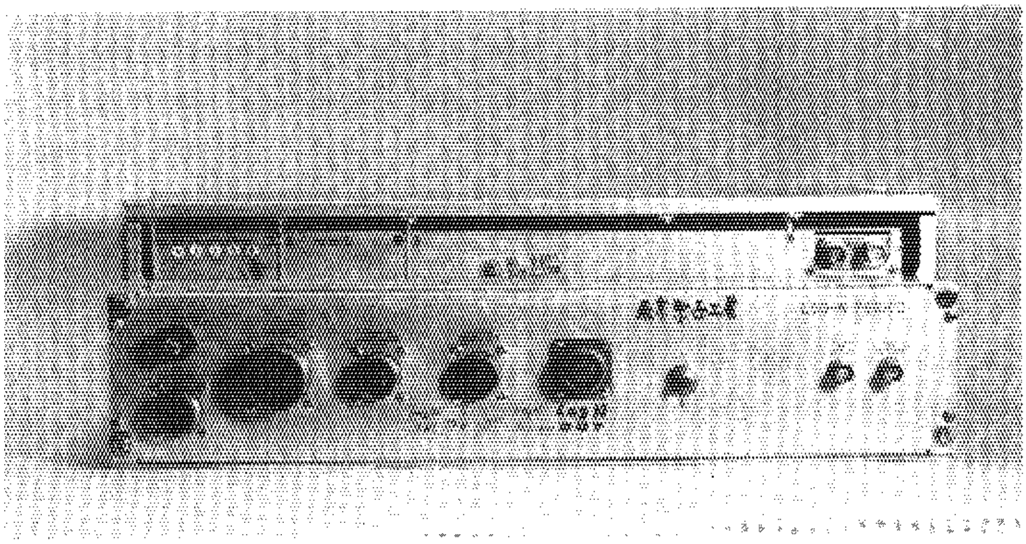


Photo 7. Log-N and period module
(Rear view)

4.3 THE SAFETY CHANNELS

JRR-2 has two independent and identical safety channels to provide redundancy of the safety circuits. Each safety channel measures and displays the reactor power from 0% to 120% (0 to 12 MW) on a single-linear scale. The safety channels are designed to provide a reactor reverse at 105% of full power (10.5 MW) and a reactor scram at 110% of full power (11.0 MW). Drawing No. CP-MOD-08 shows the safety channels.

Each safety channel consists of the following main components.

1. High Voltage Power Supply.
2. Uncompensated Ionization Chamber.
3. Safety Amplifier.
4. The Trip Unit.

4.3.1 HIGH VOLTAGE POWER SUPPLY

The high voltage power supply, supplies stabilized +300 volts D.C. to the uncompensated ionization chamber (UIC). It incorporates a comparator circuit in the output, which constantly compares the supply voltage with a fixed reference voltage, and actuates a scram relay if the voltage falls beyond 10% (270V), thus causing a low UIC voltage slow scram.

4.3.2 UNCOMPENSATED IONIZATION CHAMBER

The uncompensated ionization chamber is designed to detect thermal neutrons in the flux range from 2.5×10^{2} to 2.5×10^{10}n/cm^2-sec. It has a neutron sensitivity of 2.3×10^{-14}ampere/n/cm^2-sec. and a gamma sensitivity of 6.4×10^{-12}ampere/R/hr. For the power range from 0 to 10 MW it generates a current signal of zero to 45 μamperes.

4.3.3 SAFETY AMPLIFIER

The safety amplifier consists of two stages, as shown in Fig. 12.

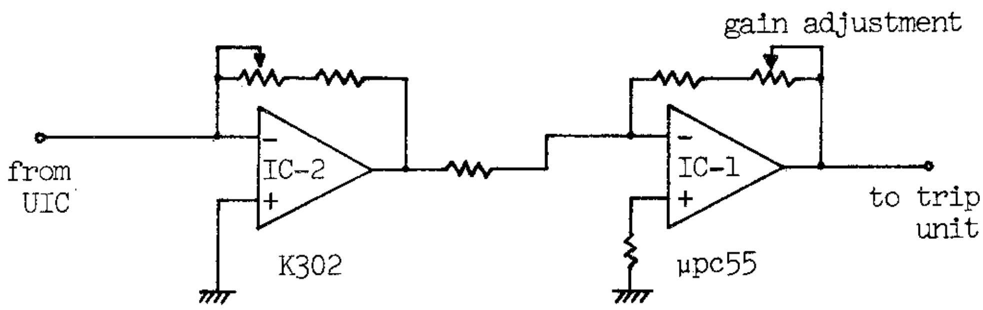


Fig. 12 The safety amplifier.

The first stage consists of IC-2, which receives UIC current signal. It is a special hybrid IC (K302) with high input impedance to maintain linearity of the output signal. It is enclosed in a specially designed sealed box, containing silica-gel. The silica-gel maintains constant humidity in the box and thus keeps the characeristics of IC-2 independent of any humidity variations. As the UIC current is fed to the inverting input of IC-2, the output is a voltage signal with negative polarity.

The output of IC-2 is fed to the second stage which consists of IC-1. IC-1 is a sign inverting amplifier, having a gain of 4. Over the full range of operation from 0 to 10 MW, it supplies a positive linear voltage signal of 0 to 4 volts, which is the output of the Safety Amplifier. Fig. 13 shows the safety amplifier characteristics.

4.3.4 THE TRIP UNIT

The safety channel trip unit initiates the necessary safety actions, if the reactor power tends to approach undesirable levels and thus keeps the power level within safe limits. It provides a reactor reverse and a reactor scram at power levels of 10.5 MW (105% of full power) and 11.0 MW (110% of full power) respectively. The design of the trip unit also incorporates a fail-safe scram network, which initiates a "FAST SCRAM"accompanied by a "BACK-UP SCRAM" if the circuit preceeding the trip unit, i.e. the Safety Amplifier fails and a negative signal appears at the input of this unit.

The design of the safety channel Trip Unit is identical to the design of the Log-N and period channel Trip Unit, with the exception that

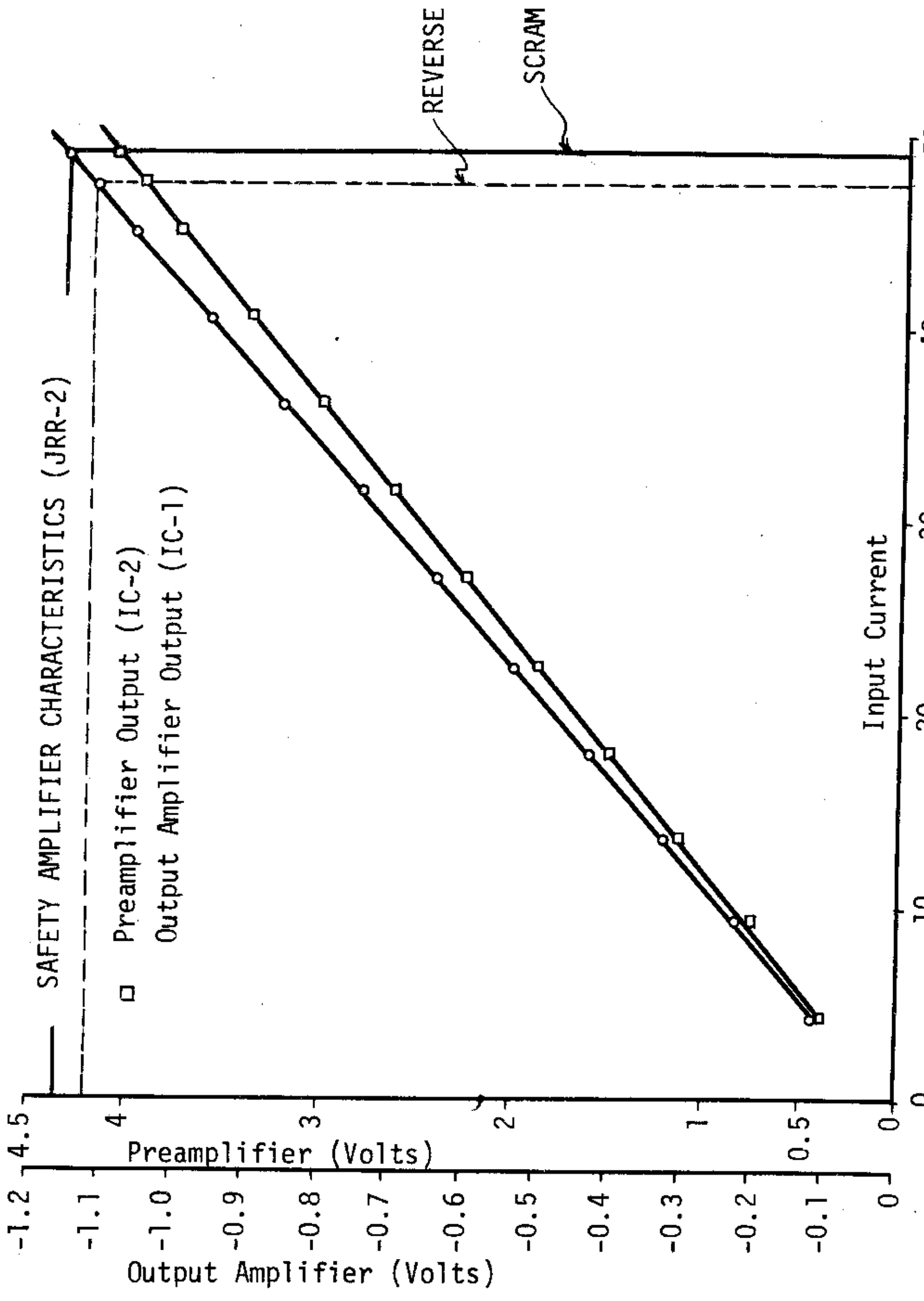


Fig. 13 Safety amplifier characteristics

the inhibition circuit is not used in the case of the safety channel.

Under normal operating conditions, a constant d.c. signal of +2 V appear at the output of the Trip Unit at point 'A', which is fed to the next stage Rod Magnet Amplifier. The safety actions of the Trip Unit are described as follows.

REVERSE:

The reversal of the control rods is initated by the trip unit if the reactor power reaches a level of 10.5 MW (105%). The reverse circuit consists of IC-8, transistors Q8, Q9, Q10 and relay RY-5 (Drawing No. CP-MOD-08). When the reactor power reaches a value of 10.5 MW, the output of the Safety Amplifier is +4.20 volts, which appear at the input terminal of the Trip Unit. When this signal appears at the inverting input of IC-8, it overides the constant positive bias of 1.93 volts at the inverting input and thus causes its output to change from +2.73 volts to -0.33 volt. This change of IC-8 output switches off the transistor Q8, as its base is directly coupled to the IC-8 output. The switching off of Q8 de-energises the relay RY-5 which initiates a reactor reverse (as the contacts of RY-5 are in the reverse bank). With the switching off of Q8 a positive bias appears at the base of Q9 which is switched on and in turn switches on Q10. With the switching on of Q10, the lamp L2 is switched on, thus providing a visual reverse indication.

SCRAM:

The reactor scram takes place if the reactor power reaches a level of 11 MW (110%). The scram signals (FAST SCRAM and BACK-UP SCRAM) are provided by two independent networks operating in redundancy. The first scram network consists of IC-7, IC-10, transistor Q5 and relay RY-4. The second scram network consists of IC-6 and transistor Q1.

If the reactor power reaches 11 MW a signal of +4.4 volts appear at the input of the Trip Unit. As this signal appears at the inverting input of IC-7, it overides a constant positive bias of 2 volts at the non-inverting input and causes the output to change from +2.8 volts to +0.68 volts. As the output of IC-7 is directly coupled to the non-inverting input of IC-10, the output of IC-10 changes from +3.22 volts to -0.38 volt and switches off transistors Q2 and Q5. With the switching off of Q2 a fast scram signal is transmitted to the Rod Magnet Amplifier (in the next stage) as the voltage at the output of the Trip Unit, at point 'A', drops from +2 volts to zero. With the switching off of transistor Q5, the relay RY-4 is de-energised and thus causes a BACK-UP SCRAM (as RY-4 has contacts in the back-up scram bank). With the switching off of Q5, transistors Q6 and Q7 are switched on, which switches on the lamp L3 and thus provide a visual scram indication. IC-10 is a self-holding circuit and witholds the scram condition, until it is reset through a switch.

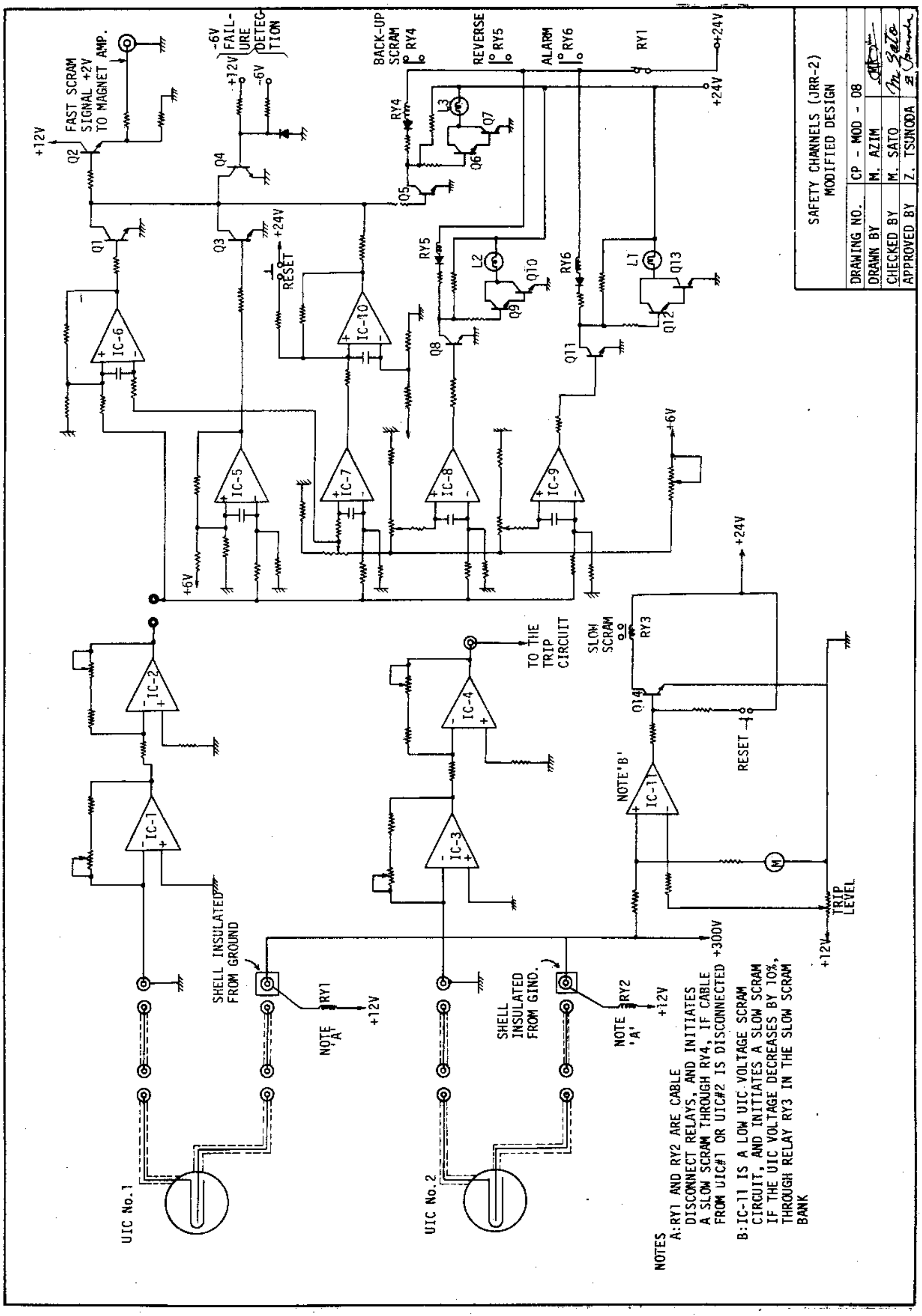
IC-6 and transistor Q1 constitute the other redundant scram initiating network. As the reactor power level reaches 11 MW, the trip unit input is applied to the non-inverting input of IC-6, which overides the constant positive bias of 2 volts at the inverting input and causes the output to change from -0.41 to +2.63 volts. The change of IC-6 output switches on the transistor Q1. With the switching on of Q1, transistors Q2 and Q5 are switched off as their base bias potentials fall from some positive values to zero. The switching off of Q2 and Q5 initiate a FAST SCRAM and a BACK-UP SCRAM respectively, as described before.

IC-5 and transistor Q3 constitute the fail-safe scram network. If the circuit preceeding the trip unit (The Safety Amplifier) fails, and a negative signal appears at the input of the Trip Unit, it is applied to the non-inverting input of IC-5. When this signal reaches a value of -1.5 volts, it overides the constant negative bias of 1.85 volts at the non-inverting input, and thus causes the output of IC-5 to change from -0.44 V to +0.72 V. This change of IC-5 output switches on the transistor Q3. Due to the switching on of Q3, the transistors Q2 and Q5 are switched off, thus causing a FAST SCRAM and a BACK-UP SCRAM, as before.

Transistor Q4 is for the detection of -12 V power supply failure. If the -12V power supply fails, a positive bias is applied to the base of Q4, which is switched on. The switching on of Q4 switches off transistors Q2 and Q5, thus causing a FAST SCRAM and a BACK-UP SCRAM respectively, as before.

The protection against cable disconnection of the safety channels is provided by the relays RY-1 and RY-2. If safety channel # 1 main signal cable is disconnected from the Safety Amplifier, relay RY-1 is de-energised, which de-energises relay RY-4 in the Trip Unit, thus causing a BACK-UP SCRAM of the reactor. Similarly if the cable of the main signal from UIC # 2 is disconnected from Safety Amplifier # 2, the relay RY-2 will be de-energised and will cause the relay RY-4 to de-energise (in the Trip Unit # 2) thus causing a BACK-UP SCRAM.

Protection against CIC low power supply voltage is provided by IC-11, transistor Q14 and relay RY-14. If the main CIC power supply voltage decreases beyond a pre-determined level, the constant positive bias at the inverting input overides the signal at the non-inverting input and causes the output to change from some positive potential to a negative potential. The change of IC-11 output switches off the transistor Q14, which de-energises the relay RY-3, and a SLOW SCRAM is initiated (as relay RY-3 has contacts in the slow scram bank).


SAFETY CHANNELS (JRR-2)
MODIFIED DESIGN
DRAWING NO. CP - MOD - 08
DRAWN BY M. AZIM
CHECKED BY M. SATO
APPROVED BY Z. TSUNODA
FAST SCRAM SIGNAL +2V TO MAGNET AMP.
-6V FAIL-URE DETEC-TION
BACK-UP SCRAM RY4
REVERSE RY5
ALARM RY6
RY1
+24V
+12V
-6V
RESET
SLOW SCRAM RY3
TO THE TRIP CIRCUIT
NOTE 'B'
TRIP LEVEL
+300V
SHELL INSULATED FROM GROUND
SHELL INSULATED FROM GND.
NOTE 'A'
UIC No.1
UIC No.2
NOTES
A:RY1 AND RY2 ARE CABLE DISCONNECT RELAYS, AND INITIATES A SLOW SCRAM THROUGH RY4, IF CABLE FROM UIC#1 OR UIC#2 IS DISCONNECTED
B:IC-11 IS A LOW UIC VOLTAGE SCRAM CIRCUIT, AND INITIATES A SLOW SCRAM IF THE UIC VOLTAGE DECREASES BY 10%, THROUGH RELAY RY3 IN THE SLOW SCRAM BANK

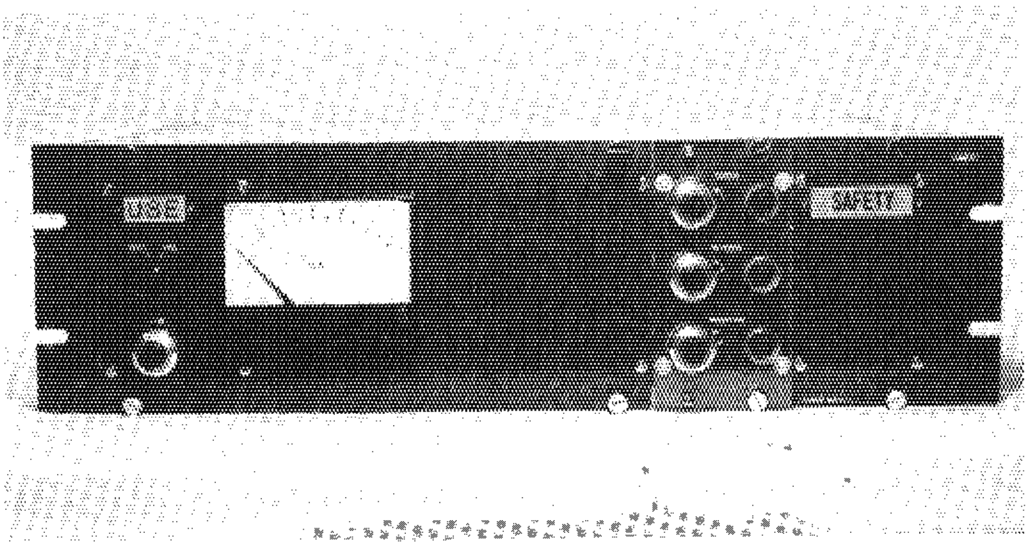


Photo 8. Safety channel module
(Front view)

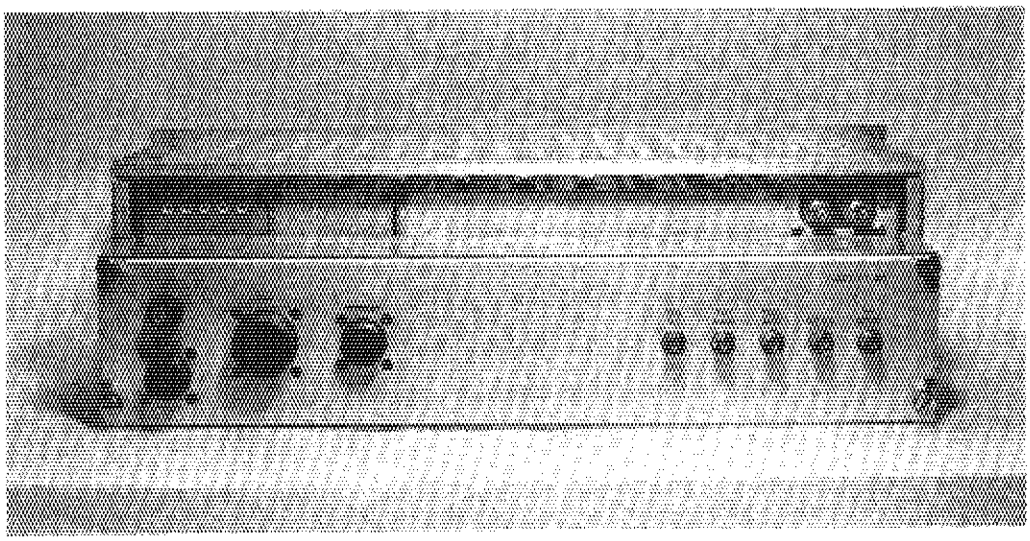


Photo 9. Safety channel module
(Rear view)

4.4 THE ROD MAGNET AMPLIFIER

The Rod Magnet Amplifier supplies the holding current to the six magnet coils of the control rods through the power transistors. It effectively interrupts the magnet current by switching off the power transistors and thus provides a 'FAST SCRAM', if it receives a signal from any of the Trip Units, which are directly coupled to this unit.

Drawing No. CP-MOD-09 shows the Rod Magnet Amplifier circuit. For simplicity, circuit for only one magnet coil has been shown. From the input to the transistor Q6, the circuit is common for all the six control rod magnets. Beyond the output of transistor Q6, the circuit divides into six independent channels, each supplying the current to the respective magnet coils through the switching power transistors TR-1 to TR-6.

The Rod Magnet Amplifier has four signal inputs at A, B, C and D. Input A is coupled to the trip unit output of Safety channel # 1, input B is coupled to the trip unit output of Safety channel # 2 and input C is coupled to the trip unit output of the Log-N and Period channel. Input D allows the provision for any additional safety channel, if to be incorporated in the safety system in future. As the input D is not presently in use, it is short circuited with the input at C, through a jumper.

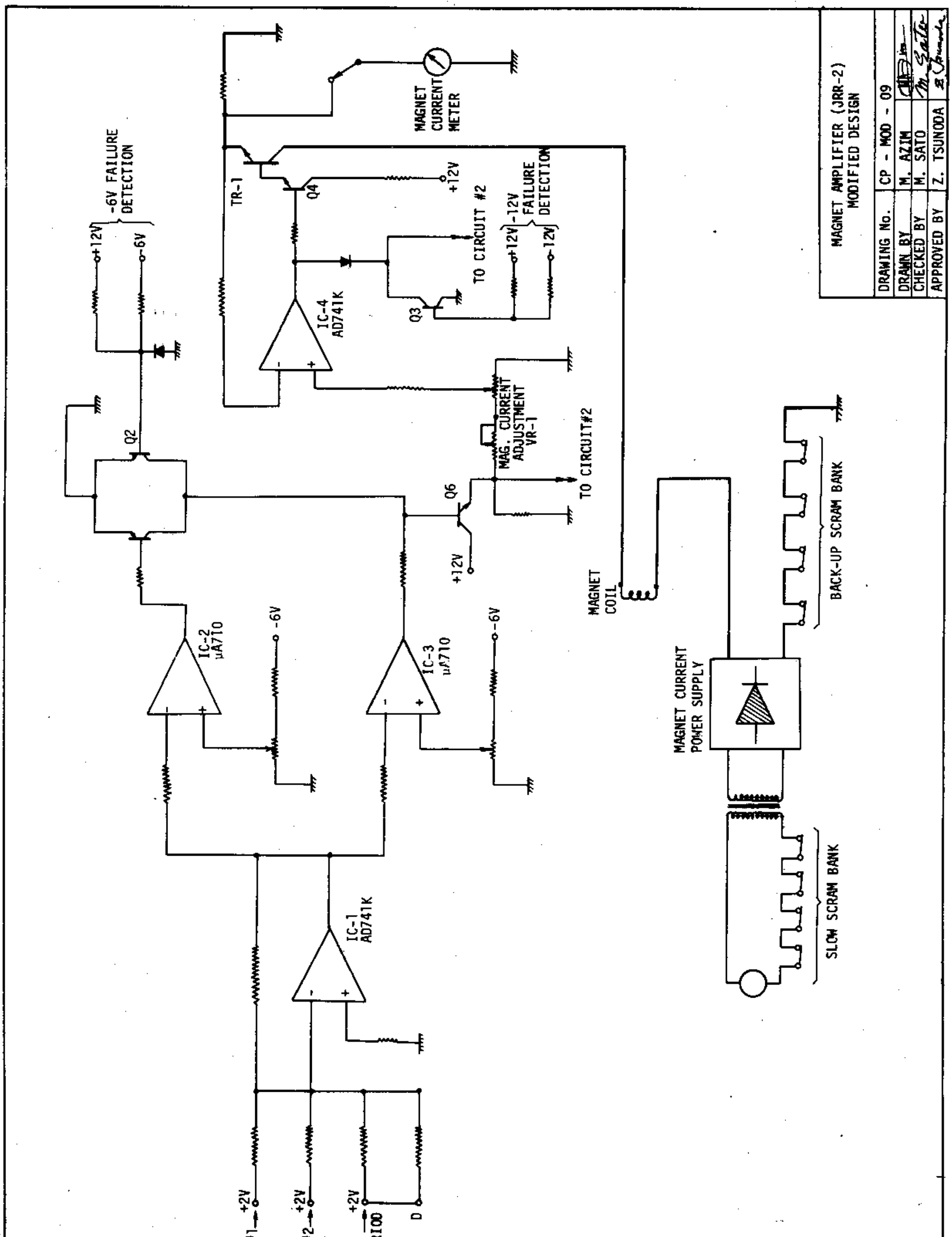
Under normal operating conditions, the voltage at all the input of the Rod Magnet Amplifier is +2 volts and the power transistor TR-1 is in on position, thus supplying magnet current to the coil.

In the event of a 'FAST SCRAM', the voltage signal at any one of the inputs falls from +2 volts to zero. This causes the output of IC-1 to change from -4 volts to -3 volts. Due to this change of IC-1 output, the output of IC-3 changes from +3 volts to -0.2 volt, as the constant negative bias at the non-inverting input overides the signal at the inverting input. As the IC-3 output changes from +3 volts to -0.2 volt, the transistor Q6 is switched off, which causes the IC-4 output to change from +10.8 volts to -2.1 volts. Due to this change of IC-4 output, the transistor Q4 is switched off, which switches off the power transistor TR-1. With the switching off of power transistor TR-1, the magnet coil current is interrupted, thus causing a 'FAST SCRAM'.

IC-2 and Q1 provide redundancy to IC-1. In the event of IC-1 failure, the output of IC-2 changes from -0.5 volt to +3.0 volts, which switches on transistor Q1. With the switching on of transistor Q1, the base potential of transistor Q6 falls from +2.33 volts to zero, and it is therefore switched off. The switching off of Q6 provides a 'FAST SCRAM' as transistors Q4 and TR-1 are also switched off through IC-4.

Transistor Q2 is for providing a reactor scram in the case of -6 V power supply failure, while transistor Q3 provides a reactor scram in the case of -12 V power supply failure. The failure of -6 V power supply switches on transistor Q2, which switches off transistor Q6 thus initiating a 'FAST SCRAM'. In the case of -12 V power supply failure, transistor Q3 is switched on, which switches off the transistor Q4 as its base potential falls from +0.57 volt to zero. The switching off of Q4 also switches off TR-1, thus providing a 'FAST SCRAM'.

The magnet current adjustment is provided by a variable resistance VR-1, which adjusts the base bias of TR-1 through Q4 and IC-4.


MAGNET AMPLIFIER (JRR-2)
MODIFIED DESIGN
DRAWING No. CP - MOD - 09
DRAWN BY M. AZIM
CHECKED BY M. SATO
APPROVED BY Z. TSUNODA
MAGNET CURRENT METER
TR-1
Q4
+12V
TO CIRCUIT #2
-12V FAILURE DETECTION
-6V FAILURE DETECTION
+12V
-6V
-12V
IC-4 AD741K
Q3
MAG. CURRENT ADJUSTMENT VR-1
TO CIRCUIT#2
Q6
Q2
IC-2 μA710
IC-3 μA710
-6V
IC-1 AD741K
MAGNET COIL
MAGNET CURRENT POWER SUPPLY
BACK-UP SCRAM BANK
SLOW SCRAM BANK
A SAFETY#1
B SAFETY#2
C LOG-N AND PERIOD
D
+2V
FAST SCRAM INPUTS FROM TRIP UNITS

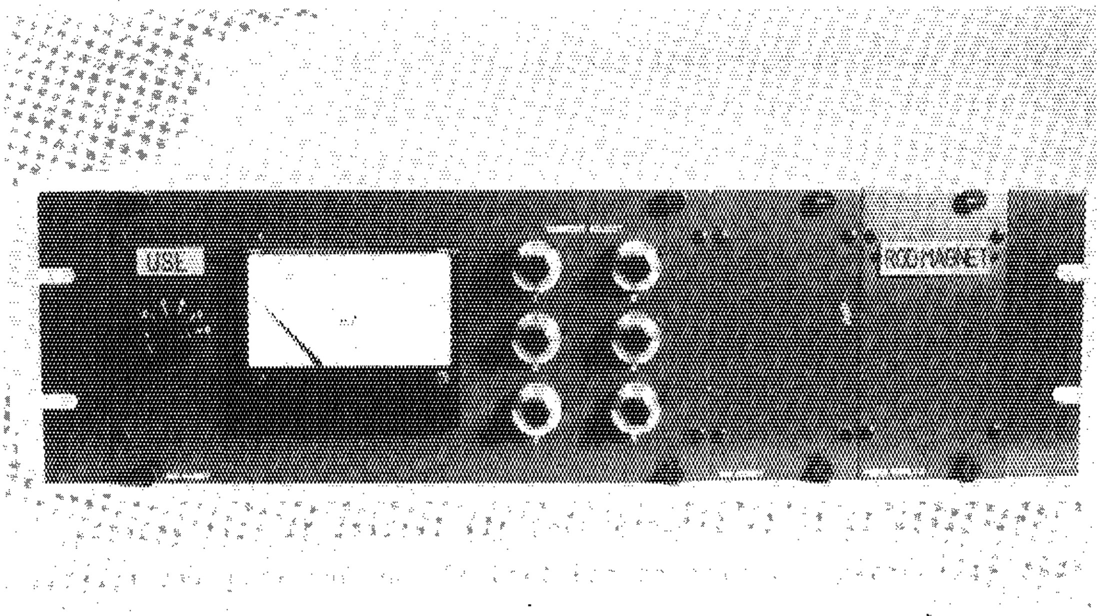


Photo 10. Rod magnet amplifier module
(Fron view)

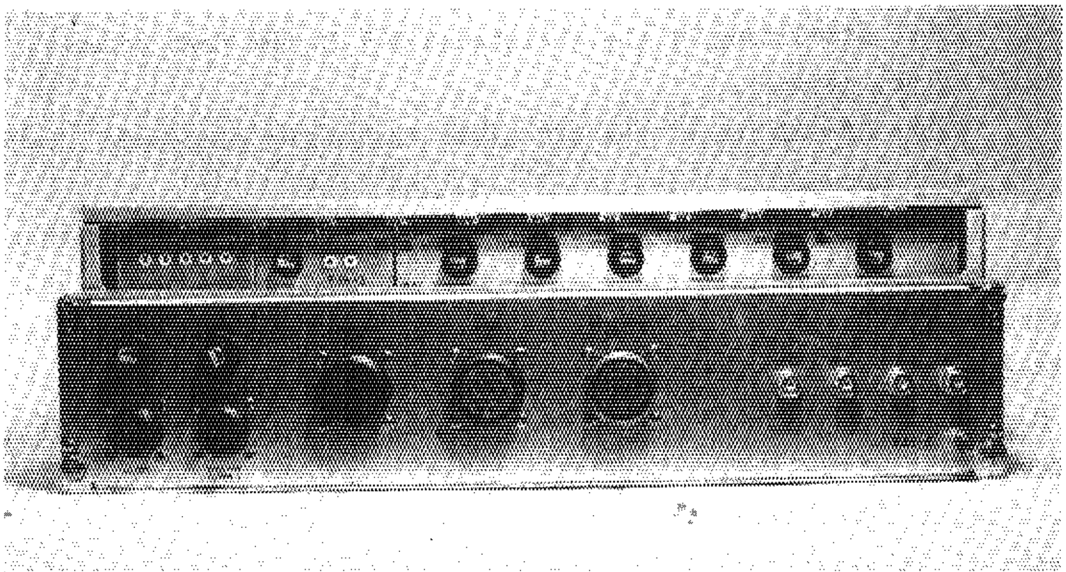


Photo 11. Rod magnet amplifier module
(Rear view)

5. A COMPARATIVE SAFETY ANALYSIS

Safety Analysis have been carried out for the original A.M.F. design and the modified design Nuclear Instrumentation Systems of JRR-2, by considering all forseeable failures in the safety networks and possible operator errors, and then observing the necessary safety action initiated to safely shut down the reactor.

Tables 1 and 2 show the safety analysis of the original A.M.F. design and the modified design respectively.

5.1 SAFETY ASPECTS OF THE ORIGINAL A.M.F. DESIGN

From Table 1, it is observed that the Reactor is well gaurded against such common failures as the loss of ion chamber power supply, loss of power supply to instrumentation systems, and open circuit in cables or instruments.

However the A.M.F. designed safety instrumentation network has two forseeable fail-dangerous features, which are listed as follows,

1. Short circuiting of the resistance R49 in the fast scram safety network.
2. Short circuiting of the UIC cable (collector electrode line) with ground.

A close observation of the fast scram safety network reveal that the main circuit component responsible for the fast scram is the shunt resistance R49, which in the event of a fast scram signal, enters the divider network and effectively drops the potentials at the grids of the Magnet Amplifier tubes beyond the cut-off value. Due to the switching off of the Magnet Amplifier tubes, the rods are released, thus initiating a 'FAST SCRAM'. A careful examination of the chances of failure of the resistance R49 is therefore necessary. A resistance can either be short circuited (zero impedance) or open circuited (infinite impedance). In the event of open circuiting of R49 the fast scram signal will not be affected as even higher negative potential will be applied to the grids of the Magnet Amplifier tubes. Although the chances of short circuiting of a resistance are very remote, however in the event of the short circuiting of resistance R49, the fast scram signal will be rendered ineffective and will fail to travel beyond the fast scram safety network as the grid bias of the Magnet Amplifier tubes will remain unaffected. The 'BACK-UP SCRAM' will however shut down the reactor by switching off the magnet power supply through relays RY-5 to RY-8. The difference in the speed of operation between the 'FAST'SCRAM' and the slow 'BACK-UP SCRAM' is about 20 milliseconds*. This delay in the reactor scram will release variable amounts of excess energy in the reactor core, depending upon the rate of rise of reactor power, i.e. the reactor period at that particular instance.

The chances of failure of the 'FAST SCRAM' can however be considerably reduced by providing redundancy for resistance R49. This can be acheived by making a minor change in the safety network by adding a resistor RA, in series with resistance R49 as shown Fig. No. 14.

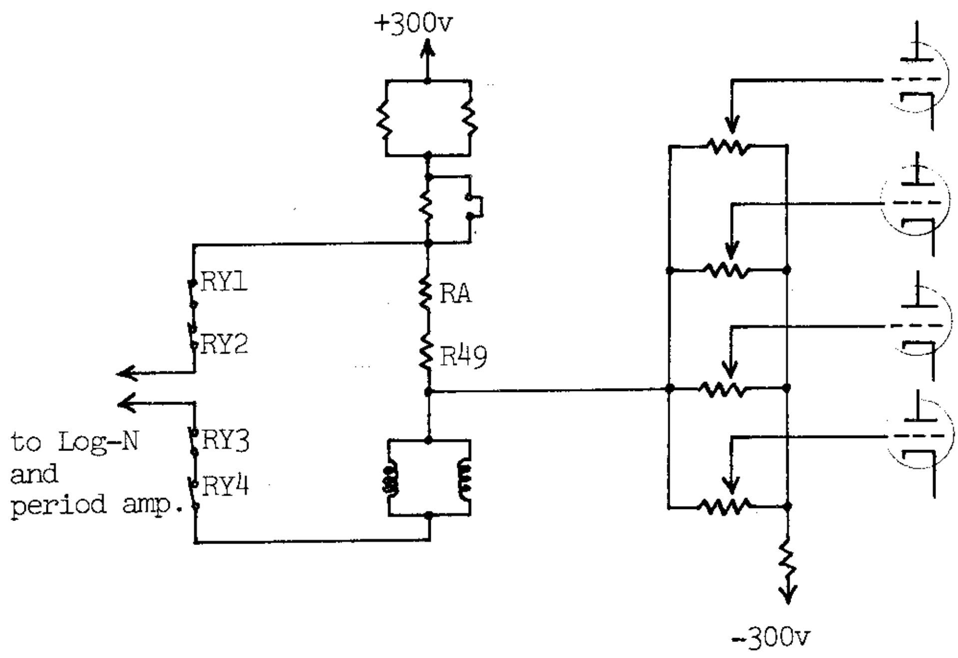


Fig. 14 Modification of the fast scram safety network.

* A.M.F. Engineering Design Manual.

In the event of the short circuiting of resistance R49, the additional series resistance will however ensure the drop of the grid potential of the Magnet Amplifier tubes beyond the cut-off value.

The other fail-dangerous feature of the original A.M.F. design is the short circuiting of the UIC cable (collector electrode line) with the ground. In the event of this fault, the respective Safety channel will be rendered out of action, without any safety action being initiated. The only visible indication to the reactor operator will be the fall of power on the respective power meter.

5.2 SAFETY ASPECTS OF THE MODIFIED DESIGN

Table 2 shows the safety analysis of the Modified Design. It is observed that the Reactor is well gaurded, against common failures, in the modified instrumentation systems of JRR-2. The new design also incorporate special fail-safe networks in the safety circuits to effectively shut down the reactor through a 'FAST SCRAM', in the event of some important instrument failures, such as the Safety Amplifiers and the Log-N and Period Amplifier and also in the event of the short circuiting of the UIC cable with ground.

The safety systems of the Modified Design, however have one fail-dangerous aspect also which have been analysed in Table 2. This fault can occur in the event of the short circuiting of transistor Q6 in the Rod Magnet Amplifier. The short circuiting of the transistor Q6 will render the fast scram signal ineffective and in the event of a power excursion or a short reactor period, the reactor will not be shut down by the fast scram signal, although the back-up scram circuit in the Trip Unit will shut down the reactor, by interrupting the magnet current through high speed relays.

The chances of failure of the 'FAST SCRAM' can be considerably reduced by providing redundancy for transistor Q6. This can be acheived by adding transistor QA in series with transistor Q6 as shown in Fig. 15. The introduction of transistor QA will ensure the drop of potential at point 'A' (during a fast scram signal) in the event of short circuiting of transistor Q6, and will thus enable the power transistors to be switched off. The chances of failure of the 'FAST SCRAM' will therefore be considerably reduced, thus resulting in more safety of the reactor.

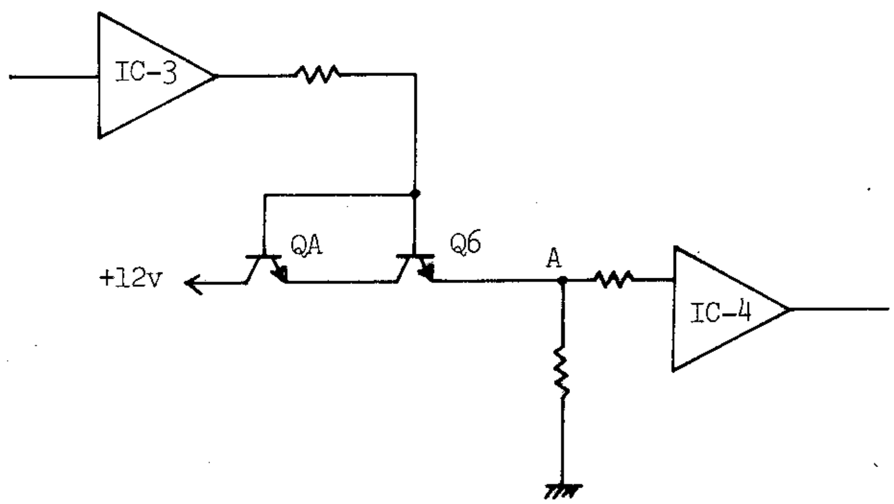


Fig. 15 Circuit for the protection of the Fast Scram signal in the event of Q6 failure in the Magnet Amplifier.

Table 1 Safety Analysis of original A.M.F. design

SERIAL NUMBER	TYPE OF FAILURE	SAFETY SHUTDOWN ACTION	FAILURE INDICATION	REMARKS
1.	Loss of Ionization Chamber Power Supply.	'BACK-UP SCRAM'. Relays RY-13 and RY-14 will de-energise and open the respective contacts 1 and 2 in the back-up scram bank.	Visual and Audible. Contacts 6 and 8 in the relays RY-13 and RY-14 will close, thus +B will be applied to the relay RY-16, through indication lamps B9 and B10. With the energising of relay RY-16 contacts 2 and 3 close, which energises the annunciator buzzer.	The failure is 'FAIL-SAFE'.
2.	Loss of +B power supply.	'FAST SCRAM' and 'BACK-UP SCRAM'. Relays RY-1 to RY-4 will de-energise, opening the respective contacts 1 and 2 in the fast scram safety network.	Visual and Audible. Contacts 6 and 8 in relays RY-1 to RY-4 will close, thus energising the external indication circuit.	The failure is 'FAIL-SAFE'.
3.	Filament failure of tubes V1 and V2 (single stage D.C. amplifiers).	'FAST SCRAM' and 'BACK-UP SCRAM'. The fast scram relay and the back-up scram relay in the respective circuit will de-energise. For example if tube V1A fails, relay RY-1 and relay RY-5 will de-energise and cause a 'FAST SCRAM' followed by a 'BACK-UP SCRAM'.	Visual and Audible. Contacts 6 and 8 of the fast scram relay will close, which causes the respective lamp to light (B1 to B4) and relay RY-16 is energised, which energises the external indication circuit.	The failure is 'FAIL-SAFE'.
4.	Open circuit in UIC cable.	'BACK-UP SCRAM'. Relay RY-13 or RY-14 will de-energise (depending upon the open circuit in UIC#1 or UIC#2 cable). Rest of the action is same as for failure #1.	Visual and Audible. Contacts 6 and 8 of the respective relay (RY-13 or RY-14) will close. Rest of the action is same as for failure #1.	The failure is 'FAIL-SAFE'.
5.	Short circuiting of UIC cable (high voltage electrode).	'BACK-UP SCRAM'. Relay RY-13 or RY-14 will de-energise (depending upon the short circuit in UIC#1 or UIC#2 cable). Rest of the safety action is same as for failure #1.	Visual and Audible. Contacts 6 and 8 of the respective relay (RY-13 or RY-14) will close. Rest of the action is same as for failure #1.	The failure is 'FAIL-SAFE'.
6.	Short circuiting of UIC cable (collector electrode).	No Safety Action.	No indication. Only fall of power on the power meter will be observed.	The failure is 'FALL-DANGEROUS' as the short circuiting of the UIC cable with ground will render the respective channel out of operation without any safety action.
7.	Magnet Amplifier vacuum tube filament failure.	In case of a single vacuum tube failure the load of the defective tube is transferred to the dummy resistor, by relays RY-9 to RY-12 in the filament circuit of the Magnet Amplifier tubes, while the operation of the reactor proceeds uninterrupted. If however more than one tube fails, the reactor is shutdown.	Visual and Audible. In the case of a Magnet Amplifier tube failure (open filament), contacts 6 and 7 of relay RY-9 to RY-12 make thus connecting +B to RY-16 coil, through indication lamps B5 to B8. Energising of RY-16 initiates an audible alarm through contacts 3 and 2.	The failure is 'FAIL-SAFE'.

Table 1 Continued

SERIAL NUMBER	TYPE OF FAILURE	SAFETY SHUTDOWN ACTION	FAILURE INDICATION	REMARKS
8.	Open circuiting of Resistance R49.	The open circuiting of the shunt resistance R49 will not affect the fast scram signal in the case of an emergency, as with the opening of the fast scram bank, the grid bias of the Magnet Amplifier will tend to be more negative than the cut off value.	No indication.	The failure is 'FAIL-SAFE'.
9.	Short circuiting of Resistance R49.	The fast scram signal will fail to travel beyond the 'fast scram safety network' and the grid bias of the Magnet Amplifier tubes will remain unaffected.	No indication.	The failure is 'FAIL-DANGEROUS', as the reactor will not be shut-down by the fast scram signal. However with the de-energising of RY-5 - RY-8 the reactor will be shotdown with the opening of the slow scram bank.

Table 2 Safety Analysis of the modified design

SERIAL NUMBER	TYPE OF FAILURE	SAFETY SHUTDOWN ACTION	FAILURE INDICATION	REMARKS
1.	Loss of Ionization Chamber Power Supply.	'SLOW SCRAM'. Transistor Q14 is switched off by the comparator IC-11. Relay RY-3 is de-energised, which opens the contacts in the slow scram bank.	Visual and audible indication of the common scram bank.	The failure is 'FAIL-SAFE'.
2.	Loss of +B Power Supply to the instruments.	'FAST SCRAM' and 'BACK-UP SCRAM'. Due to +B failure, the voltage at the output of the Trip Unit automatically falls to zero, thus initiating a fast scram.	Visual and audible indication of the common scram bank.	The failure is 'FAIL-SAFE'.
3.	Loss of -B Power Supply to the instruments.	'FAST SCRAM' and 'BACK-UP SCRAM'. Transistor Q4 is switched on, which switches off transistors Q2 and Q5. With the switching off of Q2, a FAST SCRAM is initiated, and with switching off of Q5 a BACK-UP SCRAM is initiated.	Visual and audible indication of the common scram bank.	The failure is 'FAIL-SAFE'.
4.	Open circuit in UIC cable.	'BACK-UP SCRAM'. Relay RY-1 or RY-2 will de-energise (depending upon the open circuit developed in UIC#1 or UIC#2). With the de-energising of RY-1, relay RY-4 will de-energise which will open the contacts in the back-up scram bank.	Visual and audible indication of the common scram bank.	The failure is 'FAIL-SAFE'.
5.	Short circuiting of UIC cable (H.V. electrode line).	'SLOW SCRAM'. Transistor Q14 is switched off by the comparator IC-11. Relay RY-3 is de-energised, which opens the contacts in the slow scram bank.	'LOW UIC VOLTAGE'. Visual and audible indication of the common scram bank.	The failure is 'FAIL-SAFE'.
6.	Short circuiting of the UIC cable (collector electrode line).	'FAST-SCRAM' and 'BACK-UP SCRAM'. With the short circuiting of IC-1 input with ground the output of the Safety Amplifier becomes more negative and saturates at -12 V, thus a 'FAST SCRAM' and a 'BACK-UP SCRAM' is initiated through the Fail-Safe network consisting of IC-5 and transistor Q3.	Visual and audible indication of the common scram bank.	The failure is 'FAIL-SAFE'.

Table 2 Continued

SERIAL NUMBER	TYPE OF FAILURE	SAFETY SHUTDOWN ACTION	FAILURE INDICATION	REMARKS
7.	Failure of IC-1 or IC-2 in the Safety Amplifier.	'FAST SCRAM' and 'BACK-UP SCRAM'. The output of IC-5 changes from -0.44 V to +2.67 V, which switches on transistor Q3. With the switching on of Q3, transistor Q2 and Q5 are switched off, thus initiating a fast and a back-up scram.	Visual and audible indication of the common scram bank.	The failure is 'FAIL-SAFE'.
8.	Short circuiting of transistor Q2 in the Trip Unit.	No safety action.	No indication.	The short circuiting of Q2 will render the fast scram signal in-effective for the respective chan-nel. But the 'BACK-UP SCRAM' will however shotdown the reactor. As there are three trip units, the failure is 'FAIL-SAFE'.
9.	Short circuiting of transistor Q6 in the Magnet Amplifier.	No safety action.	No indication.	The fast scram signal will fail to travel beyond Q6, and all the power transistors (TR-1 to TR-6) will remain on. The 'BACK-UP SCRAM' will however shutdown the reactor through the back-up scram relay RY-4. The delay due to the non-operation of the fast scram will however release some extra energy in the core. The failure is 'FAIL-DANGEROUS'.

6. CONCLUSION

The experience of reactor instrumentation systems modification at JRR-2 have been very encouraging, as with the replacement of the conventional type of instrumentation systems of AMF design with the modified design using solid state circuit techniques, the operating efficiency of the reactor registered an improvement of 43.38%. And finally with the replacement of the ion-chambers and the cables, it was possible to achieve an operating efficiency of 100% for the reactor.

Drawing No. CP-MOD-10 shows the instrumentation systems performance history of JRR-2. It is observed that during the five years of reactor operation (from 1964-65 to 1968-69) under the original AMF designed instrumentation systems, there was a gradual increase in the unscheduled shut-downs of the reactor per operating cycle, due to instrumentation malfunction. This indicates a gradual deterioration of the reactor instrumentation systems. On the other hand, it is observed that after the installation of the modified designed instrumentation, using solid state circuit techniques, there was a gradual decrease in the USD* per operating cycle, thus resulting in higher operating efficiency and improved reliability. Finally with the replacement of the ion-chambers** and the improved noisless cables, during the major reactor shut-down period from 1973-74 to 1975-76, it was possible to achieve an operating efficiency of 100%, thus resulting in improved reliability of the reactor instrumentation systems.

More over, the safety analysis show that the safety aspects have been fully taken care of in the modified design, and the reactor is well gaurded against all possible instrument failures and human errors. There is however one condition which can result in the failure of the fast scram signal. This can occur in the event of the short-circuiting of the transistor Q6 in the magnet amplifier. The chances of failure of the fast scram signal can however be considerably reduced by carrying out a minor improvement in the circuit, as suggested in the safety analysis.

After the installation of the modified instrumentation systems, the maintenance procedures have also been considerably simplified, because

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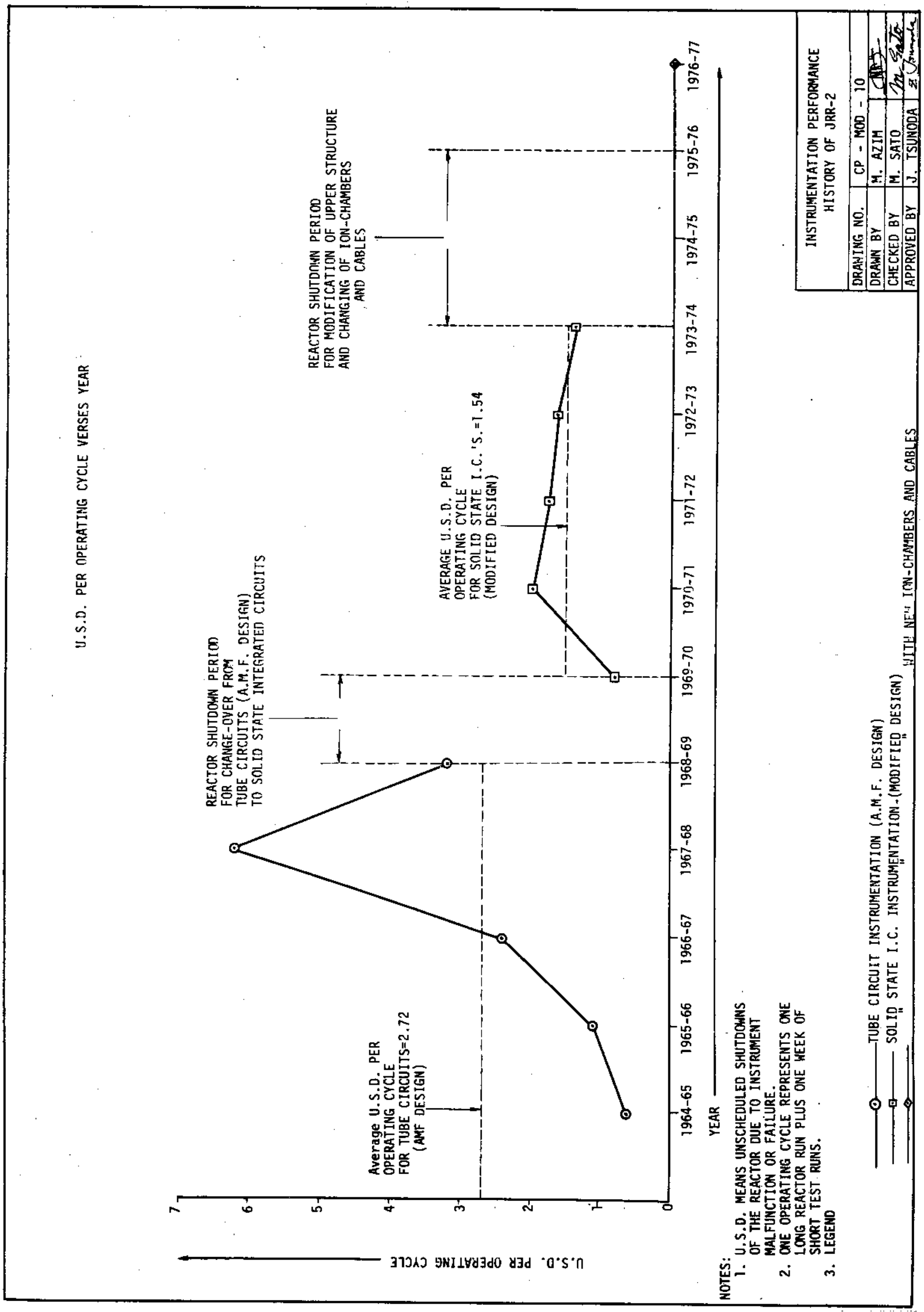
* USD - unscheduled shut downs of the reactor due to instrument failure or malfunction.

** - Appendix 1

of the fact that the operating life-time of the solid state circuit components is much longer as compared to vacuum tubes. According to the present maintenance procedures for JRR-2 instrumentation systems, the modules are checked only once a year, and no major fault have so far been experienced with the modified instrumentation systems.


U.S.D. PER OPERATING CYCLE VERSES YEAR
REACTOR SHUTDOWN PERIOD FOR MODIFICATION OF UPPER STRUCTURE AND CHANGING OF ION-CHAMBERS AND CABLES
REACTOR SHUTDOWN PERIOD FOR CHANGE-OVER FROM TUBE CIRCUITS (A.M.F. DESIGN) TO SOLID STATE INTEGRATED CIRCUITS
AVERAGE U.S.D. PER OPERATING CYCLE FOR SOLID STATE I.C.'S.=1.54 (MODIFIED DESIGN)
Average U.S.D. PER OPERATING CYCLE FOR TUBE CIRCUITS=2.72 (AMF DESIGN)
U.S.D. PER OPERATING CYCLE
0
1
2
3
4
5
6
7
1964-65
1965-66
1966-67
1967-68
1968-69
1969-70
1970-71
1971-72
1972-73
1973-74
1974-75
1975-76
1976-77
YEAR
NOTES:
1. U.S.D. MEANS UNSCHEDULED SHUTDOWNS OF THE REACTOR DUE TO INSTRUMENT MALFUNCTION OR FAILURE.
2. ONE OPERATING CYCLE REPRESENTS ONE LONG REACTOR RUN PLUS ONE WEEK OF SHORT TEST RUNS.
3. LEGEND
TUBE CIRCUIT INSTRUMENTATION (A.M.F. DESIGN)
SOLID STATE I.C. INSTRUMENTATION-(MODIFIED DESIGN)
" " " WITH NEW ION-CHAMBERS AND CABLES
INSTRUMENTATION PERFORMANCE HISTORY OF JRR-2
DRAWING NO. CP - MOD - 10
DRAWN BY M. AZIM
CHECKED BY M. SATO
APPROVED BY J. TSUNODA

ACKNOWLEDGEMENTS

In carrying out the works described in this report thanks are due to many persons without whose help, this report was not possible.

We would like to thank the Japan Atomic Energy Research Institute for providing excellent facilities for this project.

We would also like to thank the Japan International Cooperation Agency for Sponsoring this project. We are thankful to the Mr. KUNITAKE FUKAZAWA, Director, Division of research Reactor Operation, for his support and encouragement. We are also thankful to Mr. SHUNZJ HONMA for his guidance and continued interest in this project.

We are also thankful to Mr. ZUNSAKU TSUNODA and Mr. YASUHIKO MIYASAKA for carefully checking the drawings presented in this report.

Thanks are also due to Mr. KUNIO HARA, Mr. DENJIRO NEMOTO, Mr. TAKEHEKO KUNITAMA, Mr. MASAHERO NAKANO, and Mr. KENICHI SHIMIZU, the staff members of JRR-2, who provided us with the necessary information from time to time during this study.

And finally we are thankful to Mr. KAZUMA KIMURA and Mr. KIICHI KANEKO of Electronics Workshop for delivering us lectures on the Modified Instrumentation Systems.

REFERENCES

1) I.A.E.A. Safety Series No. 35, "Safe Operation of Critical Assemblies and Research Reactors", -1971 Edition.
2) Eames. A.R., "Principles of Reliability for Nuclear Reactor Control and Instrumentation Systems", SRD R I, September 1971.
3) International Electrotechnical Commission, Publication 231, "General Principles of Nuclear Reactor Instrumentation", 1967.
4) Costrell, L. "Standard Nuclear Instrument Modules", TID-20893 (Rev.3), December 1969.
5) AMF Atomics, "Engineering Design Manual", Volume 1, 1959.
6) Y. Miyasaka, "Modification of JRR-2", JAERI-M 7484, January 1978.
7) Electronics Workshop Section, "Improvement on the reactor instrumentation of the JRR-2, JRR-3 and JRR-4", JAERI-memo 3753, October 1969.
8) Minneapolis-Honeywell, "Nuclear Instrumentation Systems Instruction Manuals", (CP-5).

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8) Minneapolis-Honeywell, "Nuclear Instrumentation Systems Instruction Manuals", (CP-5).

APPENDIX 1: Specification of old and new CIC and UIC of JRR-2

SPECIFICATIONS	OLD TYPE				NEW TYPE
	CIC TYPE(WL-6377)		UIC TYPE(WL-6937)		CIC and UIC TYPE(WL-23196)
Diameter (mm)	81		76.2		51
Length (mm)	610		352.4		305
Sensitive Length (mm)	357		190.5		190.5
Material	Al 3%, Mg 97%		Al		Al
Insulator	Polyethylene Al_2O_3		Polyethylene Al_2O_3		Rexolite
Charge Gas	N_2		Ar 760mmHg Nitrogen		N_2
Neutron Reaction Material	96%, enriched ^{10}B 1 mg/cm^2		96% enriched ^{10}B		^{10}B 0.8 mg/cm^2
Thermal Neutron Flux (n/cm^2-sec)	10^{11}		10^{11}		2.5×10^{11}
Temperature (°C)	79.4		79.4		85
Internal Electrode Voltage (Max.) (V)	1500		1500		1500
Operating Range Voltage (V)	300 to 800		200 to 800		300 to 1200
Compensation Voltage (V)	-10 to -80		———		-10 to -80
Neutron Sensitivity (A/n/cm^2/sec)	4×10^{-14}		4.4×10^{-14}		2.3×10^{-14}
Thermal Neutron Flux Limit	2.5×10^{2} to 2.5×10^{10}		2.5×10^{2} to 2.5×10^{10}		4.3×10^{2} to 5.0×10^{10}
Signal Electrode Capacity (pF)	160		———		174
Movement Voltage (V)	at 2.5×10^{10}	800	at 3×10^{9}	250	
Output Current (A)	n/cm^2/sec	10^{-3}	n/cm^2/sec	1.3×10^{-4}	
Movement Voltage (V)	at 2.5×10^{9}	300	at 1.5×10^{10}	600	
Output Current (A)	n/cm^2/sec	2×10^{-4}	n/cm^2/sec	6.6×10^{-4}	
Gamma Sensitivity (Un compensated) (A/R/h)	3×10^{-11}				6.4×10^{-12}
Gamma Sensitivity (Compensated) (A/R/h)	4×10^{-14}				0

APPENDIX 2: Installation Schedule of the Modified Nuclear Instrumentation Systems at JRR-2

INSTRUMENTATION SYSTEM	Commencement of Design by the Electronics Workshop (JAERI)	Installation in the Control Room	Approximate Cost in Yen.	MAKER
Log-N and Period Channel	May 13, 1969	December 12, 1969	496,000	IKEGAMI, Mito Plant
Safety Channels (No.1 and No.2)	December 12, 1969	May 30, 1970	490,000 (per channel)	IKEGAMI, Mito Plant
Rod Magnet Amplifier	December 12, 1969	May 30, 1970	668,000	IKEGAMI, Mito Plant
Linear-N Module	May 11, 1971	April 30, 1972	1,285,000	OOYOKOOKEN, Tokyo (Formerly TOKYO ELECTRIC Co.)
Three Mode Controller Module	May 11, 1971	April 30, 1972	1,300,000	"