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COOLANT FLOW AND OUTLET TEMPERATURE
COMPUTER-MONITORS FOR THE
HALLAM NUCLEAR POWER FACILITY
PLANT PROTECTIVE SYSTEM

AEC Research and Development Report

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.

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COMPUTER-MONITORS FOR THE
HALLAM NUCLEAR POWER FACILITY
PLANT PROTECTIVE SYSTEM

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ATOMICS INTERNATIONAL

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CONTENTS

	Page
Abstract	v
I. Introduction	1
II. Summary of Results	3
III. Description of Equipment.	9
A. Application of Operational Amplifiers	11
B. Description and Application of Transistor Plug-ins	13
C. Input Section	19
D. The Arithmetical Section	21
E. The Logic Section	24
F. Flow/Flow Computer Logic	26
G. Power/Flow Computer Logic	29
H. Power Supplies	34
IV. Operation of Flow/Flow Computer.	35
V. Operation of Power/Flow Computer	37
VI. General Comments	40
References	41

FIGURES

1. Power/Flow Computer (Top and Under Chassis Views)	4
2. Flow/Flow Computer (Top and Under Chassis Views)	5
3. Power Supply for Either Computer (Top and Under Chassis Views).	6
4. Computer Test Fixture (Front and Rear Views)	7
5. Relay Coincidence Circuit	10
6. Power/Flow Computer Schematic	15
7. Flow/Flow Computer Schematic	17
8. Multiplier Circuit	22
9. Flow/Flow Computer - Operating Curves	27
10. Flow/Flow Computer - Logic Schematic (Two Required)	27
11. Flow/Flow Computer - Safe/Trip Conditions	28

FIGURES (Continued)

	Page
12. Truth Table for Flow/Flow Computer	28
13. Logic Condition Check for Flow/Flow Computer	30
14. Power/Flow Computer - Operating Curves	32
15. Power/Flow Computer - Safe/Trip Conditions.	32
16. Power/Flow Computer - Logic Schematic (Three Required)	33
17. Truth Table for Power/Flow Computer, Exclusive of n_h (High Neutron Flux Cutoff)	33
18. Logic Conditions Check for Power/Flow Computer	34

ABSTRACT

The design and application of two computers for the HNPF protective system is discussed. One of the computers calculates the ratio of sodium flow in the primary loop to sodium flow in the secondary loop; it then checks the result against two sets of limit curves and activates relays to show where the calculated ratio falls with respect to the two curves. The other computer calculates the predicted reactor outlet temperature, checks the results against three sets of limit curves and activates relays to show the calculated outlet temperature with respect to the three curves.

I. INTRODUCTION

The Hallam Nuclear Power Facility (HNPF) is a 200 thermal Megawatt sodium cooled, graphite moderated reactor under construction by Atomics International for the Nebraska Consumer Public Power District. Analytical and analog computer studies performed during the early stages of the conceptual design showed the desirability of providing automatic protective circuits to guard the reactor against the possibility of operating in excess of its design limits.

Heat generated in the reactor core is carried away by sodium in three primary cooling loops. Sodium passed through the core and becomes radioactive due to neutron absorption. Each cooling loop contains an intermediate heat exchanger where heat from the primary cooling loop is transferred to a secondary cooling loop. Sodium in the secondary cooling loops is not exposed to neutrons and does not become radioactive. Each of the three secondary loops is connected to a steam generator from which superheated steam is fed to a turbine-generator. The operator makes appropriate adjustments to the controls to obtain the desired coolant flow and temperature and thus proper power output and operating conditions.

The combination of reactor core, steam system, electrical generator and its load is a complex arrangement of subsystems and it appears possible to have apparent satisfactory external loading of the system and yet overload one or more of the major subsystems.

The protective system was designed to indicate abnormal operating conditions of the reactor and also take certain corrective actions, including shutting down the reactor, if variations from the operating norm are severe enough. The system monitors sodium temperature, rate of temperature change, sodium level, sodium flow and neutron flux; it also calculates combinations of these parameters.

Reliability and fail-safe operation of the protective system equipment are of prime importance. The latter is achieved by judicious design and in certain instances adding components to minimize ambiguity. Completely reliable operation is approached by using solid state devices throughout the circuits and avoiding use of moving components wherever possible. All major computers are installed

in groups of three using independent transducers. Off-normal conditions are indicated and corrective action taken when called for by any two of the three identical units. If one of the group of three circuits has been removed from the cabinet for maintenance, then the remaining two circuits of that group will act upon off-normal conditions on a one out of two basis.

This report covers two major circuits that are part of the protective system. One of these computes the ratio of primary to secondary coolant flow and continuously compares computed value with the desired operating range. It is called the flow/flow computer. The other circuit computes the predicted reactor outlet temperature and compares it with the desired operating limit. It is called the power/flow computer.

II. SUMMARY OF RESULTS

A pre-production prototype of each computer has been designed and built. Extensive tests were conducted on these computers to check their operation and reliability. No component or system failures occurred after the initial shake-down. The computers meet or exceed all specifications to which they have been designed. Error, under the worst expected input conditions, is less than 2%. With normal input ratios and ranges, considerably better accuracy is obtained. Photographs of both computers, the power supply and test fixture are shown in Figures 1 through 4.

It would be presumptive to claim 100% fail-safe operation. However, there are only a few instances where a single component failure can cause either one of the computers to fail unsafely. Some of these few failures must occur in a direction of small probability such as a resistor decreasing considerably in value. It is of course possible to have a computer failure occur so that the computer indicates normal reactor operation when the reactor is actually operating abnormally. When a nonfail-safe failure occurs in one computer the two out of three coincidence feature of the protective system will still cause appropriate action to be taken when abnormal operating conditions occur and the operator will be aware of computer failure by lack of off-normal indication on that computer.

Computer outputs are compared to a set of limits and straight line curves. The decision circuits which evaluate the outcome of this comparison are all digital computer-type logic circuits; circuits having only one of two possible outputs. The calculated result is therefore always actively decided upon. However there does exist a small amount of hysteresis at the boundary where the analog-type computed value is brought into the digital logic. This hysteresis is on the order of 50 millivolts in the worst case. Signal levels for average reactor operation where this hysteresis occurs have a magnitude of two or more volts.

The output relays are transistor driven. Their contacts have been subjected to over 100,000 operating cycles carrying a one ampere inductive load. An examination of the contacts after the cycling showed very little wear and only a moderate amount of carbonization.

Figure 1. Power/Flow Computer (Top and Under Chassis Views)

Figure 2. Flow/Flow Computer (Top and Under Chassis Views)

57

Figure 3. Power Supply for Either Computer
(Top and Under Chassis Views)

Figure 4. Computer Test Fixture (Front and Rear Views)

Adjustments of either computer are simple to perform and do not interact with each other; there is no component whose placement or dress is critical. The instruments are quite versatile; all curve limits are adjustable over a four to one range. With a simple resistor change any limit can be extended by several magnitudes.

A major fraction of the components are contained in plug-in assemblies which are either catalog items or have been built to our specifications by the manufacturer. This design greatly simplifies the assembly of the chassis and also simplifies signal tracing. In fact it is possible to trouble-shoot the logic section, the major portion of the computers, with a flash-light bulb.

For the following discussions certain assumptions have been made concerning the values of temperature, coolant flow, neutron flux and others. The temperature drop across the reactor core has been assumed to be 400°F. Sodium temperature at the outlet of the heat exchanger has been assumed to be 600°F or 18 millivolts. The actual values at which the reactor will operate differ slightly from those given above, and necessary adjustments of certain constants will have to be made to compensate for these differences. It is also necessary to compensate for the new reference temperature which will be 150°F in the actual reactor. These changes do not affect computer operation.

III. DESCRIPTION OF EQUIPMENT

The pre-production prototype of the flow/flow computer is a chassis 7 inches wide, 26 inches long, and 3 inches deep; the front panel is 9 inches wide and 8-3/4 inches high, Figure 1. The dimensions for the power/flow computer in the same order are: 17, 26, 3, 19 and 8-3/4 inches, Figure 2. Complete schematics for both computers are shown in Figures 6 and 7 respectively. Both computers are built up of small plug-in subassemblies. Eight different types of plug-ins containing from one to three transistors are used. Five of these are catalog items. The remaining three contain special circuits designed and specially built. High-gain, transistorized, feedback-stabilized amplifiers are used for various purposes. Two amplifiers are packaged on a single printed circuit card and encased in a small steel cabinet. These amplifiers are also the plug-in type and are used in the multiplier section of the computers and for operational amplifiers, integrators, filter networks, and differential amplifiers. Several types of the transistor circuit plug-ins and amplifiers are also used in the fuel channel outlet temperature rate of change and level detectors, which are also part of the HNPF protective system.

The flow/flow and the power/flow computers consist of three similar subsystems. These include:

- 1) The Input Section, which amplifies the incoming thermocouple, flow-meter and neutron flux signals and converts those that are of the differential type to grounded output signals.
- 2) The Arithmetical Section, which performs addition, multiplication, division, inversion and averaging.
- 3) The Logic Section, which determines where the output of the Arithmetic Section falls with respect to the desired set of operating conditions. Relays actuate indicator lights on the front panel to show when the calculated values exceed preset conditions. Other contacts on the same relays are used to energize power relays which in turn initiate other action.

The coincidence of two out of three off-normal signals is required to initiate corrective action. An off-normal output from a single computer will only be indicated; no automatic action will be taken. Removal of an active computer from its cabinet in effect places a single off-normal condition on the two out of three coincidence circuit. An off-normal output from either of the two remaining computers will now initiate the corrective action. Coincidence circuitry consists of series paralleling relay contacts. The arrangement which will be used is shown in Figure 5.

ALL CONTACTS NORMALLY OPEN

A-1 AND A-2 ARE CONTACTS ON COIL A AND SO ON

COIL A IS ENERGIZED BY THE RELAY CONTACTS OF COMPUTER I

COIL B IS ENERGIZED BY THE RELAY CONTACTS OF COMPUTER II

COIL C IS ENERGIZED BY THE RELAY CONTACTS OF COMPUTER III

Figure 5. Relay Coincidence Circuit

A. APPLICATION OF OPERATIONAL AMPLIFIERS¹

Six all-transistor feedback stabilized operational amplifiers are used in the flow/flow computer. Seventeen are used in the power/flow computer. Their nominal output range is between ± 10 volts into a maximum load of 500 ohms. Power for the amplifiers is derived from the computer power supply.

The output voltage of an operational amplifier in terms of input voltage, series input impedance and feedback impedance may be written as,

$$X_0(s) = - \left[\frac{X_1(s)}{Z_1(s)} + \frac{X_2(s)}{Z_2(s)} + \dots \right] Z_0(s) \quad \dots (1)$$

where $X_0(s)$ = Laplace transform of the output voltage
 $X_1(s), X_2(s)$ = Laplace transforms of the input voltages
 $Z_1(s), Z_2(s)$ = amplifier series input impedances in the complex frequency domain
 $Z_0(s)$ = amplifier feedback impedance in the complex frequency domain
 s = complex frequency variable.

The equation is an excellent approximation to the amplifier performance if the series and parallel impedances are large enough to prevent loading the amplifier and, of course, the input and output voltages are kept within amplifier ratings. Also the amplifier gain without feedback impedance must be on the order of 1000 or better over the operating frequency range. Current drawn by the amplifier is neglected in Equation 1. These assumptions are all valid for a well designed amplifier.

Applying Equation 1 to amplifier 5B, Figure 6: $E_{out} = -E_{in} \frac{100k}{100k} = -E_{in}$

Applying the same equation to amplifier 5A, Figure 6:

$$E_{out} = - \left[\frac{E_1}{100k} + \frac{E_2}{100k} + \frac{E_3}{100k} \right] 33.2 k$$

If $E_1 = E_2 = E_3 = E_{in}$ then $E_{out} \approx -E_{in}$. For amplifier 6B, Figure 6, in Laplace notation,

$$E_{out}(s) = \frac{-1}{(10^5 \cdot 0.01 \cdot 10^{-6})s} \cdot \frac{E_{in}}{s} = -\frac{E_{in}}{10^{-3}s^2}$$

for constant input voltage. Performing the indicated operation $E_{out} = -\frac{E_{in} t}{10^{-3}}$ where t is real time in seconds.

The output of amplifier 2B, Figure 7, may be calculated for constant E_{in} ; $Z_1 = 10^4$, $Z_0 = \frac{10^5}{0.45s + 1}$. Then

$$E_{out}(s) = -\frac{10E_{in}}{(0.45s + 1)s} \text{ or } E_{out} = -10E_{in} \left(1 - e^{-\frac{t}{0.45}} \right)$$

The transfer function of amplifier 2B, Figure 7, represents the action of an RC integrator circuit. When E_{in} is a series of pulses then E_{out} becomes the average of E_{in} . This particular circuit has a gain of 10 and can be loaded quite heavily without reducing its output. The time constant of this circuit is 450 milliseconds and ripple is on the order of millivolts. The exact ripple amplitude depends of course on the pulse repetition frequency.

Amplifier 3B, Figure 6, has a nominal gain of three. The 1N713 diode in the feedback loop is a Zener diode whose break-down voltage is 9.1 volts $\pm 10\%$. It limits the amplifier output to that magnitude preventing saturation of the amplifier. The 1N191 diode, a computer type germanium diode, is used to block reverse voltages from developing across the Zener.

B. DESCRIPTION AND APPLICATION OF TRANSISTOR PLUG-INS

Eight different types of plug-ins are used in the computers. Their schematics are shown in Figures 6 and 7.

- T-1101 A somewhat specialized circuit whose operation will be explained in detail in the Arithmetical Section.
- T-1102 A dual relay driver containing two PNP emitter followers with relay coils comprising the loads.
- T-1103 A modified Schmitt trigger circuit. It is used as a voltage level detecting device and also as a negation circuit in the Logic Section.
- T-113 A circuit containing three independent PNP emitter followers used to drive the logic elements.
- T-404 A dual two-input "AND" circuit;
- T-405 A four-input "OR" circuit;
- T-406 A dual two-input "OR" circuit;
- T-407 A four-input "OR" circuit.

All plug-ins except the T-1101 are supplied with -15 volts on the collector and either +15 volts or ground on the emitter.

T-1103's that are used to detect positive voltage levels have -15 volt bias through an external 50K potentiometer on the base of the input transistor. To detect negative voltage levels this bias is +15 volts through a 200K potentiometer. The range of detectable levels is from about 1.5 volts to 6.5 volts, in the appropriate direction.

Representative examples of two-input "AND" and "OR" circuits truth tables are shown below for future reference.²

T-404 "AND"			T-406 "OR"		
<u>I</u>	<u>Input</u>	<u>Output</u>	<u>I</u>	<u>Input</u>	<u>Output</u>
<u>0</u>	<u>0</u>	0	<u>0</u>	<u>0</u>	0
0	1	0	0	1	1
1	0	0	1	0	1
1	1	1	1	1	1

Figure 7. Flow/Flow Computer Schematic

These tables can easily be expanded for more than two inputs. It should be noted that the "OR" circuits used are non-exclusive "OR" circuits. About -1.3 volts corresponds to a "zero" and similarly -0.5 volts represents a "one." Each of the logic plug-ins contains one transistor per output operating as an emitter follower. This provides good isolation and permits the cascading of logic elements in any combination.

C. INPUT SECTION

The transducers that operate the flow/flow computer are electromagnetic flowmeters. Two of these are required for each computer, one for the primary and one for the secondary loop. Their full scale output is a minimum of 30 millivolts with floating ground.

The power/flow computer has seven inputs. Three of these are also derived from electromagnetic flowmeters. Three others are from floating output iron/constantan thermocouples whose maximum output is about 14 millivolts. This is equivalent to 600°F when the reference junction is at 150°F. The seventh input is the neutron flux signal. Its magnitude at 100% power is 10 volts positive with negative grounded. The input amplifier for the latter signal is a straight d-c amplifier and its role in the computer will be discussed later.

The flowmeter and thermocouple signals are amplified by differential type amplifiers with an overall gain range from 200 to 600. The differential amplifiers are chopper input type. Double pole choppers are used; one pole chops the input at the 60 cycle driving frequency and the other pole is used to decommutate the 60 cycle square wave back to direct voltage.

The input transformer has an impedance ratio of 50,000 ohms to 500 ohms. A 10 millivolt thermocouple or flowmeter output produces a 2 millivolt peak to peak signal across the secondary winding of the input transformer. The signal loss across the transformer is not desirable but unavoidable in order to obtain properly matching impedance levels. The d-c resistance of the full primary is about 4000 ohms; transformers better suited to this particular application are available, however the search for a more appropriate transformer was not pursued for the prototype model.

A nominal gain of 333 in the overall differential amplifier requires a gain of 500 in the amplifier itself. The voltage developed across the two series connected primary windings of the two output transformers is then 500 millivolts.

The peak to peak square wave across the series connected secondaries of the output transformers is then about 7.5 volts. Decommulating and capacitor filtering of the square wave reduces the signal to 3.3 volts d-c across the 20 mfd capacitor. The overall gain of the entire differential amplifier is then 333. This value is adjustable by varying the series input resistor of the operational amplifier.

It has been pointed out previously that operational amplifiers are chopper stabilized; a special internal feedback network containing a chopper is used to obtain gain, minimize drift and stabilize the overall operation. When the external input chopper and the internal feedback chopper are driven in phase and at the same frequency the feedback chopper will chop against ground at the same time that the pole of the external chopper makes on both contacts. This particular phasing action causes undesirable spikes on the internal chopper and an overall d-c offset. These spikes are eliminated by shifting the phase of the driving current of the external chopper by about 40 electrical degrees with respect to the internal chopper so that the internal chopper sees a signal when it chops to ground. Phase shifting is accomplished by using two 6.3 volt filament transformers. One of these drives the internal chopper, the other has a 1 mfd capacitor in its primary to shift the phase of the external chopper by the required amount. Phase shifting on the 6.3 volt side is not practical with the transformers used because of excessive voltage loss. The regulation of the transformer containing the phase shifting network is quite poor and its output contains harmonics. The following comparative readings were taken on the differential amplifiers with phase shifting capacitor.

<u>Load</u>	<u>Coil Driving Voltage</u>	<u>Dwell</u>	<u>d-c Output</u>
2 choppers	8.4 volts a-c	8°	X
6 choppers	5.1 volts a-c	20°	1.1X

The poor regulation and waveform of the external chopper driving voltage causes no problem in the power/flow computer since it always loads the filament transformer with six choppers. However, each flow/flow computer contains

only two choppers, but three computers are driven by one power supply so that the load on the transformer is again six choppers while in service. When a single flow/flow computer is under test or being setup one must load the particular transformer with an additional resistor of about 16 ohms, 2 watts. This resistor is located on the test fixture and connects to pins 7 and 15 of J-3, Figure 7.

The increase in chopper coil driving voltage does not seriously impair the operation of the flow/flow computer. It does, however, effectively increase the trip points of the computer. This will be explained in detail later.

D. THE ARITHMETICAL SECTION

The arithmetical section performs addition, subtraction, multiplication, division, integration, averaging or a combination of these operations. All of these functions with the exception of multiplication or division have been touched upon previously and will not be explained in any more detail except to state that analog techniques are used exclusively.¹ The combined function of division and multiplication is performed by a circuit which will be known as the single quadrant time-sharing multiplier/divider or simply the "multiplier circuit." A complete schematic of this circuit is shown in Figure 8. Q_1/Q_2 is the plug-in T-1101, and Q_3/Q_4 is the T-1103.

The multiplier inputs are two negative d-c signals ranging nominally from 0 to 10 volts and designated Y and Z, and one positive signal also ranging nominally from 0 to 10 volts designated as X. A constant "k" whose value should not be smaller than 2 and could be as high as 20, by proper component choice, is part of this circuit; it is comprised of resistances in series with the X input. Resistor values given in Figure 8 are for a center value of $k = 12$. The circuit calculates the function $F = \frac{XY}{kZ}$. It becomes immediately obvious that Z cannot approach zero, in fact Z must not become too small compared with X or Y. A safe design criterion is that Z is not less than $0.1XY$.

The components of this multiplier circuit are few, and its application is quite straight forward provided one can tolerate the polarity limitations. Fortunately, this condition does not limit the application of this circuit in either of

X- CONTROLS PULSE WIDTH
 Y- CONTROLS PULSE AMPLITUDE
 Z- CONTROLS PULSE REPETITION RATE

Figure 8. Multiplier Circuit

the computers. The general principle of the multiplier circuit may best be understood by starting at the integrator which has two inputs. One of these, X , is always positive, the other from the emitter of Q_1 (the Z transistor), is either equal to Z (a negative voltage), or zero depending on whether Q_1 is conducting or cut-off. The output of the integrator is a positive or negative ramp voltage that is a function of the sum of the input voltages and their respective time constants. In general, as long as the input signals remain constant and their algebraic sum is negative, the amplifier output will rise linearly until saturation occurs. If the algebraic sum of the input changes sign the output ramp will reverse direction.

The output ramp of the integrator is directly coupled to a level triggered bistable circuit consisting of Q_3 and Q_4 . The output of the bistable is taken from the collector of Q_4 . The voltage level at this point is about +8 as long as the input to the bistable is about +5.6 volts or larger. When the input signal becomes less than +5.6 volts the bistable output switches from +8 volts to about -12 volts. An input amplitude of +8.2 volts causes the bistable to switch back from -12 volts to +8 volts. The large amount of hysteresis in the operation of Q_3/Q_4 is necessary and important. The amount of hysteresis is primarily controlled by the value of the common emitter resistor.

The output of the bistable is coupled through two 100K resistors to the bases of Q_1 and Q_2 . A positive voltage on the base of Q_1 and Q_2 cuts the transistors off. The emitter signal is now zero. Negative voltage on the base allows the transistors to conduct and the voltage on the emitters of Q_1 and Q_2 now equals Z and Y respectively.

For the following explanation, we will call the output of the integrator going from 5.6 to 8.2 volts slope A and the change from 8.2 to 5.6 volts will be referred to as slope B.

An increase in Z causes no change in the magnitude of slope A; the magnitude of slope B increases because the input to the integrator is increased during the conducting time of Q_1 . Decreasing Z causes no change in slope A; but slope B now becomes smaller in magnitude. An increase in X increases slope A slightly and decreases slope B to a larger extent. Decreasing X has the opposite effect.

The increase in X makes the net input voltage to the integrator more positive. The increase in net input voltage is weighted by the resistances that make up "k." That is the reason for the changes in both slope A and B. It should be remembered that the integrator is inverting; that is, a positive input voltage gives a negative output slope and an increase in the positive input signal will make the negative output ramp steeper. Thus it can be seen that X affects the width of the output pulse of Q_4 and also the pulse width at the output of Q_1 while Z affects primarily the pulse repetition rate.

Q_1 and Q_2 are being driven in parallel. The pulse output amplitude at the emitter of Q_2 is directly proportional to Y . This point is the output of the multiplier; it is a negative square wave clamped to zero. Its d-c or average value is equal to the function F . The value of F may be measured for test purposes with any moderately damped d-c, 20,000 ohm-per-volt, voltmeter. In the computers the averaging is accomplished by an operational amplifier with a suitable feedback network.

E. THE LOGIC SECTION

The logic sections of both computers are composed of the same basic components. They are level detectors, AND circuits, OR circuits, NOT circuits, buffer stages, relay drivers and relays. After the computers have performed their respective calculations it then becomes the function of the logic section to determine where the calculated values lie with respect to certain curves.

1. Level Detectors³

The circuit is similar to the level triggered bistable used in the multiplier. The common emitter resistor is changed to 56 ohms and returned to ground instead of +15 volts d-c. This change reduces hysteresis to about 40 millivolts. The base of the input transistor is available at the socket through a 15K resistor and is connected through a 200K, 25 turn rheostat to +15 volts for negative input signals.

Positive input signals require a 50K, 25 turn rheostat, connected to -15 volts. The input level at which the detector output changes is now adjustable between the limits of about 1.8 and 6.5 volts. If the input to the detector is less

than the trip value in magnitude, and negative in sign, the detector output is about -0.5 volts. If the detector input is again considered to be less in magnitude than the trip value but positive in sign, the detector output is about -13 volt. In the logic section -0.5 volts is called "one" and -13 volts is called "zero."

2. NOT Circuit

This circuit is quite similar to the level detector. The common emitter resistor is changed to 91 ohms to obtain a more favorable operating point. Hysteresis is increased but it is of no consequence in this application since the input signal switches between its limits in a few microseconds. Two outputs are available. One has the same level as the input the other one has not. Hence the terminology "NOT circuit."

3. AND Circuit

Two- and four-input AND circuits are used. Their normal input signal is "zero" or about -13 volts. If all inputs rise to a "one" or about -0.5 volts only then will the output be a "one." The "AND" circuit uses 1N191 diodes and each output is taken off an emitter follower to provide isolation.

4. OR Circuit

The OR circuit is similar to the AND circuit. Its output is "one" if one or more of its inputs are in the "one" condition.

5. Buffer Stages

Buffer stages are pnp emitter followers. They are used to isolate level detectors and NOT circuits from the logic to prevent loading and signal interaction.

6. Relay Drivers and Relays

Relay drivers are also pnp emitter followers. The relay coil is the emitter resistor or load. A "zero" signal is required on the driver input to energize the relay. The relay has double pole, double throw contacts. Its coil resistance is 2500 ohms.

F. FLOW/FLOW COMPUTER LOGIC⁴

The flow/flow computer computes the ratio of primary to secondary coolant flow. If the calculated ratio falls between the values of 1.15 and 0.87 a "safe" condition will be indicated. If the ratio is outside of those values but between 1.2 and 0.8 an "alarm" condition will be shown. If the ratio is outside the latter two values a "scram" condition is to be indicated.

In addition to these conditions, a "safe" indication is called for when both primary and secondary coolant flow are less than 10% of rated value regardless of their ratio. Also, if both coolant flows are less than 20% but more than 10% of full scale an alarm will be indicated if the ratio is outside the limits of 1.15 and 0.87 but a "scram" will not be initiated even though the ratio is outside the set limits of 1.2 and 0.8. Figure 9 shows these conditions graphically; Figure 10 shows the logic in block diagram form to achieve these results. The derivation of the logic equation follows.

Figure 9 is broken down in two parts identified as Figures 11-A and 11-B. Using the three variables P, S' and R where P is primary coolant flow rate, S is the secondary coolant flow rate and R is their ratio one can write the eight condition Truth Table A, Figure 12-A. The geometry of these three variables indicates that conditions I or II or III or VII are conditionally favorable. Similarly, the Truth Table B using the variables P', S and R' of Figure 12-B shows that conditions I' or II' or VI' or VIII' are conditionally favorable. Referring back to Figure 9, it becomes apparent that if conditions (I + II + III + VII) (I' + II' + VI' + VIII') exist a "safe" indication is appropriate. The above expression is in Boolean notation where "+" is read "or" and "multiplication" is read "and." Cross multiplying the above equation results in sixteen terms. Inspection of Figure 9 shows that a number of these cross products are not realizable since the function from which they were derived is single valued. Such terms are (I) (VI'), (II) (III') and others. Products such as (I) (I'), (III) (I') can exist since they have a common area in Figure 9.

Writing out the equation (I + II + III + VII) (I' + II' + VI' + VIII') one obtains:

$$(PS'R + PS'\bar{R} + \bar{P}\bar{S}'R + \bar{P}\bar{S}'\bar{R}) (P'SR' + P'S\bar{R}' + \bar{P}'S\bar{R}' + \bar{P}'S\bar{R}').$$

Figure 9. Flow/Flow Computer - Operating Curves

Figure 10. Flow/Flow Computer - Logic Schematic
(Two Required)

"H" AND "L" REFERS TO SIGNAL LEVELS ABOVE AND BELOW TRIP SETTINGS RESPECTIVELY

Figure 11. Flow/Flow Computer - Safe/Trip Conditions

[A]					[B]				
	P	S'	R	OUTPUT		P'	S	R'	OUTPUT
I	L	L	L	0	I'	L	L	L	0
II	L	L	H	0	II'	L	L	H	0
III	L	H	L	0	III'	L	H	L	I
IV	L	H	H	I	IV'	L	H	H	I
V	H	L	L	I	V'	H	L	L	I
VI	H	L	H	I	VI'	H	L	H	0
VII	H	H	L	0	VII'	H	H	L	I
VIII	H	H	H	I	VIII'	H	H	H	0

OUTPUT "0" $\equiv$ RELAY ENERGIZED (SAFE)

OUTPUT "I" $\equiv$ RELAY DE-ENERGIZED (ALARM OR SCRAM)

Figure 12. Truth Table for Flow/Flow Computer

Simplifying by the rules of Boolean Algebra,

$$(PS' + \bar{S}'R) (P'S + \bar{P}'\bar{R}') .$$

Obtaining the dual,

$$(\bar{P} + \bar{S}') (S' + \bar{R}') + (\bar{P}' + \bar{S}') (P' + R') .$$

The above equation is the basis for the logic diagram shown in Figure 10. The final equation is used in dual form in order to obtain a "zero" signal for the "safe" condition to the input of the relay drivers to make the relay operation fail-safe.

Figure 13 shows a condition check on the logic circuit. It has been constructed by substituting all possible combinations of signals levels into the equation on which the logic circuit is based and calculating by inspection the result in each case.

Two independent logic sections are used in the flow/flow computer. One actuates an alarm, the other a scram. The only difference is in the setting of level detector trip values.

One pole of each of the two output relays is used to light one of three lamps to provide a visual indication of state of the ratio of primary to secondary coolant flow. The other set of contacts of each relay is the output of the computer. These contacts are normally open. It requires a "zero" signal on the relay driver to close them. As long as the contacts are closed they hold in another relay which, by its release, actuates the alarm in the alarm channel and the scram in the scram channel.

G. POWER/FLOW COMPUTER LOGIC⁴

The power/flow computer calculates the predicted reactor outlet temperature, T_o , according to the following expression: $T_o = T_{in} + \frac{Cn}{W}$; where

where $T_{in} = \frac{T_1 W_1 + T_2 W_2 + T_3 W_3}{W_1 + W_2 + W_3} = \text{mixed mean core inlet temperature,}$

LOGIC CONDITION CHECK FOR THE EQUATION

$$\left[\bar{P} + \bar{S} \right] \left[S' + \bar{R} \right] + \left[\bar{P}' + \bar{S} \right] \left[P' + R' \right]$$

	$\left[\bar{P} + \bar{S} \right]$	$\left[S' + \bar{R} \right]$	OUTPUT #1		$\left[\bar{P}' + \bar{S} \right]$	$\left[P' + R' \right]$	OUTPUT #2
I	$\begin{bmatrix} 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \end{bmatrix}$	0	I'	$\begin{bmatrix} 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 1 & 1 \end{bmatrix}$	0
II	$\begin{bmatrix} 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 1 & 1 \end{bmatrix}$	0	II'	$\begin{bmatrix} 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \end{bmatrix}$	0
III	$\begin{bmatrix} 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 \end{bmatrix}$	0	III'	$\begin{bmatrix} 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & 1 \end{bmatrix}$	1
IV	$\begin{bmatrix} 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & 1 \end{bmatrix}$	1	IV'	$\begin{bmatrix} 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \end{bmatrix}$	1
V	$\begin{bmatrix} 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \end{bmatrix}$	1	V'	$\begin{bmatrix} 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 1 \end{bmatrix}$	1
VI	$\begin{bmatrix} 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 1 & 1 \end{bmatrix}$	1	VI'	$\begin{bmatrix} 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 \end{bmatrix}$	0
VII	$\begin{bmatrix} 1 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 \end{bmatrix}$	0	VII'	$\begin{bmatrix} 1 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & 1 \end{bmatrix}$	1
VIII	$\begin{bmatrix} 1 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & 1 \end{bmatrix}$	1	VIII'	$\begin{bmatrix} 1 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 \end{bmatrix}$	0

A "0" IS REQUIRED ON THE COMBINATION OF OUTPUT #1 / OUTPUT #2
 TO ACTUATE THE RELAY FOR "SAFE" CONDITION

A "1" ON THE COMBINATION OF OUTPUT #1 / OUTPUT #2 RELEASES
 THE RELAY FOR "TRIP" CONDITION.

Figure 13. Logic Condition Check for Flow/Flow Computer

and T_1 = intermediate heat exchanger primary outlet temperature loop No. 1;
 T_2 = intermediate heat exchanger primary outlet temperature loop No. 2;
 T_3 = intermediate heat exchanger primary outlet temperature loop No. 3;
 W_1 = primary sodium flow rate, loop No. 1;
 W_2 = primary sodium flow rate, loop No. 2;
 W_3 = primary sodium flow rate, loop No. 3;
 W = total sodium flow rate in core = $W_1 + W_2 + W_3$;
 n = core thermal power;
 C = Btu/neutron flux conversion constant.

The controlling functions are T_o , n , and W . Figure 14 shows their relationship to each other and the interrelationship between alarm, setback and scram conditions. One should realize that Figure 14 is not a graph or function in the accepted sense but rather a pictorial expression of the relationship between n , W , and T_o . It is not possible to derive from Figure 14 a functional relationship between those three variables. Figure 15 is a graphic presentation of the safe and trip conditions of the computer. A block diagram depicting the logic used to accomplish this result is shown in Figure 16.

Figure 17 is the truth table for the three variables involved. The geometry of these three variables indicates that conditions I or II or III or VII should cause a safe condition. All others should trip. In Boolean notation the equation reads:

$$(\bar{n} + \bar{W} + \bar{T}_o) (\bar{n} + \bar{W} + T_o) (\bar{n} + W + \bar{T}_o) (n + W + \bar{T}) \text{ (Reference 2)}$$

It is possible to simplify this equation to:

$$(\bar{n} + \bar{W}) (W + \bar{T}_o)$$

The simplified version of the logic was not used because of possible nonfail-safe operation and improper operation when the alarm, setback and scram level detectors are operated from the same inputs.

Figure 14. Power/Flow Computer - Operating Curves

Figure 15. Power/Flow Computer - Safe/Trip Conditions

Figure 16. Power/Flow Computer - Logic Schematic
(Three Required)

	n	W	T_0	OUTPUT	
I	L	L	L	0	OUTPUT "0" = RELAY ENERGIZED (O SAFE)
II	L	L	H	0	OUTPUT "1" = RELAY DE-ENERGIZED
III	L	H	L	0	(ALARM, SETBACK OR SCRAM)
IV	L	H	H	1	
V	H	L	L	1	
VI	H	L	H	1	
VII	H	H	L	0	
VIII	H	H	H	1	

Figure 17. Truth Table for Power/Flow Computer, Exclusive of n_h
(High Neutron Flux Cutoff)

Figure 18 shows a condition check on the power/flow logic circuits.

The high power cut-off n_h is simply tacked onto the above logic through an "OR" function, so that it will always operate regardless of any other computer operation.

		I	II	III	IV	V	VI	VII	VIII
OR#1	$\bar{n}$	0	0	0	0	1	1	1	1
	$\bar{w}$	0	0	1	1	0	0	1	1
	$\bar{T}_0$	0	1	0	1	0	1	0	1
OR#2	$\bar{n}$	0	0	0	0	1	1	1	1
	w	1	1	0	0	1	1	0	0
	$\bar{T}_0$	0	1	0	1	0	1	0	1
OR#3	$\bar{n}$	0	0	0	0	1	1	1	1
	$\bar{w}$	0	0	1	1	0	0	1	1
	T_0	1	0	1	0	1	0	1	0
OR#4	n	1	1	1	1	0	0	0	0
	w	1	1	0	0	1	1	0	0
	$\bar{T}_0$	0	1	0	1	0	1	0	1

		I	II	III	IV	V	VI	VII	VIII
AND#1 INPUT	OR#1	0	1	1	1	1	1	1	1
	OR#2	1	1	0	1	1	1	1	1
	OR#3	1	0	1	1	1	1	1	1
	OR#4	1	1	1	1	1	1	0	1
AND#1 OUTPUT		0	0	0	1	1	1	0	1

→ TO RELAY

Figure 18. Logic Condition Check for Power/Flow Computer

H. POWER SUPPLIES

Power requirement for each flow/flow computer are:

- +15 volts d-c, 205 milliamperes;
- 15 volts d-c, 475 miliamperes;
- +30 volts d-c, 28 milliamperes;
- nominal 6.3 volts a-c for operational amplifiers and lights;
- nominal 6.3 volts a-c phase shifted with respect to the above by 40 electrical degrees to drive input choppers.

Power requirements for each power/flow computer are:

- +15 volts d-c, 350 milliamperes;
- 15 volts d-c, 800 milliamperes;
- +30 volts d-c, 75 milliamperes;
- 6.3 volts a-c as above.

The power supplies for both computers are identical. They consist of:

- 2 each - 12 to 17 volts d-c, 1.5 amperes;
- 1 each - 20 to 30 volts d-c, 150 milliamperes;
- 2 each - transformers, filament type, 6.3 volt, 1.2 amperes.

Each power/flow computer has its separate power supply. Three of the flow/flow computers share a common power source.

IV. OPERATION OF FLOW/FLOW COMPUTER⁴

The core of the HNPF reactor is cooled by the sodium flow in three independent pairs of coolant loops. For the purposes of this discussion these loop pairs will be identified as loops A, B, and C. Each loop contains three of the flow/flow computers identified as computers I, II, and II. Thus the second computer in the third loop would be IIC.

One power supply will operate IA, IB, IC, the second and third power supplies operate IIA, IIB, IIC and IIIA, IIIB, IIIC respectively. An off-normal indication in the coolant flow ratio of loop A requires an indication from two of the three computers, IA, IIA, IIIA. Removal or failure of the power supply that operates IIA, IIB, and IIC for instance would cause a scram on those computers. But it takes an additional trip signal on one of the remaining six computers to actually initiate any action because of the two out of three coincidence feature.

Referring now to Figure 7 which is the complete schematic diagram of the flow/flow computer it will be assumed that the overall gain of the differential "P" and "S" amplifiers has been set equal to 1000/3 by adjusting the 500 ohm potentiometers. The output measured at the 20 mfd capacitor should then be 1 volt for every 3 millivolts of input with indicated polarity. The value of "C" on pin 5 of T-1101 is fixed at 4.2 volts. The output of the multiplier, pin 8 of T-1101 is then adjusted to 0.333 volt by adjusting potentiometer "k." The reading must be taken with a 20,000 ohms-per-volt voltmeter that is well damped. The transfer function G of the multiplier section equals PC/Sk where "P" and "S" are as above, C is fixed at 4.2 volts and $k = 4.2 \times 3$ so that the transfer function reduces to the constant 0.333 when $P = S$. P, S, and C are in compatible voltage units and k is dimensionless. The output of the multiplier is a series of negative pulses clamped at zero. The average value in this example is 0.333. Operational amplifier 2-B averages the output of the multiplier. It has a time constant of 450 milliseconds and a gain of ten. Ripple at the output is ~ 40 millivolts peak to peak.

P and S vary from 0 to 10 volts. Level circuits for P and S have to be tripped at ~ 1 volt for alarm and 2 volts for scram. The best range for tripping the level detectors is 2.5 to 6 volts. Therefore amplifiers 3-A and 3-B are

inserted between P and S and their level detecting circuit to provide a gain of three and also signal isolation.

Two diodes each are shunted across the feedback resistor of the gain amplifier. The 1N713 is a Zener diode having a breakdown voltage of 9.1 volts $\pm 10\%$. This diode limits the output of the amplifier to 9.1 volts. This limiting is necessary to prevent the amplifier from saturating when P and S is larger than about 4 volts. Saturating does not in itself damage the amplifier, but when the input is reduced the amplifier goes through some rather extensive output excursions for about 30 or 40 seconds which would cause false signal indications. The 1N191 is a computer type germanium diode. It prevents a short circuit across the feedback resistor through the Zener diode if the input voltage polarity reverses. This is not likely to occur during normal computer operation but can happen when power is first applied to the unit.

The scram and alarm logic section are identical except for the trip settings of the level detectors. There is no other interconnection between the two sections except that their inputs are common. The input to the T-406 "OR" circuits for both sections is brought out to test jack J-3. There are eight such inputs, but only six of them for each section go to the test jack. Of two complementing input P' and $\bar{P}'$ only one is necessary to adjust the operation of the unit. The presence of the 6.3 volts a-c on J-3 from the xx transformer has been explained previously.

V. OPERATION OF POWER/FLOW COMPUTER

The power/flow computer measures the reactor outlet temperature during steady state operating conditions. During long time thermal transients it predicts what the outlet temperature will be after the transient has died out. The equation that the computer calculates is $T_o = T_{in} + \frac{Cn}{W}$.

The expression $\frac{Cn}{W}$ represents the temperature difference across the reactor core. When T_{in} decreases because more heat is taken out in the intermediate heat exchanger the reactor outlet temperature does not change immediately because of the large thermal inertia in the reactor and the coolant. The computer will, however, immediately predict a new power outlet temperature. The reactor operator then makes the necessary adjustments to maintain proper operating temperature levels.

The computer calculates T_{in} as follows. Coolant flow signals are amplified by amplifiers 1-A, 2-A, and 3-A, Figure 6. The output amplitude for 100% of flow is 10 volts on each channel. Amplifier 5-A sums the three flow input signals and divides the result by three. Division by three is necessary because the amplifier becomes non-linear when its output exceeds about 13 volts and it saturates at 15 volts. The divisor introduced by necessity is compensated for in the multipliers. Amplifier 5-B inverts the calculated W signal, amplifier 8-A multiplies by three and inverts the W signal again to drive the level detectors. Amplifier 8-A is limited by a Zener diode to a total output of 9.1 volts. It only has to be operative in the range when W , at the output of 5-B, is in the range from about 1 to 3 volts which is the tripping level of the detectors. Once the detectors have been tripped additional level increases have no further effect.

Three multipliers are associated with the calculation of T_{in} . They calculate the expressions:

$$\frac{T_1 W_1}{W k_1} ; \quad \frac{T_2 W_2}{W k_2} ; \quad \frac{T_3 W_3}{W k_3} ;$$

where T_1 , T_2 , T_3 , W_1 , W_2 , W_3 , and W are as defined previously. The multiplying constants k_1 , k_2 , and k_3 are equal to each other. When $W_1 = W_2 = W_3$ the expression

$$\frac{T_1 W_1}{W k_1} = \frac{T_1}{k} ;$$

and if $T_1 = T_2 = T_3$ then $T_{in} = \frac{3T}{k}$. The normal operating value of T_{in} will be $\sim 600^\circ\text{F}$.

The remaining one of the seven inputs is "n", proportional to the neutron flux. It is furnished to the computer from the nuclear panel and equals 10 volts for 100% neutron power with the polarity indicated. The signal is divided by three by amplifier 9-A to make it compatible with the division of three performed earlier on W. Amplifier 4-A inverts the polarity of the signal. The fourth multiplier in the power/flow computer calculates $\frac{Cn}{Wk_n}$. C may be varied in value with a potentiometer between the limits of 2 and 10 volts. The averaging/summer 8-B multiplies as it sums T_{in} and also multiplies the ratio $\frac{Cn}{Wk_n}$. At the output of 8-B the resulting T_o is now made up $T_{in} = 3$ volts when the intermediate heat exchanger outlet temperature is 600°F and $\frac{Cn}{Wk_n} = 2$ volts at the output of amplifier 8-B at 100% neutron flux. This corresponds to 400°F temperature rise across the core. T_o full scale is then 5 volts which corresponds to 1000°F outlet temperature. Rewriting the equation for T_o slightly

$$T_o = \frac{T_1 W_1 + T_2 W_2 + T_3 W_3 + Cn}{W_1 + W_2 + W_3}$$

it becomes apparent that T_o can still equal 1000°F at different flow ratios in the three primary loops when the intermediate heat exchanger outlet temperatures of the three loops are also different from each other. It is important that the ratio between T_{in} and neutron flux corresponds to the actual temperature ratio at full power so that the computer will always calculate the correct T_o .

In addition to a trip on high T_o the power/flow computer also has a trip provision at high neutron flux. Three level detectors, one each for alarm, set-back and scram are in the respective logic section. They are designated as n_h in Figure 6. The signal for this trip is derived from the output of amplifier 4-A; its amplitude at 100% neutron flux is 3 volts. This is the same signal that is also one of the inputs of the "n" multiplier. High flux level trips occur at 106%, 115%, and 125% of full neutron flux. The actual trip voltages are therefore 3.18,

3.45, and 3.75 volts for alarm, setback and scram respectively. The level detectors work well at those input levels and the signal requires no further amplification.

The output of the level detectors, after isolation by previously described emitter followers, becomes one of the inputs of a two input "OR" circuit. The other input to this "OR" circuit is the output of the T_o logic. Thus the appropriate output relay will be de-energized when T_o is high or when n_h is high or when both signals are high. It should be recalled that the terminology of "high" refers to calculated signal conditions. Actually a high signal will cause a "1" output on the "OR" circuit which in turn corresponds to a voltage level of -0.5 volts.

Test jack J-3, Figure 6 contains level signals for W_1 , T_o , n and n_h from each of the three logic sections. These signals are used to set up all trip points of the computer and are also quite convenient if it ever becomes necessary to trouble-shoot the computer.

VI. GENERAL COMMENTS

The components of both computers are quite rugged. Both units have been dropped with all power on from a height of 6 to 8 inches onto a hard surface with no damage or output change on the computer. After a number of drops over a period of several weeks one of the pilot lights failed and one of the output meters developed a slight rough spot at about 40% of full scale deflection. It was noted that some of the potentiometers, which are panel mounted, shifted slightly in their setting. This is not surprising since these potentiometers have no locking provisions on the shaft.

Temperature set points of the power/flow computer differ by about 3% between alarm and setback and setback and scram. The computer handles these tolerances quite well after about a 2 minute stabilization period. The stabilization time of the flow/flow computer is on the order of 40 seconds.

None of the plug-in units had to be selected but were installed in the computer chassis at random. None of the operational amplifiers ever has to put out more than 10 volts d-c even at 125% of full signal.

The choppers are the shortest lived components. Their life expectancy is limited to about 2 or 3 years of continuous operation. Some sort of preventive maintenance program should be set up to take care of expected failure.

Each power/flow computer contains 246 transistors and 120 diodes. Three of these units are actively operating in the protective system and an additional unit will be available as a spare. Each flow/flow computer contains 126 transistors and 49 diodes. Nine of these are actively operating in the protective system and an additional unit is available as a spare. A test fixture has been designed to adjust and test both computers. It is shown in Figure 4. Its description and operation will be covered in a separate report.

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