UNCLASSIFIED

# PLAN FOR
# VBWR STABILITY EXPERIMENT

by

W. H. Cook
J. A. Hodde
C. L. Howard
R. O. Niemi

August 30, 1961

Prepared for

United States Atomic Energy Commission

under

Contract AT(04-3)-189, Project Agreement No. 11

Approved by: D H Imhoff
D. H. Imhoff, Manager
Engineering Development

Approved by C. L. Howard
C. L. Howard, Project Engineer
Fuel Cycle Program

General Electric Company
Atomic Power Equipment Department
San Jose, California

UNCLASSIFIED

# TABLE OF CONTENTS

## I. INTRODUCTION

The boiling water reactor has been considered one of the most attractive reactor concepts for central station power generation because of its simplicity. It showed early promise toward favorable economics because of its ease of operation and low capital investment potential. Early in the development of the boiling water reactor, however, reports were obtained of the existence of power oscillations of large magnitude. As a result, much early development work concentrated on the problem of boiling water reactor stability limits. As experience was gained from the first generation of natural circulation boiling water reactors (Borax and EBWR), their stability characteristics became well known. A set of empirical conditions which established limits of stable reactor operation were devised from this experience and the design of subsequent reactors has followed these limits. However, the development of large boiling reactors showing improvements in economics makes the problem of power stability a real concern because the range of operating parameters and accompanying design changes make it clear that the conditions previously considered as limits for stability are far exceeded.

The stability tests to be made under the Fuel Cycle Development Program are directed toward these problems of the large, forced circulation, oxide-fueled reactor operating at high specific power.

## II. SUMMARY

The stability tests are to be made in the VBWR from September to November 1961. The tests are of three types: a) steady state measurements, b) rod oscillator tests, and c) transient tests. In each of these, the readings from in-core and out-of-core instrumentation will be recorded on both oscillograph and magnetic tape recorders. The in-core instruments are located in five instrumented fuel assemblies, each having sensors for inlet flow rate, pressure drop, inlet water temperature, and neutron flux at three elevations in the core. The tests will be repeated at a variety of operating conditions to cover variations in the following parameters: reactor power, recirculation flow rate, pressure drop in the external piping, and core bypass leakage. The different instrumented fuel assemblies represent variations in water to fuel ratio and inlet orificing.

The objectives of the reactor tests are to find the answers to the following types of questions:

1. What is the space dependence of the oscillations in neutron flux? That is, to what extent are the percentage variations in flux equal in amplitude and phase angle over the entire reactor?
2. To what extent are the oscillations in flow in the various fuel channels independent of each other? Are they random events?
3. To what extent does the oscillation in neutron flux drive the oscillation in channel flow? Conversely, to what extent does the random individual

channel flow oscillation drive the flux oscillation? Do the channels with the most voids and greatest void coefficient have the controlling influence?

4. What are the functional relationships between the flow oscillations and the various parameters affecting them?

5. Under what conditions do loop-type oscillations predominate over parallel channel oscillations?

6. What is the natural frequency of the reactor system and what is the gain at this frequency?

7. What is the amount and importance of the high frequency (over 100 cycles/second) component of reactor flux noise? This high frequency component comes from bubble formation and two-phase flow variations.

8. What experimental and analytic techniques are most useful in detecting small oscillations in the presence of random noise?

9. Does the present analytic model predict the same behavior as measured in the reactor? Is a more complex model required?

10. How can these measurements on the VBWR be applied to other reactors at other operating conditions? For instance, how can stability be predicted for a 500 MWe single-cycle boiling reactor having high voids and high specific power?

The overall objective is to make the analysis of stability a "working technology" by which the designer can specify the system requirements necessary for adequate stability in any proposed reactor system. The basis and equations of the present analytic model for calculating reactor stability are presented in this report. The model is based on solutions of the differential equations for two-phase fluid flow.

"Stability" is used in this report to mean relative stability. At steady-state conditions the degree of stability can be indicated as the amplitude of the flux oscillations occurring spontaneously. In a rod oscillator test the degree of stability is indicated as a gain (flux change amplitude per unit reactivity amplitude) which is a function of oscillator frequency. The degree of stability which is required in a reactor system is subject to engineering judgement. Absolute stability in the mathematical sense is, of course, required in any operable system. Absolute instability (diverging oscillations) is not anticipated at any conditions during these reactor tests. If such excessive oscillations occurred, the high flux scram circuits would immediately shut down the reactor.

Other tests under the Fuel Cycle Program proposed to supplement the VBWR tests in 1961 include:

(a) Hydraulic loop tests in the spring of 1962 to investigate the following parameters in a hydrodynamically clean loop: power input, downcomer length, inlet subcooling, and mechanically induced flow oscillations.

(b) Reactor tests in VBWR in the autumn of 1962 to extend the results to the higher reactor power achievable by that time, making a more detailed analysis of the 1961 test results, and extending the usefulness of the analytic model. A multi-node model will probably be formulated.

(c) Hydraulic loop tests in the spring of 1963 to investigate: step changes in flow and pressure, ramp changes in flow and pressure, variations in heated length, and use of heater assembly having the same time constant as $UO_2$ fuel.

## III. DESCRIPTION OF EXPERIMENT

The experiment is described in three sections: (a) experimental procedures, (b) instrumentation, and (c) data reduction and analysis.

### A. Experimental Procedure

The test specifications to be used will be divided into five procedures:

Test Sequence Procedure. This will give the schedule of test runs and will specify the means of reaching the desired test conditions. Since normal operating procedures will be used, references to the normal procedures will supply the detailed steps required. The following procedures give the tests to be made at each condition.

Steady-State Measurements. This will specify the means of recording the steady-state variations in the various parameters.

Rod Oscillator Tests. This will specify the procedures for operating the rod oscillator mechanism, the amplitudes and frequencies to be used and appropriate safety considerations.

Transient Tests. The means of introducing the transients, their magnitude and the amount of change to be permitted before restoring the system to the original steady-state values will be specified.

Data Recording Procedures. These will specify the variable to be recorded on each recorder channel, length of recording, and means of recording scale factors and zero suppression values.

The essence of the Test Sequence Procedure is Table I, which gives the tentative test conditions and sequence. The test conditions are tentative until completion of detailed core calculations shows that the burnout margin is satisfactory at each limiting condition. The conditions marked with an asterisk (*) are contingent upon completion of a new burnout correlation based on recent experimental work. It is thought that this new correlation will raise the burnout limit by 10 to 30% at the conditions of interest to the VBWR.

Recirculation pump No. 2 flow can be controlled by either the pump discharge valve or the speed of the pump. One column in the table gives the method of control. This determines external loop resistance which is thought to be a controlling factor in loop-type hydraulic oscillations.

The criteria used in selecting this sequence were:

1. Minimize the number of reactor shutdowns.
2. Maximize the average reactor power.
3. Minimize changes in low flow scram settings and high power scram settings.
4. Maximize spread of experimental conditions within the limits of the reactor system.

At each of these experimental conditions steady-state measurements will be made and at most of the conditions rod oscillator tests will be made. Transient tests will be made only at a limited number of conditions.

The rod oscillator tests will include oscillation of control rod 7 (center rod) at frequencies between 3 and 0.01 cycles per second and amplitudes such that the reactivity insertion is less than ≤ 10 cents. A high flux scram will be set at 125% of the average power to insure that power changes do not become excessive. The response to the rod oscillation will be recorded on the flux, flow, termperature and pressure instruments.

The transient tests will consist of recording the response to "step changes" in recirculation flow, steam flow, feedwater flow and control rod position. In practice, step changes cannot be achieved, but this will be approached as closely as possible with the existing reactor system.

Safety criteria to be included in the procedures will include the following:

1. The power-flow relationship at the scram settings for power and flow will be such that a burnout margin of at least 1.5 is maintained at all times, including the transient following accidental loss of a recirculation pump.
2. Neutron flux transients or oscillations, as indicated on the external ion chambers, will always be maintained within ≤ 25% of the nominal value. The high flux scram setting will be within 25% of the nominal power during all rod oscillation and transient tests.
3. Operation of test equipment will be only by persons specifically instructed in the particular operating requirements and authorized by the reactor test programs engineer.
4. Operation of the rod oscillator will be started only from a steady-state condition. Operator will monitor at all times the recorder traces of rod position and neutron flux to insure that amplitude-frequency limits for the oscillator mechanism and reactor flux oscillation limits are not exceeded. At each new test condition the rod oscillator amplitude will be started at zero and increased cautiously to the desired value.

## B. Instrumentation

This section will describe the in-core and out-of-core instrumentation, and the readout equipment.

### 1. In-Core Instrumentation

All in-core instrumentation has been designed primarily around three instrumented fuel assemblies which belong to the Fuel Cycle Program and two others which belong to the High Power Density Research and Development Program. Each fuel assembly will contain a flow-meter, six thermocouples, three ion chambers and two pressure drop systems.

The Fuel Cycle assembly drawing is shown in Figure 1. Sections B and C show a cross-section of the fuel bundle in the assembly. Two diagonally adjacent center fuel rods have been removed. In their place an instrumentation probe will be placed which consists of two dummy rods. One of the rods contains the three ion chambers, located at the lower quarter point, mid-point and upper quarter point with respect to the active fuel. A flux-wire guide tube is also located in this rod. The other rod contains stainless steel-sheathed instrument leads for three thermocouples located in the flow stream just below the fuel bundle. Partial Section E shows the positioning of the thermocouples. The web between the two instrument tubes contains an instrument lead from a turbine-type flowmeter situated in the nosepiece of the assembly. Another three thermocouples are positioned just above the fuel bundle. The use of three thermocouples allows for spares in the event of thermocouple failure. The readout equipment is designed to permit reading either temperature below the fuel, temperature above, or the temperature rise across the fuel.

The pressure drop system makes use of three pressure taps, one located below the fuel (shown in partial section E), one above the fuel and one at the top of the riser portion of the assembly. It is thus possible to monitor the pressure drop across either the fuel or the riser. A back flow system is included to occasionally purge th pressure lines of steam voids. The backflow water is provided from the reactor feed pump. In operation, when drift in the pressure drop signal is observed, solenoid valves may be remotely opened from the readout panels allowing the backflow water to purge the pressure lines of steam voids. Diaphragm-type pressure transducers provide a fast response readout of the pressure drops.

The instrument probe has been designed so that it can be removed from the assembly for repair or replacement of the instruments.

In addition to three instrumented fuel assemblies described above, which were fabricated under the Fuel Cycle Program, an additional two assemblies will be in the core during the stability tests. These latter two assemblies were fabricated under the High Power Density Research and Development Program. The instrumentation of these two assemblies is similar in type and location to the three Fuel Cycle instrumented assemblies. The main differences between the two types of assemblies are in the fuel geometry. These differences are summarized in Table II.

Prior to irradiation of the assemblies, the instrumentation will be calibrated in the General Electric Heat Transfer Facility in San Jose, California. During the stability experiment a flux wire irradiation test will be performed to calibrate the ion chambers.

## 2. Out-of-Core- Instrumentation

In addition to the instrumentation provided by the three Fuel Cycle and two High Power Density instrumented assemblies, the following instrumentation will be provided:

(a) Out-of-core neutron flux. A gamma-compensated ion chamber located at the neutron window of the VBWR reactor vessel will be used. The neutron window is at the south face of the reactor vessel, positioned vertically to see the neutron flux approximately half-way up the active core height. The signal from this ion chamber is led to an existing micro-microammeter.

(b) Reactor vessel pressure. A fast response (Pace reluctance transducer) pressure transducer will be positioned to read the gauge pressure in the steam line leaving the reactor vessel.

(c) Reactor circulation pumps No. 1 and 2, feedwater and mainsteam flows. A fast response differential pressure transducer (Pace, reluctance-type) will be positioned to read the pressure drop across the ASME flow nozzles in the reactor recirculation loops No. 1 and 2, the feedwater line and the main steam line.

(d) A linear potentiometer located on the control rod oscillator mechanism will be used to provide a signal of the control rod position. This potentiometer will indicate the position within a range of plus or minus one inch of the mean control rod level. The mean level will be read from the control rod position indicators on the reactor control panel. It is thus possible to know the position of the control rod to within about 0.03 inches or 1/1000 of the full control rod travel.

(e) The conventional process control instruments installed in the system will be utilized for steady-state measurements. Figure 2 is a diagram of the VBWR reactor system.

## 3. Rod Oscillator Mechanism

This mechanism is designed to impart a sinusoidal position displacement of variable amplitude and frequency to a VBWR control rod. It consists primarily of two sub-assembly members: a frame and an actuator arm pivoted to the frame. A double acting hydraulic cylinder is pinned to each member for actuation. Additionally, a linear motion potentiometer is pinned to the frame with the slide rod connected to the actuator arm such that the output from the potentiometer is directly proportional to the position of the actuator arm.

The mechanism is pictured in Figure 3. In this picture the hydraulic piston is seen between the two support frame members at the upper left of the picture, a servo-valve unit is shown at the center and the actuator arm is shown at the bottom. Two support arms, one of which is shown just to the right of the servo-valve, are fastened to the drive screw split nut of the control rod drive. When installed, the free end of the actuator arm extends under the split nut carriage and bears on a wear plate installed on the control rod drive "stop." Thus, during rod oscillation the oscillator mechanism drives the rod down and the operating air of the control rod drive system provides the force for the return stroke. In the event of a scram, rod movement will be as if the oscillator were not installed. Rod separation limit switches are actuated by a roller arm in contact with the oscillator mechanism. This arrangement allows the rod to be oscillated without actuating the separation switches, but restricts the total peak-to-peak movement to two inches.

Rod oscillation is achieved by controlling the flow of fluid to the double-acting hydraulic cylinder with a servo valve. The fluid is supplied to the pressure port of the valve by a wobbling plate piston pump unit equipped with a variable bypass relief valve allowing a maximum operating pressure range of 0 to 2500 psi. Flow of hydraulic flud, hence rod position and oscillation, is controlled by means of a rod position servo control circuit. In operation of this circuitry, a generated sine wave is amplified by a feedback amplifier to control the servo valve, initiating fluid flow to drive the hydraulic cylinder. The position signal supplied by the feedback potentiometer is summed with the generated signal, supplying an error signal to the amplifier to reposition the servo valve. Thus a sine wave displacement of the control rod is obtained. Amplitude of stroke length is controlled by the amplitude of sine wave voltage input to the amplifier. Remote readout of rod position is taken from the feedback potentiometer and recorded. Frequency is controlled by adjustment of an audio amplifier which supplies power to a synchonous motor which drives a circular "sinepot," to generate the reference sine wave.

### 4. Read-Out System

A special fast-response readout system was designed for recording 20 parameters during the experiment. The system is shown schematically in Figure 4. Signals from a total of 51 possible locations are brought to the switchboard represented on the left in **Figure** 4. Out of these 51 variables, any twenty may be selected for recording during one test run. The twenty signals are each put through a "signal conditioning" circuit in which their direct-current components are removed, the signal is amplified and any 60 cycle electrical noise is filtered.

Twelve of the signals will be simultaneously recorded on a 12-channel tape recorder and on 12 direct-writing oscillograph channels. Eight of the signals will be recorded only on the remaining 8 direct writing oscillograph channels. The frequency response of the direct writing oscillographs is flat from DC to approximately 30 cycles per second. The response of the tape recorder is flat from DC to about 2500 cycles per second.

## C. Data Analysis

Four methods of data analysis will be used on the parameters recorded during the experiment.

1. A visual examination of the data will be made after the signals have been recorded. A qualitative estimate of frequency and phase relationships of the signals will be determined. From these examinations a judgement will be made of the most appropriate parameters to record for the subsequent test runs.

2. The frequency analyzer, shown schematically in Figure 5, will be used to determine amplitudes versus frequency of some parameters. In practice, the frequency analyzer will be used in conjunction with the tape recorder. After a given signal has been recorded on the tape, it will be played back into the frequency analyzer. One playback will be required for each frequency to be analyzed. A complete

determination of frequency versus amplitude for the range of interest (0.01 frequency 10 cps) will take about one hour. However, it is evident that this must be done after the test is completed and will not require reactor time.

3. Two signals on the tape recorder will be played back simultaneously into an analog type of cross-correlation analyzer. The analyzer is pictured schematically in Figure 6. By this method it will be possible to determine the phase relationship between the two signals.

4. A portion of the tape recorded signals will be played back into an analog-to-digital converter. The signal will be sampled at some specified interval, say 40 times per second, by the converter and the samples will be stored on magnetic tape or computer cards.* The stored digital information may then be analyzed by a digital computer. An autocorrelation-cross correlation-statistical analysis computer program has been prepared for the digital analysis of the data.

The two analog data analysis schemes described in items 2 and 3 above are intended to complement the digital data analysis scheme described in Item 4. It turns out that the analog schemes are less costly and more accurate at higher frequencies, particularly above about one-third of the frequency of the analog-to-digital conversion sampling rate. Conversely, the digital scheme is more accurate and less costly in the low frequency range of interest. It is intended that the former schemes be used to analyze primarily for higher frequencies (above, say 1 cycle per second) and that the latter scheme be used primarily below this frequency. In some cases a concurrent reduction of data will be done by both schemes to verify the accuracies of the digital versus the analog data analysis

---

*An equivalent, but less efficient method of making the analog-to-digital conversion is by a manual method. This method will be used only on selected parameters not recorded by the tape recorder. The cost of the manual conversion process is approximately 15 times the cost of the automatic process.

## IV. ANALYTICAL MODEL

This section describes the analytical model in use for the VBWR stability experiment. A comparison is made of the parameters defined in the analytical model with variables chosen for both reactor and loop tests.

### A. Approach to Analytical Work

The usual course of development of methods for predicting physical phenomena is:

1. Establishment of the most simple model estimated to be capable of predicting the physical event. This is based on fundamental theoretical concepts as understood at that time.

2. Experimental determination of the range of applicability of the model, if any.

3. Revision of the model to extend its range of applicability or improve its accuracy. This may involve the addition of more variables or complete rejection of the original model in favor of a different one.

The approach to the problem of predicting boiling water reactor stability is basically outlined above. The reactor system model is based on feedback control theory. The various models that make up the total system model are reasonably well known with the exception of the hydraulic model. This particular model is derived from straightforward applications of the basic principles of momentum conservation, energy conservation and continuity. The introduction of a time delay term and the use of average values permits the reduction of the equations from space-time functions to functions only of time. The hydraulic model is believed to be as simple as possible and yet be capable of predicting the hydrodynamic phenomena.

The reactor system model equations are non-linear. To obtain a solution for small perturbations, the equations have been linearized about the operating point. The parameters have been normalized so that variations are given in terms of percentages of normal operating values. Each of the six original equations are relatively simple in appearance; however, the mathematical solution transforms them into a relatively complex form.

The combination of reactor tests and hydraulic loop tests will define the range of applicability and accuracy of the model. Since the biggest unknowns of the reactor system model are in the hydraulics model, it is evident that the out-of-pile hydraulic loop tests will be an efficient method of testing the accuracy of the assumptions made in the hydraulics model.

The efficiency of the loop tests arises because the experimental parameters may be varied over wider ranges and are not subject to so many physical and thermodynamic restrictions, the safety considerations are less severe in the loop, access for instrumentation is easier, and equivalent amounts of data may be obtained in hydraulic loop experiments for less money. However, it is also necessary to verify that the hydraulics model will function properly as a member in the feedback loop of the reactor system model and that the assumptions in the system model are valid. For this latter reason the reactor tests are vital.

## B. Description of Reactor System Model

The logic block diagram for the reactor system model is shown in Figure 7. As indicated above, the reactor system model is composed of a reactor kinetics model which describes the effect of six groups of delayed neutrons. A derivation of the equation defining this model may be found in many standard reference books$^{(1),(2)}$. The fuel model duplicates the time delay between fission heat generation in the fuel by thermal neutrons and conduction through the fuel and cladding to the coolant. The void coefficient of reactivity model is the expression of either calculated void coefficient of reactivity, or, preferably, measured data.

## C. Description of Hydraulic Model

The hydraulics portion of the feedback network is the distinguishing feature of the analytical model. It is described in Reference (3). It has its origin in the principles which were developed for the steady-state calculation of two-phase flow$^{(4)}$. These principles were broadened to include the transient behavior of vertical two-phase flow$^{(5)}$ and the resulting analytical model has produced predictions which correspond well with experimental data$^{(6)}$. Initially the transient analytical model was confined to only natural circulation solutions. During the course of this investigation, however, the model was modified to accept forced circulation problems.

The transient two-phase flow model is based on an analysis which was developed for the description of a single node natural circulation loop$^{(5)}$. In this single node model, shown in Figure 8, the heat is added at a single point, the initial boiling boundary. The vertical lengths in the system are important in the gravity head terms while the total lengths are important in the inertia terms.

The analysis can be described by a system of six equations, given below, which are established on the basic physical principles of momentum, energy and continuity. In particular, the relationship of steam voids to quality is not based on steady state data correlations of steam voids to quality, steam velocity ratios, or steam velocity and water velocity differences. The steam to water velocity relationship is derived from basic momentum principles and should, therefore, be capable of more accurate description of transient processes than empirical correlations of steady-state experimental data. The quality, voids, and steam and water velocities are related through the continuity equation.

Five of the six equations are applied directly to a description of the flow behavior in the two-phase region of the loop and the remaining equation relates the pressure contribution of the downcomer or external loop to that of the two-phase region.

The equations are:

Momentum-steam phase
(Steam velocity-water
velocity relationship)

$$\Upsilon + F_{WS}\frac{(S-W)^2}{2}\left(1-x+\frac{x}{\beta}\right)\delta(R)+\frac{W^2}{2}\left[\mathrm{POLY}(u)\right]\frac{K_R}{L_E+L_{RZ}}=0 \quad (2A)$$

Momentum - Combined Steam and water phases

$$\pi + \left(\frac{1 - R(1 - 1/\beta)W^2 - V^2}{L_B + L_{RZ}}\right) +$$

$$+ \left(\frac{L_B + L_R}{L_B + L_{RZ}}\right)\left(\left[1 - R(1 - 1/\beta)\right]\frac{dW}{dt} - \frac{dR}{dt}\left[W(1 - 1/\beta)\right]\right) + \qquad (3A)$$

$$+ (1 - R)S + \frac{W^2}{2}\left[\frac{F_{WR}L_R + F_{WH}L_B + K_R}{L_B + L_{RZ}}\right]\left[\mathrm{P_{OLY}}(u)\right] = 0$$

Volume condition at point of heat addition (x = 0) (Combination of energy and continuity)

$$R(S - W) + W =$$

$$V(1 + \alpha - \alpha\beta) + (\beta - 1)\gamma \qquad (4A)$$

Water volume condition at point of heat addition (x = 0) (Combination of energy and continuity alternate form)

$$(1 - u)W = V(1 + \alpha) - \gamma \qquad (5A)$$

External loop pressure drop equation (Friction and momentum)

$$\pi + S - \frac{V^2}{2}\left[\frac{K_D + K_H + F_{WD}L_D + F_{WH}(L_H - L_B)}{L_B + L_{RZ}}\right] + \qquad (6A)$$

$$+ \left[\frac{\mathrm{P_{OLY}}(P)}{L_B + L_{RZ}}\right] - \left[\frac{(L_D + L_H - L_B)}{L_B + L_{RZ}}\right]\frac{dV}{dt} = 0$$

Time delay, relationship of average void fraction to void fraction at boiling boundary. This is also a measure of the transit time of a void variation across the two-phase section

$$R = \frac{1}{L_B + L_{RZ}} \int_0^{L_B + L_{RZ}} u \, dx \tag{7A}$$

In Laplace transfer form

$$\frac{R}{\mu} = \frac{1 - e^{-\mu}}{\mu}$$ where $\mu$ = complex Laplace operator

or approximately: $$\frac{d^2R}{dt^2} + \frac{6}{T}\frac{dR}{dt} + \frac{12}{T^2} R = \frac{12}{T^2} U$$

where:

$\pi$ = Average two-phase pressure gradient divided by liquid density, $\frac{1}{\rho_w}\left(\frac{\Delta P}{\Delta L}\right)$

S = Average steam velocity, feet per second

W = Average water velocity, feet per second

V = Inlet velocity at fuel element, feet per second

$\alpha$ = Subcooling factor = $\frac{h_w - h_{sc}}{h_{fg}}$ = $\frac{\text{subcooling enthalpy}}{\text{vaporization enthalpy}}$

$\beta$ = $\rho_s/\rho_w$ = ratio of steam to saturated water density

$\gamma$ = Heat factor = $\frac{Q}{A \rho_w h_{fg}}$ = heat input per unit flow area divided by product of water density and vaporization enthalpy.

$\delta(R)$ = Polynomial in average void fraction, steam-water shear force relationship

u = Void fraction at boiling boundary after heat input

R = Average void fraction in two-phase section

t = Time, seconds

T = Transit time of void fraction change from point of heat input to exit

$L_D$ = Length of downcomer (external Loop) feet

$L_H$ = Length of heated section (fuel), feet

$L_B$ = Length of boiling section, feet; $L_B = L_H\left(1 - \frac{\alpha V}{\gamma}\right)$

$L_R$ = Length of riser, feet

$L_{RZ}$ = Vertical length of riser, feet

$x$ = Quality, percent

$K_D$ = Sum of loss coefficients in downcomer or external loop, expressed relative to velocity V.

$K_H$ = Sum of loss coefficients in single phase section of heated section.

$F_{ws}$ = Shear coefficient relating drag between steam and water phases. ($ft^{-1}$)

$F_{WD}$ = Friction factor in downcomer or external loop relating friction pressure drop in terms of velocity, V. ($ft^{-1}$)

$F_{WH}$ = Friction factor in single phase heated region relating pressure drop to velocity, V. ($ft^{-1}$)

Poly (P) = $b_0 + b_1 V + b_2 V^2 + \cdots\cdots + b_n V^n$ , a polynomial relating pump head to velocity.

Poly (u) = two-phase friction multiplier for shear stress on wall as function of void fraction

$F_{WR}$ = Friction factor in single phase riser relating pressure drop to velocity, V. ($ft^{-1}$)

The six equations which comprise the hydraulics model are non-linear in form. Loop flow dynamics can be investigated for small distrubances about the steady-state condition, by the linearization and normalization of these non-linear equations. The solution of these equations yields the variables in terms of percent of steady-state values. The normalized and linearized equations have the following form for constant boiling length.

$$\pi^* = 2(S-W)^* + K_1 R^* \qquad (2B)$$

$$\frac{dW^*}{dt} = K_6 R^* + K_7 \pi^* + K_8 w^* + K_9 V^* + K_{10} W^* K_{11} \alpha^* \qquad (3B)$$

$$(S-W)^* = -R^* + K_2 W^* + K_3 V^* + K_4 \gamma^* + K_5 \alpha^* \qquad (4B)$$

$$\frac{dV^*}{dt} = K_{12} \pi^* + K_{13} \gamma^* + K_{14} V^* + K_{15} \alpha^* \qquad (5B)$$

$$U^* = K_{16} W^* + K_{17} V^* + K_{18} \gamma^* + K_{19} \alpha^* \qquad (6B)$$

$$\frac{d^2R^*}{dt^2} = K_{20} U^* - K_{21} \frac{dR^*}{dt} - K_{20} R^* \qquad (7B)$$

The coefficients $K_i$ are functions of the geometrical conditions and the initial steady-state conditions. They are relatively long expressions, but for each set of conditions the $K_i$'s are constants.

For variable boiling length the linearized, normalized equations are of the form:

$$\pi^* = C_1 (S - W)^* + C_2 R^* + C_3 W^* + C_4 V^* + C_4 \gamma^* - C_4 \alpha^* \qquad (2C)$$

$$\frac{dW}{dt}^* = C_8 S^* + C_9 \pi^* + C_{10} R^* + C_{11} W^* + C_{12} V^* + C_{13} \gamma^* + C_{14} \alpha^* \qquad (3C)$$

$$(S-W)^* = R^* + C_5 W^* + C_6 V^* + C_7 \gamma^* - C_7 \alpha^* \qquad (4C)$$

$$\frac{dV}{dt}^* = C_{15} \pi^* + C_{16} S^* + C_{17} V^* + C_{18} \gamma^* + C_{19} \alpha^* \qquad (5C)$$

$$U^* = C_{20} V^* + C_{21} W^* + C_{22} \gamma^* + C_{23} \alpha^* \qquad (6C)$$

$$\frac{d^2R^*}{dt} = C_{24} U^* + C_{25} \frac{dR^*}{dt} + C_{26} R^* \text{ approximation for } \frac{1-e^{-\mu}}{\mu} \qquad (7C)$$

The coefficients ($C_i$) are functions of the geometrical conditions and the initial steady state conditions, as were the $K_i$. The parameters involved in the coefficients $C_i$ are the same as those appearing in the set of equations 2A through 7A.

In Table III is a summary of the parameters which can be varied. The table compares the test loop and the reactor from the standpoint of conducting tests with variable parameters. The greater flexibility of the test loop is apparent.

An analog model of the reactor system will be used to predict the performance of the reactor for the various test conditions. Comparison of the analog data and the reactor data will yield the effectiveness of the model. The variation of test parameters will aid in locating the specific strengths and weaknesses of the model so that whatever revisions are necessary can be made.

# REFERENCES

1. Glasstone, S., Principles of Nuclear Reactor Engineering, Van Nostrand, New York, 1955.

2. Schultz, M. A., Control of Nuclear Reactors and Power Plants, McGraw-Hill, New York, 1955.

3. Case, J. M., "Neutron and Parallel Flow Channel Coupling Effects on the T-7 Flux Trap Reactor," GEAP 3508.

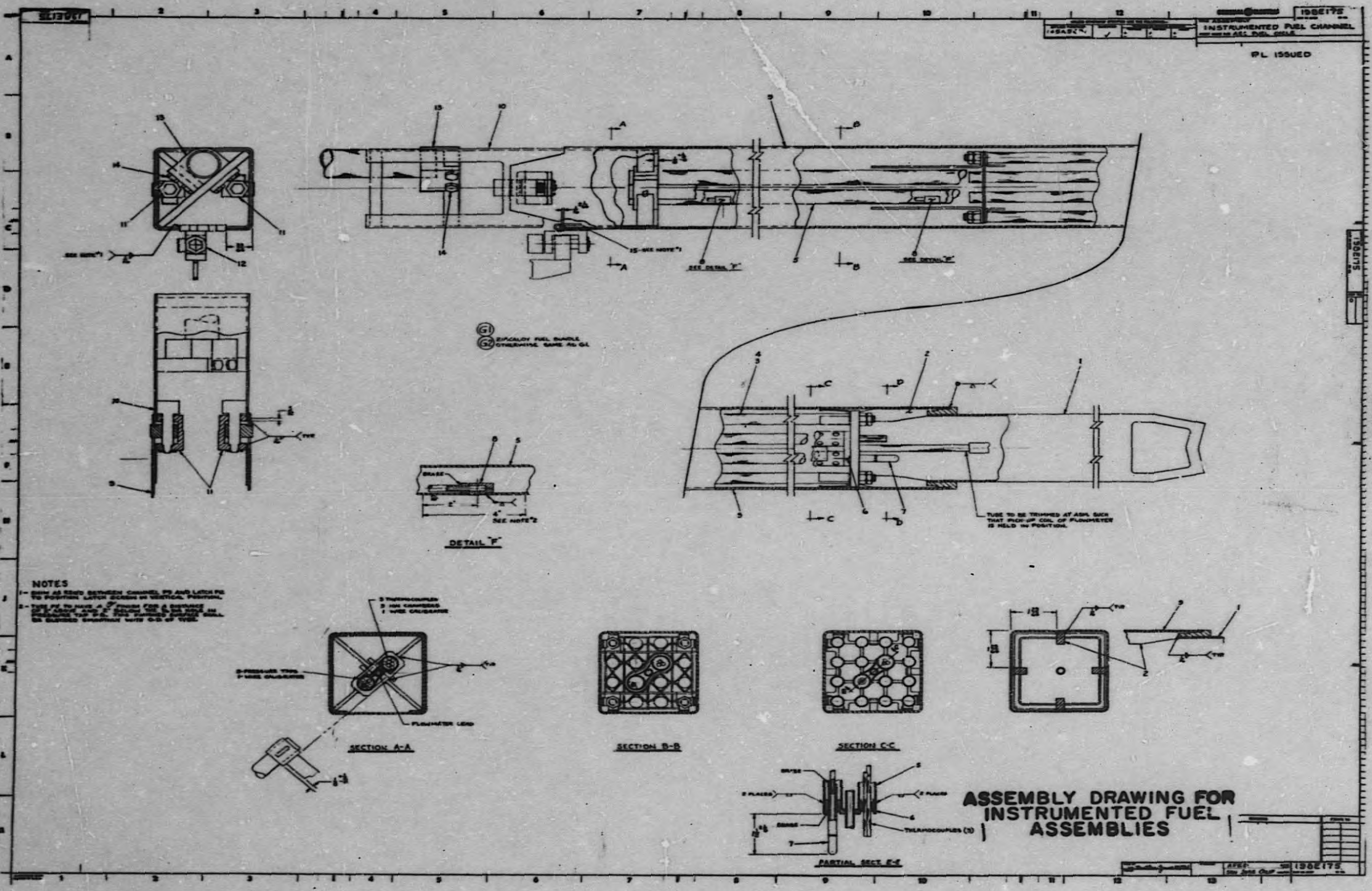
4. Beckjord, E. S., and Harker, W. H., "The Steady-State Calculation of Vertical Two-Phase Flow," GEAP 3261.

5. Beckjord, E. S., "The Stability of Two -Phase Flow Loops," GEAP 3493 (Revision 1).

6. Quinn, E. P., and Case, J. M., "Natural Circulation Loop Performance at 1000 psia Under Periodic Accelerations," GEAP 3397 (Revision I).

## LIST OF FIGURES

## LIST OF TABLES



ASSEMBLY DRAWING FOR INSTRUMENTED FUEL ASSEMBLIES

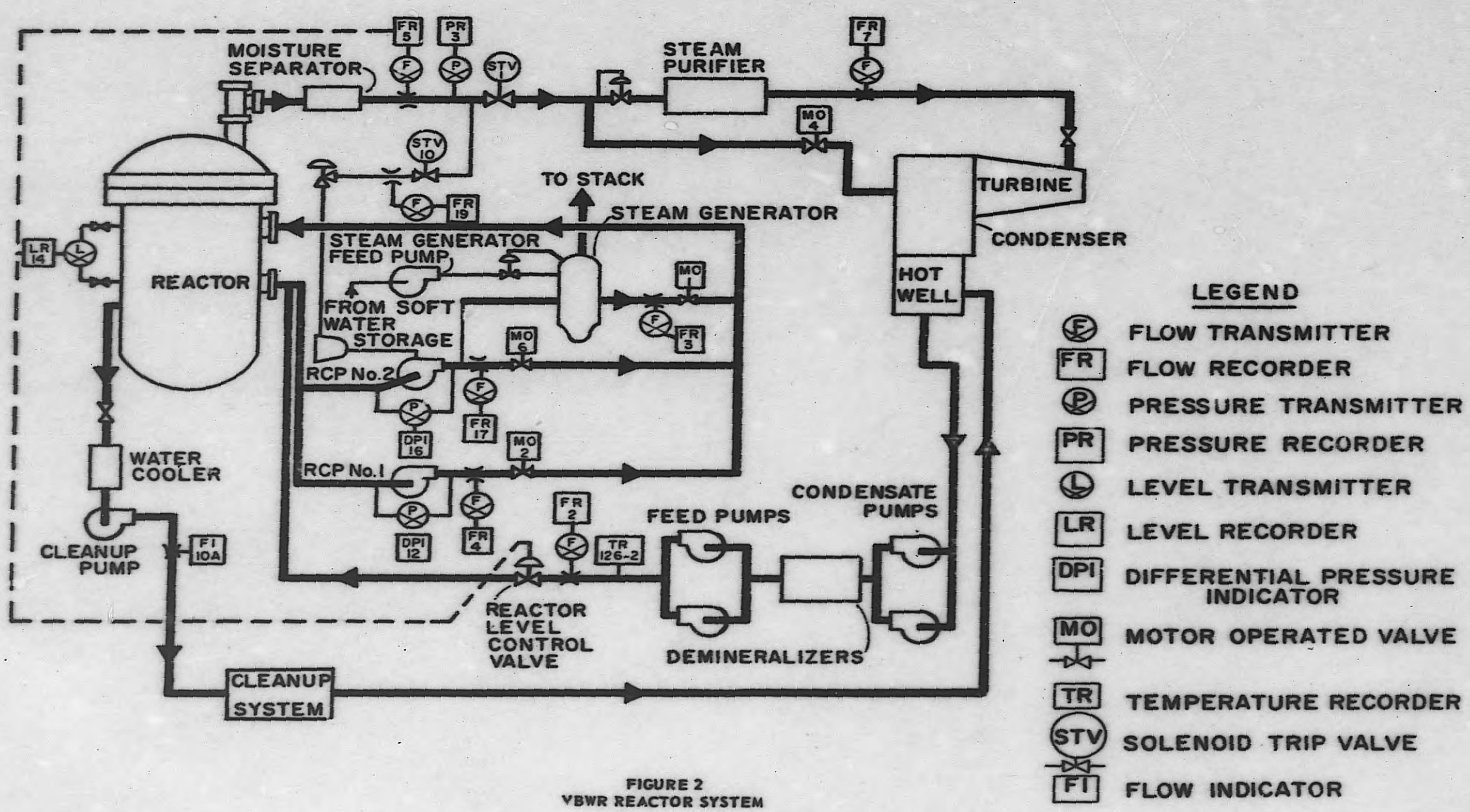


FIGURE 2
VBWR REACTOR SYSTEM

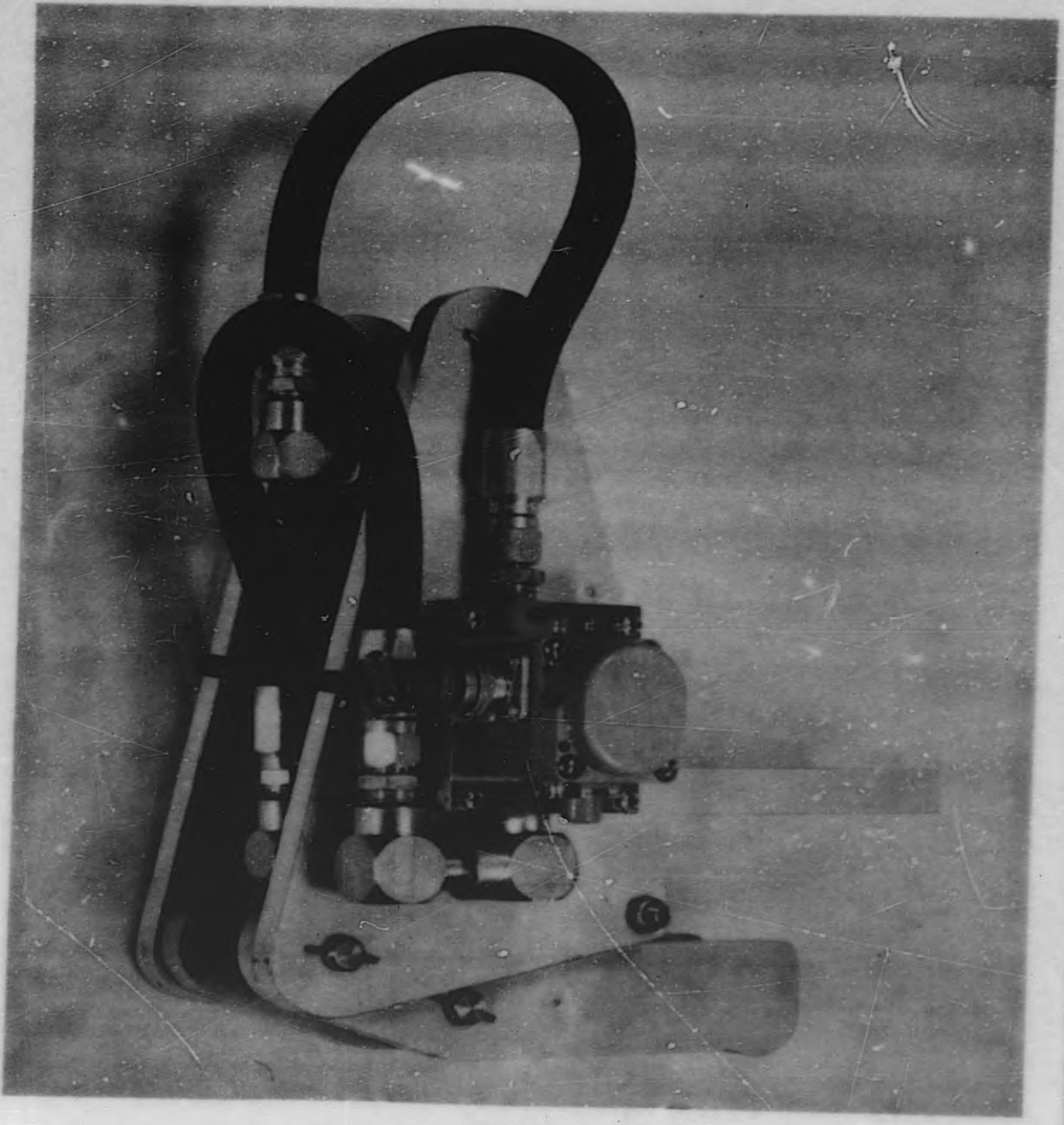


FIGURE 3
ROD OSCILLATOR ASSEMBLY

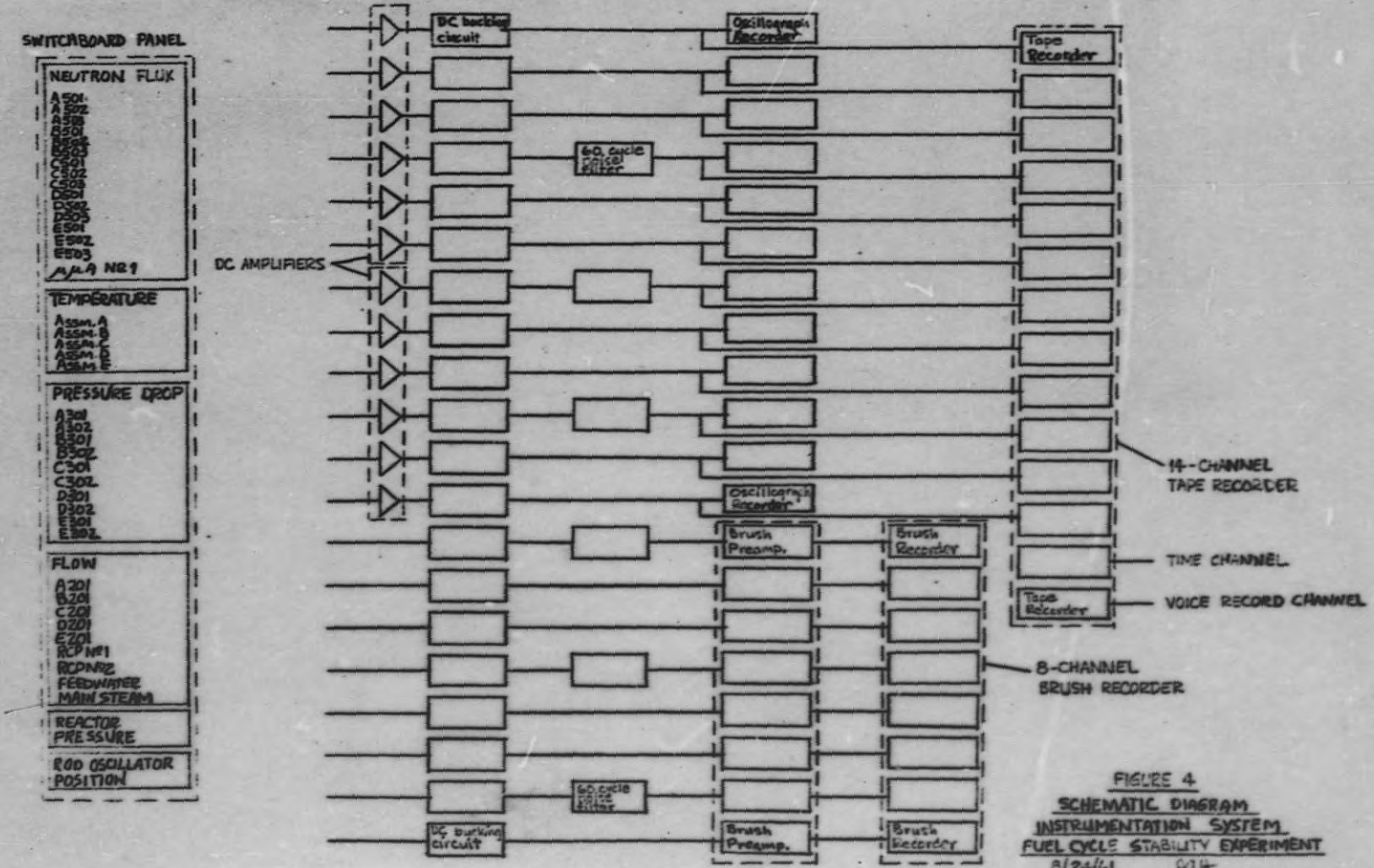


FIGURE 4

SCHEMATIC DIAGRAM

INSTRUMENTATION SYSTEM

FUEL CYCLE STABILITY EXPERIMENT

8/24/61 gah

FIGURE 5
FREQUENCY ANALYZER

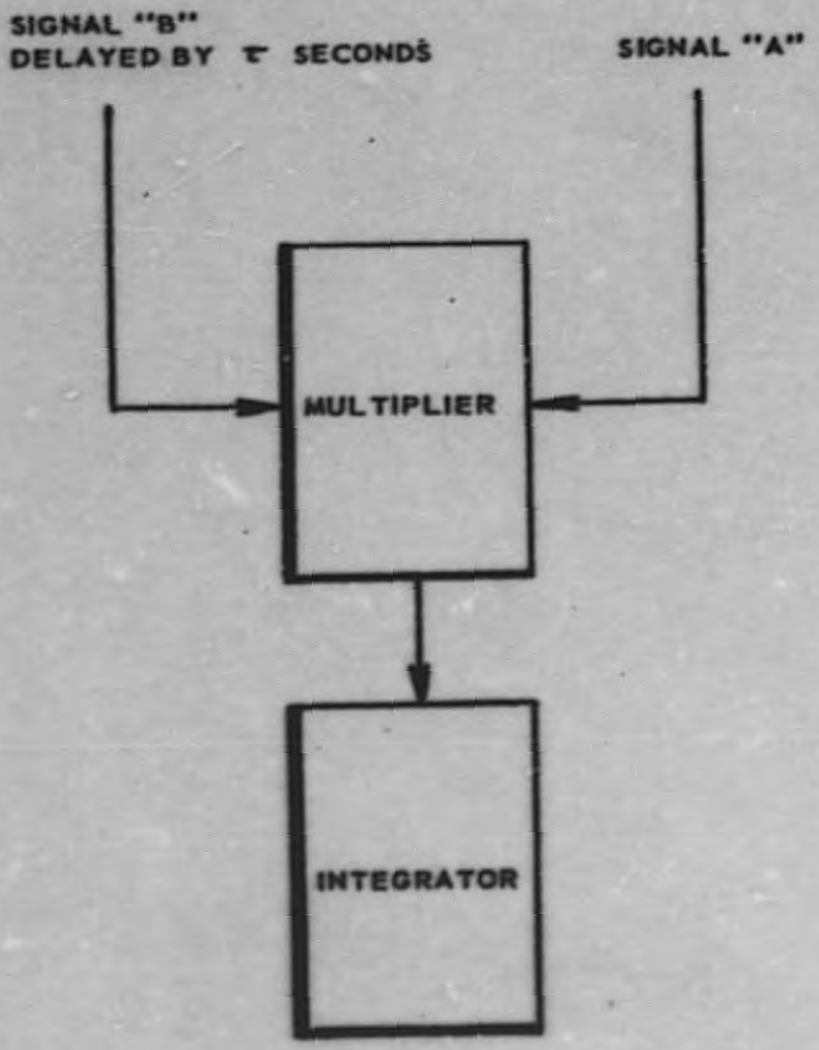


FIGURE 6
ANALOG CROSS-CORRELATING ANALYZER

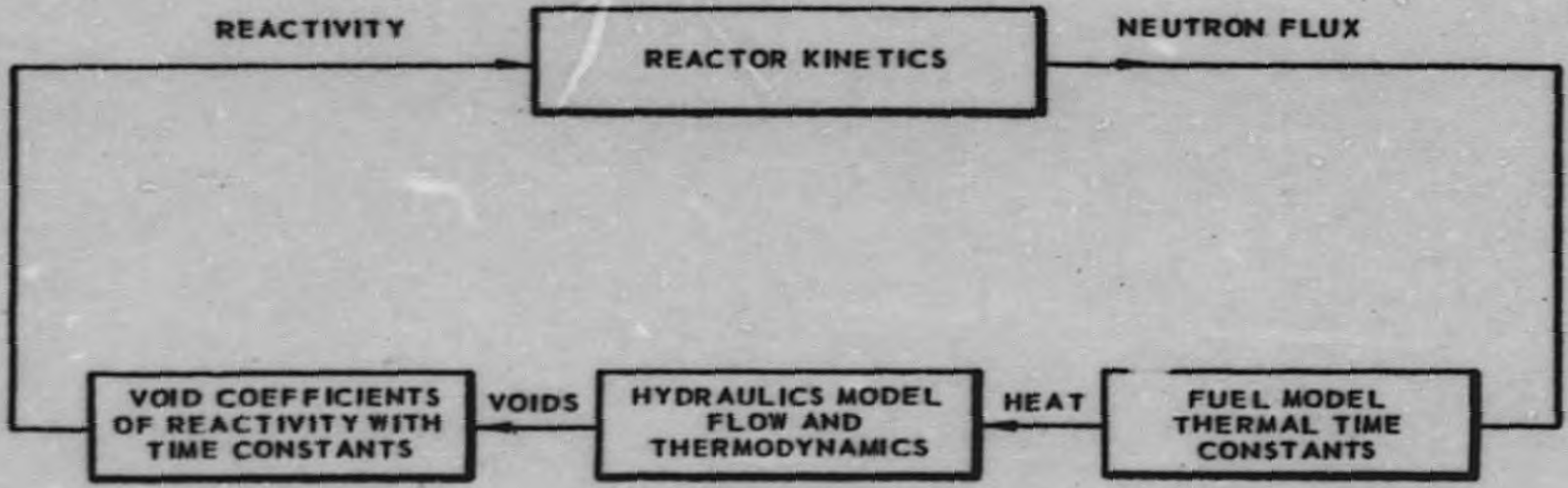


FIGURE 7
LOGIC BLOCK DIAGRAM OF REACTOR ANALYTICAL MODEL

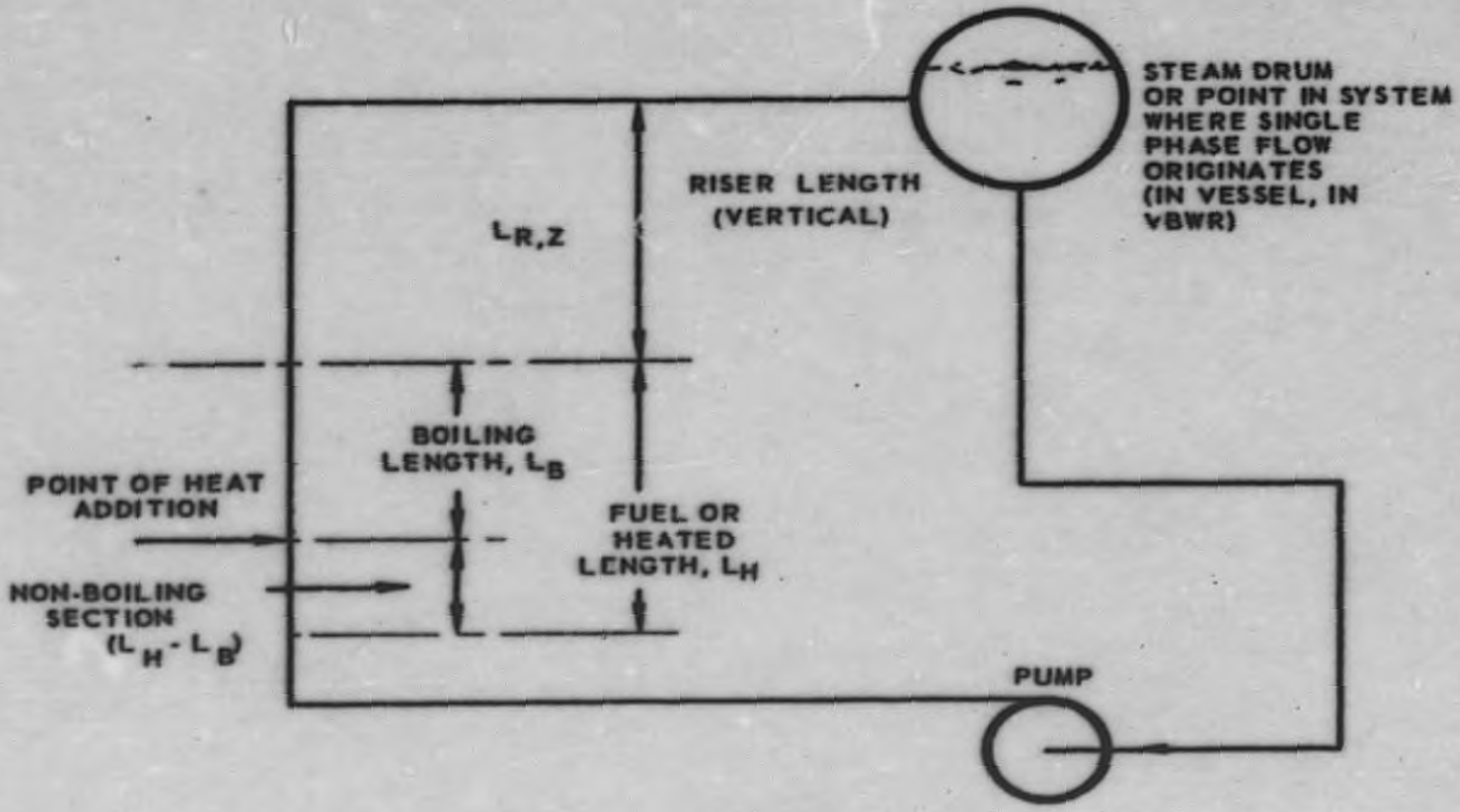


FIGURE 8
SINGLE NODE HYDRAULICS MODEL

# TABLE I
## STABILITY TEST SEQUENCE

| Test No. | Power MWT | Flow 1000's gpm Loop 1 | Loop 2 | Total | Pump 2 Control | Remarks |
|---|---|---|---|---|---|---|
| 0-1 | ½ | 13 | 0 | 13 | -- | Zero power test & Instrument check. |
| 30-1 | 30 | 10 | 10 | 20 | -- | Reference Test |
| 30-2* | 30 | 13 | 0 | 13 | -- | Min. Resistance |
| 30-3* | 30 | 10 | 3 | 13 | Valve | High Resistance |
| 22.5-1 | 22.5 | 10 | 10 | 20 | -- | |
| -2 | 22.5 | 13 | 0 | 13 | -- | Min. Resistance & Water level change test. |
| -3* | 22.5 | 10 | 0 | 10 | -- | High Resistance |
| -4 | 22.5 | 0 | 10 | 10 | Speed | Min. Resistance |
| -5 | 22.5 | 10 | 3 | 13 | Valve | High Resistance |
| 15-1 | 15 | 10 | 10 | 20 | -- | |
| -2 | 15 | 13 | 0 | 13 | -- | Min. Resistance |
| -3 | 15 | 10 | 0 | 10 | -- | High Resistance |
| -4 | 15 | 0 | 10 | 10 | Speed | Min. Resistance |
| -5 | 15 | 10 | 3 | 13 | Valve | High Resistance |
| Max-1 | Max | 10 | 10 | 20 | -- | Not at Xenon Equilibrium |
| 30-4 | 30 | 10 | 10 | 20 | -- | Ref. condition re-test & Water level change test |
| --- | -- | -- | -- | -- | -- | Change low flow scram settings |
| 15-6 | 15 | 0 | 4 | 4 | Speed | Min. Resistance |
| -7 | 15 | 0 | 7 | 7 | Speed | Min. Resistance |
| -8 | 15 | 3 | 4 | 7 | Valve | Max. Resistance |
| 22.5-6 | 22.5 | 0 | 4 | 4 | Speed | Min. Resistance |
| -7* | 22.5 | 0 | 7 | 7 | Speed | Min. Resistance |
| -8* | 22.5 | 3 | 4 | 7 | Valve | Max. Resistance |

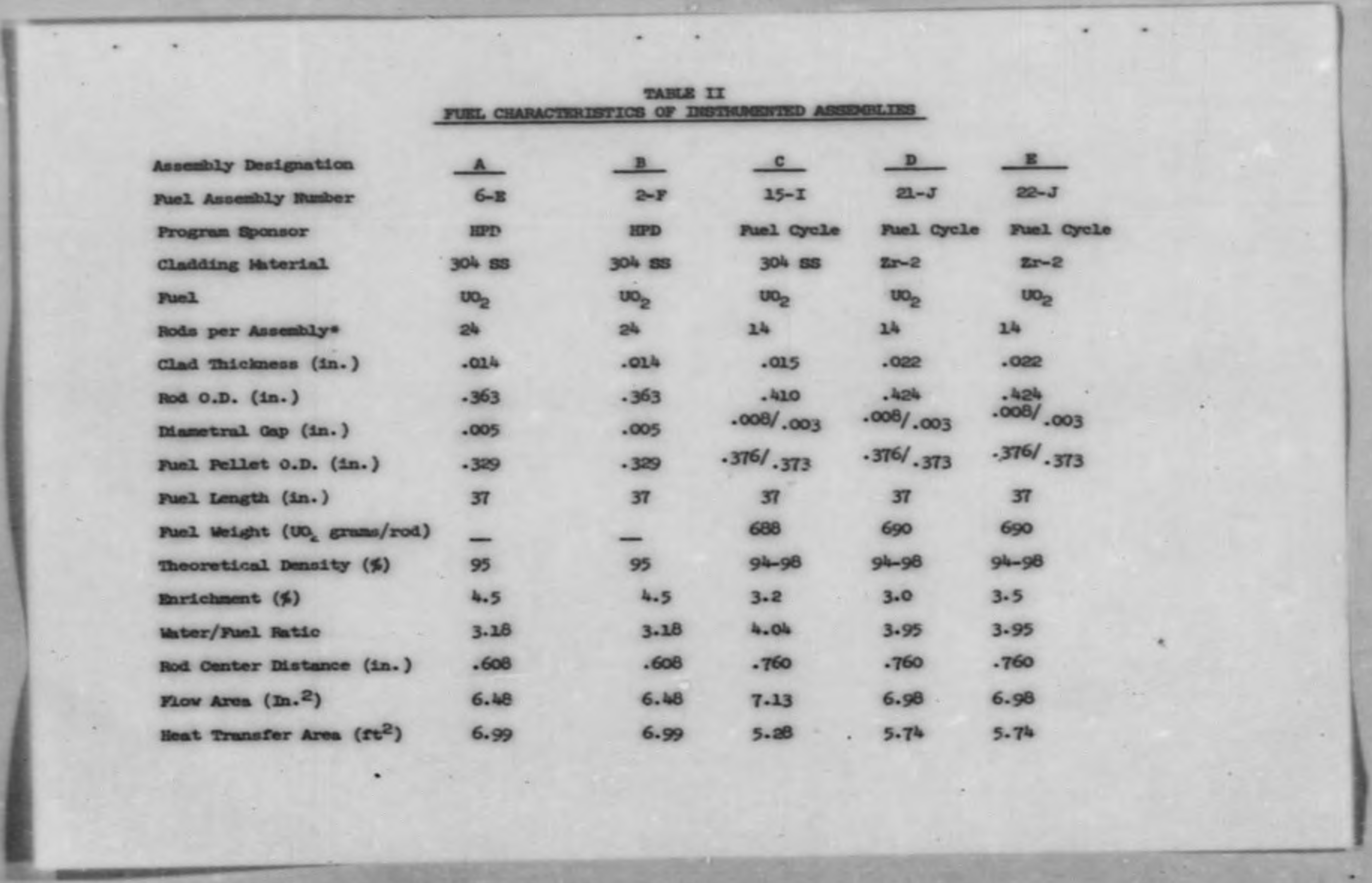
TABLE 1 - STABILITY TEST SEQUENCE (Cont.)

| Test No. | Power MWT | Flow 1000's gpm Loop 1 | Loop 2 | Total | Pump 2 Control | Remarks |
|---|---|---|---|---|---|---|
| S.D. | -- | -- | -- | -- | -- | Remove 3 channel plugs; Change low flow scrams. |
| 0-2 | ½ | 13 | 0 | 13 | -- | Zero Power re-test |
| 30-5 | 30 | 10 | 10 | 20 | -- | |
| 22.5-9 | 22.5 | 13 | 0 | 13 | -- | |
| S.D. | -- | -- | -- | -- | -- | Change to natural circulation; replace channel plugs. |
| 15-9 | 15 | -- | -- | -- | -- | |
| Max | Max | -- | -- | -- | -- | |
| S.D. | -- | -- | -- | -- | -- | Remove orifice from instrumented assembly (may be deleted, depending on previous results) |
| 30-6 | 30 | 10 | 10 | 20 | -- | |
| 30-7* | 30 | 13 | 0 | 13 | -- | |
| 22.5-10 | 22.5 | 10 | 10 | 20 | -- | |
| 22.5-11 | 22.5 | 13 | 0 | 13 | -- | |
| 22.5-12* | 22.5 | 10 | 0 | 10 | -- | |
| 22.5-13 | -- | 0 | 10 | 10 | Speed | |

---

*Operation at these conditions is contingent upon use of a burnout heat flux correlation approximately 30% higher than the present correlation.

S.D. - Reactor Shutdown



## TABLE II
## FUEL CHARACTERISTICS OF INSTRUMENTED ASSEMBLIES

| Assembly Designation | A | B | C | D | E |
|---|---|---|---|---|---|
| Fuel Assembly Number | 6-E | 2-F | 15-I | 21-J | 22-J |
| Program Sponsor | HPD | HPD | Fuel Cycle | Fuel Cycle | Fuel Cycle |
| Cladding Material | 304 SS | 304 SS | 304 SS | Zr-2 | Zr-2 |
| Fuel | $UO_2$ | $UO_2$ | $UO_2$ | $UO_2$ | $UO_2$ |
| Rods per Assembly* | 24 | 24 | 14 | 14 | 14 |
| Clad Thickness (in.) | .014 | .014 | .015 | .022 | .022 |
| Rod O.D. (in.) | .363 | .363 | .410 | .424 | .424 |
| Diametral Gap (in.) | .005 | .005 | .008/.003 | .008/.003 | .008/.003 |
| Fuel Pellet O.D. (in.) | .329 | .329 | .376/.373 | .376/.373 | .376/.373 |
| Fuel Length (in.) | 37 | 37 | 37 | 37 | 37 |
| Fuel Weight ($UO_2$ grams/rod) | — | — | 688 | 690 | 690 |
| Theoretical Density (%) | 95 | 95 | 94-98 | 94-98 | 94-98 |
| Enrichment (%) | 4.5 | 4.5 | 3.2 | 3.0 | 3.5 |
| Water/Fuel Ratio | 3.18 | 3.18 | 4.04 | 3.95 | 3.95 |
| Rod Center Distance (in.) | .608 | .608 | .760 | .760 | .760 |
| Flow Area (In.$^2$) | 6.48 | 6.48 | 7.13 | 6.98 | 6.98 |
| Heat Transfer Area (ft$^2$) | 6.99 | 6.99 | 5.28 | 5.74 | 5.74 |

## TABLE III
## STABILITY MODEL PARAMETERS

| Parameter | Test Loop | Reactor |
|---|---|---|
| 1. **Inlet Orificing** | | |
| a. Loop oscillation - vary single phase resistance | *Possible | Requires large number of orifices, major shutdown. |
| b. Parallel channel oscillation - single phase resistance | *Possible - requires parallel channel arrangement | **Orifice one element or group of elements. |
| 2. **Subcooling,** | *Control with heat exchanger. | Use dual cycle. |
| 3. **Fuel Section** | | |
| a. Heated length, $L_H$ | Possible. | Fixed with present design. |
| b. Friction - two-phase section. | | |
| (1) uniform, $F_{WB}$ | May be difficult | Extremely difficult and costly - not planned. |
| (2) exit, $K_B$ | *Possible - use orifice | Not planned - inconvenient at present time - possible burnout. |
| (3) spacer, $K_B$ | Possible by changing spacers. | Difficult at this time. |
| c. Velocity, V | *Controlled primarily by recirculation flow. | **Controlled by recirculation flow, change flow in individual element by changing orifices. |
| 4. **Riser Section** | | |
| a. Length, Vertical $L_{RZ}$<br>Horizontal $(L_R-L_{RZ}$ | *Variable<br>Variable | Channel fixed.<br>Variation not planned, difficult. |
| b. Area, $A_R$ ('a' and 'b' influence two-phase transit time) | *Variable. | Fixed. |

TABLE III - STABILITY MODEL PARAMETERS (Cont.)

| Parameter | Test Loop | Reactor |
|---|---|---|
| c. Friction | | |
| (1) uniform, $F_{WR}$ | *variable - use egg crate type structure. | Possible - not planned. |
| (2) exit, $K_R$ | *variable - orifice at exit | Possible - not planned. |
| (3) spacer, $K_R$ | *Variable - change spacers | Possible - not planned. |
| (4) inlet - same as fuel exit | *Variable | Possible - not planned. |
| | | These changes are possible, but not convenient. |
| 5. **External Loop** | | |
| a. Length, $L_D$ (momentum) | *Variable. | Fixed. |
| b. Area, $A_D$ | Variable - not planned since equations do not indicate any influence directly, indirectly see friction below. | Fixed. |
| c. Friction, $F_{WD}$ Vary valve resistance, important in loop type oscillation. | *Planned - variable, valve resistance and pump speed varied. | **Planned, vary valve resistance and pump speed. |
| 6. **Quality at Exit** (Also exit voids) | *Variable - function of power input, subcooling, flow rate. | **Variable - function of power, flow rate and subcooling. Tests planned. |
| 7. **Pressure Level** | Variable - tests at 1000 psi planned. | Variable - tests at **1000 psi planned. |
| 8. **Parallel Channel Oscillation** | | |
| a. Bypass leakage path variation | Possible in parallel channel arrangement. | **Variable - Remove channel plugs. |
| b. Natural circulation | Possible. | **Planned. |

TABLE III - STABILITY MODEL PARAMETERS (Cont.)

| Parameter | Test Loop | Reactor |
|---|---|---|
| 9. Capacitance | | |
| a. Fuel | Possible, but not simple. | Fixed. |
| b. Riser | Variable - planned. | Fixed: extremely difficult except at exit. |
| 10. Physics | | |
| a. Void coefficient | Not possible. | Not controllable. Test data to be analyzed to determine the effects of these parameters. |
| b. Doppler coefficient | Not Possible. | |

---

* Loop tests planned.

** Reactor tests planned.