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A fluid control system for nuclear reactors

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A FLUID CONTROL SYSTEM FOR NUCLEAR REACTORS

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ABSTRACT

This thesis presents both an experimental and analytical analysis of the scram characteristics of a fluid control system for a nuclear reactor. This control system utilizes a control tube containing a neutron-absorbing fluid. The level of the fluid inside of the tube is then regulated by means of a pressurized gas and offers a number of unique advantages over the conventional control rod system using linear absorber rods.

The effect of varying the level-control pressure and initial height of the fluid column is determined and evaluated. The time required to complete a scram with the fluid control system is compared to the rod drop times of an operating reactor.

The dynamic response of the liquid control system during scram was found to be as fast or faster than a linear-control-rod system of an operating reactor.

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LIST OF SYMBOLS

Ar	Cross sectional area of the reservoir, ft^2
At	Cross sectional area of the control tube, ft^2
F	Instantaneous force acting upon the fluid, lb
Fl	Friction losses due to fluid flow, lb
g	Acceleration of gravity, ft/sec^2
g_c	Gravitational constant, lb_m-ft/lb_f-sec^2
hr	Instantaneous height of the fluid in the reservoir, ft
hro	Initial height of the fluid in the reservoir, ft
hrf	Final height of the fluid in the reservoir, ft
ht	Instantaneous height of the fluid in the control tube, ft
hto	Initial height of the fluid in the control tube, ft
htf	Final height of the fluid in the control tube, ft
k	Ratio of specific heats
L	Length of resistor leg, ft
Pa	Atmospheric pressure, psfa
Po	Pressure inside of the reservoir when the fluid in the control tube is at the 0-inch level, psfa
Pr	Instantaneous gas pressure inside of the reservoir, psfa
Pro	Initial pressure inside of the reservoir, psfa
Rb	Constant electrical resistance in parallel with the brush recorder, ohms
Rx	Resistance of the resistance leg, ohms
t	Wall thickness, ft

Vb	Voltage drop across the brush recorder, volts
Vi	Voltage input from D. C. power supply, volts
VL	Voltage drop across resistor leg, volts
Vo	Initial gas volume in the reservoir, ft^3
Vr	Instantaneous gas volume in the reservoir, ft^3
XL	Height of the reservoir, ft
γ	Fluid specific weight, lb/ft^3

I. INTRODUCTION AND LITERATURE SURVEY

A number of means have been devised to control the rate of the neutron chain reaction in a nuclear reactor. Basically, however, they depend upon the movement of fuel elements, neutron absorbers, moderator or reflector. Each of these methods of control has been used or proposed in various reactor design concepts (1)*. Present technology, however, relies primarily on the use of a linear neutron-absorbing rod which is allowed to move vertically through the heterogeneous core of a reactor.

While this means of control has proved effective, there are a number of inherent disadvantages. The first such disadvantage is the excessive length required for the pressure vessel in order to permit withdrawal of the control rods. Since the rod is driven in and out of the core, the primary-containment vessel must be at least twice the height of the core. With this design, however, when the rods are removed, a liquid moderator is often allowed to fill the remaining void. In such a case, the neutron flux may "peak" in these areas and cause excessive power production in the adjacent fuel elements (1). Since these fuel elements have a maximum operating temperature, the operating temperature level of the entire core must be lowered so that the temperatures at these "peaks" do not exceed the maximum

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*Numbers in parenthesis refer to reference listed in the Bibliography.

allowable value. As a result, the overall system efficiency is reduced.

One solution to this problem has been to attach a non-absorbing, non-moderating follower below the control rod proper. This follower will fill the void left by the control rods eliminating the problem of flux peaking while also preventing increased coolant flow through the control rod channel. The primary disadvantage of this solution is that it adds another core length to the minimum height of the pressure vessel.

Another disadvantage of linear control rods has been their weight. A control section proper will weigh from 50 to 100 pounds and, with the rod drive included, the weight is raised to from 100 to 300 pounds (2). Since up to 89 control rods have been used in a pressurized water power reactor, support structures are often necessarily quite large and complex (3).

The placement of control rods within the core lattice is often based on a compromise between reactor physics and engineering requirements (2). Control-rod drives must be spaced a sufficient distance apart to allow for operating clearance, and experience has shown that sufficient space should be left to allow for easy installation, maintenance, and replacement.

The use of linear control rods requires a rather complex mechanism to permit reactor scrams. A means must be incorporated to quickly drive the rods into the core even when all power is lost. One method presently used is to hold the lead screws on the rod drives with an electromagnetic locking device; if power is lost the electromagnet releases the rod allowing it to fall under the force of gravity. It has also been found necessary to employ some sort of shock absorber to decelerate the rod when it has been fully inserted into the core. This prevents damage to the rods and core support structure by eliminating the severe shock when the control elements strike a rigid structure.

While it is certainly not a common occurrence, linear control rods have been known to bind and stick in the reactor core. This situation could prevent proper control of the reactor possibly resulting in damage to the reactor core. The one reactor accident that has occurred in this country that resulted in fatalities involved a reactor with rods that had a history of "sticking".

One alternative to the use of linear control rods has been the utilization of a cylindrical control element. These control elements are constructed so that 180° of the element is composed of a neutron absorber and the other 180° of a neutron moderator. When this section is rotated the rate of neutron absorption and moderation is varied. Unfortunately, these elements may only be used in the periphery of the core because the poisoned section is not completely withdrawn.

In order to develop a control system which will not encounter most of these problems, a fluid neutron absorber system was investigated. Both gas (4) and liquid (5) absorbers have been proposed but, while both appear practical, consideration was given here only to the liquid absorber system.

II. DISCUSSION

Fluid Control Systems

A schematic diagram of the proposed system is shown in Figure I (6). The absorber section consists of a non-absorbing, non-reflecting tube extending through the core and into a sealed reservoir located below the core. The tube is completely filled with a neutron absorbing liquid while a small volume of inert gas is allowed to remain in the reservoir. When a pressure is applied to the liquid in the top of the tube, it is forced into the reservoir, compressing the inert gas. Slowly varying the pressure applied to the fluid in the tube will regulate the height of the fluid column in the core. In case of a scram, the pressure at the top of the tube is released through the scram solenoid valve, allowing the gas in the reservoir to expand, driving the level of the neutron absorbing fluid to above the core.

The gas pressure on the fluid-absorber column is to be fed from a high-pressure supply through a modified dead-end-type pressure regulator. A schematic drawing of the regulator is shown in Figure II. The regulated-gas pressure coming from the valve is controlled by the movement of the diaphram inside the valve. The diaphram pushes against a spring and the tension of the spring and the downstream pressure are adjusted by the control knob. Should the

SCHEMATIC OF THE FLUID CONTROL SYSTEM

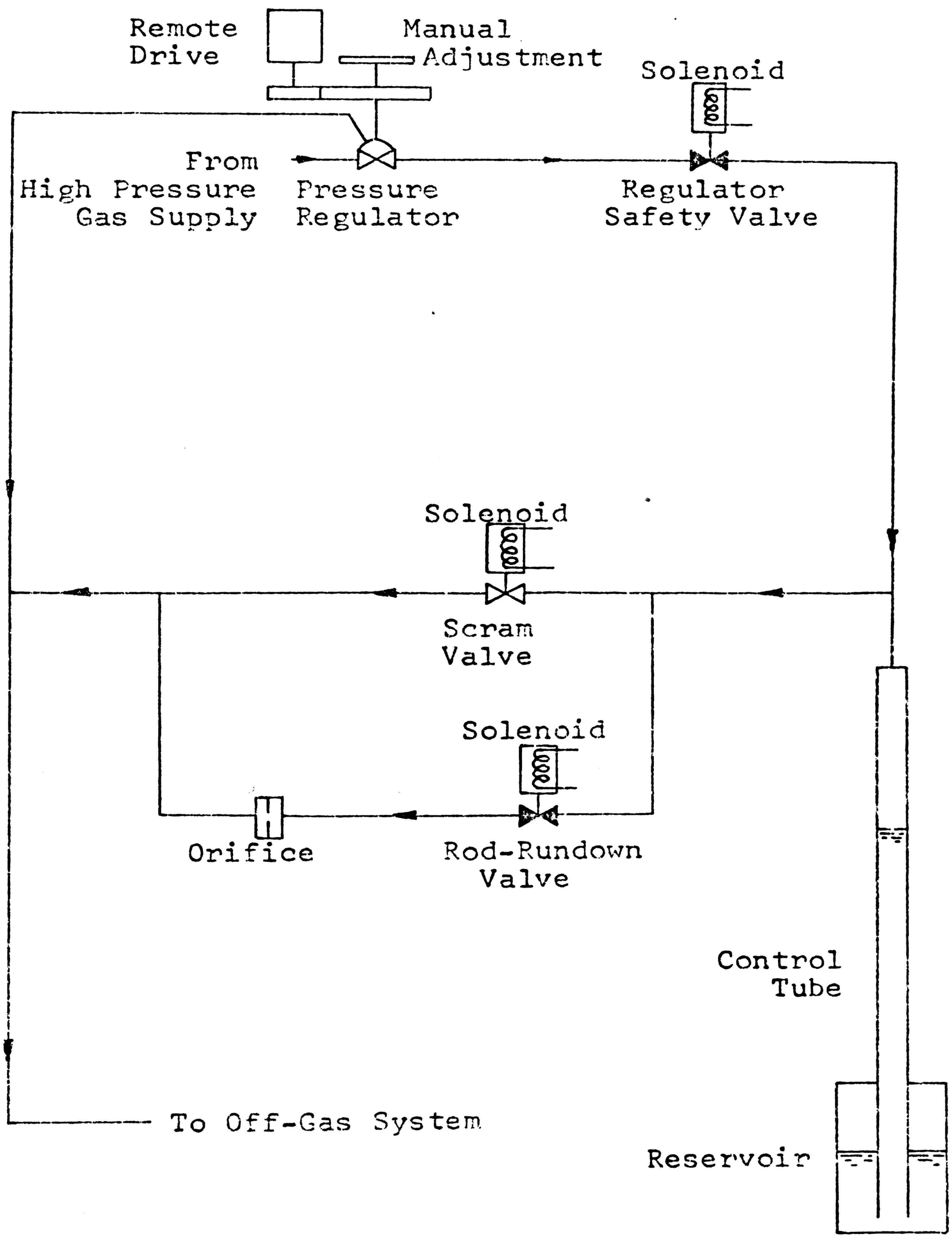

FIGURE I

downstream pressure drop below the desired value, the spring will push against the reduced pressure thereby enabling it to expand. This movement of the spring in turn opens a valve plug allowing high pressure gas to flow downstream. As the downstream pressure approaches the desired value, the spring is recompressed, gradually closing the valve plug. Should the downstream pressure exceed the predetermined value, the bellows compresses the spring exposing a hole in the bellows, thereby allowing system pressure to escape. The pressure regulator is modified so as to prevent the leakage of radioactive air to the atmosphere.

Some precaution must be taken in case of a regulator failure. This could be accomplished by using a regulator safety valve in series with the regulator. Should the regulator fail, a scram signal would be activated such that the circuit containing the solenoid on the regulator safety valve would be broken, stopping the flow of high pressure gas to the control rod.

The scram mechanism is quite simple. It consists of a single line leading from the level control line through a normally-open scram solenoid valve into the off-gas system. When the scram signal is activated, power to the solenoid is interrupted, opening the valve. This releases pressure in the control system allowing the neutron absorbing fluid to rise to a level above the core.

MODIFIED PRESSURE REGULATOR

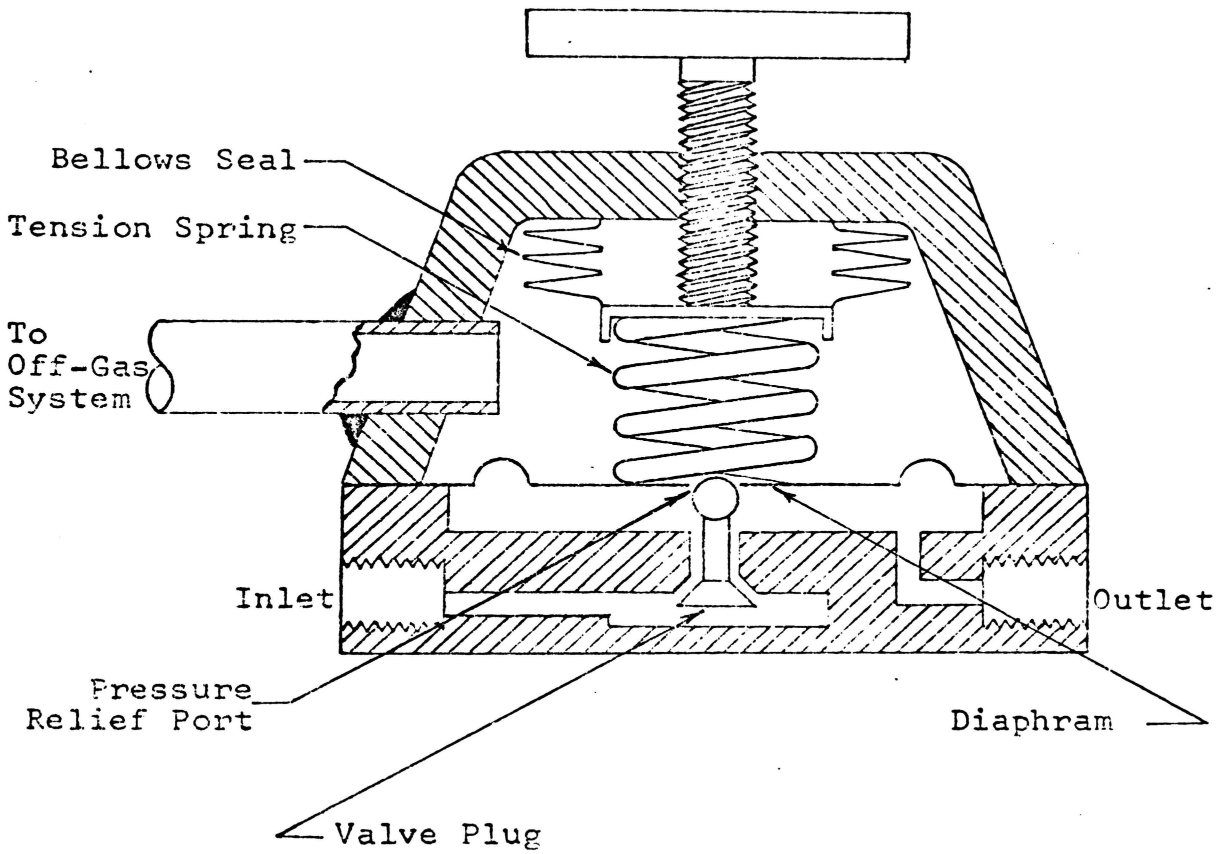

FIGURE II

The equivalent of a rod run-down is obtained in the liquid control system by having a normally closed solenoid valve in parallel with the scram valve. The rod run-down valve discharges to the off gas system through a small orifice. When this valve is activated, the regulator safety valve is automatically closed, thereby allowing pressure in the control system to be slowly "bled off".

The "rod prohibitive" condition is achieved by simply interrupting the power to the regulator safety valve. Thus the liquid control system has the capability of "rod prohibitive", "rod run-down", and "scram" actions.

This fluid control system has a number of inherent advantages. The control section can be made in almost any desirable geometry; that is, thin plates, straight or spiral tubes, or tubes of varying cross section. Components are all simple, reliable, and relatively inexpensive. There are no in-core moving parts and all electrical connections may be made outside the primary vessel (a possible exception might be the remote-level indicator). Repeatability, the time lapse between the instant that a signal is emitted to stop rod movement and the time when the rod actually stops, (2) is an important design consideration. While certain types of electrical motors, because of their momentum, will continue to drive the rod for a short interval after power is interrupted, no such problem should occur with the fluid control system. It is also expected that the fluid control system will be more efficient; while the linear control rod and the fluid control system should appear "black" to thermal neutrons, the water in the fluid solution will also thermalize fast neutrons so that they may be more easily absorbed. Finally, the fluid control system would be relatively compact, requiring only enough extra room in the primary vessel for a reservoir at the top or the bottom of the core.

In view of these basic design considerations, this investigation was undertaken to gain further information on the feasibility of this concept. Of primary concern is the reaction of such a system during a scram. A test section was built to study the dynamic response of such a system and to obtain a comparison with the response of a conventional control rod system.

Description of Scram-Test Apparatus

The reservoir was constructed as shown in Figure III. It consists of a 5-inch section of 3.75-inch aluminum tubing closed on each end by aluminum plates. The aluminum tubing was machined on both ends to insure a proper gasket surface. The lower aluminum plate was constructed from 1/2-inch aluminum sheet cut into a 6-inch square. One side of the plate was machined to a depth of 1/8 inch leaving approximately a 3.75-inch diameter circle in the center.

CROSS SECTION OF THE NEUTRON ABSORBER RESERVOIR

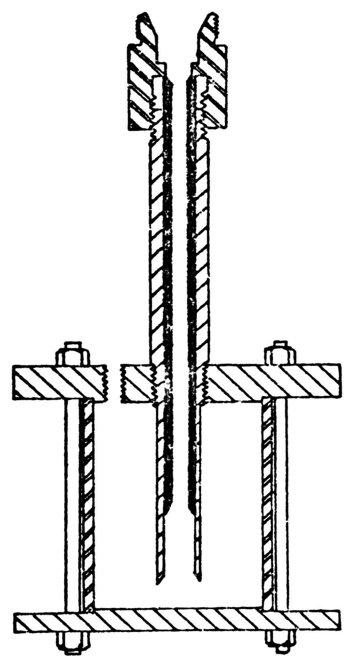

FIGURE III

The machined surface of the plate aligned with the aluminum tube so that the two machined surfaces were mated with a paper gasket, forming a seal. The upper plate was constructed similarly from 1-inch aluminum plate. Eight evenly-spaced holes were drilled through both aluminum plates around the outer diameter of the cylinder. Studs were placed through the holes and bolts were tightened on each end forming a pressure seal between the cylinder and the plates.

A hole was drilled and tapped for 1-inch pipe threads in the center of the upper aluminum plate. A 15-inch length of 1-inch, O. D., steel pipe was machined to a diameter less than the root diameter for a 1-inch pipe thread for a length of 4 inches on one end and the end of the pipe with a machined surface was cut with a taper on the inside and outside surface to aid fluid flow. A 1-inch pipe die was then run on each end of the unmachined pipe surface. A "Swedgelok" female fitting was then screwed onto the unmachined end of the pipe, the fittings were attached, and the pipe was screwed into the hole in the center of the upper plate.

In an operating fluid-control system it would be expected that the tube walls would be relatively smooth. In order to closely approximate this condition and to reduce turbulence, smooth, tapered sleeves were inserted in the pipe sections where water would be flowing.

A second hole was drilled and tapped for 1/4 inch pipe in the upper plate. A piping section, including a tee and a 1/4-globe valve, was screwed into this hole. The purpose of this pipe section was to allow filling and venting of the reservoir.

One of the major design problems encountered in this study was determining and recording the instantaneous level in the control tube. After investigating several possibilities, the system in Figure IV was selected. The basic idea was to insert a high electrical resistance leg through the tube. As the fluid level rose, portions of this resistance leg would be shorted out reducing the overall resistance in the circuit which increased the voltage drop across a fixed resistance in the circuit. A Brush Recorder was used to indicate the variation in voltage across the fixed resistor. In the final design, a series of high-ohm resistors were used, rather than a continuous wire which had been tried previously. It was found that in order to achieve an approximately constant voltage drop per foot, a varying resistance along the wire was required (refer to the Appendix for the method of determining the required resistance). The series of resistors should cause a step-change in the reading of the Brush Recorder whenever the fluid level would rise above the top of the resistor.

A modified spark plug was used for the electrical penetration into the system to insure that the electrical

LEVEL INDICATING SYSTEM

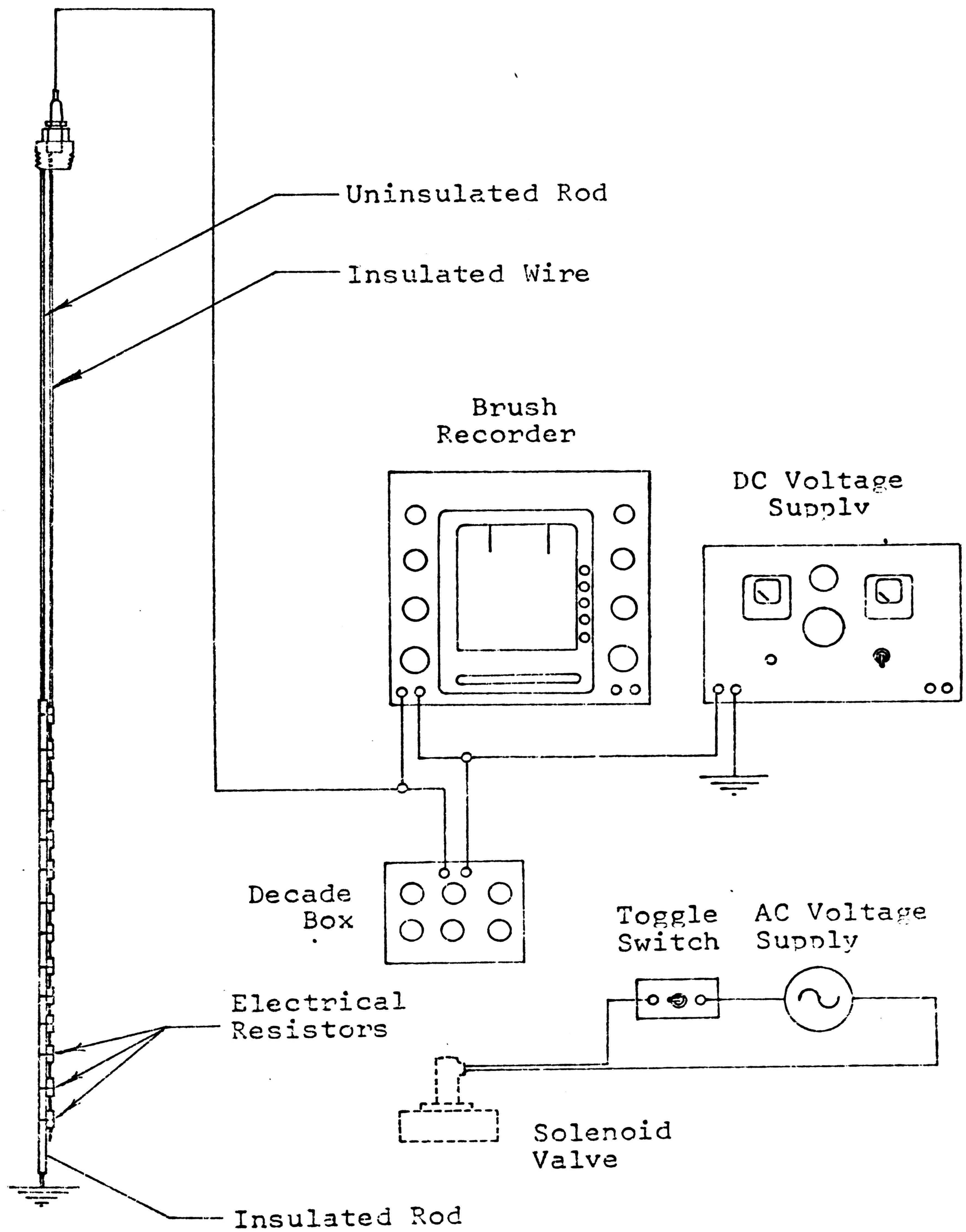

FIGURE IV

leads were not shorted and to maintain a pressure seal. It was also important that the level-indicating system have the capability of being removed for repairs.

The ground terminal was machined from the spark plug and an electrical lead was soldered to the electrode. An adaptor was made, threaded on the inside for the spark plug and threaded on the outside for a standard 1-inch pipe thread. One end of the adaptor was surface finished to allow a proper seal with the spark plug and a small hole was drilled part way into the other end. Two 3-foot-long brass welding rods, welded end to end, were inserted in the small hole and silver brazed in place. These rods serve both as a support structure for the resistors and as an electrical lead in the level-indicator system. The lower welding rod was covered with an electrical insulation in order to prevent shorts between the rod and the resistors.

The electrical resistors were soldered together in series in such a way that, as the fluid level rose, they would be shorted out in 2 ± 1/8 inch intervals. The resistance leg was wired to the insulated welding rod and connected electrically to the wire from the spark plug electrode. An electrical wire was connected from the spark plug electrode into a DC voltage supply and from the DC voltage supply to the Brush Recorder. A variable resistance box was placed in parallel with the Brush Recorder in order to achieve the proper voltage drop across the recorder.

Initially, the electrical leads from the switch to the solenoid valve were run to the second channel of the Brush Recorder. It was thought that when the switch from the solenoid was activated that this signal would be read on one channel while the level-indicator signal would be read on the other channel. By comparing both signals and knowing the chart speed, the fluid level height could be determined as a function of time after the solenoid had been energized.

This arrangement caused difficulty in that the level-indicating channel picked up noise from the solenoid channel. It was noticed during these runs that the fluid-level-indicating channel also picked up the click of the solenoid switch. When the Brush Recorder was disconnected from the solenoid-valve circuit it was noticed that the indication of the switch being thrown was still detectable. It was decided to use only this signal to indicate the initial time thereby eliminating noise, improving the accuracy of the level-indicating system, and simplifying the reading of the Brush charts.

The control tube used was a 30-inch section of 1-inch, O. D., high-pressure pyrex tubing. The use of glass in the test section allowed observation of the fluid column during test runs, aided in the calibration of the fluid level indicator and provided an electrical insulator around the test section. It was connected to the steel pipe on each end by means of "Swedgelok" fittings.

Care was taken to avoid excessive turbulence in the flow downstream of the test section. A sleeve was used in the pipe connection to the Swedgelok fittings downstream of the test section. The line from the high pressure supply was welded into a hole drilled in the pipe section to avoid extra threaded connections and irregularities in pipe diameter. All other components located downstream of the test section were constructed of standard pipe and copper tube fittings as shown in Figure VI.

Considerable difficulty was experienced in assembling the test section. The pyrex tubing could not withstand moderate tension, compression, or torque. To aleviate this problem, the piping downstream of the test section was supported by two pipe hangers from above and four studs were run from the upper reservoir plate through a support plate attached to the downstream test section to take up the end thrust. When bolts were drawn upon these studs, both sections were brought together and connected without causing excess stress on the pyrex tubing. After the assembly was complete, a small platform was placed under the reservoir. The entire apparatus was then lowered onto the platform by readjusting the pipe hangers.

Flow Theory

The equation for the dynamic response of the control system during scram may be developed from basic concepts.

In this derivation the following assumptions are made:

1. Air will behave as a perfect gas.
2. Air expansion will be isentropic.
3. Fluid flow will be frictionless.
4. The fluid will behave as a continuous mass.
5. The solenoid valve opens instantaneously at time 0 and the downstream air pressure instantaneously becomes atmospheric.
6. The tube has negligible wall thickness inside the reservoir.

From the continuity of mass relationship it may be seen that:

$$hr(Ar - At) + (ht)At = hro(Ar - At) + (hto)At$$

$$= C, \text{ a constant.}$$

Differentiating with respect to time:

$$(Ar - At)\frac{dhr}{dt} + At\frac{dht}{dt} = 0,$$

$$(Ar - At)\frac{d^2hr}{dt^2} + At\frac{d^2ht}{dt^2} = 0 \quad .$$

Summing forces on the fluid mass upon opening of the solenoid as shown in Figure V:

$$\Sigma F = (Pr - [\gamma(ht - hr) - Pa - Fl\,])(At) \quad .$$

In order to simplify the solution, friction losses, Fl, will be neglected. Since these frictionless losses are a

FORCE DIAGRAM ON THE TEST APPARATUS

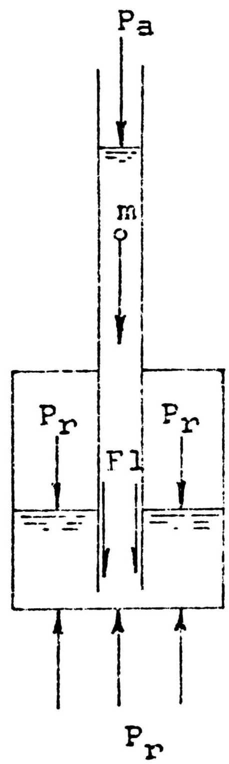

FIGURE V

form of viscous damping the result of this approximation would be expected to decrease the time required for the fluid column to rise to any given level. A second result of this approximation would be to cause larger "overshoot" than those found in the actual system and also to produce an undamped oscillation. The resulting equation is:

$$\Sigma F = [Pr - Pa - \gamma(ht - hr)] (At) \quad .$$

The instantaneous gas pressure in the reservoir, Pr, will vary as the gas expands. In order to approximate this pressure, a reasonable assumption would appear to be that the expansion is isentropic. The expansion is adiabatic since the gas expands so quickly that there is no time for any measurable heat transfer to take place. If the response is isentropic the following relationship holds:

$$Pr = Po \left[\frac{Vo}{Vr} \right]^k = Po \left[\frac{(Ar - At)(XL - hro)}{(Ar - At)(XL - hr)} \right]^k$$

$$= Po \left[\frac{XL - hro}{XL - hr} \right]^k$$

Combining the isentropic-expansion relationship with the relations for the summation of forces and continuity of mass,

$$\Sigma F = \left\{ Po \left[\frac{(XL - hro)}{(XL - hro) + \frac{At}{(Ar - At)}(ht - hto)} \right]^k \right.$$

$$\left. - \gamma \left[hf - hro - \frac{At}{Ar} (hto - ht) \right] - Pa \right\} (At) \quad .$$

The rate of change of momentum for the fluid system may be written as:

$$\frac{d(mv)}{dt} = \frac{d}{dt}\left[\frac{\gamma}{g}(Ar - At)\ hr\ \frac{dhr}{dt} + \frac{\gamma}{g}(At)\ ht\ \frac{dht}{dt}\right] g_c \ .$$

Differentiating,

$$\frac{d(mv)}{dt} = g_c \frac{\gamma}{g}\left\{(Ar - At)\left[\left(\frac{hr}{t}\right)\left(\frac{hr}{t}\right) + hr\ \frac{\partial^2 hr}{\partial t^2}\right]\right.$$

$$\left. + At\left[\left(\frac{ht}{t}\right)\left(\frac{ht}{t}\right) + ht\ \frac{\partial^2 ht}{\partial t^2}\right]\right\} .$$

Combining the relationship from conservation of mass with the rate of change of momentum:

$$\frac{d(mv)}{dt} = g_c \frac{\gamma}{g}\left\{\frac{d^2 ht}{dt^2}\left[At\ ht - At\left(hro + \frac{At\ (hto - ht)}{(Ar - At)}\right)\right]\right.$$

$$\left. + \left(\frac{dht}{dt}\right)^2\left[At - \frac{(Ar - At)}{(Ar - At)^2}(At)^2\right]\right\} ,$$

Where the derivatives are now total derivatives. From conservation of momentum;

$$F = \frac{d(mv)}{g_c dt} \ .$$

$$\left\{Po\left[\frac{(XL - hro)}{(XL - hro) + \frac{At(ht - hto)}{(Ar - At)}}\right]^k - \gamma\left[ht - hro - \frac{At}{Ar}(hto - ht)\right]\right.$$

$$\left. - Pa\right\} At = \frac{\gamma}{g}\left\{\frac{d^2 ht}{dt^2}\left[At\ ht - At\ hro - \frac{At^2(hto - ht)}{(Ar - At)}\right]\right.$$

$$\left. + \left(\frac{dht}{dt}\right)^2\left[At - \frac{(At)^2}{(Ar - At)}\right]\right\} .$$

Let $x = ht - hto$, then $x' = \frac{dx}{dt} = \frac{dht}{dt}$; $x'' = \frac{d^2x}{dt^2} = \frac{d^2ht}{dt^2}$

After making the above substitution and rearranging,

$$\frac{gPo}{\gamma}\left[\frac{(XL - hro)(Ar - At)}{(XL - hro)(Ar - At) + Atx}\right]^k + g\left[hro - hto - x\frac{At}{Ar} - 1\right]$$
$$- \frac{gPa}{\gamma} = x''\left[x\left(1 + \frac{At}{(Ar - At)}\right) + hto - hro\right] + (x')^2\left[1 - \frac{At}{(Ar - At)}\right].$$

The above equation may be recognized as being both nonlinear and nonhomogeneous. The solution may be found by a number of different series solutions. A solution of the equation by the Runge - Kutta method using a forth order approximation may be found in the Appendix.

Test Procedure

In these tests, ordinary tap water was used to simulate the neutron absorber. It is believed that water will behave dynamically in a fashion similar to a boric acid and other solutions having similar properties. Other possible neutron absorbers such as liquid metals or liquid metal alloys would be expected to behave quite differently.

Primary interest was centered upon a control system designed to operate with a core height of 2 feet. This height was selected because the UMR reactor has a core of this height giving access to similar data on an operating linear control rod system.

EXPERIMENTAL FLUID SYSTEM

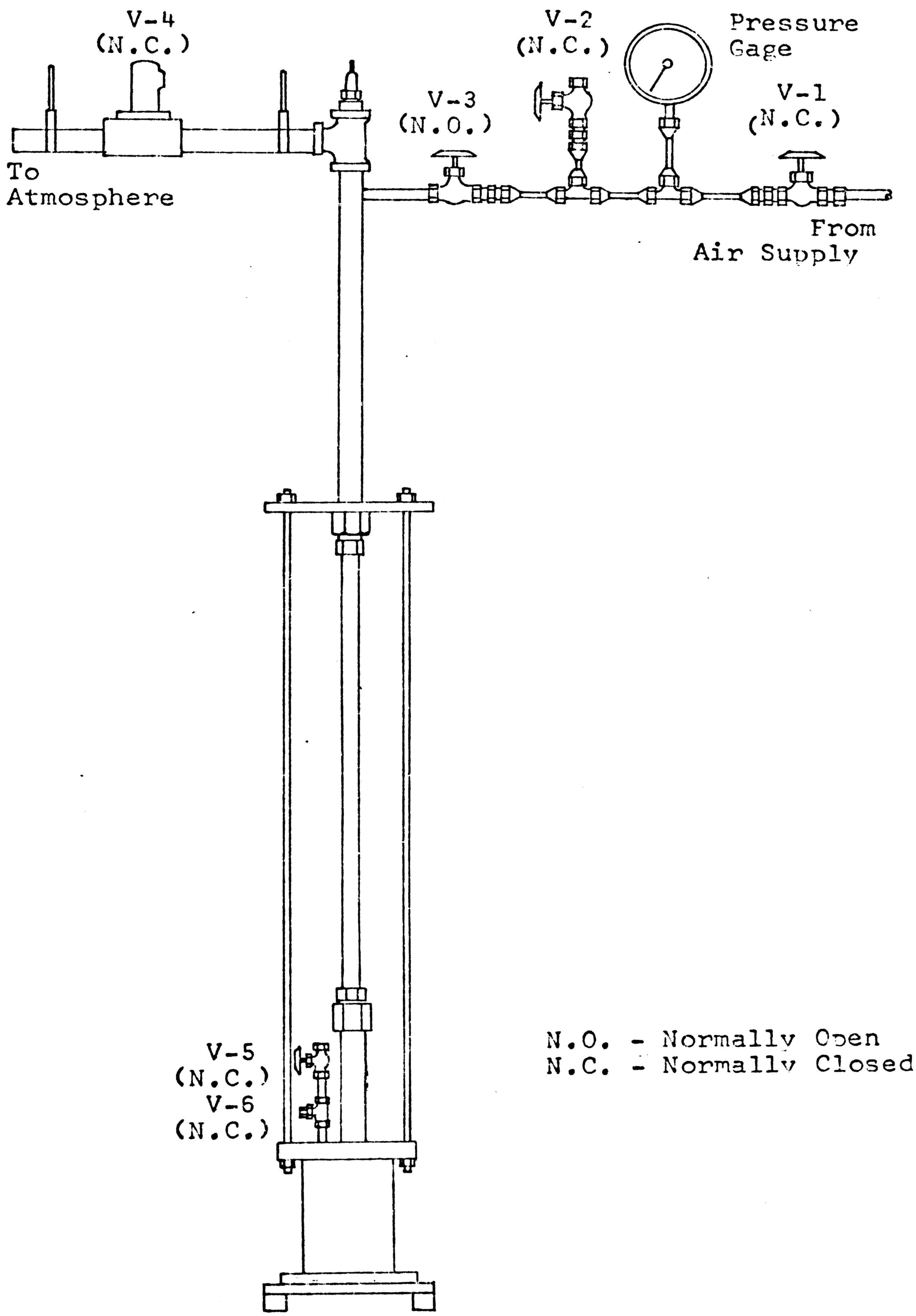

FIGURE VI

Reference will be made to Figure VI for operations. For initial fill, valves V-2, V-3, V-4 and V-5 were opened with V-1 closed and water was poured through a funnel placed above valve V-2 until water was visible in the test section. Air pressure was then applied through valve V-5 until the fluid level in the test section was raised to 24 inches and valve V-5 was then closed. Valves V-2, and V-4 were then closed and valve V-1 was throttled open, raising the pressure in the system so that the water level in the test section dropped to 0 inches. A trial run was then made by closing the switch on valve V-4.

The Brush Recorder and DC power supply were then turned on, warmed up, and adjusted during several trial runs so that a full scale deflection was achieved across the brush chart when the fluid level varied from 0 to 27 inches. The Brush Recorder was calibrated by cracking open valve V-1 and slowly pressurizing the system. As the fluid level dropped, the instantaneous reading of the Brush Recorder was correlated with the fluid height. In a similar manner, pressure readings were recorded as a function of height.

After calibrating the instrument, the solenoid was opened and data was taken as the fluid height varied from 0 to 27 inches with the recorder running at the maximum chart speed of 125 mm/second. The system was then repressurized in successive runs to heights of 6, 12, and 18 inches

BRUSH CHART FOR SCRAM FROM 24 INCHES

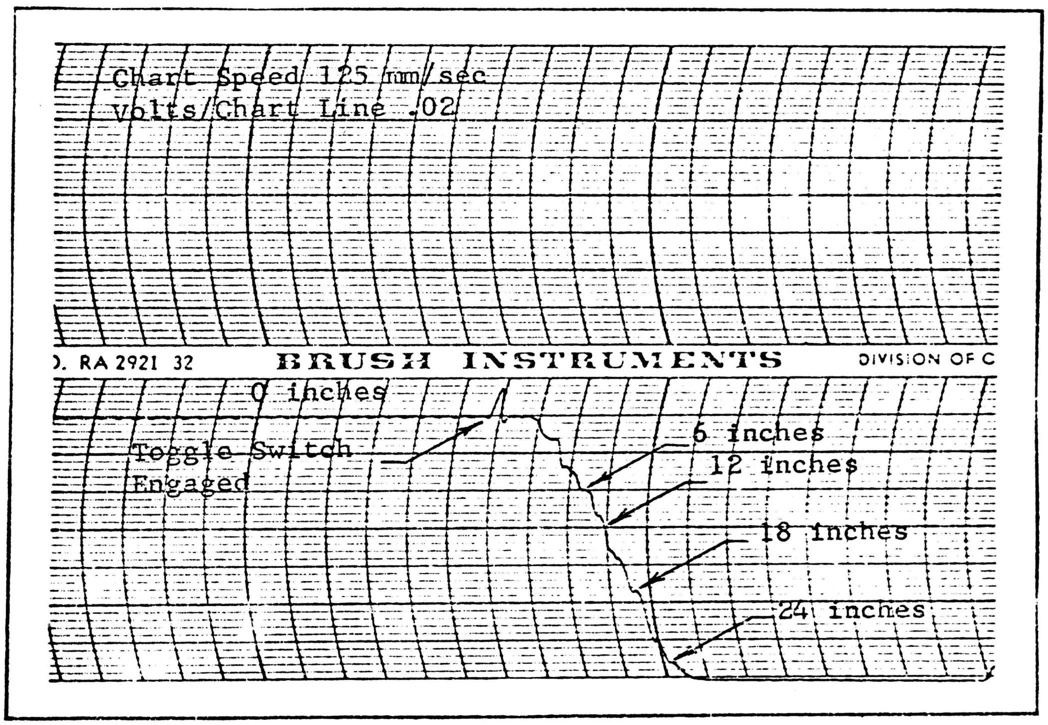

FIGURE VII

and data was taken at each of these levels. A similar run was made in which the fluid level was allowed to vary from 0 to 24 inches. Before performing this final run, it was necessary to vent a small amount of gas from valve V-5 while valve V-4 remained open; in this manner the fluid level could be readjusted to 24 inches. In succeeding runs, the volume of air trapped in the reservoir was varied by opening the plug V-6 and pressurizing the system by cracking valve V-1. When the proper amount of water had been forced from the reservoir through V-6, the switch on valve V-4 was closed, opening the valve and venting the system pressure. Valve V-1 was then closed and the plug was reinserted.

Data was taken in succeeding runs with line pressures varying from 10 psi to 30 psi.

Discussion of Test Procedure and Results

During the initial experimental runs, two facts became apparent which would limit the operating capabilities of a fluid-control system. First, the rising fluid column did not always behave as a continuous medium. Shortly after the fluid started to rise in the tube, it obtained its maximum velocity. As the gas in the reservoir continued to expand the force acting on the fluid was reduced, thereby reducing the velocity of the fluid flowing into the tube. As a result, the fluid would separate at the higher initial pressures. The problem of separation did not occur noticeably during the runs in the 9.5 psig range, and did not appear to be serious in runs up to 15 psig. As initial reservoir pressure was further increased, the problem became more acute, eventually achieving sufficient separation to force water through the solenoid valve. As a result, data was taken for runs only up to 15 psig.

Secondly, during the runs from 0 to 24 inches, at lower pressures, it was noted that the fluid column rose quickly for about the first 22 inches, paused, and then gradually continued to rise to the 24 inch level. As a result the total scram time was found to be about 10 seconds for these runs.

In order for the fluid-control system to be practical, it must be capable of achieving nearly as fast, or a faster scram time than those currently obtained with linear control rods. For purposes of comparison the rod drop times for the UMR reactor were compiled as shown in the Appendix. This is a common "swimming pool" type reactor, with no springs or pneumatic-hydraulic systems to aid in driving in control rods. When the control rods are dropped, they fall under their own weight through the water. To simulate the scram time in a gas-cooled reactor, a frictionless free fall is assumed; that is, the relationship $x = 1/2gt^2$ was assumed to hold. The comparison of the linear control rod to the experimental and analytical control system are shown in Figures VIII through XV.

SCRAM RESPONSE FROM 24 INCHES

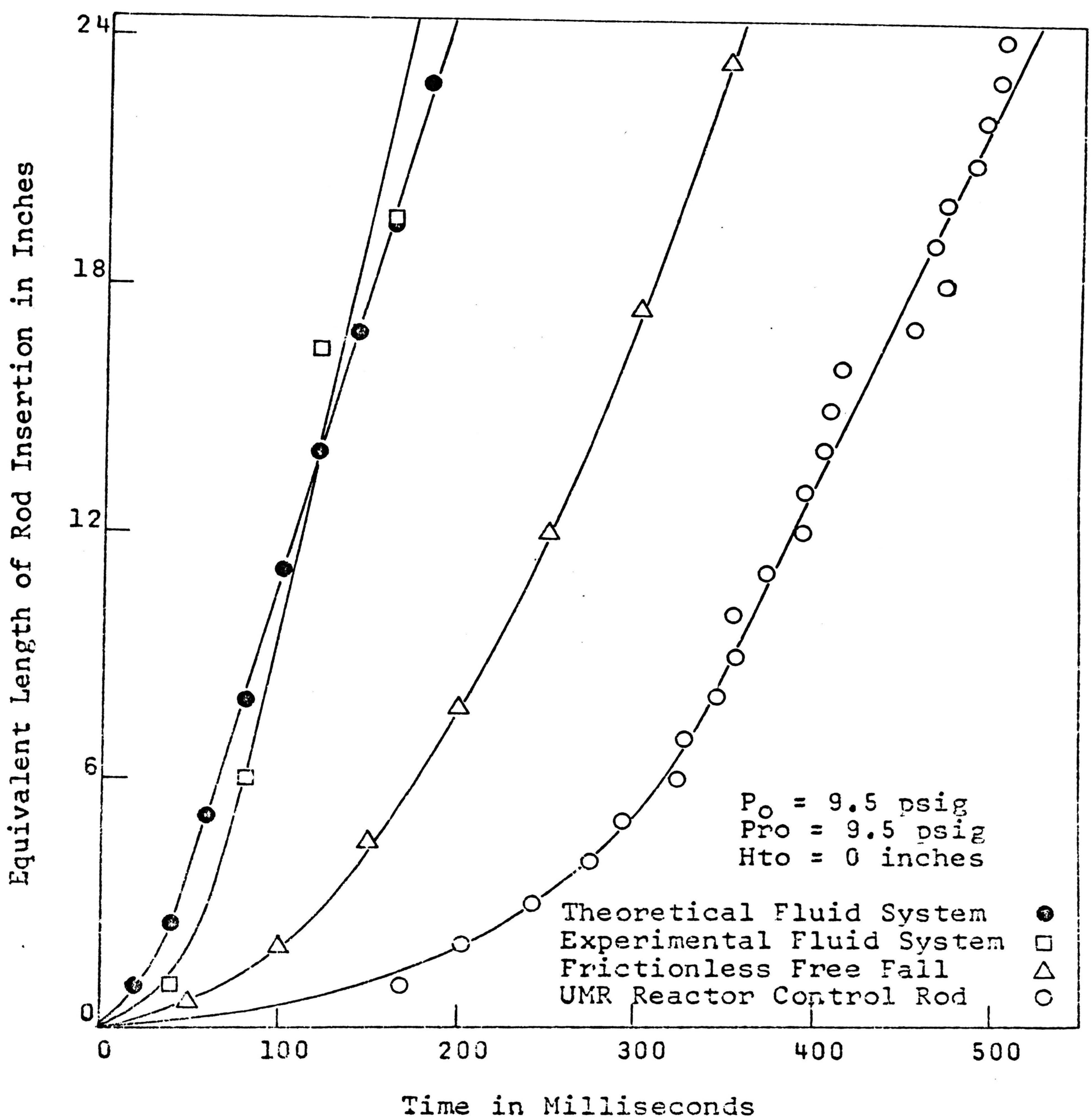

FIGURE VIII

SCRAM RESPONSE FROM 18 INCHES

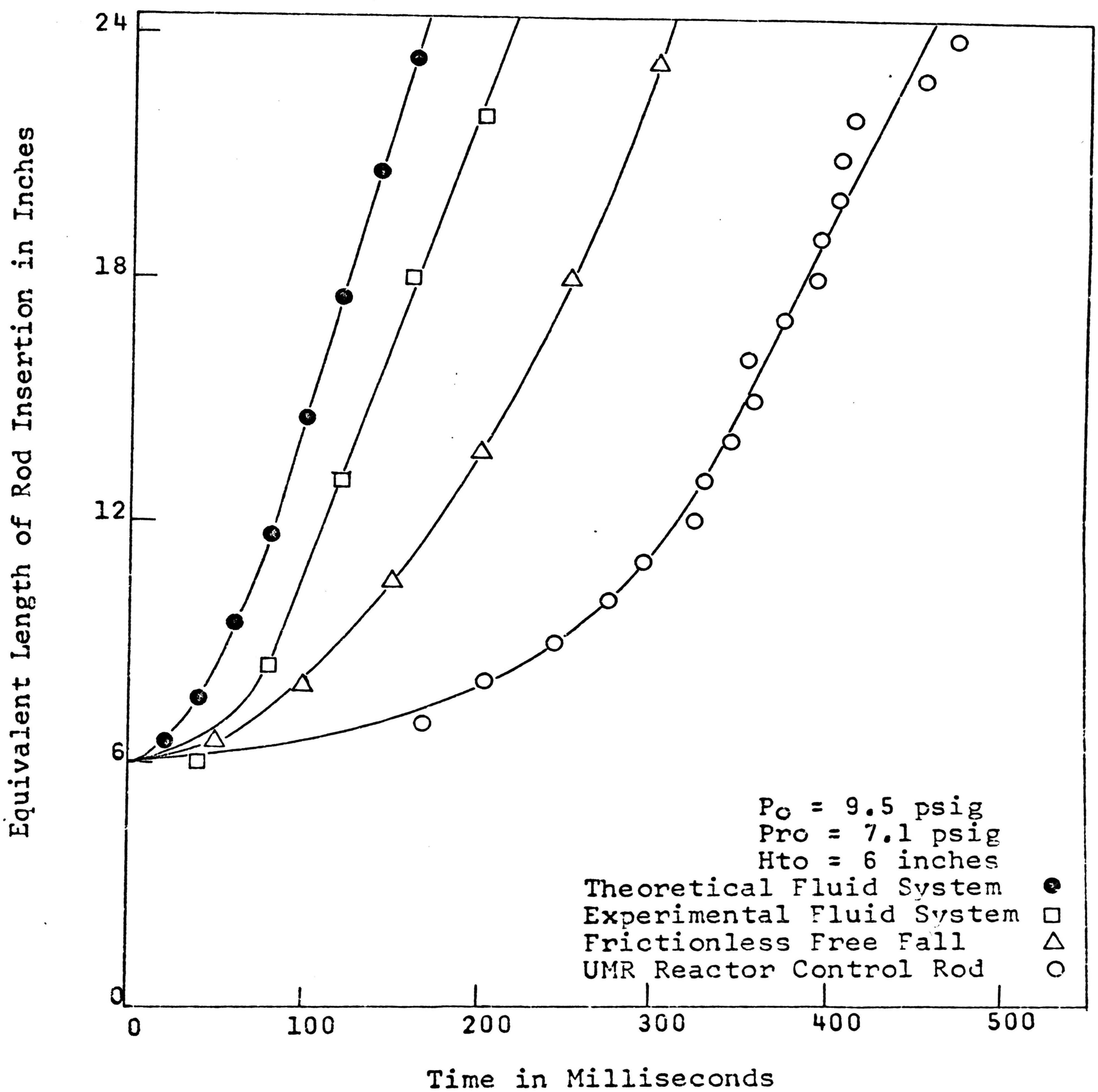

FIGURE IX

SCRAM RESPONSE FROM 12 INCHES

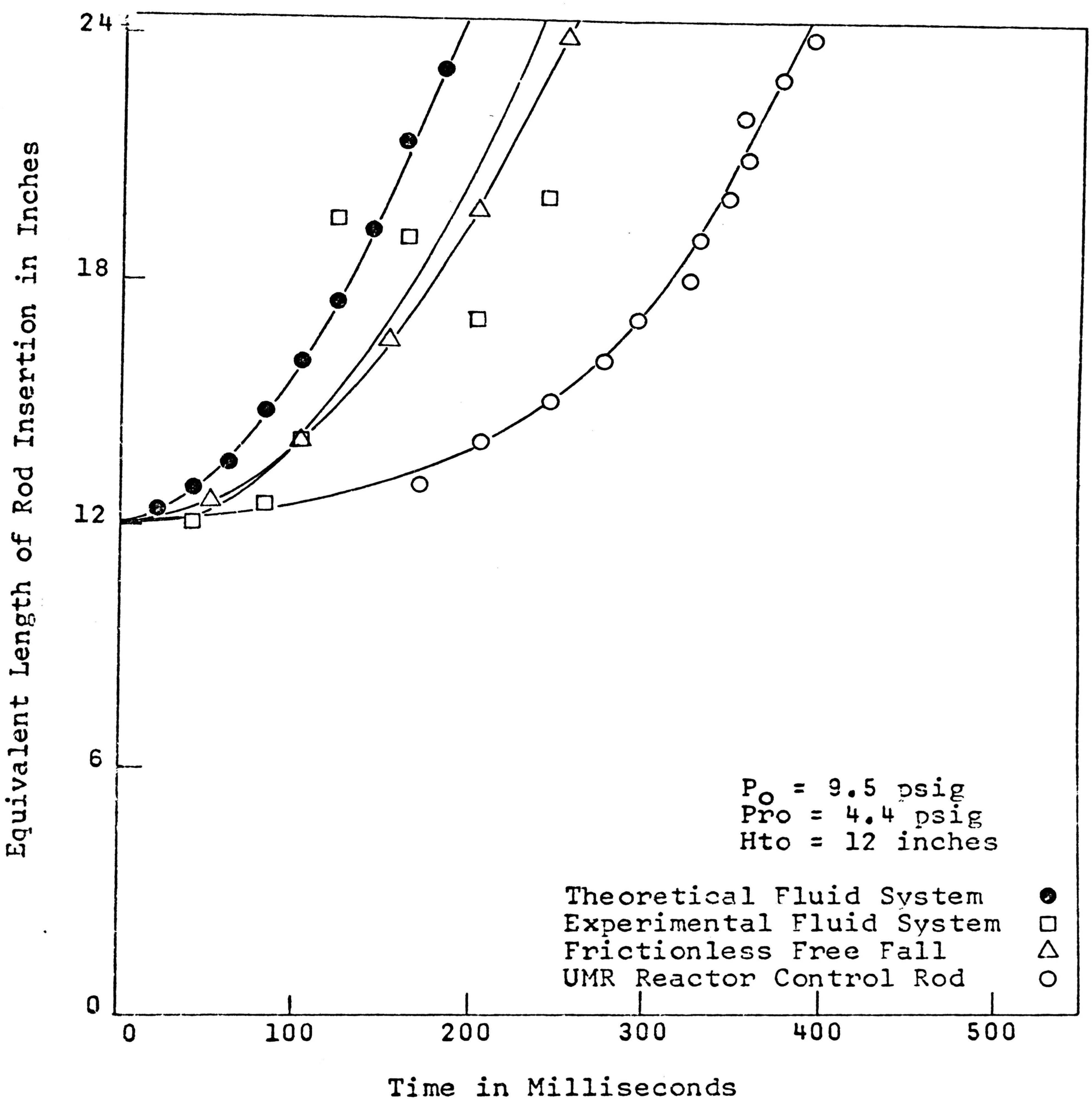

FIGURE X

SCRAM RESPONSE FROM 6 INCHES

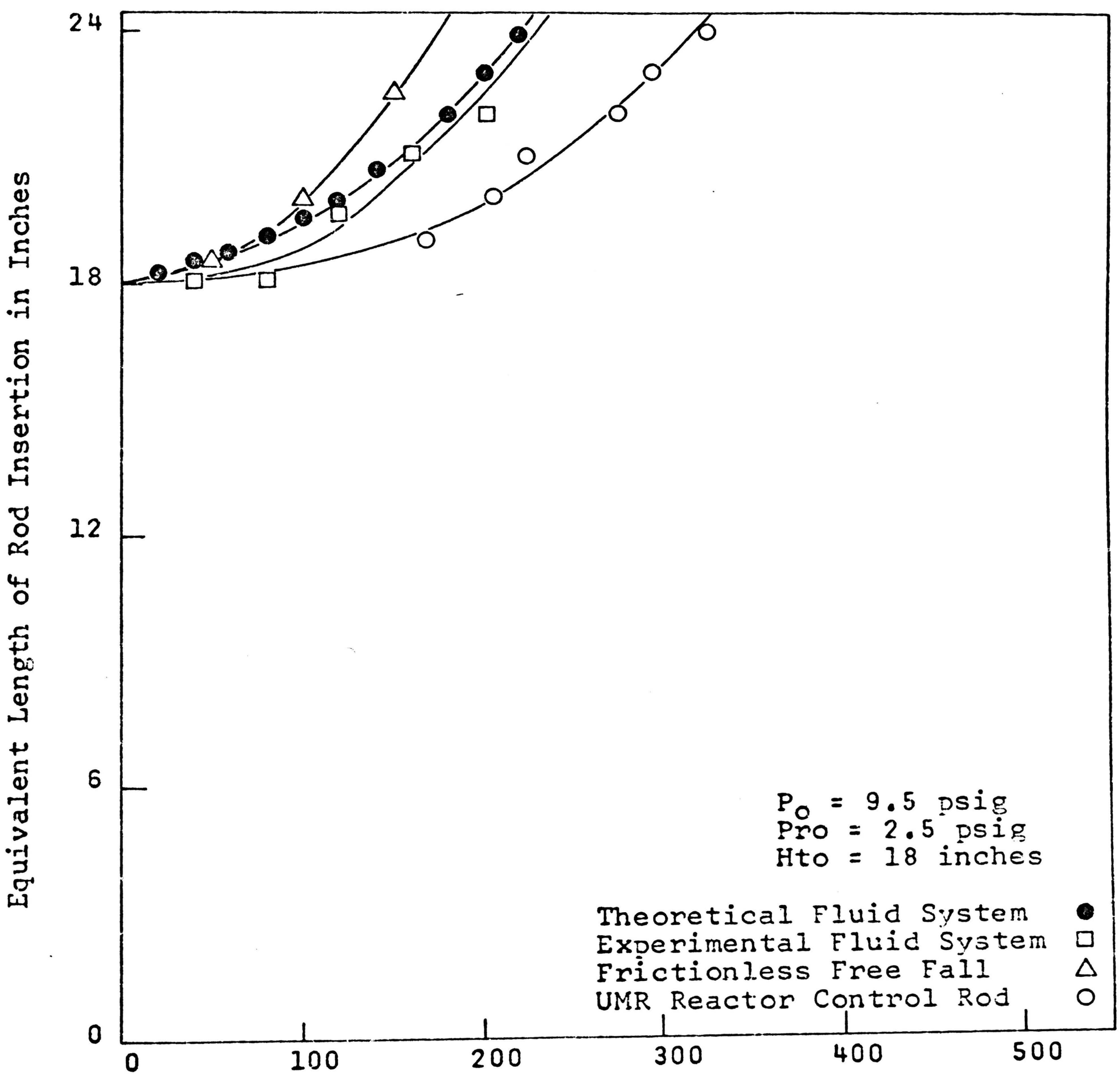

FIGURE XI

SCRAM RESPONSE FROM 24 INCHES

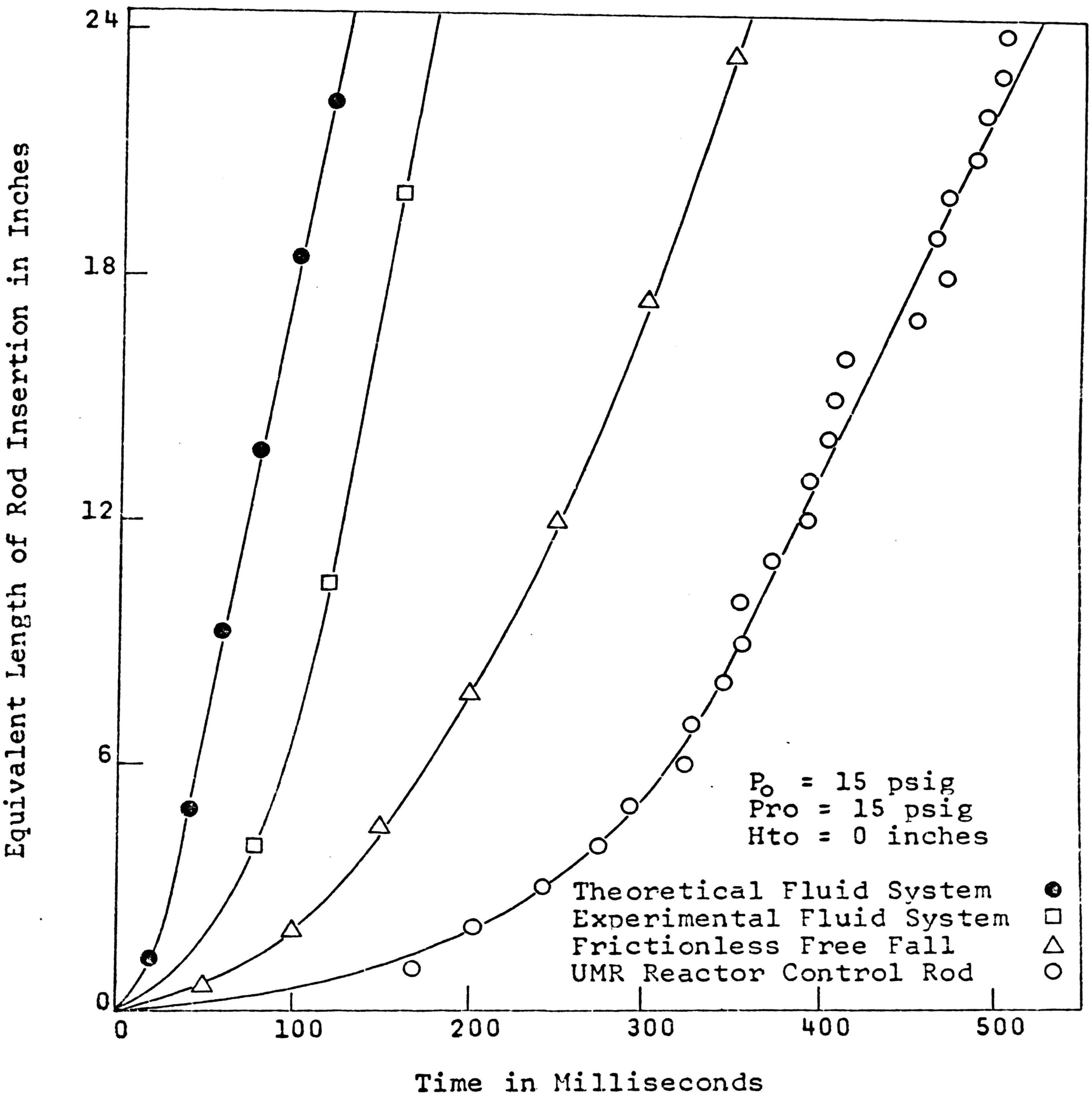

FIGURE XII

SCRAM RESPONSE FROM 18 INCHES

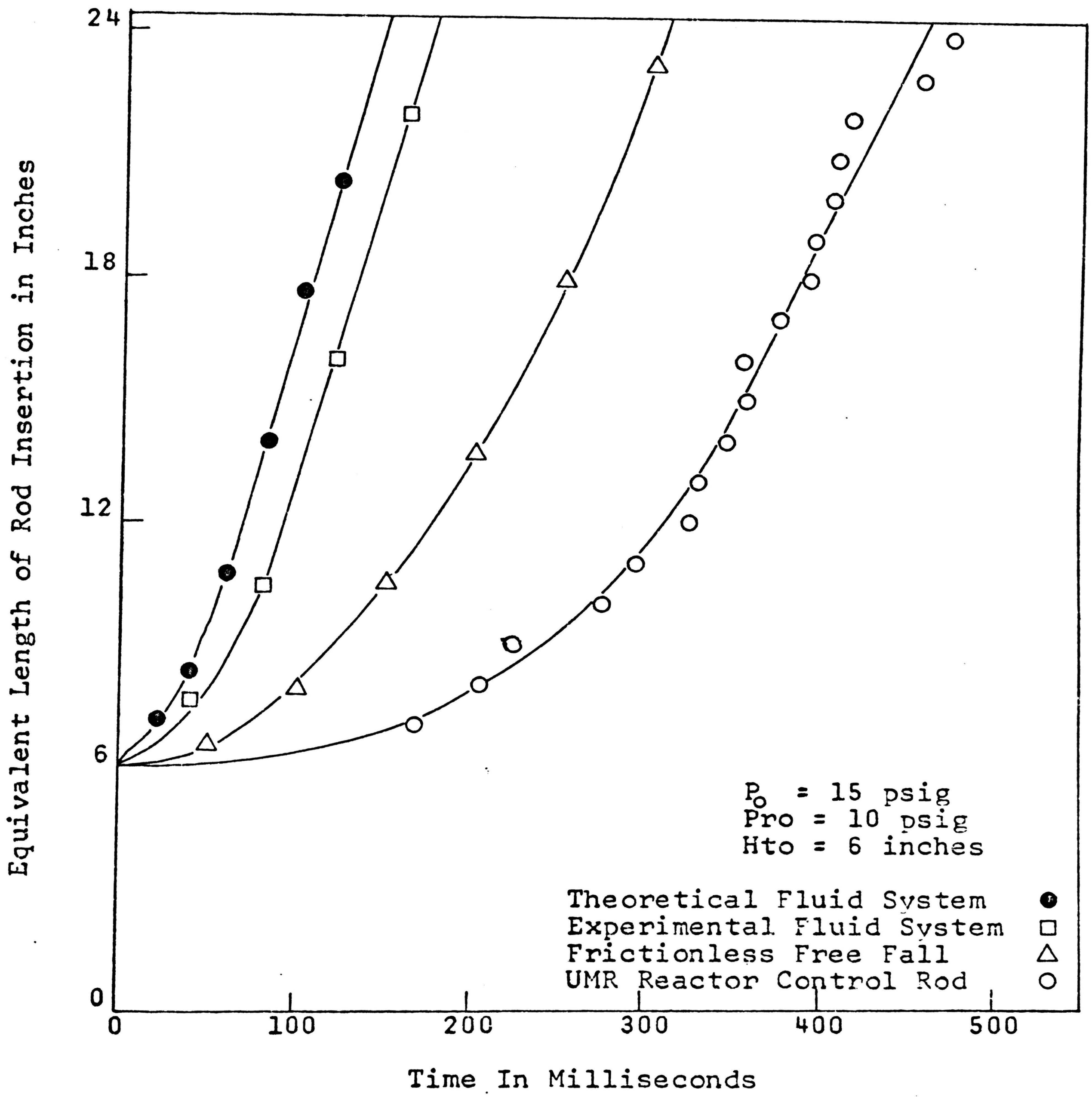

FIGURE XIII

SCRAM RESPONSE FROM 12 INCHES

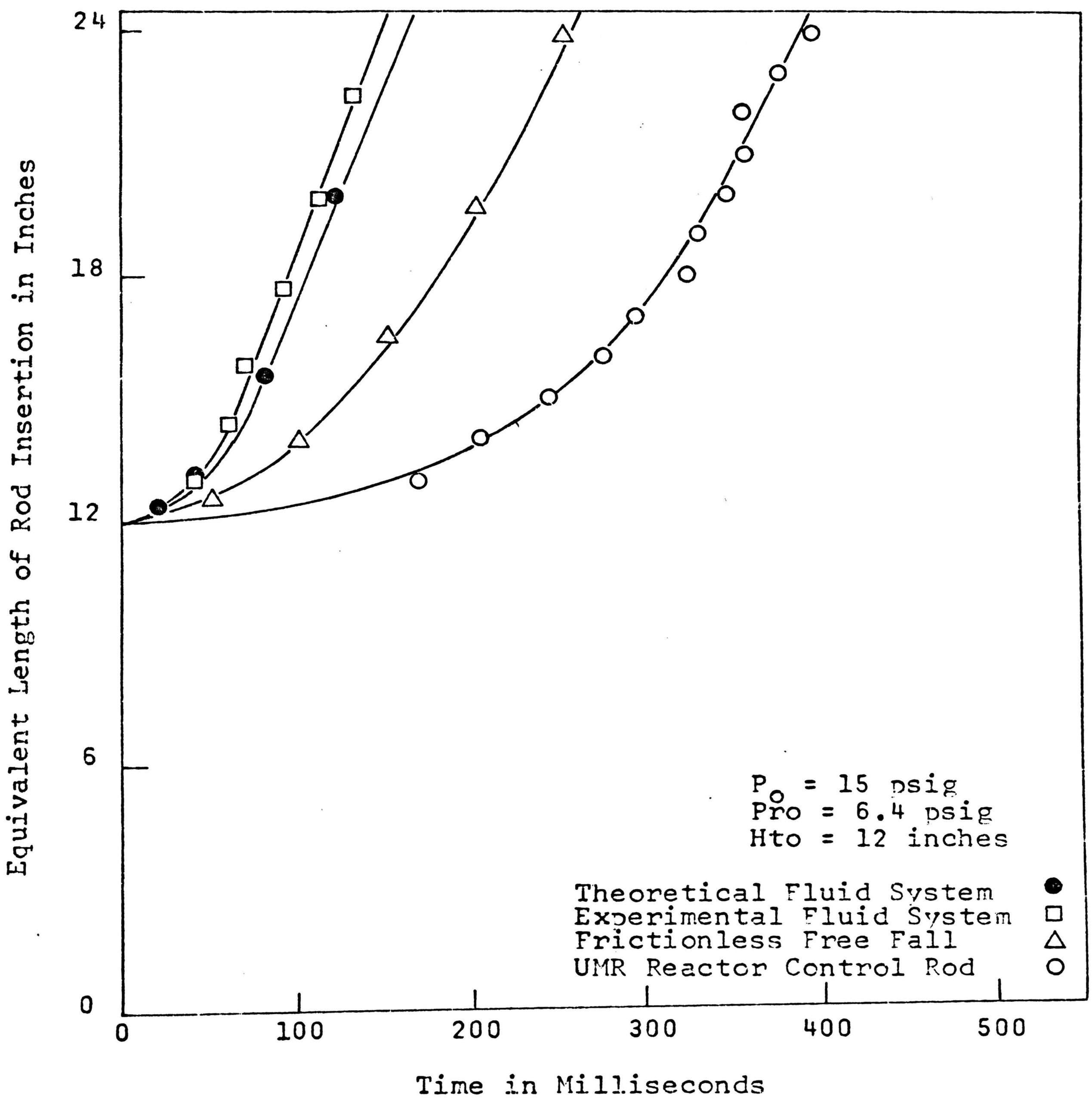

FIGURE XIV

SCRAM RESPONSE FROM 6 INCHES

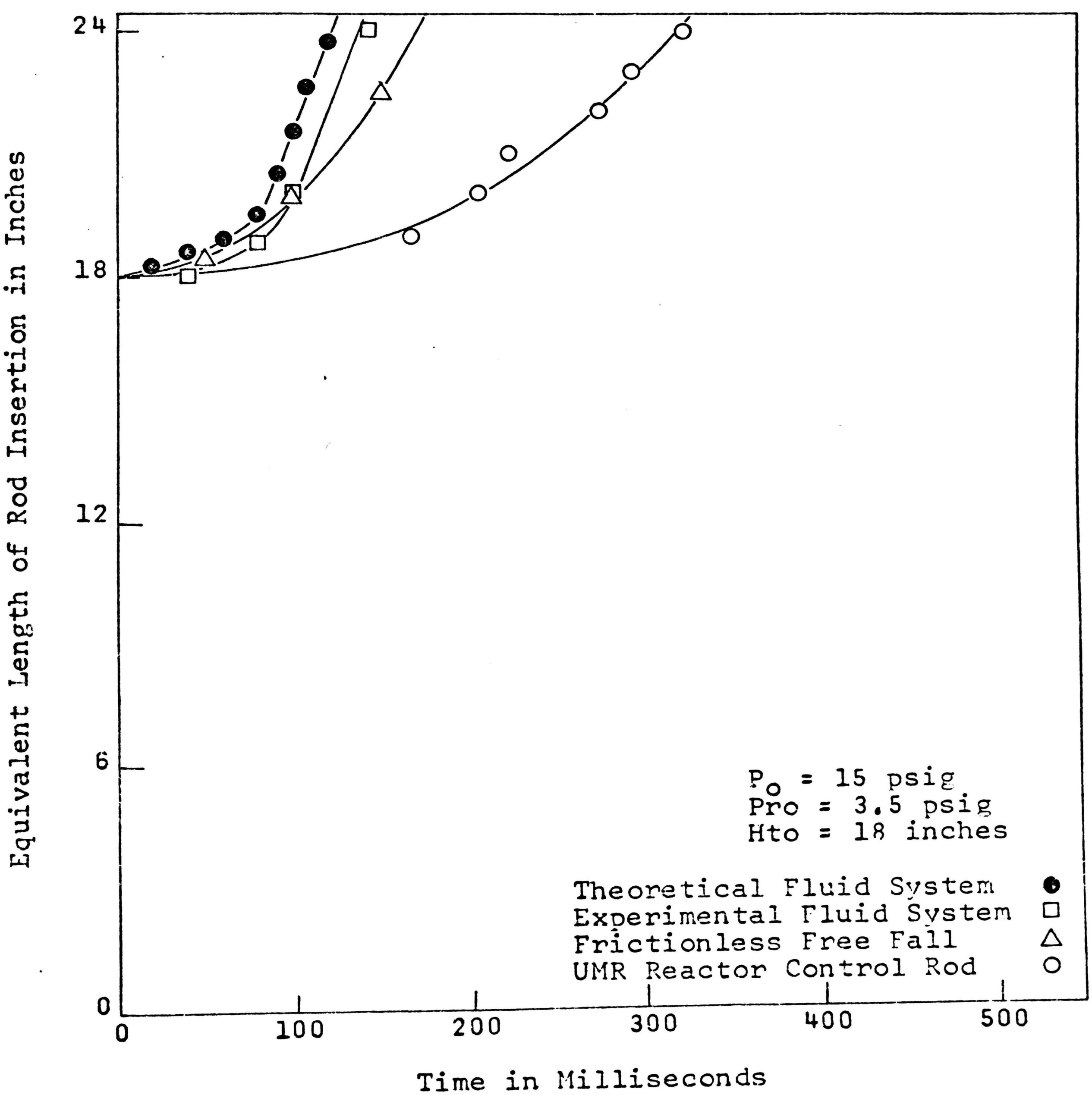

FIGURE XV

The scram-response diagrams show that at a P_o of 9.5 psig the scram times increase while, at a P_o of 15 psig, scram times decrease with increasing initial control fluid height. In both cases the scram time is approximately equal for the scram from 0 to 27 inches. Apparently the system reaches a mean velocity where flow losses increase sufficiently with velocity to nullify the slight increases in pressure. As the initial height of the fluid column in the control tube is raised initial pressure decreases as shown in Figure XVI and Figure XVII. In the case of a P_o of 9.5 psig this decrease in pressure is sufficient to significantly lower the velocity obtained by the control fluid during a scram. With a P_o of 15 psig the initial pressures at higher fluid levels remain relatively high, the velocities obtained in the control tube are not substantially reduced so that the scram times decrease. It is therefore apparent that it would be highly desirable to use as high a P_o as possible without causing significant flow separation.

It may be seen from the scram response diagram that it was possible to better the scram time of the UMR reactor and, in most cases, to better the time of the hypothetical gas-cooled reactor. The UMR reactor scramed from 24 inches in 510 milliseconds whereas the fluid control system scramed in only 180 milliseconds. The fluid control system did scram in a shorter time than that for the gas-cooled reactor

PRESSURE DEPENDENCY OF COLUMN HEIGHT

$P_o = 9.5$

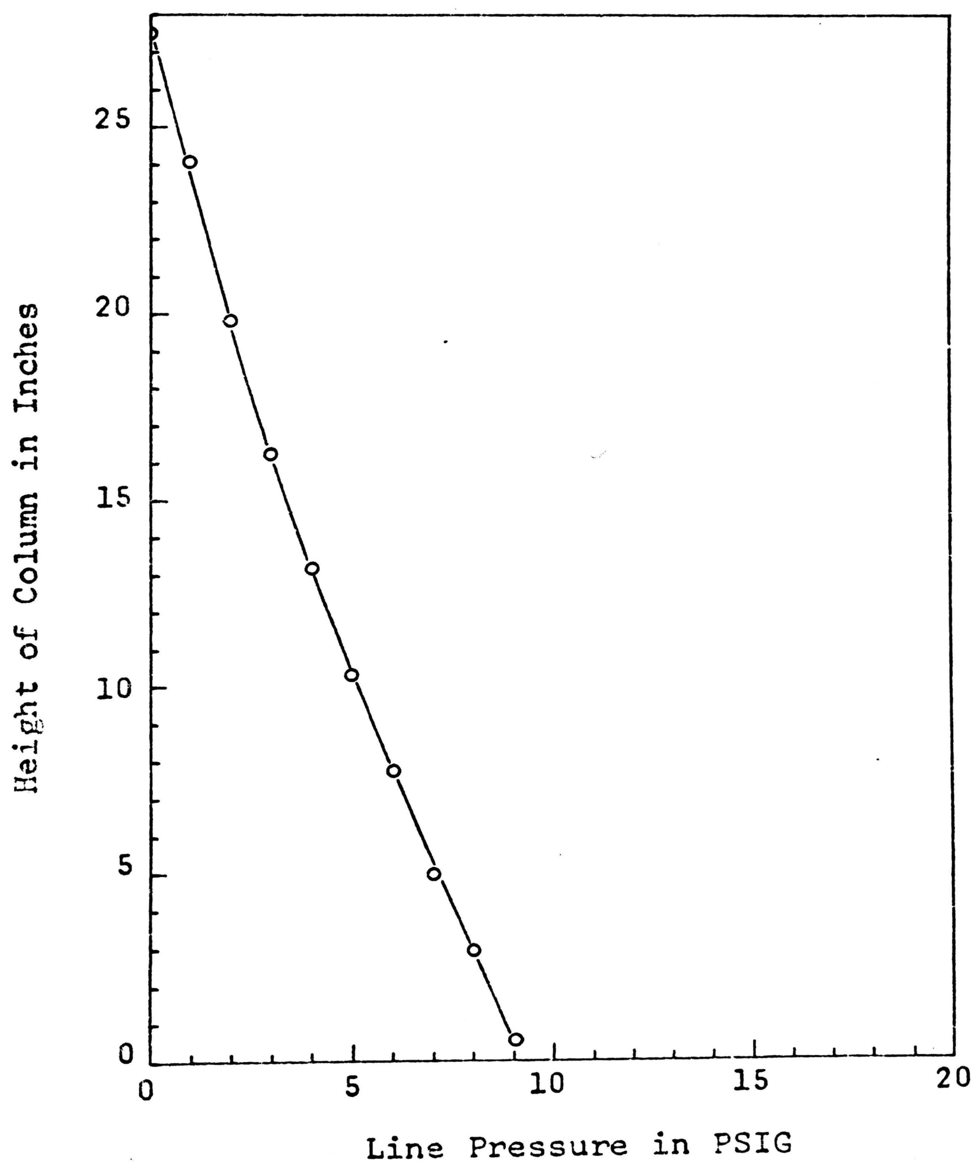

FIGURE XVI

PRESSURE DEPENDENCY OF COLUMN HEIGHT

$P_o = 15$

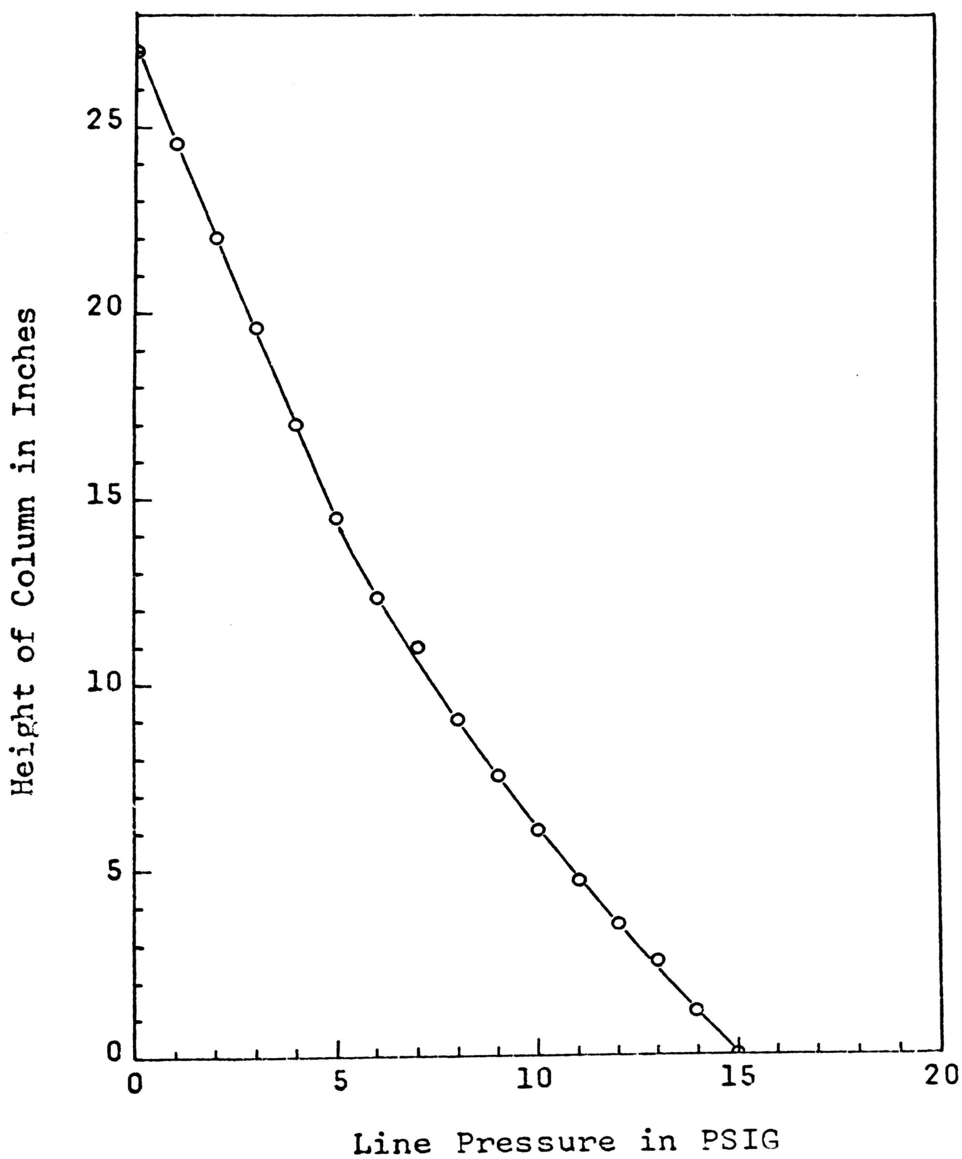

FIGURE XVII

during each run from an initial reservoir pressure of 15 psig; only in the run from 18 to 27 inches at 9.5 psig initial reservoir pressure did the gas-cooled reactor control system obtain a shorter scram time. It should be pointed out, however, that the effectiveness of a control system during scram is a function not only of speed, but also of its ability to capture neutrons. If, as would be expected, the fluid control system can capture not only a large percentage of the thermal neutron flux, but also can "thermalize" and capture fast neutrons, then it might overcome this slight difference in speed. Also the initial acceleration of the liquid-control system is substantially higher than that of the linear-control-rod systems which is important for fast shutdowns.

Analytically-derived and experimentally-derived scram times compare within about 25%. This variation might be expected as a result of neglecting all friction losses. Friction losses in the experimental apparatus were relatively large due to the sudden change in the inside diameter at the entrance and exit to the glass tube and also to the presence of the resistance leg which offered flow resistance. The electrically-insulated welding rod was about 3/16 inches in diameter, and the resistors varied up to about 7/32 inches in diameter. When both are placed in a tube of only 47/64 inches inside diameter they form a major obstruction to fluid flow. As a result experimental data shows what is probably somewhat long scram times.

An example of a Brush chart from a typical run is shown in Figure VII. As can easily be seen the initial indication of the toggle switch being closed is quite distinguishable. After the switch is thrown, an initial pause is noticeable where the valve is opening and before the fluid gains momentum. The shorting of various resistances is then detectable, although the indication from all resistances are not immediately noticeable. This is probably due to the response of the Brush Recorder. The vertical lines represent the shorting of a resistor. It may be noted that these lines are not completely parallel to the constant time line on the chart strip. In other words, there is a time lapse between the instant that a resistor is shorted out and when the Brush Recorder is able to reach a new voltage level. When the fluid velocity reaches a critical value with respect to voltage drop, there is no time lapse between the instant the Brush Recorder reaches one voltage level and the following resistor is shorted out. In this case, the chart will show one continuous line with no lapse between resistors. An example of such an occurrence is shown at the 12-inch level.

It was initially believed that the reason the resistors were not detectable on the Brush Recorder chart was due to a failure of the moisture-proof coating on the resistors. If this were the case, the resistors would short out leaving only a very small or no indication on the chart. After all runs were made the resistance leg was removed and all resistors were checked. The results of this check showed only slight changes in resistance in some resistors. Data from this check is included in the Appendix.

III. CONCLUSIONS AND RECOMMENDATIONS

The experiment has shown that from the aspect of fluid flow, a neutron-absorbing-fluid control system is not only feasible, but may offer significant improvements in the time required to complete a scram. It is desirable to use as high a P_o as possible without causing significant flow separation at end of travel. To further increase initial reservoir pressures it might be desirable to utilize a flow spoiler near the end of the control tube.

A second reservoir could be located above the reactor core which would effectively be the same as a longer control tube without the accompanying large increase in reactor vessel height. This second reservoir might produce a higher mean fluid velocity during reactor scram.

A number of related problems have not been considered during this experiment, however, and these may cause major problems in the design of an operating system. The first such problem would be that of providing an accurate and reliable level indicating system. One possibility might be to construct a variable resistance leg, not from individual resistors, but from a continuous material. The resistance leg could then be fitted into the inside wall of the control tube. Another possibility for a level indicating system would be the use of remote resistors with only small electrical probes running into the control tube. These small probes would provide less flow resistance than the system used in this study in addition to preventing submersion of the resistors. Pressure containment, leakage, reactor chemistry, and metallurgy could also cause major design problems.

Nevertheless, these initial experiments have shown enough promise to warrant continued study of the feasibility of this method of reactor control.

IV. BIBLIOGRAPHY

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7. UMR REACTOR RECORDS (1964) Rod Drop Time.

V. APPENDIX

The following Appendix contains the computer solution for the fluid flow equation, together with the tabulated data on pages 46 through 48. Pages 49 through 54 includes design data for the experimental apparatus. FIGURE XVIII is a calibration curve for the pressure gage shown in FIGURE VI. The method of determining rod drop times and the tabulated data are to be found on pages 56 and 57.

Computer Program for the Solution to the Fluid Flow Equation

```
C       FØRTRAN 2
C       RUNGE - KUTTA METHØD (4TH ØRDER)
        R(X) = X*(1.+(AT/(AR-AT))) + HTØ - HRØ
        S(X) = G*((PØ*((XL-HRØ)*(AR-AT)/((XL-HRØ)*(AR-AT)+AT*X
       1((**1.4)-PA(/RHØ
        T(X) = G*(HRØ-HTØ+X*(AR-AT)))
        W(XP) = (XP**2)*(1.-(AT/(AR-AT)))
        F(X,XP) = (S(X)+T(X)-W(XP))/R(X)
        DIMENSIØN  P(4),U(100),TI(100),TH(100)
        READ 100,M
        PI = 3.1415927
        G = 32.2
        PA = 2116.8
        AR = (PI*(3.75/2.)**2)/144.
        AT = (PI*(47./128.)**2)/144.
        DØ 50 LL = 1,3
        Q = M
        READ 101,PØ,RHØ,XL,A,B,HTØ,HTF
        PRINT 201,PØ
        H = ABSF(B-A)/Q
        HRØ = XL+((HTF-HTØ)*AT/((AR-AT)*(1.-(PØ/(PA+HTF/.016))**(1./1.4))))
        TH(1) = 0
        U(L) = 0
        TI(1) = 0
        PRINT 102
        DØ 15 I = 2,M
 15     TI(I) = TI(I-1) + H
        DØ 20 K = 1,M
        P(1) = H*F(TH(K),U(K))
        P(2) = H*F(TH(K)+.5*H*U(K),U(K)+.5*P(1))
        P(3) = H*F(TH(K)+H*U(K)+.25*H*P(1),U(K)+.5*P(2))
```

```
      P(4) = H*F(TH(K)+H*U(K)+.5*H*P(2),U(K)+P(3))
      TH(K+1) = TH(K)+H*U(K)+((H*(P(1)+P(2)+P(3)))/6.)
      U(K+1) = U(K)+(P(1)+2.*(P(2)+P(3))+P(4))/6.
   20 PRINT 103,TI(K),TH(K)
   50 PRINT 200
      CALL EXIT
  100 FØRMAT(I10)
  101 FØRMAT(7F10.5)
  102 FØRMAT(28X,4HTIME,34X,6HHEIGHT
  103 FØRMAT(2(21X,F18.8))
  200 FØRMAT(////)
  201 FØRMAT(10X,2HPØF10.1//)
      END
```

Tabulated Results to Analytical Solution

Time in seconds	Fluid height in feet			
	Po = 9.5 psig Pro = 9.5 psig Hfo = 0 ft	Po = 9.5 psig Pro = 7.1 psig Hfo = .5 ft	Po = 9.5 psig Pro = 4.4 psig Hfo = 1 ft	Po = 9.5 psig Pro = 2.5 psig Hfo = 1.5 ft
.00	.0000	.5000	1.0000	1.5000
.02	.0838	.5353	1.01451	1.5045
.04	.3032	.6361	1.05739	1.5179
.06	.6028	.7910	1.1269	1.5402
.08	.9405	.9862	1.2205	1.5709
.10	1.2943	1.2092	1.3349	1.6098
.12	1.6538	1.4504	1.4667	1.6564
.14		1.7026	1.6127	1.7102
.16		1.9605	1.7697	1.7706
.18			1.9347	1.8370
.20				1.9088
.22				1.9853

Time in seconds	Fluid height in feet			
	Po = 15 psig Pro = 15 psig Hfo = 0 ft	Po = 15 psig Pro = 10 psig Hfo = .5 ft	Po = 15 psig Pro = 6.4 psig Hfo = 1 ft	Po = 15 psig Pro = 3.5 psig Hfo = 1.5 ft
.00	.0000	.5000	1.0000	1.5000
.02	.1304	.5550	1.0228	1.50818
.04	.4459	.7066	1.0890	1.5325
.06	.8404	.9274	1.1935	1.5723
.08	1.2582	1.1897	1.3291	1.6266
.10	1.6844	1.4739	1.4886	1.6942
.12		1.7685	1.6654	1.7734
.14			1.8540	1.8627
.16				1.9602

Design and Operating Characteristics of the Level Indicating System

Design Calculations:

The level-indicating system was designed so that the voltage drop across the Brush Recorder would be linear with respect to the change in fluid level. As may be seen from Figure V the variable voltage drop across the Brush Recorder will be;

$$Vb(x) = \frac{Rb}{Rb + R(x)} Vi \qquad \text{(equation 1)}$$

Differentiating the voltage drop with respect to the change in the length of unshorted resistance in the resistance leg and setting this derivative equal to a constant will make the voltage drop linear.

$$\frac{dVb}{dx} = - \frac{Rb}{[Rb + R(x)]^2} Vi \frac{dR(x)}{dx} = C \qquad \text{(equation 2)}$$

Then separating variables, integrating, and solving for R(x),

$$\int_0^x \frac{Cdx}{(Rb)Vi} = \int_{R(L)}^{R(x)} \frac{-1}{[Rb + R(x)]^2} dR(x)$$

$$\frac{Cx}{(Rb)Vi} = \frac{1}{Rb + R(x)} - \frac{1}{Rb + R(L)}$$

$$R(x) = \frac{[Rb+R(L)]ViRb}{Cx[Rb + R(L)] + Rb(Vi)} - R_b \qquad \text{(equation 3)}$$

These values of resistance and voltage may be chosen arbitrarily. Since the available DC voltage supply was capable of producing only 16 volts, it was decided to use its full output. It was anticipated that this larger voltage drop would aid in the reading of the Brush Recorder by reducing the voltage amplification and thereby reducing electrical noise. The resistors selected were required to have large electrical resistance. In this manner any resistance in the conductivity fluid would be negligible. The values of resistance and voltage selected were:

$Vi = 16$ v

$Vb = 8$ v with the full resistance leg in the circuit

$Rb = 10{,}000$ ohms

Solving equation 1 for R(L) with these values;

$$R(L) = Rb\,\frac{Vi}{Vb} - Rb = 10{,}000\left(\frac{16}{8} - 1\right) = 10{,}000 \text{ ohms}$$

Determining the value of C from equation 2;

$$C = \frac{V}{L} = \frac{16 - 8}{3} = \frac{8}{3}$$

Where L is chosen to be 3 ft.

Using the values obtained above the value of R(x) may be determined from the solution of equation 3.

$$R(x) = \frac{Rb[Rb + R(L)]\ Vi}{Cx[Rb + R(L)] + Rb\ Vi} - Rb$$

$$= \frac{(10{,}000)(20{,}000)(16)}{(8/3) \times (10{,}000 + 10{,}000) + (10{,}000)(16)} - 10{,}000$$

$$= \frac{20{,}000}{1/3\ x + 1} - 10{,}000$$

Where R(x) is to be composed of individual resistors the value of the resistors may be found by subtraction. For example, where, as in the design used in this experiment, the resistors are spaced at 2-inch intervals, the resistor required between 26 and 28 inches will be:

$$R(26") - R(28") = \frac{20{,}000}{1/3(26/12) + 1} - \frac{20{,}000}{1/3(28/12) + 1}$$

$$= 11{,}620 - 11{,}250 = 370 \text{ ohm}$$

After the final run the resistance leg was removed and all resistances were checked to determine whether the water might have altered the resistances of the individual resistors after several runs. A tabulation of the resistances is given below. Variation in the rated resistance and that before they were wetted is due to the accuracy rating of the resistors, $\pm$ 10%.

Design of the Fluid-Control-System Reservoir

During preliminary design studies, it was not known at what pressure the control system would operate satisfactorily.

Effect of Moisture Upon the Rated Value of Resistors

Rated Resistance in ohms	Dry Resistance in ohms	Wet Resistance in ohms
700	680	680
820	810	810
1000	1100	1150
1100	1050	1095
1400	1420	1480
1600	1650	1680
2000	1980	2050
2700	2800	2800
3600	3950	3800
5100	5300	5100
3300	4000	4000
3800	4000	4000
5100	5300	5200
7500	7400	7600
10,000	12,000	12,000
15,000	18,000	18,000
75,000	77,000	75,000

Since air pressure up to 90 psig was available, it was decided to design a system capable of operating at this pressure. With this design criteria in mind and allowing for the factor of safety the design limits of from 10 to 200 psig were used for the entire system.

The minimum allowable wall thickness may be calculated by the basic stress equation using a maximum allowable stress for aluminum of 7000 psi,

$$\text{stress} = \frac{\text{Force}}{\text{Area}} \qquad 7000 = \frac{200 \times 2 \times 1.875}{\text{t min}}$$

$$\text{t min} = .1071 \text{ inches}$$

The minimum height for the reservoir may be calculated using basic thermodynamic relationships and assuming isentropic expansion.

$$\frac{Po}{Pr} = \left[\frac{Vr}{Vo}\right]^k = \left[\frac{(Ar - At)(XL - x)}{(Ar - At)(XL - x) - At(Htf - Hto)}\right]^k$$

Substituting the proper values in the above equation, the value of XL - x, the minimum required height of the reservoir above the lower edge of the tube, may be found.

$$\frac{24.9}{16.0} = \left[\frac{(.07376)(XL - x)}{(.07376)(XL - x) - (.00294)(2\ 1/2)}\right]^{1.4}$$

Where:

Po is equal to the atmospheric pressure plus 10 psi line pressure plus the pressure head from 1/2-feet of water.

Pr is equal to the atmospheric pressure plus the pressure head from 3-feet of water.

Htf - Hto, the total change in fluid height in the tube is assumed to be 2 1/2 feet.

Solving for XL - x,

XL - x = .369 feet = 4.44 inches

Then allowing 1/2 inch for flow between the entrance to the rod and the bottom of the reservoir, the total height of the reservoir will be at least 4.94 inches.

The minimum allowable stud size for the reservoir may quickly be found as follows;

Total force = Po Ar = (200)(144)(.076699)

= 22,100 lb.

Allowing for a factor of safety of two and using eight studs, the total force per stud will be,

Force/stud = 2(22,100)/8 = 552.5 lb.

After checking the recommended load per stud it was found that the next available larger load rated stud was 1/2-inch.

PRESSURE GAGE CALIBRATION CHART

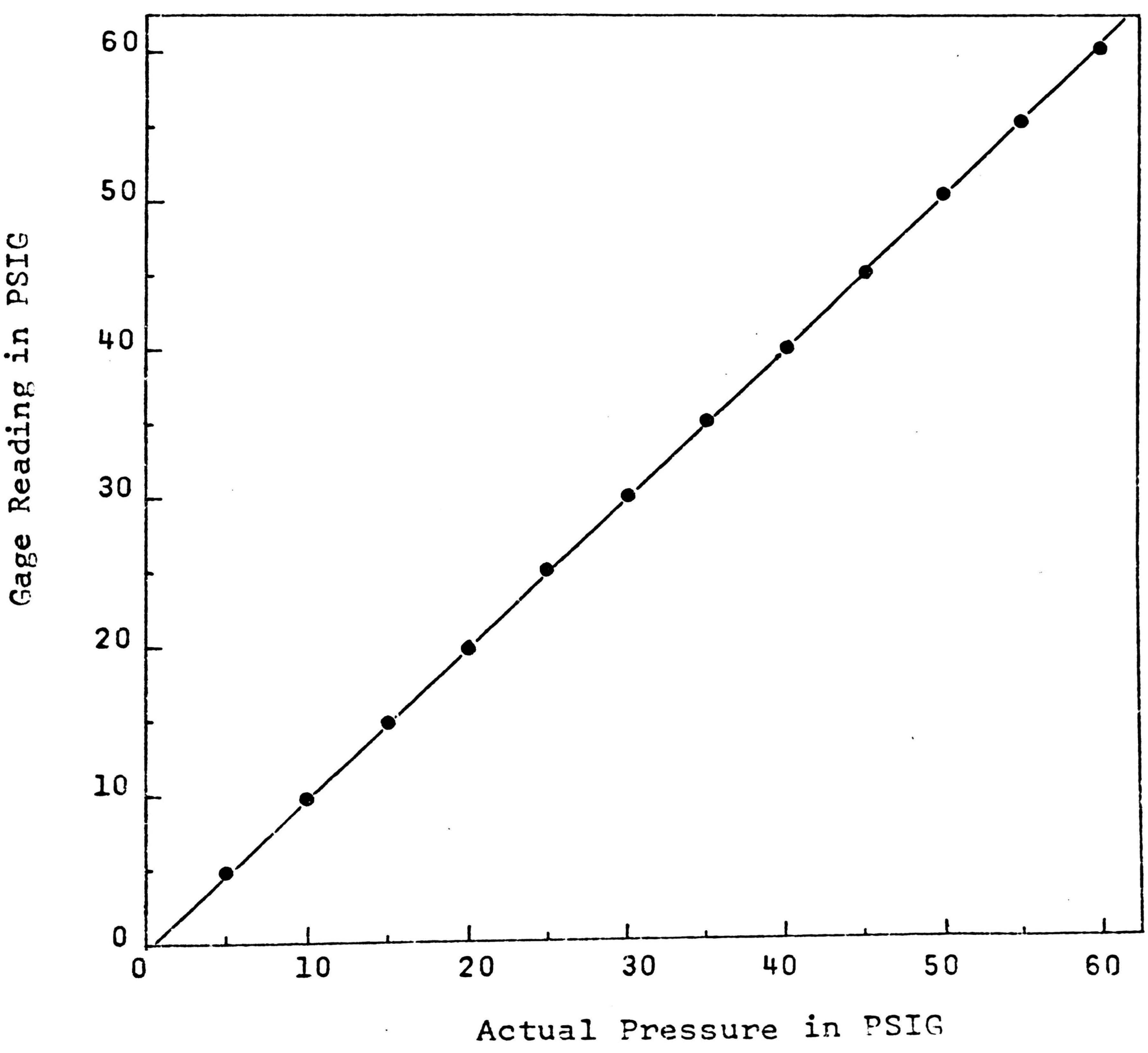

FIGURE XVIII

UMR Reactor Drop Times

Rod drop times are checked at the UMR Reactor every six months, as required by the Atomic Energy Commission. This is done in order to detect any swelling or binding of the control rods.

Measurements of the time necessary for the rods to drop are taken by the acoustical method, and reads out in the milliseconds from the time magnet power is interrupted until the rod in entering a dashpot assembly at the end of its travel.

The rod-drop signal is detected by a microphone which is taped to one of the control rod drives and picks up the sound of the rod while dropping, producing an indication on the scope when the piston assembly on the rod enters the dashpot assembly on a special element. The microphone is fed into an audio amplifier whose output is fed into the vertical input of a scope. The trigger of the scope is wired so that closure of the scram switch, which interrupts the magnet current, starts the trace across the CRT tube. By noting the length of time the trace travels from start to the indication when the rod is seated determines the rod drop time. The accuracy of this test is ± 20 milliseconds (7).

Data From Rod Drop Tests

Rod height in inches	Drop Time in Milliseconds						
	Rod 1		Rod 2		Rod 3		Average
	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2	
0	0	0	0	0	0	0	0
1	170	170	180	170	160	160	168
2	200	200	210	230	190	190	203
3	250	265	260	260	210	210	242
4	300	300	270	270	260	240	273
5	300	320	290	300	280	260	292
6	360	360	310	310	300	290	322
7	360	380	320	320	290	290	327
8	380	400	340	330	300	310	343
9	400	400	340	350	320	320	355
10	400	400	340	340	320	320	353
11	420	400	360	360	340	360	373
12	440	420	390	380	360	360	392
13	420	420	390	390	380	360	393
14	420	410	420	420	380	380	405
15	420	420	420	420	380	380	407
16	420	420	420	420	400	400	413
17	560	440	460	480	440	460	456
18	460	450	480	500	460	480	472
19	450	460	480	480	460	480	468
20	460	460	480	480	480	480	473
21	480	470	500	500	480	500	488
22	480	480	510	500	500	500	495
23	490	500	500	510	500	510	502
24	500	500	510	500	510	510	505

VI. VITA

The author was born November 27, 1942, in Des Moines, Iowa. He received his elementary and secondary education in the public schools of Raytown, Missouri. He was graduated from Raytown High School in 1960. In September of 1960 he entered Kansas City Junior College, Kansas City, Missouri. In June, 1962 the author received the degree of Associate of Science in Engineering. In September of 1962 he entered the Missouri School of Mines and Metallurgy, Rolla, Missouri. In June 1964 he received the degree of Bachelor of Science in Mechanical Engineering.

Upon graduation the author accepted a position as a designer in the Atomic Power Design section of the Newport News Shipbuilding and Dry Dock Company. He was later transferred to the Reactor Test Group and promoted to supervisor.

In September of 1965 he returned to the University of Missouri at Rolla to pursue graduate study. He is presently pursuing a program leading to a degree of Master of Science in Mechanical Engineering.