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PROJECT PLUTO CONTROL SYSTEM DEVELOPMENTS AND TEST RESULTS

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ABSTRACT

During the spring of 1961, Tory II-A, the first experimental reactor in the Pluto nuclear ramjet missile program, was successfully tested at the Nevada Test Site of the Atomic Energy Commission. It is currently undergoing advanced testing. This paper summarizes the methods of control which are employed on Tory II-A and presents unclassified test results pertaining to the major control systems.

Recent control system developments for Tory II-C, a flight-type ramjet reactor, are also described. The Tory II-C application requires 40-inch, linear-stroke servo actuators capable of operating in a high radiation environment throughout the temperature range of 70°F to 1200°F. The problem areas and recent advances in the development of high-performance electropneumatic control systems for this application are discussed. In concluding this paper, the major control problems confronting the Pluto program are outlined and the further development efforts required are indicated.

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Project Pluto Control System Developments and Test Results

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INTRODUCTION

Project Pluto has as its objective the demonstration of the feasibility of a nuclear reactor capable of propelling a supersonic ramjet missile. Here, feasibility is defined as the successful ground operation for limited periods of time of a flight-type reactor in a near flight-type environment. However, neither missile accelerations nor g-loads can be realized during ground tests. Because stored air is used as the reactor coolant, ground tests are limited to a period of several minutes; hence, the lifetime of the reactor and its associated control system must be ascertained by conducting many tests in series or by extrapolation from long-term component or module tests.

Thus far, the Pluto Program at the Lawrence Radiation Laboratory has been divided into two distinct reactor development programs: Tory II-A and Tory II-C. Tory II-A, the first experimental reactor in the Pluto program, was successfully tested at intermediate power levels at the Nevada Test Site in May 1961 and is currently undergoing advanced testing. The fundamental objective of the Tory II-A program is to demonstrate that a high-power-density, high-temperature, air-cooled reactor can be successfully designed, constructed, and operated. Design point parameters for Tory II-A are as follows:

Power level	155 megawatts
Airflow rate	708 lb/second
Maximum core temperature	2250°F

Inlet air temperature	1060°F
Exit air temperature	1975°F

As the capacity of the Tory II-A air supply is approximately 120,000 pounds of air at 3600 psi, the duration of reactor operation at design point is limited to less than one minute.

The Tory II-C reactor, which will be tested following completion of the Tory II-A tests, will be a full-scale, missile-like reactor which will demonstrate the feasibility of the Pluto ramjet reactor. A major point of difference between Tory II-A and Tory II-C is the use of control rods inside the core on the latter. This imposes severe environmental problems on the control-rod actuators which were not present on Tory II-A, and also limits significantly the space which can be allocated to these actuators.

As the Pluto program is fully described in other literature[1,2,3] to which the reader is referred for further programmatic details, this paper will be limited in scope to the major control systems developed for Project Pluto. The three specific objectives of this paper are: (1) Description of major Tory II-A control systems and presentation of significant results obtained during reactor field tests; (2) Evaluation of Tory II-A control systems based on test results; and (3) Outline of Tory II-C control system developments. Because of the rather broad scope of this paper, no attempt will be made to present detailed system analysis. Much of the analysis has been presented in earlier works on the Project Pluto control systems.[4,5,6]

TORY II-A CONTROL SYSTEMS

The Tory II-A reactor variables which must be controlled or held within limits are: (a) reactor power level; (b) minimum period; (c) pressure and rate of change of pressure at the reactor inlet; (d) air temperature at the reactor inlet; and (e) core component temperatures and temperature derivative. Control of the reactor is effected by three major control systems:

1. Nuclear control system: This system maintains desired power level or inverse-period by automatic or manual positioning of control rods and vanes.

2. Airflow rate control system: This system maintains desired flow rate by automatic or manual positioning of a pressure control valve upstream of the reactor.

3. Air-temperature control system: Control of reactor inlet air temperature is established by manual positioning of two differentially-driven control valves which determine the proportion of air which goes through the heater and that which bypasses it.

It can be seen that, in this system, core temperature is a dependent variable and can be controlled only indirectly through control of one or more of the other variables. Figure 1 shows how reactor power and airflow rate might be varied during a typical design-point run, in order to maintain the desired core temperature. Air inlet temperature is manually programmed to the desired value over a period of one to two minutes and held constant throughout the run. The nuclear operator can trim core temperature by means of manual adjustments of the demanded power level. In addition, he has the capability of completely overriding the automatic program at all times.

"Manual control," when referred to in this paper indicates operator control of the position demand signal to any particular control element actuation system. All control elements are normally servo-positioned. "Automatic control" of any particular variable refers to closed-loop control of that quantity with the operator setting the demand level. "Programmed automatic control" indicates completely automatic control using preprogrammed function generators to schedule a particular variable. As indicated by Fig. 1, startup and shutdown of both power-level and flow-rate control systems are carried out in manual control; automatic control is used for programming to and from intermediate levels; programmed automatic control is used for the relatively rapid programming to the design point and back to intermediate levels.

An emergency "override" mode has been provided for all Tory II-A control-element actuation systems (nuclear, flow rate, and air temperature). In this mode, the cognizant operator can electrohydraulically position a control element in an open-loop, on-off manner using solenoid valves and batteries.

The major Tory II-A control systems are next briefly described.

Nuclear Control System

As this system has been described in considerable detail in the literature,[4, 5, 6] only an overall summary is included here.

The reactor control elements used by the nuclear control system consist of eight electrohydraulically actuated shim vanes and four electrohydraulically actuated control rods located symmetrically in the reactor reflector as shown in Fig. 2. The shim vanes are used to set the reactor power level and to compensate for reactor temperature changes. Any one of the four control rods can be selected as the fine-control rod, while the remaining three act as safety rods. All control elements are normally operated as position-servo systems, but can also be operated by means of an override actuation system which employs electrohydraulic open-loop positioning.

Figure 3 shows a block diagram of the nuclear control system indicating location of the various components while Fig. 4 shows the radiation-tolerant electrohydraulic actuators mounted on the flat car. The hydraulic pump is seen in the lower center portion of the latter picture.

Instrumentation

Nuclear instrumentation is used for operator presentation while the power control system is in the manual control mode. In addition, this instrumentation is used for feedback information while the system is in automatic control.

In the startup range, four boron-triflouride detectors are used. The pulses from these detectors are fed through pre-amplifiers to scalers and then to logarithmic count-rate meters and period amplifiers. These count rate and period signals, which are recorded and visually indicated, are used for scram initiation. Two of these BF_3 detectors can be remotely moved from a normal location near the reactor. The other two are remotely located to provide instrumentation in the intermediate power range.

Three compensated ion chambers are used over the upper six decades of power level. The signals from these chambers are fed to logarithmic power and period amplifiers. This log power and period information is used for feedback in the automatic control and the fast reset modes. In addition, this information is transmitted to the control point where it is used for visual indication and scram initiation.

Over the top two decades of power level, three uncompensated ion chambers can also be used. In addition to providing linear feedback for the automatic control loop, they are used by the fast-reset safety system (at the bunker) and are transmitted to the control point for visual indication and scram initiation.

In addition to these various presentations, the nuclear operator is also provided selected core temperatures and exit-air temperatures which provide sufficient information for operator core-temperature "trimming."

Modes of Control

In conjunction with the remaining system electronics, the above-described control elements and reactor instrumentation provide four modes of nuclear control. In addition to the usual manual, automatic, and "scram" modes of control, a fourth mode, known as "fast reset" has been added. This is a non-locking safety mode which is described in detail below. A brief description of each mode follows:

1. Manual Control: In this mode, manual positioning of the shim vanes and control rod is used for reactor control. The shim vanes have two velocities which can beselected remotely; these result in a reactivity rate of 1.8¢/second or 9¢/second. Any one of the four control rods may be used as a vernier control with a fixed velocity resulting in a reactivity rate of 3¢/second. The remaining three rods are used as safety rods and are fully withdrawn at all times.

2. Automatic Control: Closing the loop on the log power signal enables the power control system to automatically control the reactor power level over six decades. By closing the loop on the linear power signal, the system is capable of automatic power control over two decades with a resolution $< 1\%$. Figure 5 depicts a block diagram of the power level-period control system. If the demand power exceeds the actual power by $> 2\%$, the system automatically switches to period control when using either log or linear power control. This programs the power up to its demanded value at the preset period demand which is adjustable between one second and infinity.

Figure 6 shows the linear power level automatic control system in finalized transfer function form. The system has been designed to exhibit a bandwidth (-90° phase-shift point) of approximately 10 cps, using a control rod which has 16 - 18 cps response (small-signal). The inverse-period control system also demonstrates a 10 cps response. Both systems are insensitive to power level or temperature variations. Because of their relatively fast response, both demonstrate adequate "stiffness" to reactivity perturbations.

3. Fast Reset: When two out of three preset levels are exceeded in either power level or period, a fast reset action is initiated. This action causes the three safety rods to be inserted at their maximum servo-controlled velocity, which results in a negative reactivity rate of $5.40/second. The reset also causes the shim vanes to integrate inward with a resultant negative reactivity

rate of 31¢/second. Following the reset, the safety rods integrate out at a slow velocity resulting in a positive reactivity rate of 9¢/second. The shim vanes integrate outward at a velocity dependent upon system conditions, but never greater than that which will cause a positive reactivity rate of 28¢/second. The reset action described here is nonlocking, so, after the power and period are reduced by the insertion of negative reactivity, the system is returned to the preselected control mode. Because of this nonlocking feature, very little filtering is required for the electrical circuitry; thus the transport delays involved in initiating a fast reset action can be held to approximately three milliseconds.

4. Scram: In the startup range, a scram is initiated whenever the count-rate preset scram levels are exceeded. In the power range, however, scram is initiated only when two out of three levels of either power level or period exceed their preset limits. Because the fast-reset points can be set at values fairly close to operating values (e.g., 1.5 × design power, 2-second period) without causing spurious shutdowns, the scram set points can be moved much farther out (e.g., 10 × design power, 0.1-second period) without endangering reactor safety. In fact, a scram can only occur following the complete failure of the fast-reset safety system. In addition, much more filtering can be inserted in the scram circuitry. Consequently, the transport delay in the scram chain is set at approximately 300 milliseconds.

Summary

These four modes of nuclear control represent a method of maintaining safe, stable, and reliable control of the reactor through control of two primary reactor parameters; power level and inverse period. Basic safety considerations require (a) restriction of the amount of fast positive excess reactivity available to the control system, and (b) provision of sufficiently fast negative reactivity to allow recovery from all foreseeable accident situations. A unique feature of the Tory II-A control philosophy is the reliance on the fast reset action rather than on scram action to provide reactor safety at high power levels. The fast reset action attempts to maintain the demanded power level in the face of power perturbations, thus avoiding core-component thermal stress problems.

Airflow Control System

The Tory II-A air supply facility shown in Fig. 7 is capable of storing up to 120,000 lb of air at 3600 psi and 70°F. The airflow control system must deliver this air to the reactor at temperatures approaching 1060°F and at programmed flow rates as high as 800 lb/second. To accomplish this, two control elements are used: (a) AV-3, a 24-inch electrohydraulically actuated pressure-control valve which can deliver up to 8000 lb/second of air at 3600 psi tank-farm pressure. This valve is used for design-point runs (708 lb/second); (b) AV-4, a six-inch electrohydraulically actuated pressure-control valve which is used during runs involving intermediate flow rates (up to 400 lb/second). The position-control system of each of these valves has been designed to fulfill the following dynamic requirements: (a) 2 cps frequency response (-90° phase-shift point); (b) no overshoot to a step; (c) position resolution of 0.05% of full stroke; and (d) static stiffness sufficient to prevent a position deflection greater than 0.1% of full stroke with maximum aerodynamic load. In the case of AV-3, aerodynamic loads are encountered in a range up to 25 tons of force. Because of this, the control system has been designed to exhibit a static stiffness of 10-million lb/inch.

Figure 8 shows AV-3 during checkout and optimization at the Lawrence Radiation Laboratory factility in Livermore, California.

Both AV-3 and AV-4 may be operated during any test. Although they are normally controlled in a position-servo mode, they can be operated in a hydraulic override mode in the event of servo-system failure. The override "hold" mode is energized whenever pressure, rate of change of pressure, or valve error signal exceed certain preset limits which indicate an unsafe operating condition.

Instrumentation

Figure 9 shows a block diagram of the overall flow-control system. The flow system instrumentation used for feedback to the operator in manual control and to the automatic control system is as follows:

1. Three pressure transducers are located upstream of the diffuser to sense inlet air pressure. These signals provide visual indication to the operator, are used in the flow computer for feedback in the automatic control system, and, through a two-out-of-three logic, are used to initiate override hold action. These signals are also differentiated to provide rate of change of pressure indication to the operator.

2. Three thermocouples located upstream of the diffuser sense inlet air temperature which is used in the airflow computer.

Modes of Control

The reactor airflow rate is controlled in three different modes: (1) manual; (2) override; and (3) automatic.

1. Manual: In the manual mode the airflow operator positions the appropriate pressure-control valve to program the airflow rate. Airflow rate is determined from stagnation pressure gauges or the flow-rate computer.

2. Override: The control system is placed in the override mode whenever the reactor inlet pressure or pressure rate exceeds preset values. It is also placed in this mode whenever the error signal in the valve subsystem

(AV-3 or AV-4) exceeds a preset limit indicating a component malfunction or loss of feedback. Two-out-of-three circuitry is used to prevent false override actions. In the override mode the operator can position either control valve accurately using electrohydraulic on-off circuitry which provides three functions: (1) hold; (2) in-slow; and (3) out-slow.

3. Automatic: In this mode the operator can program flow rate using either a flow rate demand potentiometer or a preprogrammed function generator for automatic scheduling of flow rate. In either case, the pressure-control valve is automatically positioned by the control system to maintain the desired flow rate.

The most stringent requirements placed on the automatic airflow control system is that of programming flow rate from 70 lb/second to 708 lb/second in a period of 15 to 60 seconds and then returning to a rate of 70 lb/second in approximately the same length of time. It is required that it maintain flow rate within 1% throughout the transient. The control system shown in Fig. 9 meets these requirements and, in addition, permits safe startup and shutdown of the airflow system.

Only AV-3, the large pressure-control valve, has been wired for use in the automatic mode of control. In this mode, the control system senses diffuser stagnation pressure. However, the latter is used with diffuser stagnation temperature to calculate flow rates according to the relationship

$$\frac{\dot{W} = 0.53\, P_{to}\, A_d}{\sqrt{T_{to}}} \qquad (1)$$

where

$\dot{W}$ = flow rate at diffuser (lb/second)
P_{to} = stagnation pressure at diffuser inlet (psia)
T_{to} = stagnation temperature at diffuser inlet (°R)
A_d = diffuser nozzle area (in^2) .

Since the diffuser normally operates in a choked condition throughout most of the design-point run (above 50-70 lb/second), airflow rate control can be simply and accurately achieved using P_{to} and T_{to}.

The airflow automatic control system is shown in linearized transfer function form in Fig. 10. As shown, it is necessary to compensate for the drop in air-supply pressure (P_{AS}) in order to hold loop-gain constant throughout the run. In Fig. 10, $V_D'(s)$ represents the demand voltage to AV-3 while X_v represents valve position. The flow process transfer function, $P_{to}(s)/X_v$ can be accurately determined from a modified lump parameter analysis and has been shown[7] to be

$$G_{p_1}(s) = \frac{\delta P_{to}(s)}{\delta X_v} = \frac{K_p \sqrt{T_{to}} \; P_{AS} \, e^{-T_\tau s}}{(1 + \tau s)} \tag{2}$$

In Equation (2)

$$\tau = \left| \frac{P_{to}}{\dot{W}} \right|_{ss} \frac{1}{R} \sum_j \frac{V_j}{\gamma_j T_j} \tag{3}$$

$$T_\tau = \sum_j \frac{L_j}{\sqrt{\gamma_j R T_j}} \tag{4}$$

where

R = gas constant

T_j = stagnation temperature (°R) at various stations in the ducting

L_j = physical length (ft) of ducting or heater

V_j = physical component volume (ft^3)

γ = specific heat ratio for air at T_j

$\left| \frac{P_{to}}{\dot{W}} \right|_{ss}$ = steady-state ratio of diffuser stagnation temperature to air flow rate

K_p = valve flow gain

s = complex variable

δP_{to} = small-signal variation of stagnation pressure at diffuser inlet

δX_v = small-signal variation of valve position.

For T_{to} = 1060°F (hot run), it can be shown that:

T_τ = 0.25 seconds

τ = 3.15 seconds

When T_{to} = 0°F (cold run), then

T_τ = 0.5 seconds

τ = 3.3 seconds

The automatic control system was designed so that it could tolerate these changes in process transfer function without corresponding instability. With such a large transportation lag (T_τ), it is obvious that the required system must be one with a very slow response time.

The resultant system, which has a frequency response of 0.2 cps, utilizes pure integral compensation at the input to the pressure-control valve. The system has been successfully field-operated in all control modes for almost one year over a broad range of temperature and flow rates.

Other Control Systems

In addition to the power and flow control systems, there are numerous other systems (approximately 100), most of which are operated in an "on-off" manner. Typical of these systems are the low-pressure blowers which have the capability of continuously blowing air at 25 lb/second through the ducting and reactor. These blowers are used for preheating and aftercooling the core components.

The only other continuous control system which can directly affect the prime reactor variables is the air-temperature control system. This system uses two electrohydraulically actuated flow valves, differentially positioned, to control the temperature of reactor inlet air. In the Tory II-A phase, this system is operated manually by the air-temperature operator who adjusts valve position demand. Normally, inlet air temperature is varied quite slowly and periods of 1-5 minutes are allowed to take the temperature to 1060°F.

Overall Reactor Control

Before discussing how overall control of the reactor is carried out, it might be well to examine how the major control systems discussed above interact through the process variables. Figure 11 represents a signal flow diagram of the Tory II-A system when operating in the following manner:

1. Power-control system in automatic mode
2. Flow-control system in automatic mode
3. Air-temperature control system in manual mode
4. Diffuser operating choked
5. All variables operating around steady state.

The unidentified variables are next defined:

V_D'' = position demand voltage, temperature control valve

X_{v_1} = AV-5A position (hot line)

X_{v_2} = AV-5B position (cold line)

δT_{g_1} = variation of inlet air temperature

T_h = temperature of heat mass in heater

$N\,X_{v_1}$ = nonlinear function

$N\,X_{v_2}$ = nonlinear function

$N\,T_{h_1}$ = nonlinear function

$G_{T_1}(s)$ = transfer function of heat transfer process

$G_{T_2}(s)$ = transfer function of inlet temperature process

$G_{\dot{W}}(s)$ = transfer function of flow-core temperature process

$K_{\dot{W}}$ = airflow rate reactivity worth.

It can be easily shown that the frequency variant portion of $G_{T_1}(s)$, $G_{T_2}(s)$ and $G_{\dot{W}}(s)$ is approximately the same and can be accurately represented in a lumped parameter single-time constant τ_h where

$$\tau_H = \frac{C_{pr}}{c_{pg}\,\dot{W}}\, f(\dot{W}) \qquad (5)$$

C_{pr} = heat capacity of core

c_{pg} = specific heat of air

$f(W)$ = nonlinear function.

In the design-point region $\tau_h \sim 4$ seconds.

From the signal flow diagram shown in Fig. 11, it can be shown that there is very little interaction among the three major control systems. The air-temperature and flow-control systems are unaffected by changes at the reactor whenever there is a choked condition at the diffuser. The power-control system is insensitive to changes in flow rate or inlet air temperature because these changes are introduced by relatively slow systems through large time constants. In addition, it can be shown that $K_{\dot{W}}$, airflow rate reactivity worth, is quite small (about 5¢/100 lb/second); hence, all major reactivity perturbations to the power control system are inserted through a time constant of 4 seconds or greater.

When the diffuser becomes unchoked, the diagram shown in Fig. 11 no longer applies and some interaction between the systems results, since reactor temperature perturbations are reflected back to the flow process. Thus far, no appreciable interactions or control problems have been observed when operating in this region. Note that the airflow rate computer no longer computes flow rate in this region.

Since it is desirable to hold reactor core-temperature constant rather than power level, the control scheme shown in Fig. 12(a) has been recommended for design-point operation. Here, a sudden variation of airflow rate programs power-level demand correspondingly. The program to full flow can be scheduled manually or automatically. When using the latter method, the nuclear operator has full override trim capability. Figure 12(b) shows an alternate method which does not rely on transducers to provide an input signal to the power-control system. When using this method, the function generator must be stopped or reversed whenever the safety circuits in the flow-control system detect an unsafe condition and perform corrective action (i.e., place the system in override-hold mode). The filter shown between $V_{\dot{W}\,DEMAND}$ and the logarithmic function generator has the same time constant as the flow process.

Figure 13 shows the response of the slaved power-control system during a typical startup and shutdown, while Fig. 14 shows the response of the flow-control system during the same startup. The response of the two systems is identical whether using the method of Fig. 13 or 14. The data were obtained using actual hardware, but with the use of an analoged process.

Many other combinations of control are possible besides those shown. For example, one could use programmed automatic flow-rate control with operator-programmed automatic power-level control during initial nuclear runs where temperature information is being sought. The Tory II-A control systems have been designed to provide the maximum amount of flexibility in keeping with the experimental nature of the test program.

Test Results

Prior to delivery at the Nevada Test Site (NTS), all control systems and components were completely checked out at Livermore through the use of an analog representation of the process. Following installation at NTS, the system was again checked out using a simplified process analog.

The following tests were performed at NTS in order to fully qualify the control systems:

1. Measurement of the transfer dunction of the airflow process.

2. Demonstration of safe, stable, and accurate control of airflow rate in the automatic control mode over the range 70-800 lb/second.

3. Measurement of the reactor transfer function.

4. Measurement of the reactor temperature coefficient.

5. Demonstration of safe, stable, and accurate control of the reactor in the automatic power control mode.

6. Demonstration of safe, stable, and accurate control of the reactor at an intermediate power under actual airflow conditions.

1. Measurement of Airflow Process Transfer Function

The airflow process transfer function was measured at three flow rates: 160 lb/sec., 400 lb/sec, and 800 lb/sec. The inlet air temperature used during this test was approximately 1060°F. This measurement was made using the large control valve with a sinusoidal position demand input resulting in a sinusoidal air-flow rate of 100 lb/sec peak-to-peak. The reactor core was not installed during these tests. The calculated value for the process transfer function as determined from a modified lumped parameter analysis is:

$$G_{P_1}'(s) = \frac{1}{P_{AS}\sqrt{T_{to}}} \frac{\delta P_{to}(s)}{\delta X_v} = \frac{0.0078e^{-0.25s}}{1 + 3.15s}$$

The measured process transfer functions were found to be:

(a) $\dot{W}$ = 160 lb/second

$$G_P'(s) = \frac{0.0075e^{-0.25s}}{1 + 3.3s}$$

(b) $\dot{W}$ = 400 lb/second

$$G_P'(s) = \frac{0.007e^{-0.25s}}{1 + 3.8s}$$

(c) $\dot{W}$ = 800 lb/second

$$G_P'(s) = \frac{0.008e^{-0.25s}}{1 + 3.1s}$$

From this can be seen the close correlation between the measured transfer functions and the calculated value. It is also noted that the transfer function does not vary appreciably with flow rate. As a result of this close correlation, no redesign of the airflow control system was required before demonstrating automatic flow control.

2. Airflow Control System Demonstration

The flow-control system test consisted of a programmed automatic control run over the total range of flow conditions. Once again, the reactor core was not installed on the test vehicle. At the start of the run, the large control valve was manually opened until approximately 10% of full flow was attained. The air-temperature operator adjusted the inlet air temperature to approximately 1060°F. Then the airflow system was transferred to automatic control. An initial perturbation in demand inserted by the operator demonstrated the stability of the system. As shown in Fig. 15, the flow-rate demand was automatically programmed to 800 lb/second on a 60-second ramp. Following a short period at full flow, it was programmed back to 10% flow in 60 seconds. At this point the system was transferred back to manual servo control and then shut down.

During this run, the inlet air temperature dropped to 716°F because of heater energy limitations. Despite this variation, the control system maintained the demanded flow rate throughout the run.

3. Measurement of Reactor Transfer Function

Prior to a demonstration of the automatic nuclear control system, the reactor transfer function was measured. This measurement, which was made at two power levels, 30 watts and 7 kw, utilized a detector placed near the reactor. The signal from this detector was fed to a logarithmic power amplifier, thus providing a large-amplitude signal at the low power levels desired. The shim vanes were used to bring the reactor critical and to program power to the desired power level. At that point, a control rod was sinusoidally driven to obtain a peak-to-peak reactivity of 7¢. The resulting plots of gain and phase versus frequency are shown in Fig. 16. The phase curves are identical to the calculated curve for $\ell^* = 70$ microseconds. Since $\ell^* = 50$ microseconds was used in system design, this close correlation obviated the necessity for system redesign.

4. Measurement of Reactor Temperature Coefficient

Although the nuclear control system does not depend upon a negative temperature coefficient of reactivity for stability, it was determined that Tory II-A does indeed have a negative temperature coefficient before any attempt was made to use the automatic control system.

5. Automatic Nuclear Control System Demonstration

In order to verify system performance, an automatic control run was performed to fully qualify the power-control system for nuclear operations. The significant parameters are shown in Fig. 17. The reactor was brought critical and then taken to a power level of 180 watts in manual control. At this point the transfer to automatic control was performed with no power-level perturbations evident. Next, a rapid 50% increase in demand to 270 watts was inserted causing the system to switch to period control. The system attained the demanded 20-second period in a stable manner, leveled out smoothly, and maintained the demanded power level. A step increase in demand power level to 1050 watts was then inserted, and again the system responded as predicted. At this point, a negative demand to 720 watts was rapidly inserted with the system responding in a stable manner. Following this, a large, rapid, negative demand to 180 watts was inserted. The system recovered from this very severe test and large-signal stability was demonstrated.

6. Intermediate Power Run

The purpose of the intermediate power run was to operate the reactor at a power level of ≥ 40 megawatts with an inlet air temperature of 400°F while maintaining the core temperature at a value in excess of 2000°F. The control modes used for this test were as follows:

1. Airflow rate was controlled throughout the run using AV-4, the small control valve, in the manual servo mode.

2. Power level was controlled in the manual servo mode up to 400 kw and in operator-programmed automatic logarithmic power control above this level.

The run was begun by bringing the reactor critical and to 400 kw of power in manual control. The power-control system was then transferred to the automatic log power control mode, at which time a test of system stability was made. This consisted of a sudden change in power-level demand to 820 kw and then a rapid reduction in demand to 400 kw. The system exhibited good stability and the test proceeded as scheduled.

The airflow rate was then brought to 30 lb/second and inlet air temperature to 400°F. Following this, the power level was increased to approximately 10 Mw and held there until the core temperature reached 1900°F. The power level was then reduced sufficiently to maintain this core temperature. After evaluation of all parameters, the planned programs of power and flow were begun. The airflow was increased to 122 lb/second. Simultaneously, power level was increased bringing core temperature to a value in excess of 2000°F. These conditions were held for two minutes, after which both airflow and power were reduced in a linear manner. The flow rate was maintained at 30 lb/second while power level was further reduced to 200 kw. At this point, the 80-second delayed neutron group prevented further rapid decrease of power in the automatic control mode so the reactor was scrammed. After the reactor temperature had decreased sufficiently, the airflow control valve was closed. Everything performed as predicted during this run (including the reactor), and it was declared an "unqualified success."

The runs described above are typical of those required in the test of an experimental reactor. Initially, considerable operator participation is required while process performance and instrumentation are being evaluated by the scientific personnel. Following evaluation of these process unknowns, a high degree of automation is desired to remove as much of the human variable as possible. Advanced tests are currently being conducted which involve pre-programmed automatic control of airflow rate and power level. The extremely flexible Tory II-A control systems provide for many differing test requirements without system change or modification.

Conclusions

Concepts Proven

From the experimental results obtained during nuclear and non-nuclear tests, the following conclusions may be drawn:

1. The automatic logarithmic power-control system has ample stability margin and accuracy in both the large- and small-signal regions. The system stability margin does not change appreciably with reactor power level. It is concluded that this control mode can be used to control power level in a stable and accurate manner for power levels > 100 kw (a six-decade range is possible).

2. The automatic inverse-period control provides accurate and stable control of reactor period for period demands < 30 seconds and power levels > 100 kw (a six-decade range is possible).

3. The dual-mode concept (power-period control combination) is a desirable method of reactor control, particularly when controlling the logarithm

of power. Here, a small demand-voltage change appears as a relatively large power change.

4. The "fast reset" safety principle minimizes the probability of a false scram by allowing the operator to set scram levels quite high without jeopardizing safety considerations.

5. A large-capacity airflow process can be controlled automatically in a safe manner over a large dynamic range.

6. Simplified mathematical models of complex processes have been developed. These have proved to be of considerable value in the design and optimization of the automatic control systems. Their value has been proven by the fact that control systems using these models have been applied "as is" to the actual process.

Improvements Needed

1. Several factors warrant the addition of a semi-automatic checkout system. At present, several days are required to prepare and validate the complex control systems prior to an operational test. A system capable of checking some variables automatically and others with a minimum of human assistance would serve to materially reduce this time. In addition, a system of this type would reduce checkout time on actuator and other subsystems with a limited life expectancy, as well as provide accurate and complete checkout records.

2. A great deal of time is expended during startup because of human-caused delays in taking action and verifying test conditions. This delay causes excessive depletion of stored air and makes startup a tedious job. A semi- or completely-automatic system to begin a test quickly is desirable.

3. Because scram and fast-reset levels must be changed frequently as power levels and airflow rates change during the course of a test, a method of adjusting these automatically, yet safely, is desirable.

4. A method for reliably programming and maintaining the proper relationship between power and airflow rate during a test is needed.

5. A more complete analog simulation of processes and electrohydraulic components is desired. This would provide more accurate system checkout, more thorough operator training, and may be used to verify system performance.

6. A new approach to the system electronics and analog computer is necessary to improve reliability and increase versatility in changing test requirements.

TORY II-C CONTROL SYSTEM DEVELOPMENTS

Outline of Requirements

Tory II-C, like Tory II-A, will be a ground-test reactor. However, it is intended to be a full-scale, missile-like reactor with regard to core configuration, core components, and method of reactor control. Generally, the control methods outlined above for Tory II-A will be used as well for Tory II-C. As many of the hardware improvements which have been indicated will be included as time will permit.

The principal difference between Tory II-A and Tory II-C is the requirement for reactor control within the core. This change from reflector control as used in Tory II-A considerably increases the control-rod actuation problem. The difficulties arise from the severe environmental conditions which exist at the reactor inlet during design-point runs in which inlet air at temperatures above 1000°F is used to cool the reactor. Figure 18 shows a typical Tory II-C power, flow rate, and inlet air-temperature program, indicating the rates at which the nuclear, airflow rate, and air-temperature variables (hence, the actuator environment) are changed. The environmental limits in the inlet ducting are listed below:

1. Temperature: upper limit 1200°F (including radiation heating)

2. Nuclear: 10^8 rads total

   5×10^7 rads fast neutron

   3×10^7 rads thermal neutron

   2×10^7 rads gamma.

3. Ducting air velocity: 0 to 100 feet/second

4. Ducting air temperature: 0 to 1060°F

5. Ducting pressure: 12 to 360 psia

6. Acceleration: 6 g continuous axial load

7. Vibration: 0 to 20 cps - 0.1-in. amplitude

   20 to 800 cps - 6 g

   800 to 1400 cps - 12 g

   1400 to 2000 cps - 20 g .

As this extreme environment precluded the use of Tory II-A-type actuators directly connected to control rods at the reactor face, alternate solutions which involve actuation from outside the duct were examined. All such methods involved flexible control rods and couplings, thus replacing actuator problems with control-rod problems. A serious question arose relative to the ability of the control actuation system to meet the dynamic requirements because of mechanical and material limitations. Important dynamic and life requirements which the fine (vernier) control-rod system must fulfill are:

1. Stroke: 40 inches

2. Saturation velocity: greater than 60 inches/second

3. Acceleration: greater than 10 g.

4. Resolution: 0.04 inches

5. System stiffness (static and dynamic): must be capable of holding 20-lb load within resolution under environmental conditions specified

6. Frequency response: -90° phase-shift at 15 cps

7. Life requirements: (assuming numerous cyclic and performance tests in the position servo mode):

a. 120-hour operating life under normal conditions

b. 30-hour operating life under nonradiation extreme environmental conditions

c. 3-hour operating life under extreme conditions (high temperature and radiation

8. Fail-safe requirements: must be capable of inserting a 20-lb control rod 40 inches into reactor in a maximum of 0.25 seconds.

The dynamic and life requirements for the coarse or shim rods are quite similar. However, a much slower saturation velocity (1-in./second) and frequency response (1 to 3 cps) is required. In addition to the above requirements, the maximum cross-sectional area of a duct-mounted actuator package was specified in order to avoid "blacking-out" too great a percentage of the total reactor inlet area.

After evaluating the various control methods in view of the state-of-the-art and the system specifications, the Lawrence Radiation Laboratory decided in early 1959 on the development of high-performance actuators which could withstand the severe environmental conditions imposed by Tory II-C. It was felt that this approach had the greatest chance of meeting the system requirements in the time period allotted and would represent a significant "breakthrough" in the design of flyable environmental systems. In the event the development effort did not meet with complete success, cooling air from the air supply could serve as coolant for the individual actuators. In addition, the temperature of the inlet air to the reactor could be lowered. This approach, however, would involve a serious digression from the desired design-point conditions.

Figure 19 shows how the actuator package will be duct-mounted on the test vehicle.

The scope of the development program was limited to those components which must be mounted in the area of extreme environment, i.e., servo valve, motor, clutch and transmission, rack, position transducer, and appropriate electrical and pneumatic connectors and couplings. Environmental electronics were specifically excluded from the development effort for the following reasons:

1. Reliability of the electronics was an absolute requirement for the Tory II-C ground test, dictating use of solid-state components in the time period imposed.

2. No specification had been written for the flyable electronic hardware. It was felt that components then undeveloped (such as tunnel diodes) might be introduced between the time of ground and flight test, thus satisfying the flight environmental and performance requirements. The recent tunnel-diode work being carried on at IBM under WADD sponsorship shows great promise for this application.

3. The Tory II-C test could be conducted without environmental electronics but not without environmental actuation systems. Concentration of the development effort on the critical area was necessary in view of this.

After extensive study of electropneumatic, pneumatic, electrical, and electrohydraulic methods of actuation, LRL decided upon the use of electropneumatic actuation for the Tory II-C reactor. At the time of this decision, all methods of actuation were unproven over the temperature range 70°F to 1200°F. Despite this, the electropneumatic method was chosen for the following reasons:

1. There is no apparent environmental limit which restricts its use above a certain temperature, radiation level, etc. Conversely, both hydraulic and electrical methods do have limited temperature and radiation capabilities.

2. Small actuator size and weight is possible while still meeting the system dynamic requirements.

3. The electropneumatic method of actuation is compatible with the requirement for remote operation and control where electrical inputs and outputs are needed. The fully pneumatic method is deficient in this respect. In addition, high-performance requirements dictate that electrical compensation be employed in the actuation subsystem.

4. There is no danger of contamination of the reactor if leakage of the actuator working fluid occurs.

5. Both in the ground test and the flight situation, there is an abundant air supply available at all times (approximately 1.2 million lb at the Tory II-C facility).

Review of Actuator Development Programs

Two development efforts have been directed toward meeting the actuator requirements of the Tory II-C reactor. The status of each of these efforts, which are being carried out under LRL technical direction, is described here.

Model 1240 Actuator

One phase of the actuator development program has resulted in a prototype called the Model 1240 actuator. This prototype, which can be used over the pressure range 90 to 1000 psia, employs position feedback to accomplish closed-loop control. This system, which is shown schematically in Fig. 20, employs a two-stage, electropneumatic servo valve to actuate a gear motor which drives the control rod through a rack and pinion. A high-temperature, linear variable differential transformer (LVDT) attached to the rack is used for control-rod position feedback and indication. The Model 1240 actuator is shown in exploded form in Fig. 21. Figure 22 shows the Model 1240 motor before high-temperature test, while Fig. 23 depicts the actuator as it was prepared for test at the contractor's facility. Figure 24 shows the motor-servo-valve combination following extensive testing above 1000°F. An exploded view of the motor following high-temperature tests is shown in Fig. 25.

At the time of this writing, the Model 1240 actuator has undergone specified ambient and high-temperature life tests with a considerable degree of success. Under simulated environmental conditions in the laboratory, it has accumulated over 10 hours of cyclic testing. The system exhibits a frequency response of 10 to 15 cps and 0.1% resolution over the temperature range of 70°F to 1200°F. It has operated under servo control in an acceptable manner during vibration tests carried out at room temperature. The major deficiencies noted during the above tests were:

1. Repeated failure of position transducer due to breaking of the electrical winding at temperature.

2. Inability of servo valve to withstand the large differential between ambient and supply temperature.

3. Failure of scram snubbing springs at temperature due to lack of lubrication.

These problem areas have been or are being corrected with corresponding improvement of reliability.

The Model 1240 actuator is currently undergoing advanced testing in the laboratory to evaluate component improvements. A full-scale environmental test in the Tory II-A facility is anticipated following reactor tests.

To provide the specified shim-rod actuation, the Model 1240 must be modified to include a gear transmission and clutch assembly. LRL is currently sponsoring a development effort which is directed toward producing high-temperature versions of each of these components.

<u>RAHS Actuator</u>

The RAHS (Reactor Actuator, High-Speed) actuator is the result of a parallel development effort. It differs from the Model 1240 actuator in that it utilizes a nutating disc motor in place of the gear motor. Other related components such as servo valve, position transducer, etc., operate in a similar manner. The nutating disc motor has effectively demonstrated its promise for high-temperature operation through the use of a breadboard version over a period of two years.

The RAHS actuator system shown in Fig. 26 has successfully passed room-temperature tests and is currently undergoing environmental tests. No test data are available at the time of writing.

Tory II-C Control System Improvements

Following the successful implementation of the Tory II-A control system at NTS, an extensive review of reactor control philosophy and methods was initiated in order to evaluate methods for achieving the various control functions required in Tory II-C with an objective of recommending a specific system design. Various approaches to this new control system design problem were considered[8] including continuous and discontinuous analog, digital, hybrid, etc. The state of development of each approach was assessed in evaluating its possible application in the Tory II-C control system.

The criteria used for evaluation of a particular system design in order of importance were: (1) safety; (2) simplicity; and (3) adaptability.

1. Safety: Safety requires protection of operating personnel from nuclear hazards through inherent safety of the nuclear control system. In addition, the requirement for safety is also necessary at the reactor core since destruction of the core involves a severe economic and programmatic penalty.

2. Simplicity: Simplicity of design is required because a simple system is inherently more reliable and less costly. The need for reliability is obvious in view of the number of systems involved in a test and the cost of conducting the test.

3. Adaptability: The design approach selected must have a great degree

of adaptability in order to meet the test requirements of the various Tory programs. The Tory II-A tests described above provide an indication of the required flexibility during just a small portion of the experimental program.

Following evaluation of the various control methods in light of the criteria given, it was decided that few major departures should be made from the control concepts employed for Tory II-A. This decision was based on: (1) expenditures already made; (2) proven reliability experience with the present system; (3) proven performance already achieved; and (4) short Tory II-C time schedules. It was felt that for Tory II-C further development effort would be better expended in upgrading the components, subsystems, and systems and adding certain desirable features rather than performing a complete redesign. In addition, the substitution of digital techniques would be impractical in many of the analog subsystems (such as the control-rod actuation subsystems). For on-line system control, data collection, etc., it was felt that digital techniques were lacking at the moment in adequate reliability and flexibility for this type of experiment. Also, the tight Tory II-C schedule did not permit a major change in control philosophy or techniques.

Some significant improvements are being introduced in the Tory II-C control systems. They are next considered.

Semi-Automatic Checkout System

A semi-automatic checkout system which is being designed will measure and record power supply and calibration voltages and other similar variables automatically. In addition, it will have the semi-automatic capability to isolate and measure subsystem gains, frequency response, transient response, and switching logic accuracy. For these tests, an operator will make the actual measurements and evaluate performance.

The final stage of preoperational checkout will be done by closing the loop with an accurate simulation of the overall process.

Use of Solid-State Components

An evaluation of commercially available solid-state electronic components has resulted in the decision to use these for the Tory II-C control systems. These include operational amplifiers, multipliers, logarithmic and variable function generators, and compatible power supplies. These have demonstrated a high degree of accuracy and have correspondingly high reliability. They are built in small modular units which permit simplified functional changes and relatively easy maintenance.

Startup

Two sets of three compensated ion chambers driving log power and period amplifiers will be included in this system. As is now the case, one set will be remotely located to provide automatic power control over the top six decades of power level. The other set will be remotely movable by a reliable, high-precision positioning system. When positioned close to the core, they will be used for feedback in the automatic power-control system at power levels down to 10 watts. By switching between the two sets of chambers, simple and reliable automatic log power control over approximately 10 decades will be provided.

By means of these movable detectors, power level can be programmed through the low and intermediate ranges into the power region by retracting the detectors while demanding a fixed detector voltage output. Shutdown would be initiated by the reversal of this procedure. A similar method, using fission chambers driving log-count rate meters and period amplifiers, is currently being evaluated for possible use in automatic startup in Tory II-C.

Programming

A more versatile method of programming the controlled variables is being evaluated with an analog computer solution. This would replace the present electromechanical programmers with a solid-state electronic type and would permit adjustment of the automatic program from the control point during the test. It would also permit program stop or reversal at any time. In Tory II-C, it will be possible to program flow rate, power level, and core or exit gas temperature during any run. It is possible that core temperature will become a controlled variable if Tory II-A high power-level tests demonstrate that the thermocouples yield accurate and reliable readings at high power densities. Automatic temperature control would then replace the operator for the purpose of carrying out a slow "trimming" action on power demand.

Reactivity Computer

An on-line analog-type reactivity computer is to be included to allow the operator to continuously monitor reactivity. This may also be used in the reset system to insure complete reactor safety at all times.

The analog simulation for system checkout and operator training will also be used as an on-line computer. Significant variables will be provided for comparison with actual system conditions. This will simplify evaluation of any abnormal condition.

Variable Setpoints

Since the fast reset and scram set points must be frequently changed during a run, provision is being made for automatically adjusting them as a function of the existing demand power level. The adjustment will be made at a slow rate so that the reactor will still be protected against rapid perturbations. Maximum limits will be independently set. Typically, power-level reset set points might be set at 150% of demand power level, and the scram set points at 200 to 400% of demand power.

In the flow-control system, set points are provided to limit maximum inlet air pressure and maximum rate of change of pressure. These also frequently must be changed during the course of a test. Provision will be made to automatically change these as the test progresses. However, they will not be "floating" set points as in the power-control system.

LONG RANGE DEVELOPMENT EFFORT

The outstanding control problem facing the Pluto program at this time is that of obtaining reliable environmental hardware to provide control actuation. All other problems are insignificant by comparison when considering just the Tory II-C application. To provide the reliable hardward needed, an extensive development effort is being conducted on electropneumatic actuation systems. Test results and reliability data are being accumulated during the course of this program and are being used for continuous upgrading of component and system reliability. Electropneumatic actuation systems have already exhibited reliability equal to that of electrohydraulic systems at room temperature. Through optimization of actuator design parameters, materials, and lubricants, it is felt that this same reliability can eventually be demonstrated throughout the entire Tory II-C environment.

The major control problems which are foreseen in Project Pluto in progressing to an actual flight engine are:

1. Development of reliable environmental hardware for actuation and control. Both electronic and electropneumatic components and subsystems which operate reliably at elevated temperatures in a radiation field are needed.

2. Development of a simple, reliable, and safe startup method. As compared to chemical engines, nuclear reactors lend themselves to simple startup. However, safety considerations have made most startups a complicated and tedious task. A simpler way must be found.

3. Development of a simple, reliable method of engine control in the power region. The methods thus far outlined for control of the ramjet reactor

in the power region involve control or limiting of many variables simultaneously (such as power level, period, core temperature, Mach number, etc.). A simple method of engine control would considerably increase reliability of the corresponding flight vehicle.

The efforts being carried on at the Lawrence Radiation Laboratory are directed toward solving many of these problems within the Tory II-C time period. The specific steps being taken are:

1. Further development of environmental hardware (electropneumatic and electronic).

2. Development of multi-decade power-period control systems for automatic fast startup, using movable detectors with logarithmic amplifiers.

3. Continued development of simple, but reliable, control concepts which can easily be incorporated into overall engine control.

ACKNOWLEDGMENT

The work presented here represents the accomplishments of the entire Controls Group, both at Livermore and NTS. The authors are indebted to these people for their help in carrying out this work and for making much of the material available for presentation. The authors wish to thank Robert Yentema for his help in preparing this manuscript.

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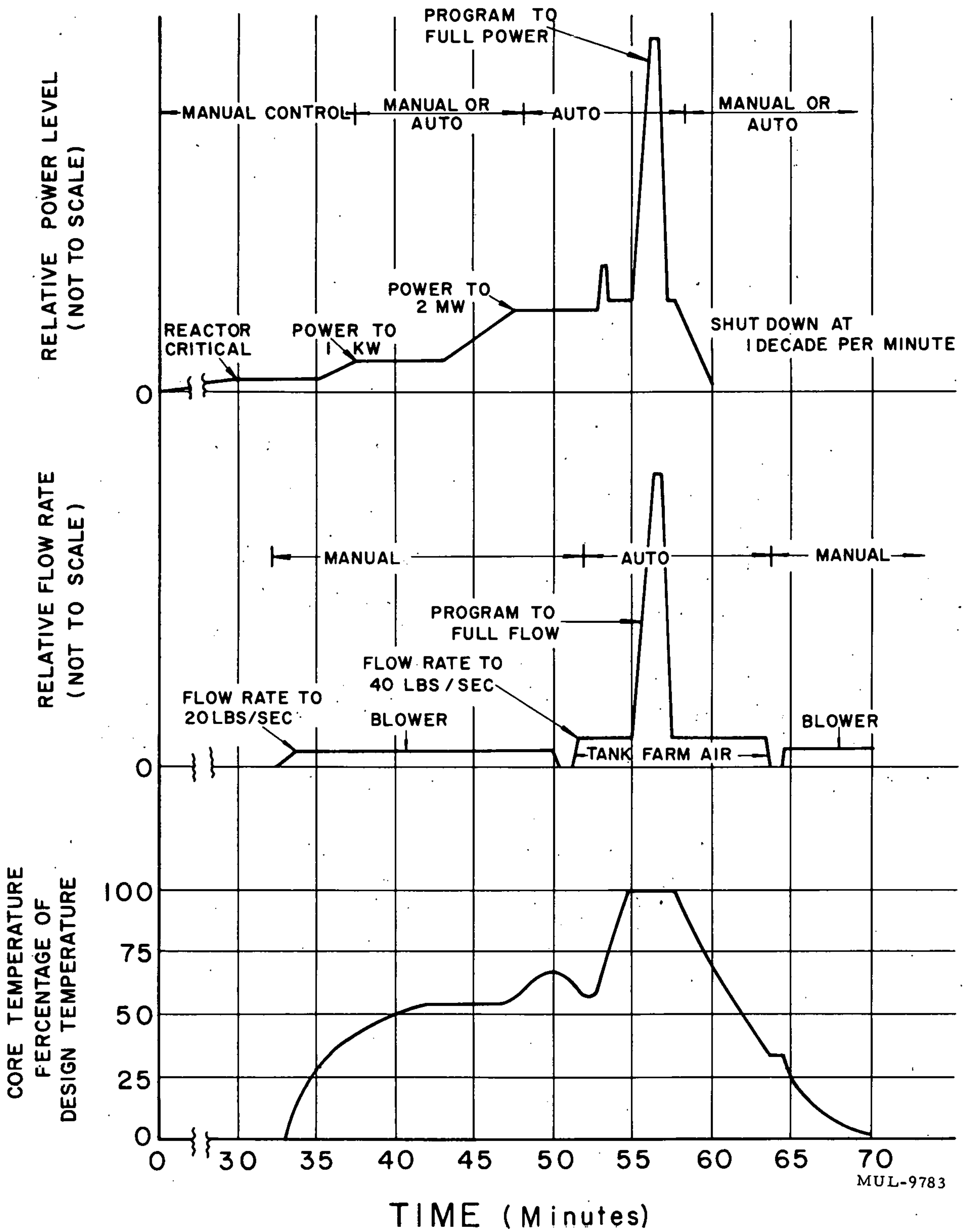

Fig. 1. Plot of reactor variables during typical design-point test.

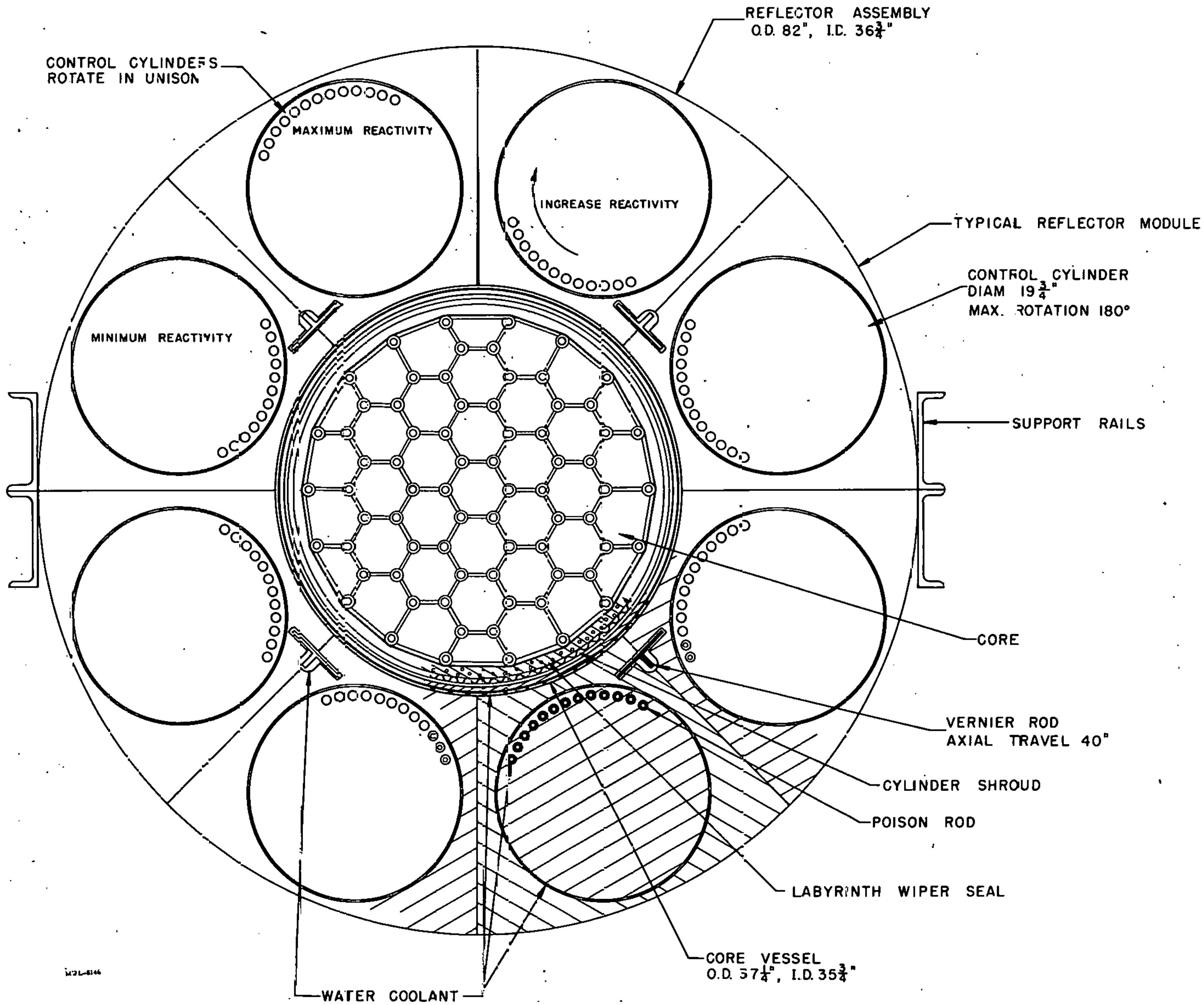

Fig. 2. Cross section of Tory II-A core showing location of control elements.

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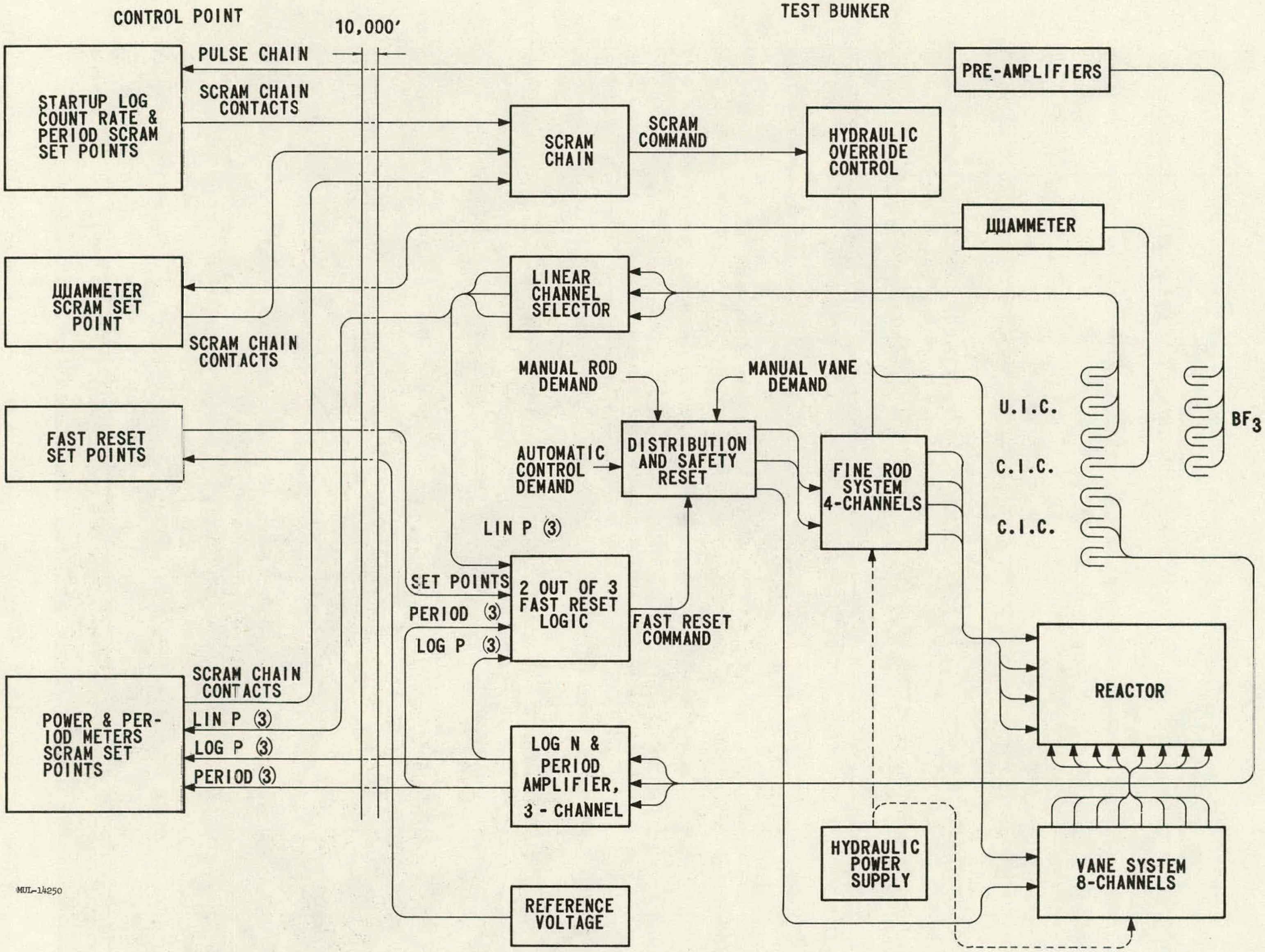

Fig. 3. Block diagram of Tory II-A nuclear control system.

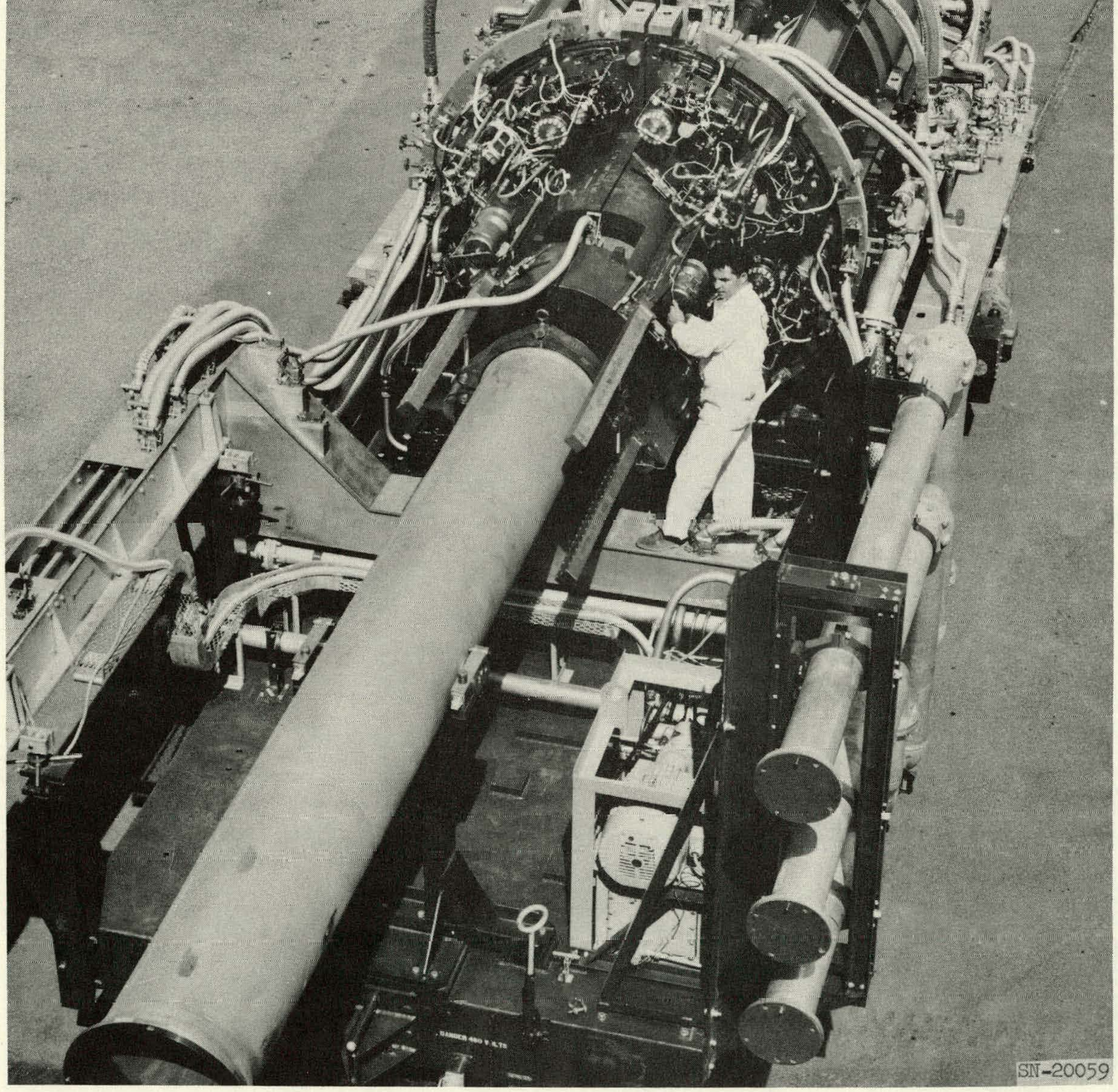

Fig. 4. View of Tory II-A test vehicle showing electrohydraulic actuation systems and pump (lower right).

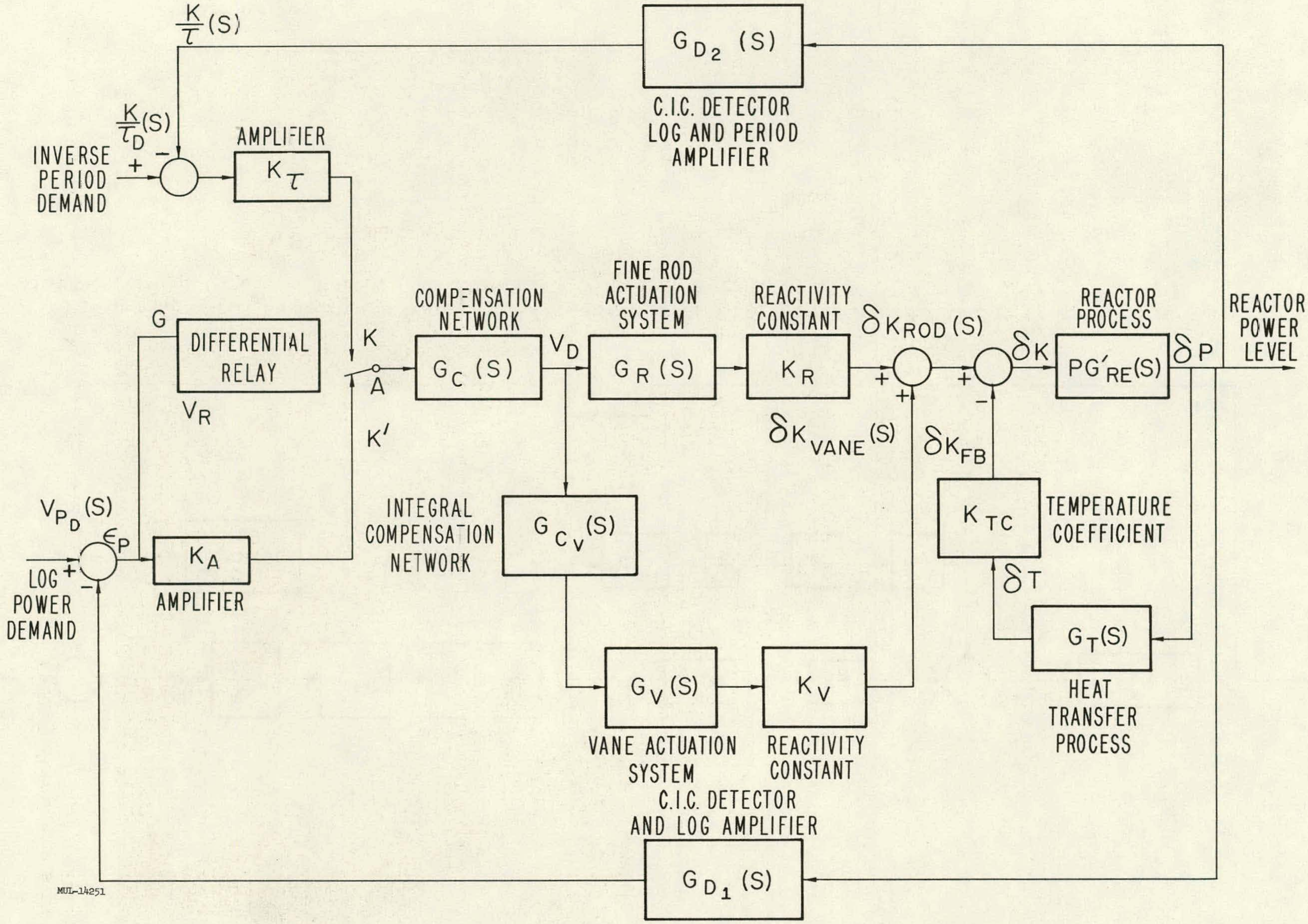

Fig. 5. Block diagram of power level, inverse-period automatic control system.

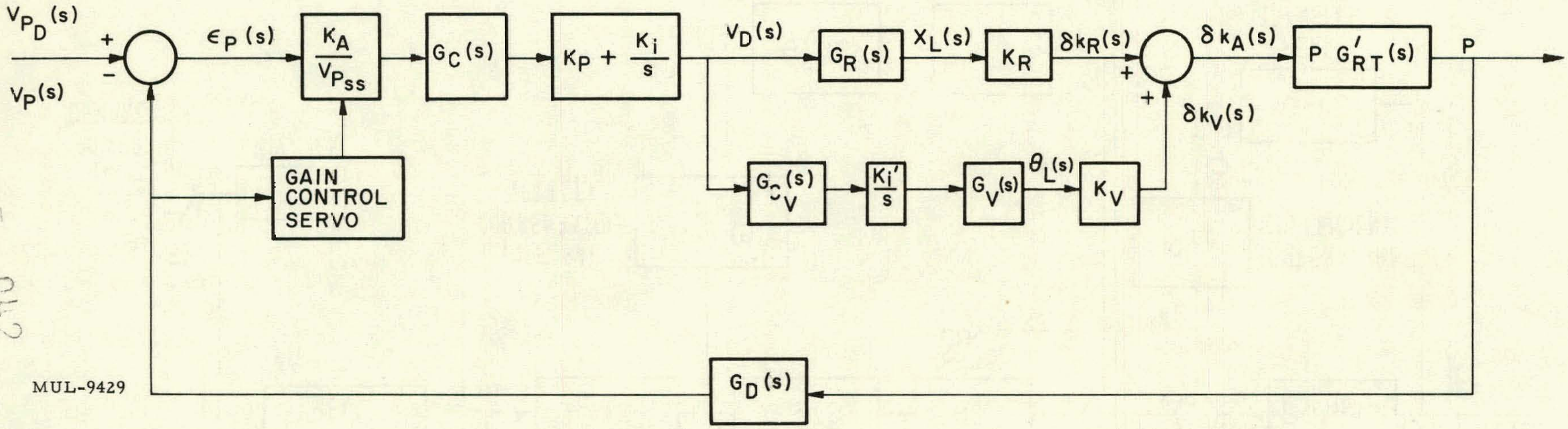

Fig. 6. Control system configuration for nuclear control system in finalized transfer function form.

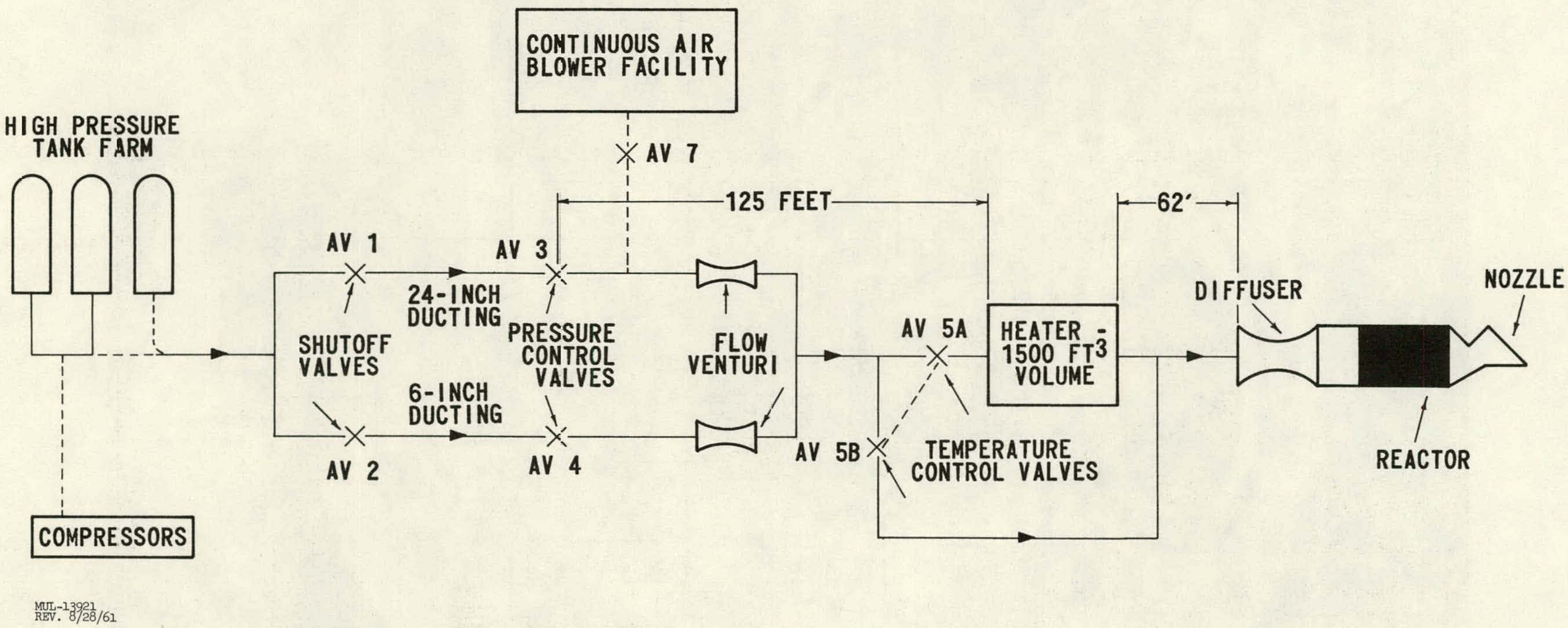

Fig. 7. Schematic of Tory II-A air supply facility.

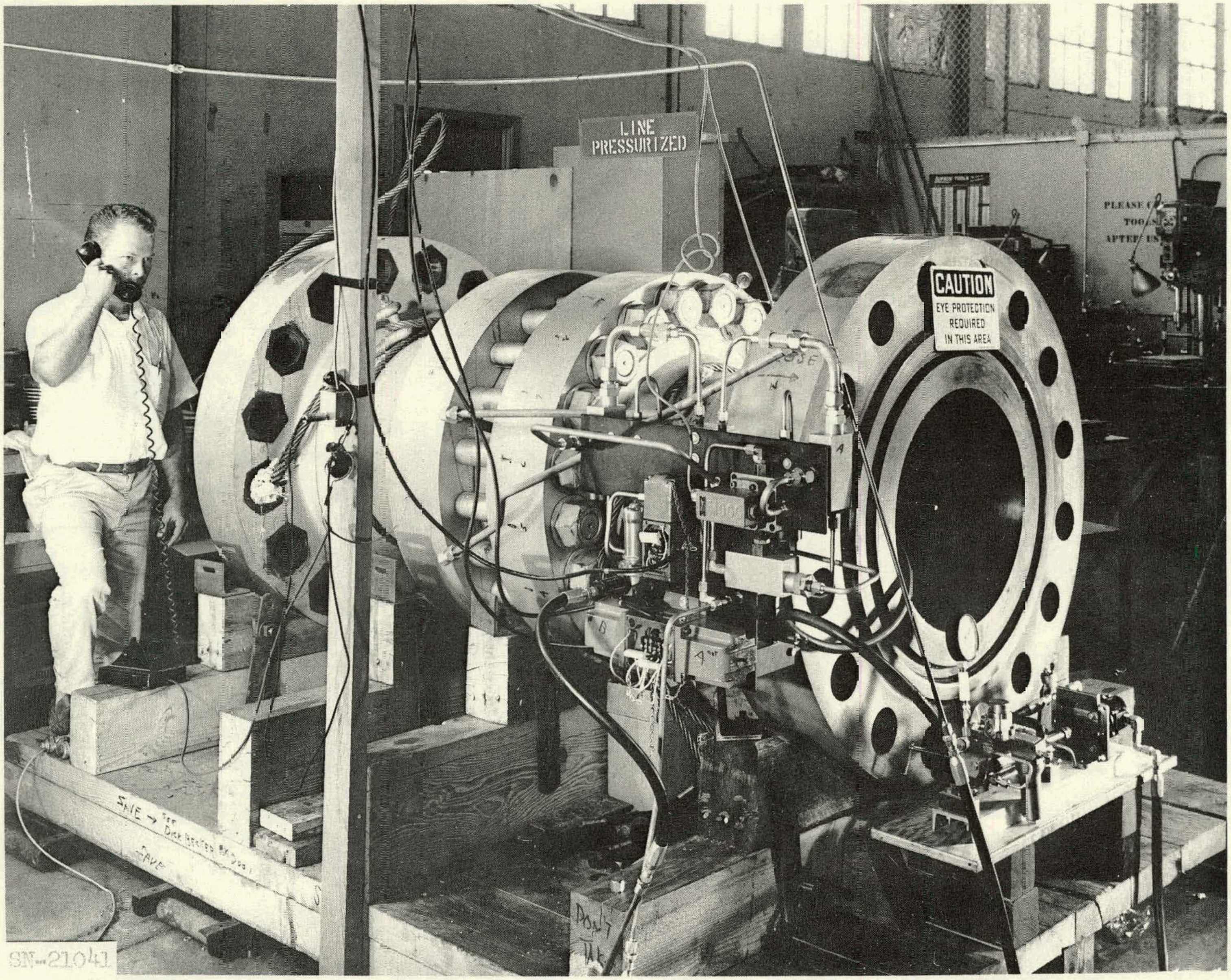

Fig. 8. Large pressure-control valve during optimization tests at Livermore.

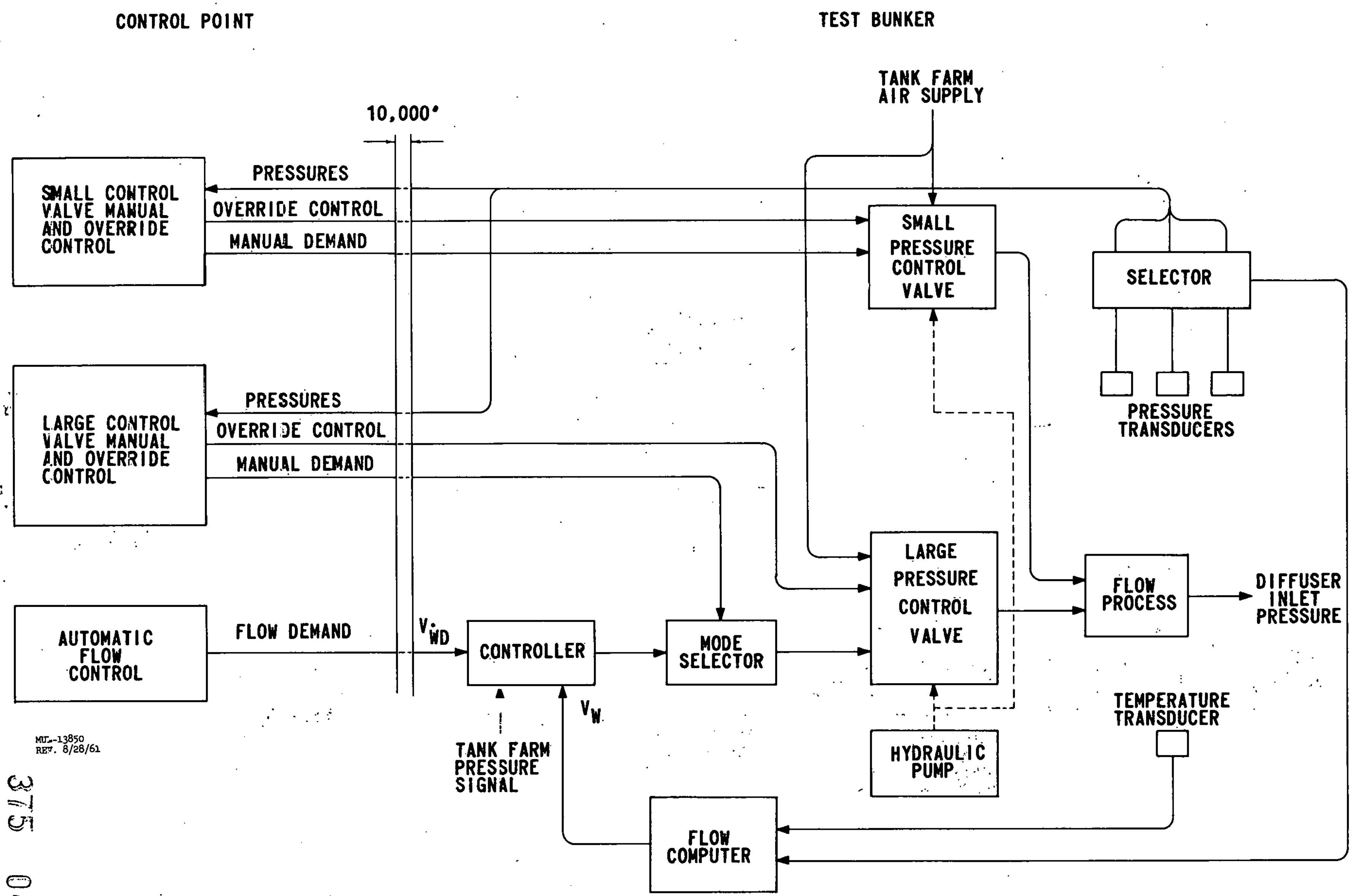

Fig. 9. Block diagram of Tory II-A flow-rate control system.

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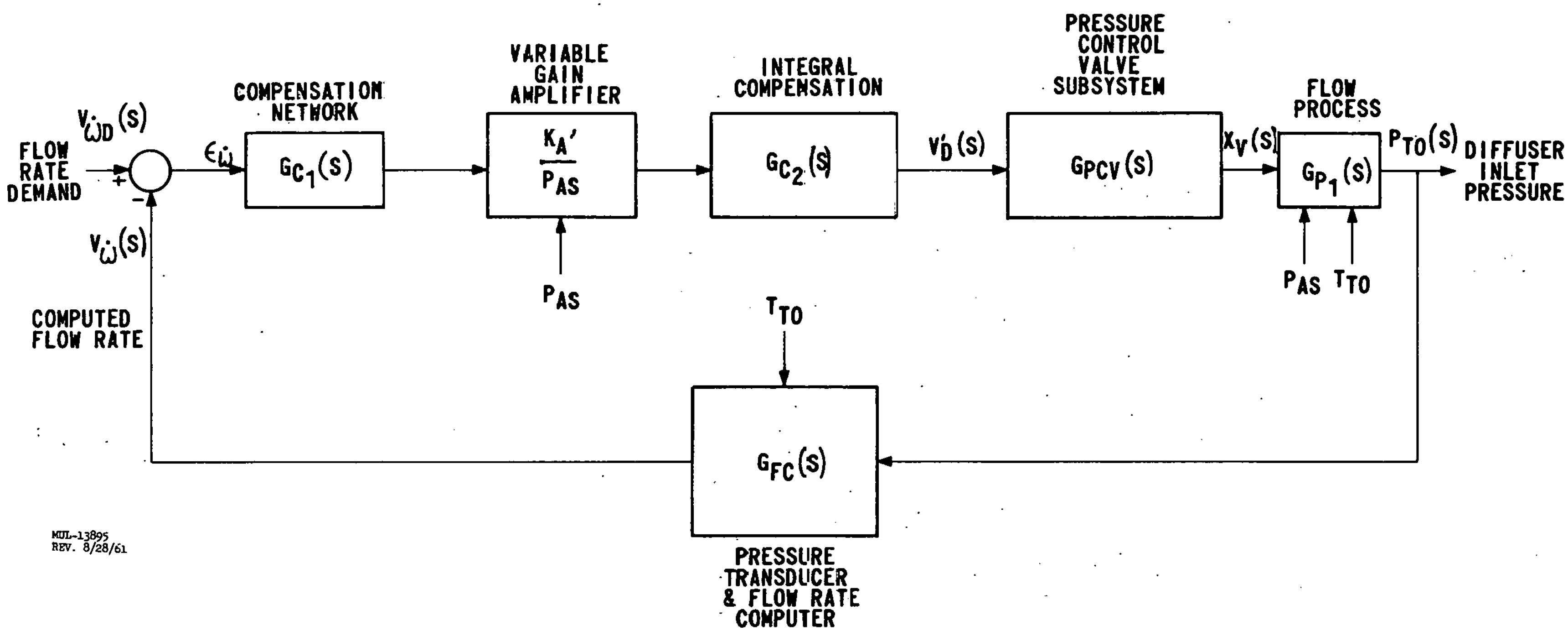

Fig. 10. Control system configuration for airflow control system in finalized transfer function form.

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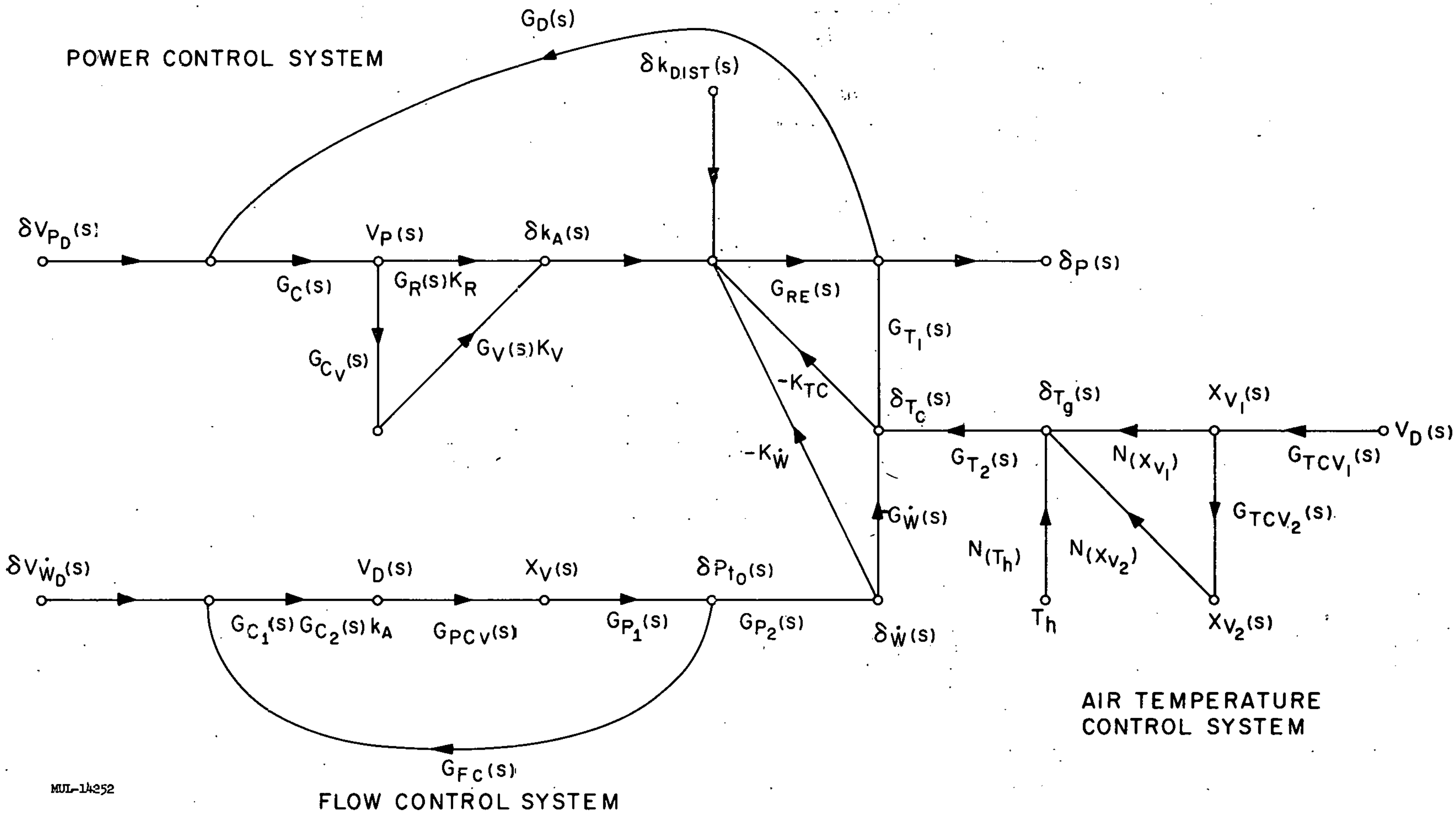

Fig. 11. Signal-flow diagram of Tory II-A process-control system.

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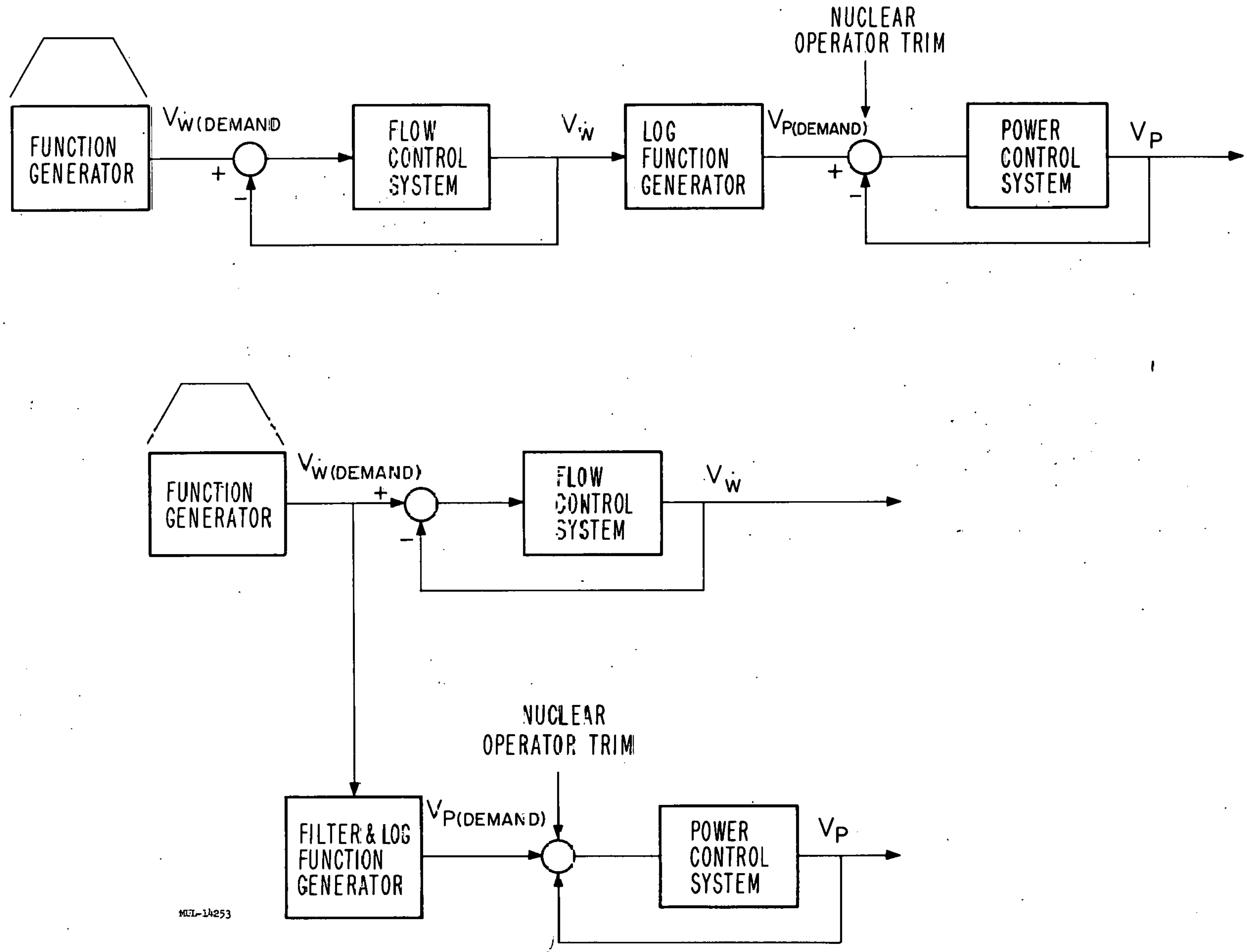

Fig. 12. Two methods for automatic programming of power level and flow rate.

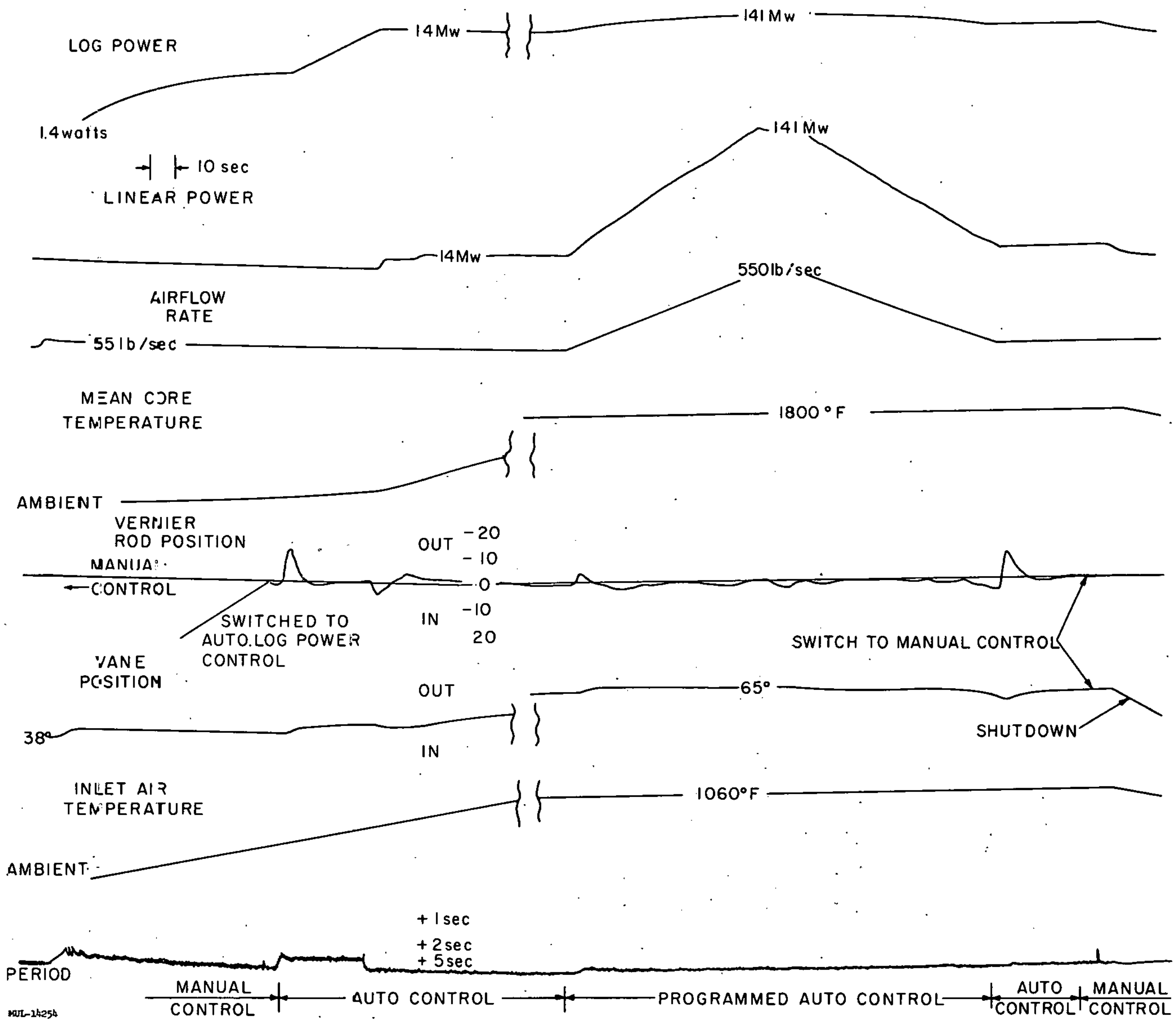

Fig. 13. Response of nuclear control system during a typical design-point run.

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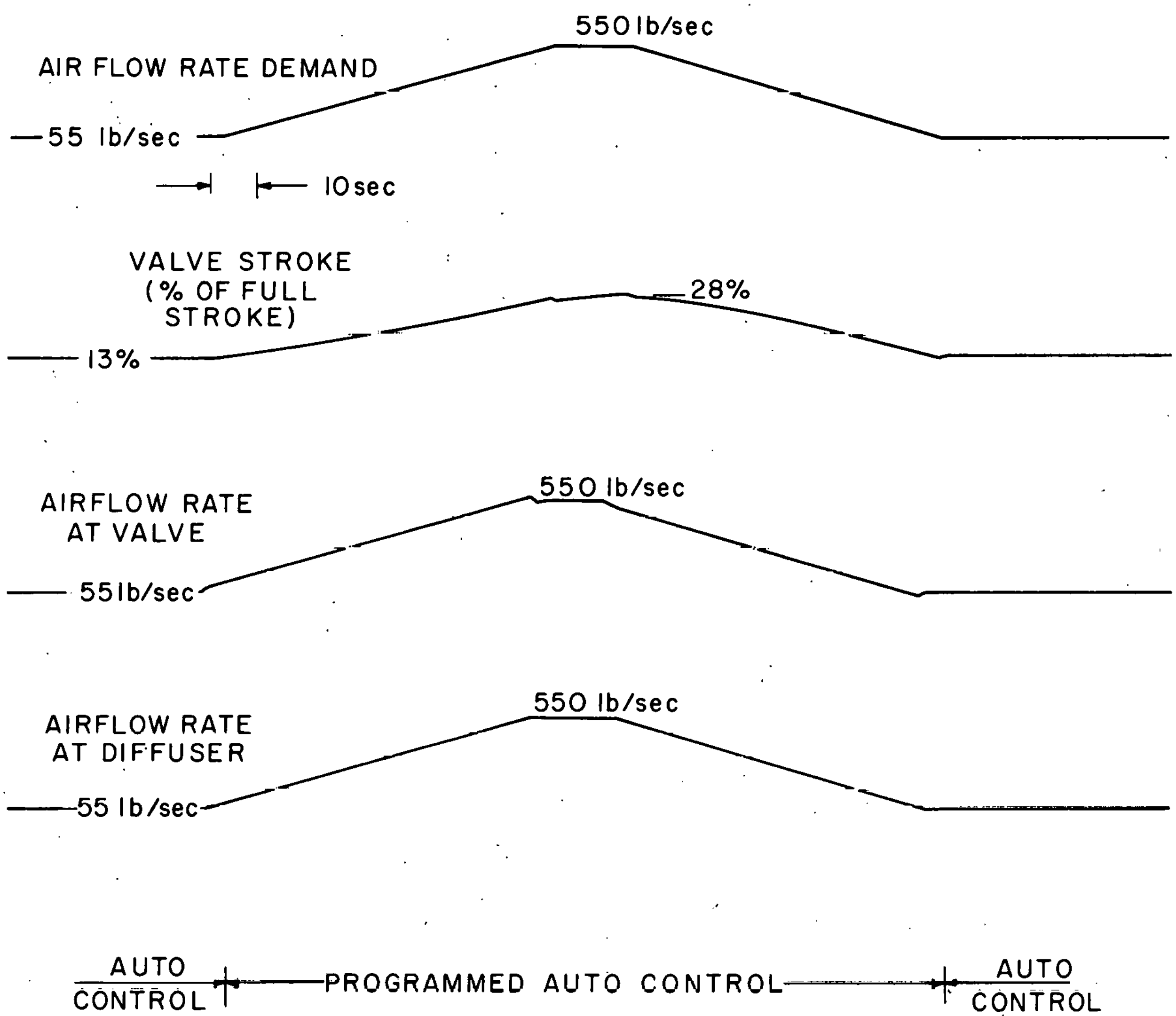

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Fig. 14. Response of flow-control system during a typical design-point run.

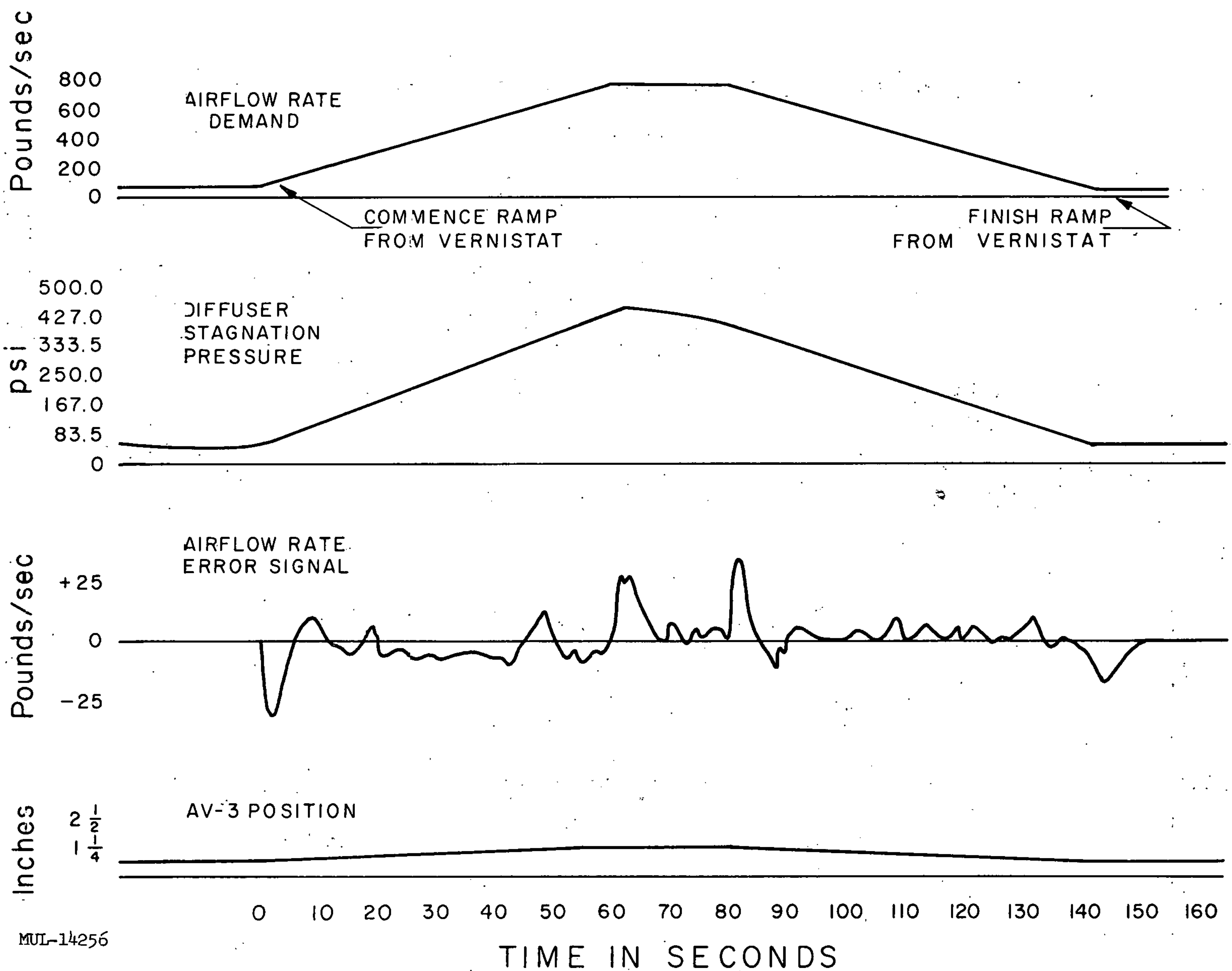

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Fig. 15. Experimental data recorded during automatic flow-control system demonstration.

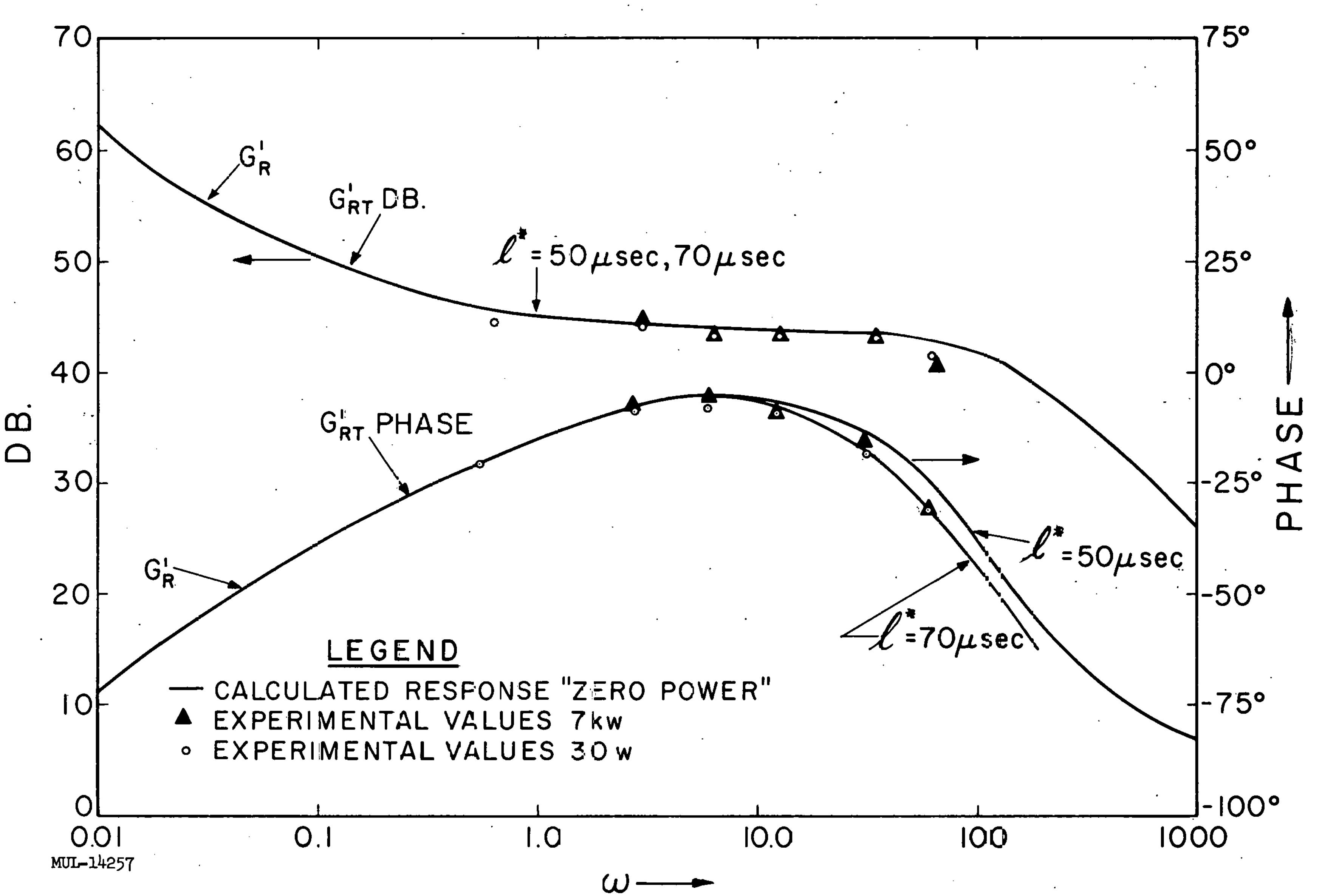

Fig. 16. Plot of theoretical and measured Tory II-A transfer function.

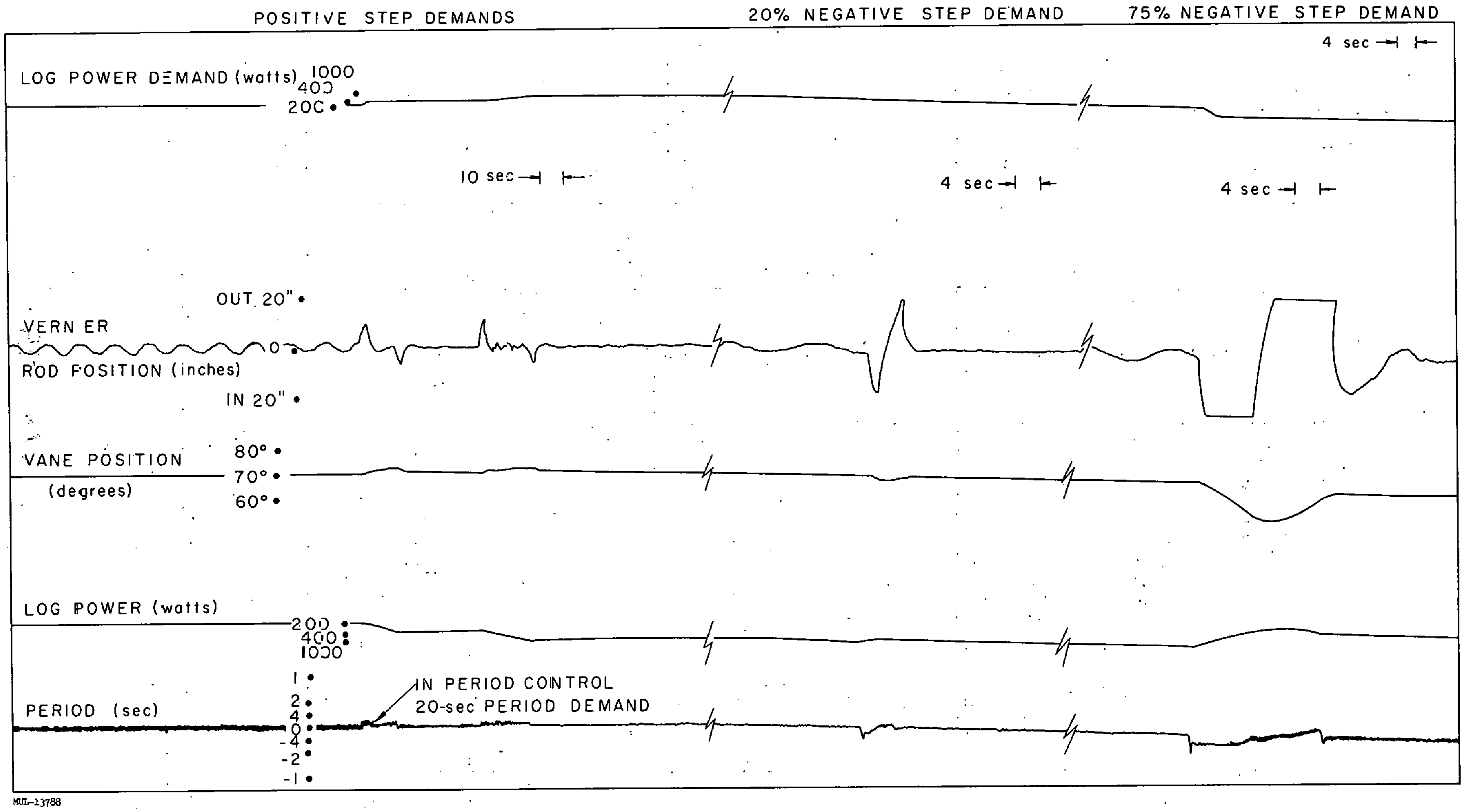

Fig. 17. Experimental data recorded during automatic nuclear control system demonstration run.

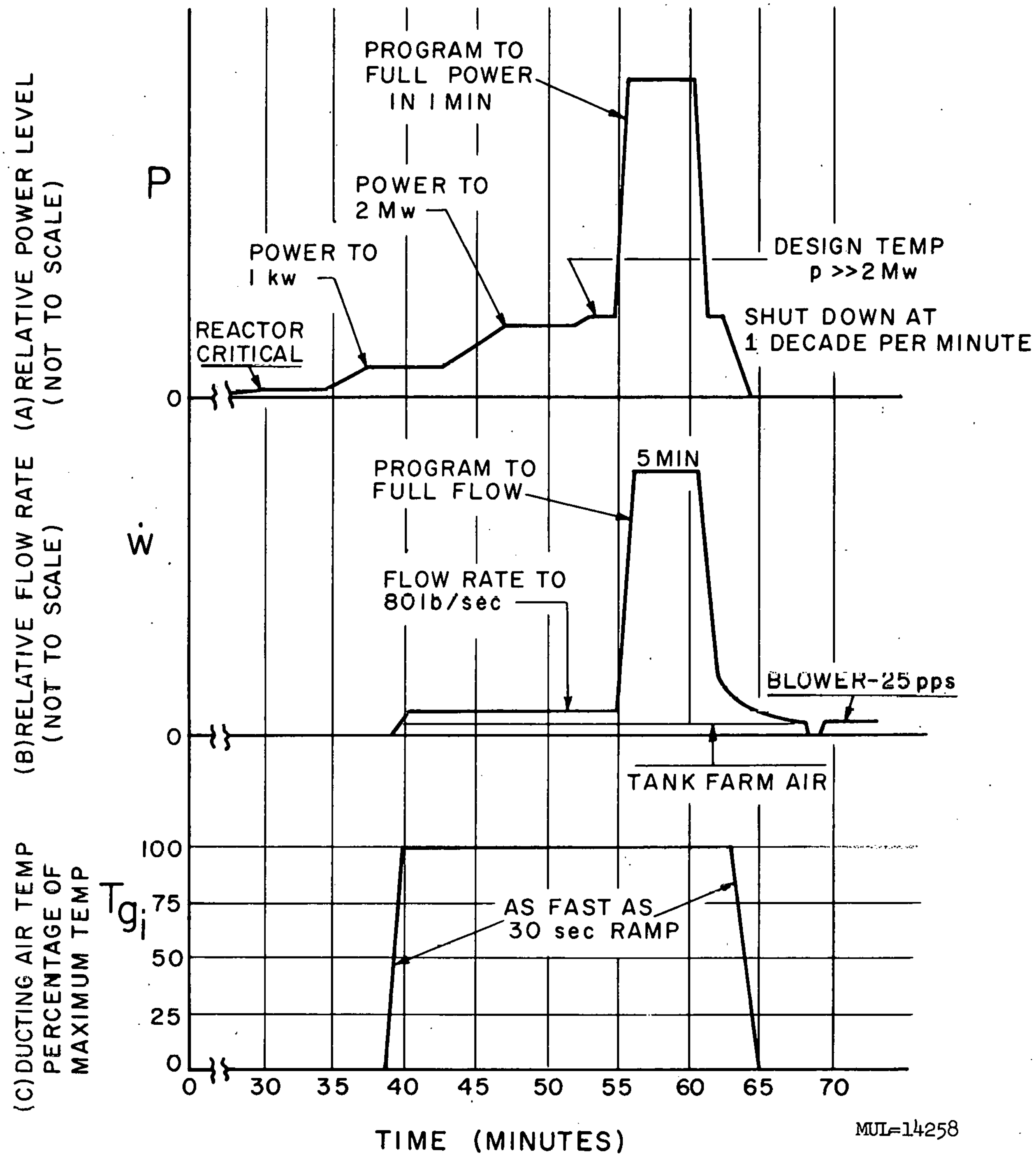

Fig. 18. Plot of reactor variables during a typical Tory II-C design-point test.

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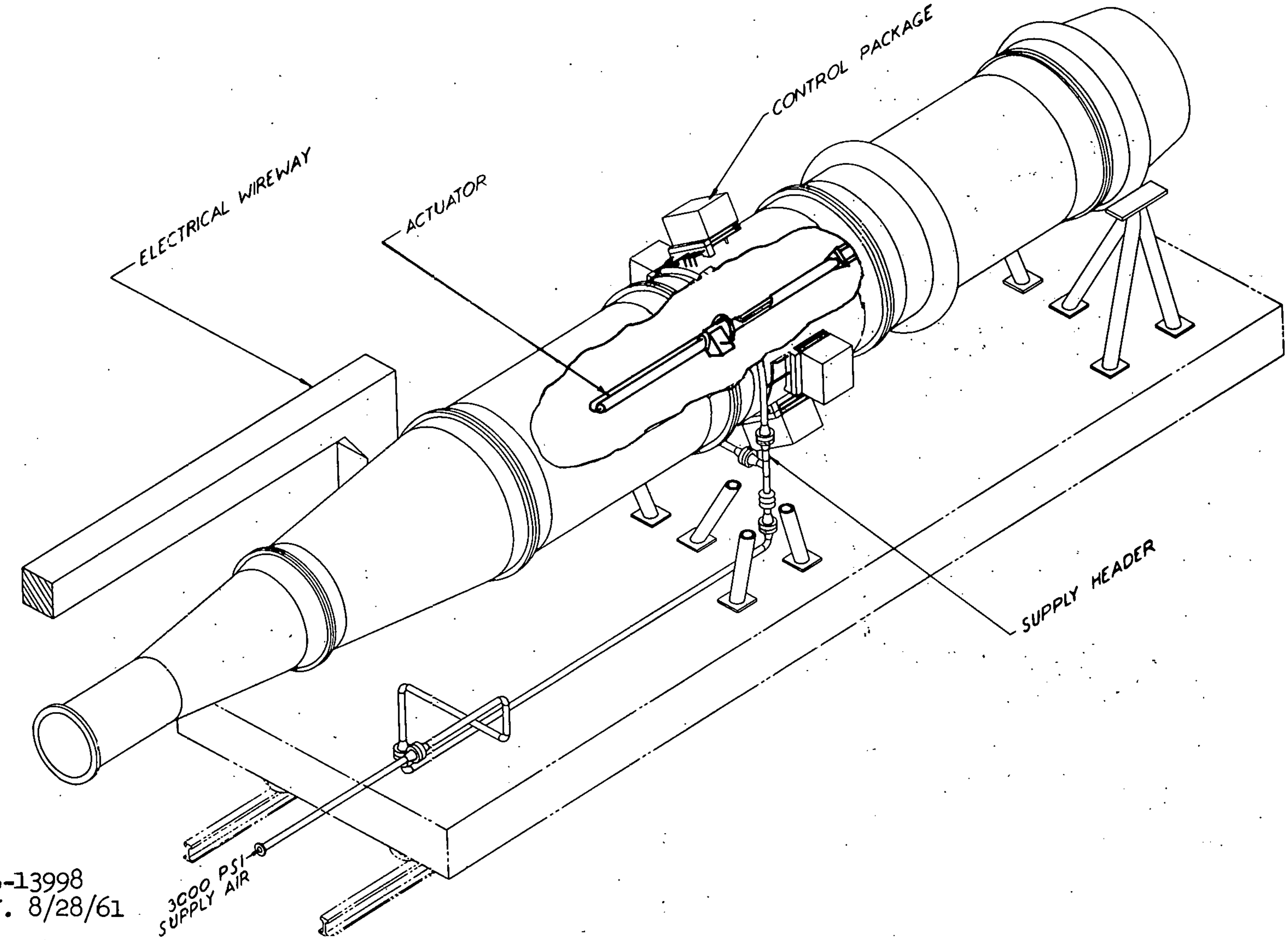

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Fig. 19. View of Tory II-C reactor, showing control actuation components.

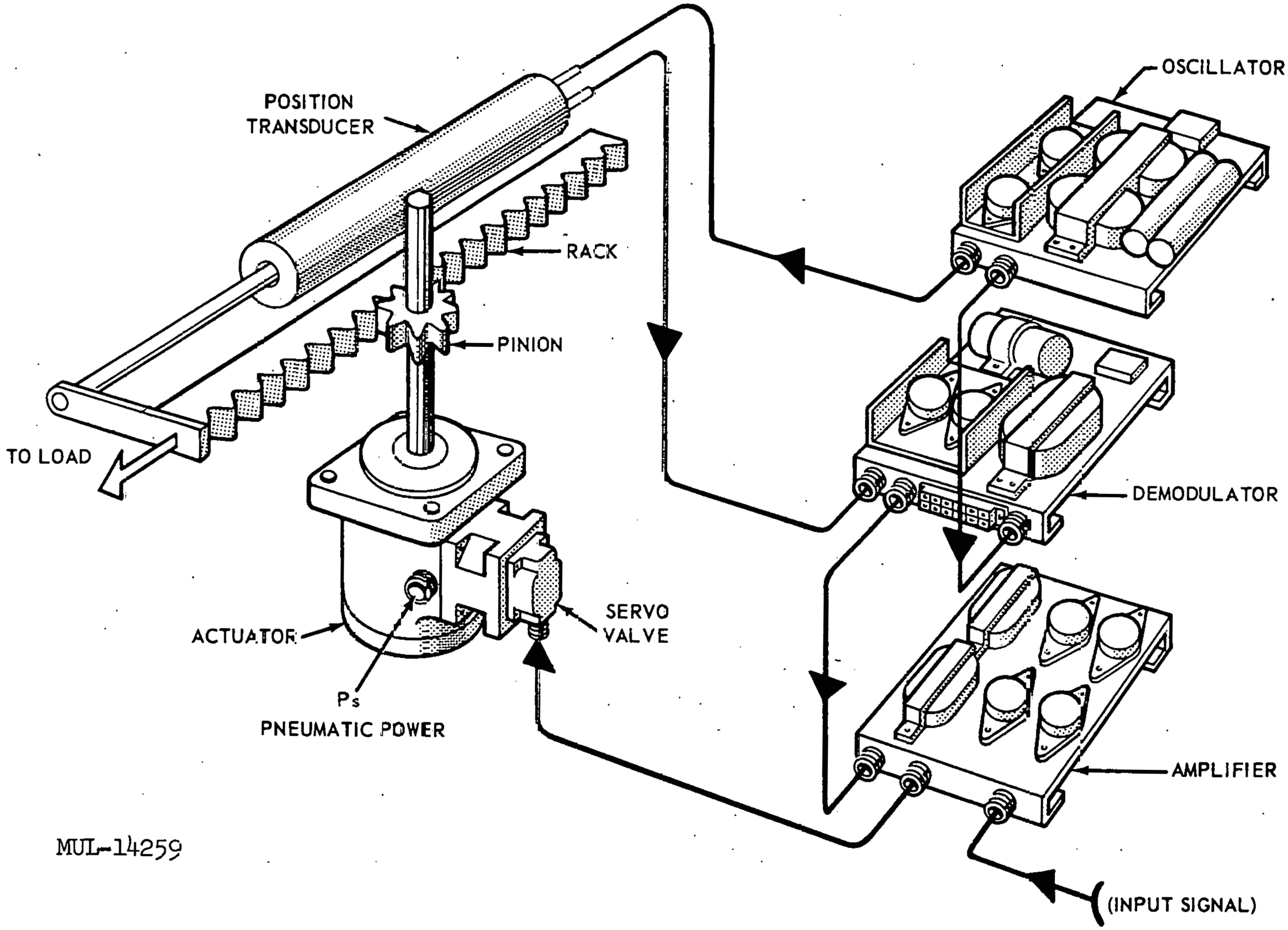

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Fig. 20. Schematic of Model 1240 actuator.

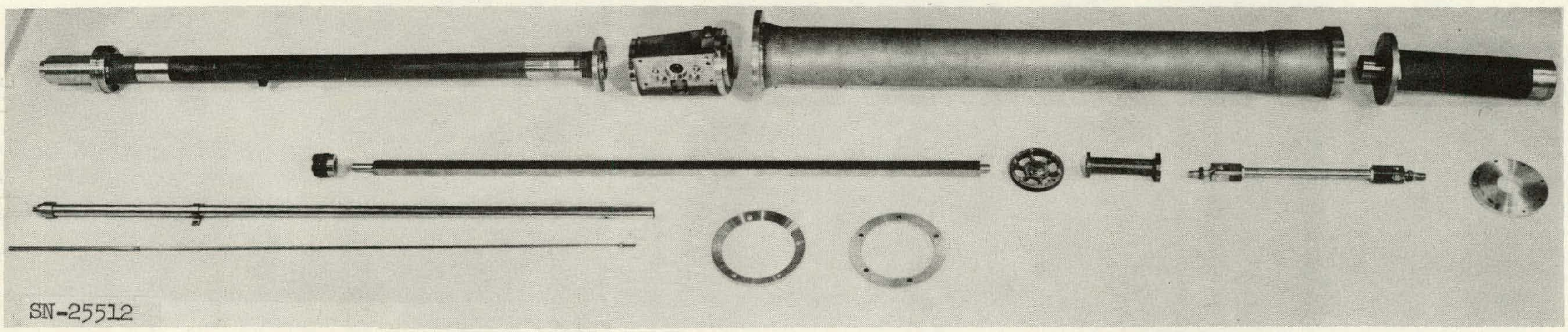

Fig. 21. Exploded view of Model 1240 actuator.

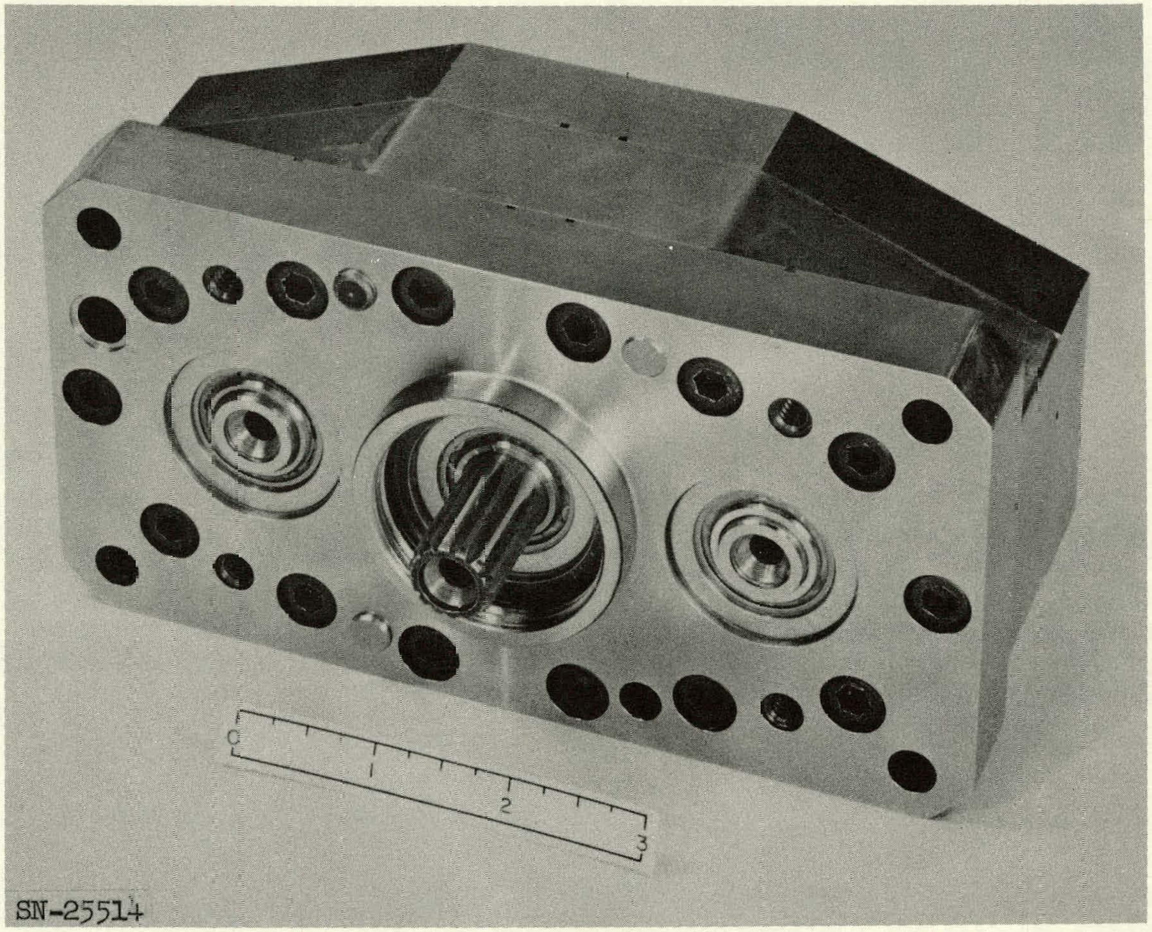

Fig. 22. Model 1240 motor prior to elevated-temperature tests.

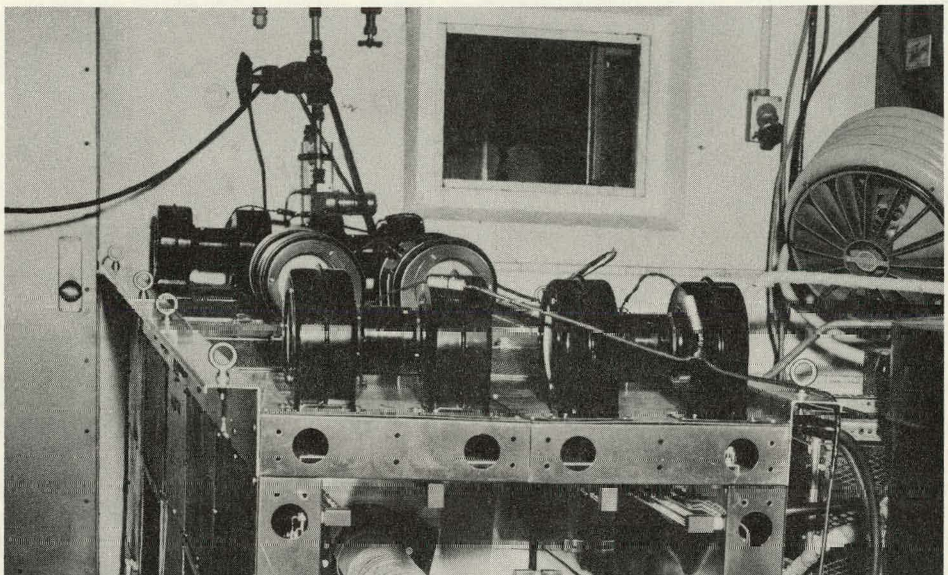

Fig. 23. Model 1240 actuator being prepared for high-temperature test.

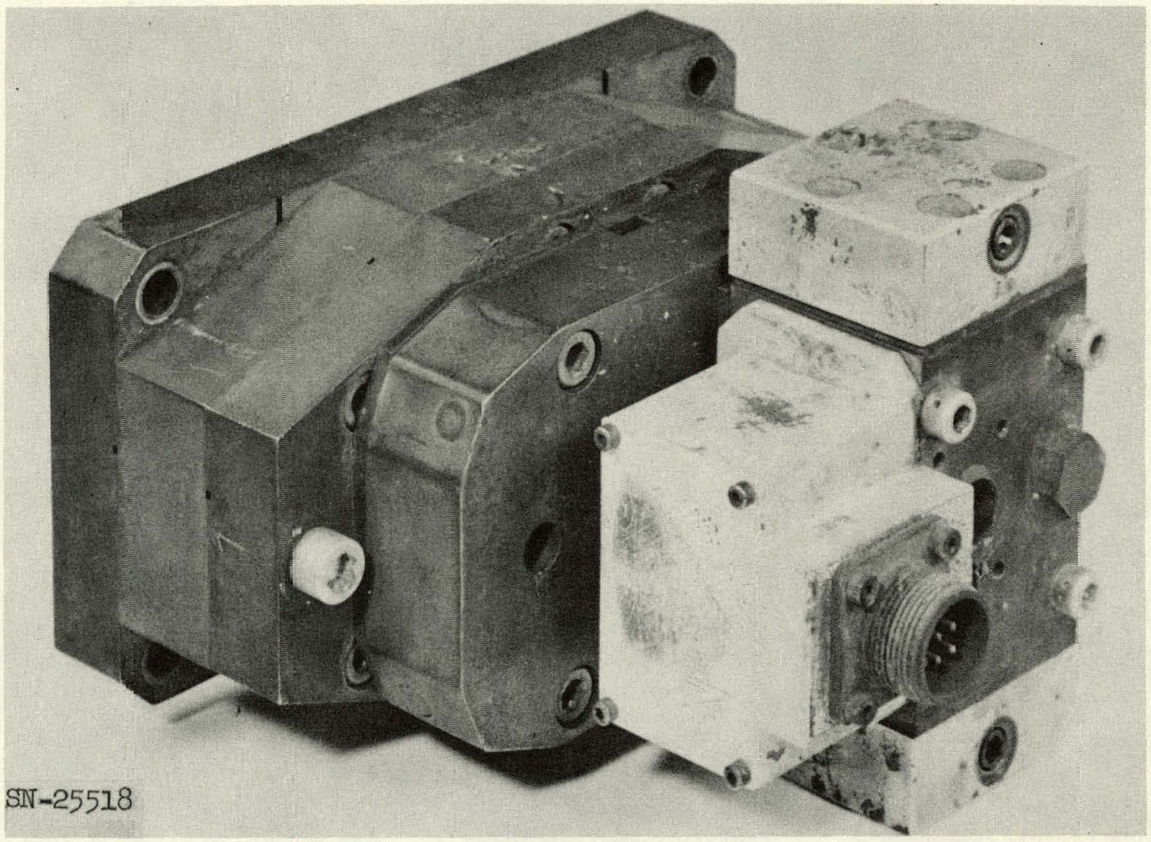

Fig. 24. Model 1240 servo valve and motor following high-temperature operation.

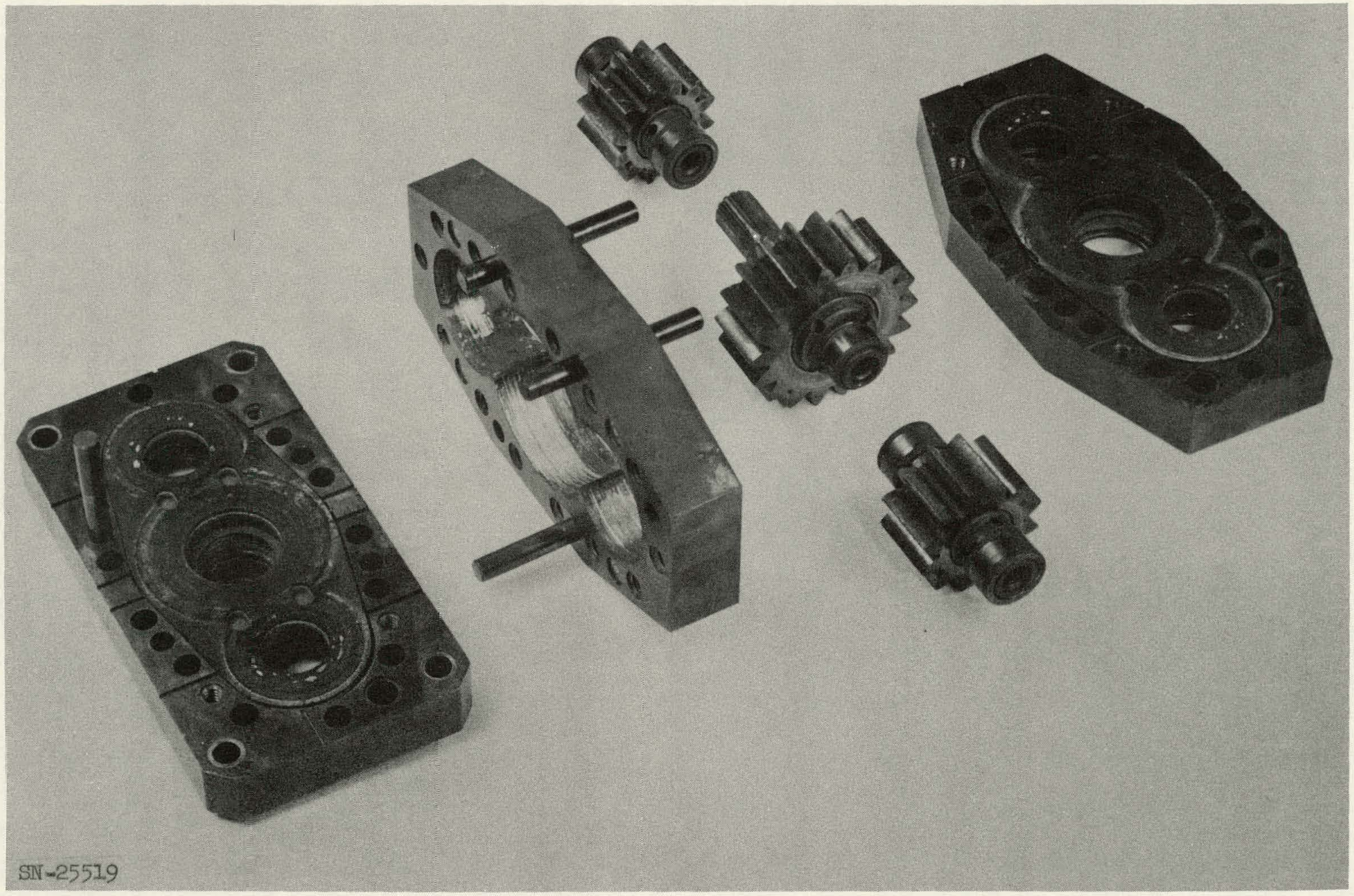

Fig. 25. Exploded view of Model 1240 motor following high-temperature tests.

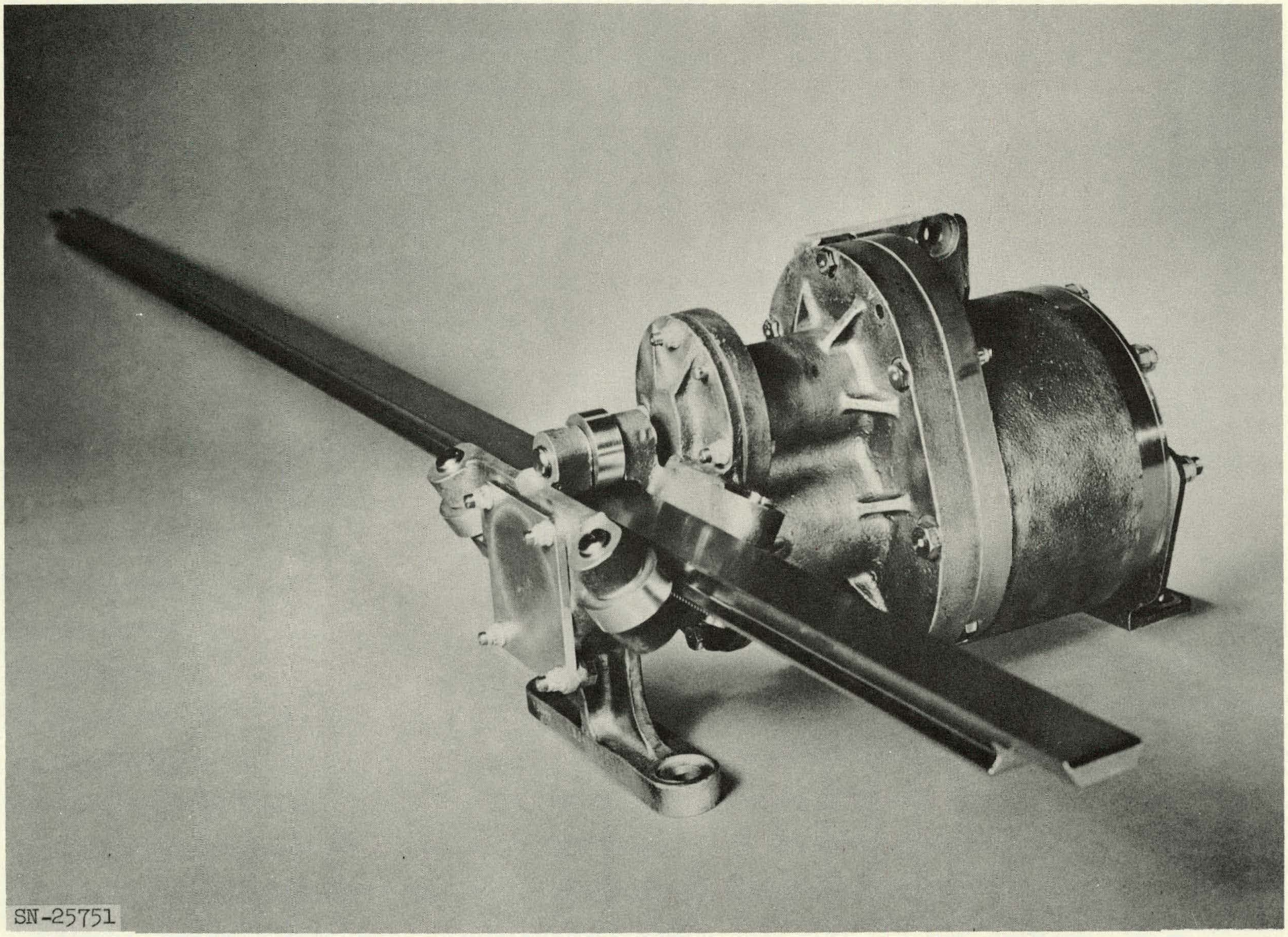

Fig. 26. RAHS actuator shown prior to high-temperature test.

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