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DESIGN AND PERFORMANCE ANALYSIS
OF A PRESSURE CONTROL SYSTEM
FOR THE TEST CELL A FEEDSYSTEM

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SUMMARY

A gas pressure control system has been designed for the test cell "A" feedsysteM to improve the reliability and performance of the turbine speed system. This pressure system normally functions to control the gas pressure at the inlet to the turbine throttle valve, PCV 50. However, in the event of a failure in the turbine speed system, the pressure control system automatically takes over to control the turbine speed.

An analog simulation for the test cell "A" feedsysteM has shown satisfactory performance for the pressure-speed system at all required liquid flow rates and various storage tank pressure levels.

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1. Introduction

To ensure successful nuclear reactor tests, the reliability of the present facility control system needs to be improved. One of the critical facility components is the gas turbine which drives the liquid hydrogen pump for providing propellant to a liquid cooled reactor.

A gas pressure control system has been designed for the test cell "A" feedsystem to improve the reliability and performance of the turbine speed system. This pressure system is used to control the gas pressure at the inlet to the turbine throttle valve PCV-50.

Under abnormal operation whereby a failure occurs in the turbine speed system, the pressure control system automatically takes over to control the turbine speed.

Under normal operation the performance of the turbine speed system is improved with its response characteristics made independent of the storage tank pressure. The turbine throttle valve PCV-50 also operates in a better region of its operating map.

The desired location for the additional control valve, PCV-60, was found to be in the flow control room, about 40 feet upstream of valve PCV-50.

A detailed reliability analysis was performed by G. L. Wagner⁴, WANL Reliability and Quality Assurance.

The reliability analysis has shown a significant reliability improvement of $0.9999999868 R_c^*$ for the proposed pressure-speed system compared to $0.999785 R_c^*$ for the present speed system and $0.999938 R_c^*$ for the speed system with redundant RPM feedback signals. Symbol R_c^* represents the reliability of the other system controls outside the pressure-speed control systems.

2. Control System Description

The pressure-control system shown in Figure 1 consists of an electro hydraulic valve (PCV-60), a pressure controller, pressure transducer and a 40 ft GH_2 pipe line.

Under normal operation the pressure control system is used to control the gas pressure at the inlet to valve PCV-50. The pressure is measured by the transducer at this point, compared with the pressure demand, producing the pressure error signal voltage. The pressure controller operates on this error signal to give a stem position demand to the pressure control valve PCV-60. The stem position of valve PCV-60 is thus controlled to give the desired pressure at the inlet to valve PCV-50. During the course of facility and/or nuclear reactor tests the tank farm pressure decreases from about 3000 psi to a value somewhat below 1000 psi. Since the response of the PCV-50 turbine speed system is dependent on the pressure at the inlet to valve PCV-50, the performance of the PCV-50 speed system deteriorates during a test run. The response of the PCV-50 system thus becomes slower as the tank farm pressure decreases and can result in the termination of a test due to a sluggish PCV-50 turbine speed system.

Under abnormal operation whereby a failure occurs in the PCV-50 speed system, the PCV-60 system functions as a backup speed control, using the speed error signal as an additional input. In the event of a failure which results in PCV-50 going full open, the PCV-60 system automatically takes over to control the turbine speed. For this failure mode, the increase in speed error signal is used by the pressure controller to partially close valve PCV-60 and thus reduce the speed error. In the event of a failure which causes the closure of PCV-50, trip circuit No. 1 shown in Figure 2 is activated, resulting in the 60 GPM Moog control valve switching open PCV-50. The PCV-60 system then controls the turbine speed for this failure mode in the same manner as above.

3. Control System Design

The pressure control is designed to be compatible with the turbine speed control, avoiding any undesired interaction between these two systems. Thus, besides the pressure control being stable with the desired damping and accuracy, it should also be sufficiently

2A

FIGURE 1 PRESSURE SPEED SYSTEM

FIGURE 2 TRIP CIRCUIT

FIGURE 3 PRESSURE CONTROLLER SCHEMATIC

faster than the turbine speed control. In addition, the combined pressure and speed control system should be more reliable than the present PCV-50 turbine speed control system by itself.

The open loop response for the pressure control is,

$$\frac{P_c(S)}{P_e(S)} = \frac{X_{60D}(S)}{P_e(S)} \cdot \frac{X_{60M}(S)}{X_{60D}(S)} \cdot \frac{A_{60}(S)}{X_{60M}(S)} \cdot \frac{P_c(S)}{A_{60}(S)} \quad (1)$$

where,

P_c = controlled pressure of hydrogen upstream of PCV-50 (psi)

P_e = pressure error

$$= P_D - P_c$$

P_D = pressure demand

X_{60D} = demanded position of the pressure-control valve (PCV-60), (in)

X_{60M} = measured position of the pressure-control valve (PCV-60), (in)

A_{60} = cross-sectional area of the pressure-control valve (PCV-60), (in²)

and, $\frac{X_{60D}(S)}{P_e(S)}$ = transfer function of pressure controller

$\frac{X_{60M}(S)}{X_{60D}(S)}$ = transfer function of valve PCV-60 actuator

$\frac{A_{60}(S)}{X_{60M}(S)}$ = coefficient of valve PCV-60

$\frac{P_c(S)}{A_{60}(S)}$ = transfer function of pipe between valves PCV-60 and PCV-50

3.1 Valve Characteristics

From system time response considerations a valve at least as fast as PCV-50 is required. Although it would make the system design easier if a valve with a much faster response than PCV-50 was used, other problems of costs, availability, and reliability would have to be resolved. From the above considerations, a valve with the same characteristics as PCV-50 was selected for the pressure control system, and was named PCV-60. The static characteristics of valve PCV-60 are listed below:

C_v	76
Area (in ²)	2.0
Type of Plug	Linear

The dynamic characteristics of valve PCV-60 consist of a second order lag with a damping factor of 0.6 and an undamped natural frequency of 100 radians/sec. Its transfer is thus,

$$\frac{X_{60M}(S)}{X_{60D}(S)} = \frac{1}{1 + .012 S + 10^{-4} S^2} \quad (2)$$

3.2 Pipe Line Transfer Function

An approximate pipe line transfer function has been derived in the Appendix section of this report and is stated below:

$$\frac{P_c(S)}{A_{60}(S)} = \frac{2.07 P_T \psi_{60/A_{50}}}{(1 + 0.19 S/A_{50})} \quad (3)$$

where,

P_T = pressure of the gaseous hydrogen in the storage tank (psi)

A_{50} = cross-sectional area of turbine inlet valve (PCV-50), (in²)

$$\psi_{60} = 1.87 \left[\left(\frac{P_c}{P_T} \right)^{1.43} - \left(\frac{P_c}{P_T} \right)^{1.71} \right]^{0.5} \quad \text{for } P_c/P_T > 0.528 \quad (\text{subsonic flow})$$

$$\psi_{60} = 0.484 \quad \text{for } P_c/P_T \leq 0.528 \quad (\text{sonic flow})$$

The pipe line transfer function is nonlinear since it has a variable gain term, $P_T \psi_{60}/A_{50}$, and a variable time constant, $0.19/A_{50}$. Table 1 shows tabulations for various values of P_T with P_c fixed at 850 psi.

3.3 Pressure Controller Design

The pressure controller was designed to produce the desired pressure system performance with the given pipe, valves and turbine speed responses. Since the turbine speed system has a maximum bandwidth of about 2.5 cps, the pressure control system was designed for a minimum bandwidth of 10 cps. A larger bandwidth improves the compatibility requirement for the pressure and turbine speed systems. On the other hand, the pressure controller must be a practical design with regard to signal voltages, noise susceptibility and component requirements.

With the above considerations and using Bode plots for the pipe and PCV-60 valve, the pressure controller was designed resulting in the following transfer function.

$$\frac{X_{60D}(S)}{P_e(S)} = \frac{.03 \left(1 + \frac{S}{6.5} \right) \left(1 + \frac{S}{100} \right)}{S \left(1 + \frac{(S)}{650} \right)} \quad (4)$$

where,

TABLE I

$$P_c = 850 \text{ psi}$$

$$G = 2.07 P_T \psi_{60}$$

P_T (psi)	P_c/P_T	ψ_{60}	G
3000	≤ 0.52	0.484	3006
2000	≤ 0.52	0.484	2004
1600	0.53	0.482	1596
1500	0.57	0.481	1494
1200	0.71	0.445	1105
1100	0.77	0.415	945
1000	0.85	0.350	724.5
900	0.94	0.220	409.9
875	0.97	0.130	235.5
850	1.0	0	0

X_{60D} = valve PCV-60 position demand

P_e = pressure error
 $= P_D - P_c$

P_D = pressure demand

P_c = controlled pressure at valve
 PCV-50 inlet

S = Laplace operator

4. Analysis

4.1 Methods Used

The analysis of the pressure-control system was performed using an analog-computer simulation. The preliminary design of the pressure control system was made by using hand calculations to obtain estimates of the gain and phase shift in the system. Bode plots were then used to design a pressure controller which would give the desired system response. The equations used for each element of the system are given in Appendix "1."

The valves in the system (PCV-50 and PCV-60) were either sonic or sub-sonic, depending upon the pressure drop across them. For the simulation of the valves the general equation which governs compressible nozzle flow was used. This equation is⁽¹⁾

$$W = CA P_i (2g/RT)^{1/2} \left[\psi (P_o/P_i) \right] \quad (5)$$

where

A = throat area, ft²

(1) R. C. Binder, Fluid Mechanics, Prentice Hall, (1955)

$$R = 766.4 \text{ ft/}^{\circ}\text{R}$$

C = flow coefficient

T = temperature, $^{\circ}\text{R}$

P_i and P_o are input and exit pressures, lb/ft^2

and

$$\psi (P_o/P_i) = 0.484; P_o/P_i \leq 0.528 \text{ (sonic flow) and} \quad (6)$$

$$\psi (P_o/P_i) = 1.871 \left[(P_o/P_i)^{1.43} - (P_o/P_i)^{1.71} \right]^{0.5}; P_o/P_i > 0.528 \quad (7)$$

(subsonic flow)

Since the hydrogen is at ambient temperature the term involving $T^{1/2}$ is a constant and equation (5) reduces to

$$W = (g/c^*) A P_i \left[\psi (P_o/P_i) \right] \quad (8)$$

where

c^* = sonic velocity for gaseous hydrogen, ft/sec.

Equation (8) along with (6) and (7) was used on the analog-computer model to simulate the turbine-inlet-control valve (PCV-50) and the pressure-control valve (PCV-60).

The pipe line upstream of PCV-60 was not simulated on the computer and the assumption was made that the pressure drop in this line was a constant for the flow rates involved. For the pipe between the two valves, Euler's equation was used to compute flow. This equation is, ⁽²⁾

(2) J. C. Buker, "Analog Computer Analysis of Split Flow Control in NRX-A1 Test," WANL-TME-670 (CRD) (January 29, 1964)

$$-\frac{L}{Ag} \frac{d\bar{W}}{dt} - \frac{144}{\bar{\rho} A^2 g} (W_o^2 - W_i^2) + \frac{144 \bar{W}^2}{A^2 g} \left(\frac{1}{\rho_i} - \frac{1}{\rho_o} - \frac{fL}{2D\bar{\rho}} \right) = P_o - P_i \quad (9)$$

where

- L = pipe length, (ft.)
- A = pipe cross-sectional area, in.²
- g = 32.2, ft/sec²
- W = mass flow rate, lb/sec
- t = time, seconds
- $\bar{\rho}$ = density, lb/ft³
- f = friction factor
- D = pipe diameter, ft
- P = pressure, psi

Subscripts i and o refer to inlet and outlet of pipe, respectively, and bar (-) denotes an evaluation of variable at average $X = \bar{X} = (X_o + X_i)/2$.

The complete set of equations used on the computer to simulate the pipe is given in Appendix I.

The model used for the remainder of the turbine drive system and for the liquid portion of the feedsystem is as given in reference 3 with the exception that the mixing chamber was deleted. The turbine equations are given in Appendix I for reference.

4.2 Limitations

The development of the turbine-drive system model used for the analog-computed simulation required the use of a number of assumptions. The assumptions, justification for

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3. G. H. Steiner, "Analysis of Temperature-Control System for Test Cell "A" Feedsystem Mixing Chamber," WANL-TME-731 (To be published)

each assumption, the consequence of them, and the limitations which are imposed upon the model due to these assumptions are discussed below.

1. The gaseous hydrogen in the drive-system is at a constant temperature throughout the system. Because the hydrogen in the storage tanks is at ambient temperature and the pipes in the system are not insulated, this appears to be a very reasonable assumption.
2. The pipe line between the storage tank and PCV-60 was completely neglected. It was assumed that the pressure loss in this line was constant. Since the flow rates involved in the turbine-drive system are relatively small (about 6 lb/sec at 70 lb/sec liquid flow), and about constant, effect of this assumption can be neglected. However, the model is not applicable to systems where large flow rates are encountered or where the flow rate varies by any appreciable amount.

4.3 System Models Used

The study of the hydrogen feedsystem was performed by combining two analog-computer models. The equations and computer diagram of the turbine-speed portion of the model are given in Appendix I. The model used for the liquid portion of the feedsystem is given in Reference 3. The two models were connected at the turbo-pump system. The speed of the turbine (N) being the output of the turbine-speed portion of the system was used as the input to the liquid-hydrogen portion of the feedsystem. The speed demand (N_D) and pump torque (L_p) were computed by the liquid section of the system and used as inputs to the turbine-drive system. The combined models were then used to evaluate the performance of the entire feedsystem.

5. System Response Characteristics

5.1 Calculated Pressure Response

Calculated frequency response characteristics for the pressure control system with the controlled pressure at the inlet to PCV-50 set at 1200 psi are shown in Figures 4, 5, and 6 with liquid flow rates of 15 lb/sec, 35 lb/sec and 70 lb/sec respectively. The bandwidth for the pressure control system as shown by these figures is about 11 cps for all liquid flow rates and with the storage tank pressure at 3000 psi.

5.2 System Response Tests

A large number of functional and failure mode tests were run using an analog simulation of the test cell "A" feedsystem with various liquid flow rates, storage tank pressures and controlled pressures at the inlet to PCV-50. Step response tests for the liquid flow control, using the pressure control system, are shown in Figures 7, 8 and 9, with liquid flow rates of 70 lb/sec, 35 lb/sec and 15 lb/sec respectively.

Some typical failure mode tests are shown in Figures 10, 11, and 12 for valves PCV-50 and PCV-60 with a liquid flow rate of 70 lb/sec.

FIGURE 4 PRESSURE CONTROL FREQ. RESPONSE

FIGURE 5 PRESSURE CONTROL FREQ. RESPONSE

FIGURE 6 PRESSURE CONTROL FREQ. RESPONSE

FIGURE 7 - FLOW STEP RESPONSE AT 70 LB./SEC.

FIGURE 8 - FLOW STEP RESPONSE AT 35 LB./SEC.

FIGURE 9 - FLOW STEP RESPONSE AT 15 LB./SEC.

FIGURE 10

FIGURE 11

FIGURE 12 - FAILURE PCV-60 CLOSED--SWITCHED OPEN LIQUID FLOW AT 70 LB./SEC.

6. Conclusion

A gas pressure control system has been designed for the test cell "A" feedsysteM to improve the reliability and performance of the turbine speed system.

An analog simulation for the test cell "A" feedsysteM has shown satisfactory performance for the pressure-speed system at all required liquid flow rates and various storage tank pressure levels.

It is recommended that the proposed pressure-speed system be installed and tested in the test cell "A" feedsysteM prior to the NRX-A3 tests.

The desired location for the additional control valve, PCV-60, was found to be in the flow control room, about 40 feet upstream of valve PCV-50.

The controlled pressure at the inlet to PCV-50 should be set within the range of 850 to 1200 psi.

ACKNOWLEDGEMENTS

The author wishes to thank A. H. Stock and G. H. Steiner for their analog model work; G. L. Wagner for his reliability analysis and the other members of WANL and NTO control groups for their discussions.

APPENDIX I

EQUATIONS: TURBINE-SPEED SYSTEM

Valve PCV-60

$$1. \quad W_p = (g/c^*) A_{60} P_T \left[\psi (P_p/P_T) \right]$$

$$2. \quad A_{60} = 0.57 X_{60}$$

Pipe between PCV-60 and PCV-50

$$3. \quad \frac{dW_1}{dt} = \frac{v_i}{A_1 L_1} (W_p^2 - W_c^2) + \frac{v_1}{A_1 L_1} (v_p - v_c - \frac{v_1 f L_1}{2 D_1}) + \frac{A_1 g}{L_1} (P_p - P_c)$$

$$4. \quad \frac{d\rho_1}{dt} = \frac{1}{A_1 L_1} (W_p - W_c)$$

$$5. \quad P = RT\rho$$

$$6. \quad P_1 = (P_p + P_c)/2$$

$$7. \quad W_1 = (W_p + W_c)/2$$

Valve PCV-50

$$8. \quad W_i = (g/c^*) A_{50} P_c \left[\psi (P_i/P_c) \right]$$

$$9. \quad A_{50} = 0.57 X_{50}$$

Turbine (see Reference 3)

$$10. \quad \frac{dP_o}{dt} = \frac{RT}{AL} (W_i - W_o)$$

11. $W_o = 0.484 \text{ (g/c}^*) A_T P_o$
12. $L_t = (2050 - 0.0185 N) W_o$
13. $\frac{dN}{dt} = 6.63 (L_t - L_p)$
14. L_p is obtained from the liquid-hydrogen feedsystem model.⁽³⁾

APPENDIX II

PIPE LINE TRANSFER FUNCTION

A schematic diagram of the pipe line between valves PCV-60 and PCV-50 is shown in Figure 7.

Figure 7: Diagram of Pipe Between PCV-60 and PCV-50

The following analysis was used to obtain an approximate relationship for the pressure P_c as a function of the valve area A_{60} .

$$W_p = (g/c^*) A_{60} P_T \left[\psi (P_p/P_T) \right] \quad (1)$$

$$W_i = (g/c^*) A_{50} P_c \left[\psi (P_o/P_c) \right] \quad (2)$$

$$\frac{dP_c}{dt} = \frac{RT}{A_1 L_1} \left[W_p - W_i \right] \quad (3)$$

Eliminating W_p and W_i from 3, and using Laplace notation

$$sP_c = \frac{RT}{A_1 L_1} \frac{g}{c^*} \left(A_{60} P_T \psi_{60} - A_{50} P_c \psi_{50} \right) \quad (4)$$

where $\psi_{60} = \psi (P_p/P_T)$ and $\psi_{50} = \psi (P_o/P_c)$.

Equation 4 is then solved for P_c/A_{60}

$$\frac{P_c}{A_{60}}(S) = \frac{P_T \psi_{60}/A_{50} \psi_{50}}{1 + \frac{RT}{A_1 L_1} \frac{g}{c^*} A_{50} \psi_{50}} \quad (5)$$

where

$$\begin{aligned} R &= 766.4 \text{ ft/}^\circ\text{R} \\ T &= 550 \text{ }^\circ\text{R} \\ g &= 386.4 \text{ in/sec}^2 \\ A_1 &= 7.065 \text{ in}^2 \\ L_1 &= 40 \text{ ft, and} \\ c^* &= 53.10^3 \text{ in/sec} \\ \psi_{50} &= .484 \text{ (sonic condition)} \end{aligned}$$

Then Equation 5 becomes

$$\frac{P_c}{A_{60}}(S) = \frac{2.07 P_T \psi_{60}/A_{50}}{(1 + .19 S/A_{50})} \quad (6)$$

Equation 6 was then evaluated for various values of P_T , A_{50} and ψ_{60} .

To obtain transfer function for pipe line when $A_{50} = 0$, rearrange equation 6 by multiplying through by A_{50} then let $A_{50} = 0$.

Thus,

$$\left. \frac{P_c(S)}{A_{60}} \right|_{A_{50}=0} = \frac{10.87 P_T \psi_{60}}{S} \quad (7)$$

NOMENCLATURE

W_p	-	mass flow rate of gaseous hydrogen through the pressure control valve (PCV-60), (lb/sec)
g	-	gravitational acceleration (in/sec ²)
c^*	-	sonic velocity for gaseous hydrogen (ft/sec)
A_{60}	-	cross-sectional area of the pressure-control valve (PCV-60, (in ²)
P_T	-	pressure of the gaseous hydrogen in the storage tank (psi)
P_p	-	gaseous hydrogen pressure leaving PCV-60 (psi)
X_{60}	-	position of the pressure-control valve (PCV-60), (in)
W_l	-	average mass flow rate of gaseous hydrogen in line between PCV-60 and PCV-50 (lb/sec)
v_l	-	average specific volume of gaseous hydrogen in line between PCV-60 and PCV-50 (ft ³ /lb)
A_l	-	cross-sectional area of pipe (in ²)
L_l	-	length of pipe between PCV-60 and PCV-50 (ft)
W_c	-	mass flow rate of hydrogen into turbine inlet valve (PCV-50), (lb/sec)
v_p	-	specific volume of hydrogen through PCV-60 (ft ³ /lb)
v_c	-	specific volume of hydrogen into PCV-50 (ft ³ /lb)
f	-	friction factor for pipe between PCV-60 and PCV-50
D_l	-	diameter of pipe (ft)
P_c	-	pressure of hydrogen upstream of PCV-50 (psi)
ρ_l	-	average density of hydrogen in line between PCV-60 and PCV-50 (lb/ft ³)
R	-	hydrogen gas constant (ft ² /°R)
T	-	temperature of gaseous hydrogen (°R)
P_l	-	average pressure of hydrogen in line between PCV-60 and PCV-50 (psi)
W_i	-	mass flow rate of hydrogen out of PCV-50 (lb/sec)

- A_{50} - cross-sectional area of turbine inlet valve (PCV-50), (in^2)
- P_o - pressure of hydrogen in line between PCV-50 and turbine (psi)
- X_{50} - position of turbine inlet valve (in)
- W_o - mass flow rate of hydrogen into turbine (lb/sec)
- A_T - turbine inlet nozzle flow area (in^2)
- L_t - turbine torque (lb-in)
- N - turbine speed (RPM)
- L_p - pump torque (lb-in)
- C_v - flow in gallons per minute of water through a full open valve that will result in a one pound per square inch pressure drop across the valve

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