ARMY RESEARCH LABORATORY

Control System Analyses for the Driver Gas Fill System of the BRL 1/6th Scale LB/TS Test Facility

Duane T. Hove
Gregory P. Mason

ARL-CR-46 April 1993

prepared by

Sparta, Inc.
3828 Carson Street, Suite 102
Torrance, California 90503

under contract

DAAA15-90-D-1002

NOTICES

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 1993	Final, Aug 90–Feb 92

4. TITLE AND SUBTITLE
Control System Analyses for the Driver Gas Fill System of the BRL 1/6th Scale LB/TS Test Facility

5. FUNDING NUMBERS
C: DAAA15-90-D-1002
Task 1

6. AUTHOR(S)
Duane T. Hove and Gregory P. Mason

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Sparta, Inc.
3828 Carson St., Suite 102
Torrance, CA 90503

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-OP-CI-B (Tech Lib)
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARL-CR-46

11. SUPPLEMENTARY NOTES
Contracting Officer Representative is Mr. Richard Pearson; Alternate Contracting Officer Representative is Mr. Klaus Opalka, Nuclear/Directed Energy Division, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD 21005-5066. Contract No.: DAAA15-90-D-1002; Delivery Order 0001.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report covers the design of an automatic control system for the gas supply of a blast simulator facility. The control system regulates the output temperature of a heat exchanger used to evaporate liquid nitrogen and heat the resulting gas to high temperature. An analytical model is developed for the two phase flow through the heat exchanger. A design is developed for the valves used in the control system. The properties of the valves in the design and the analytical model of the flow are used to analyze the dynamics of the control system.

14. SUBJECT TERMS
heat exchange; control theory; cryogenics; blast simulation; liquid nitrogen; shock tubes

15. NUMBER OF PAGES
42

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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FOREWORD

This report is submitted to the Ballistics Research Laboratory in partial fulfillment of Delivery Order 0001 of Contract No: DAAA15-90-D-1002.

The BRL Project Officer is Mr. Richard Pearson. The SPARTA Program Manager is Mr. Gregory Mason. Mr. Daniel Nowlan performed the elegant control system dynamic analysis and Dr. Irving Osofsky provided valuable technical advice.

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PREFACE

On 30 September 1992, the U.S. Army Ballistic Research Laboratory (BRL) was deactivated and subsequently became part of the U.S. Army Research Laboratory (ARL) on 1 October 1992.

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1. INTRODUCTION

The US Army Ballistic Research Laboratory (BRL) is currently modifying an existing shock tube located at the Aberdeen Proving Grounds to demonstrate Large Blast/Thermal Simulator technologies and to provide high fidelity air blast environments for nuclear effects testing. This facility will be the first large shock tube to use heated driver gas to achieve desired air blast waveforms in the test section. The driver gas must be heated and the driver quickly pressurized to minimize heat loss to the driver walls; this required innovative solutions to pumping hot gas.

Under BRL sponsorship SPARTA developed and demonstrated a driver filling method which pumps liquid nitrogen (LN) through a previously heated Pebble Bed Heater (PBH) thereby vaporizing the liquid and raising its temperature to the desired value in one pass (Figure 1). A bypass system allows precise control of the output gas temperature by selectively mixing LN with the heated gas exiting the Pebble Bed Heater. This approach has the advantages that: pumping a liquid is more efficient than pumping a gas (if indeed pumping a hot gas can be done at all), the LN pump is much smaller and much more robust than a gas compressor system and the constant displacement pump mass flow rate is independent of back pressure.

SPARTA installed a 22 ton Pebble Bed Heater working unit at BRL and successfully demonstrated its performance (Reference 1). Manually operated valves were used to route the liquid nitrogen to the Pebble Bed Heater in these initial tests. However, an automatic control system is preferable to manual operation for safety, precise gas temperature control and efficiency of operation.

1.1 Objectives

The objectives of the present study were to design an automatic control system which meets established requirements, analyze its performance, prepare drawings and provide a system cost estimate.

1.2 Requirements

Four driver gas design conditions were established by BRL (Table 1). The driver filling strategy is to pump a constant temperature gas (at or above the design temperature) until the driver gas reaches the design pressure (Reference 2). During the filling process, the PBH back pressure will rise from ambient to the peak value approximately linearly (depending on the magnitude of the heat loss to the walls).

1.3 Scope

Valves and valve properties were selected from vendor supplied information. Appropriate valve settings were established based on a thermal hydraulic model which considered pressure drops in the primary and bypass paths. Control system response was established based on analytical models of the valve/actuator motion. Cost estimates were based on vendor quotes and engineering estimates by experienced personnel.

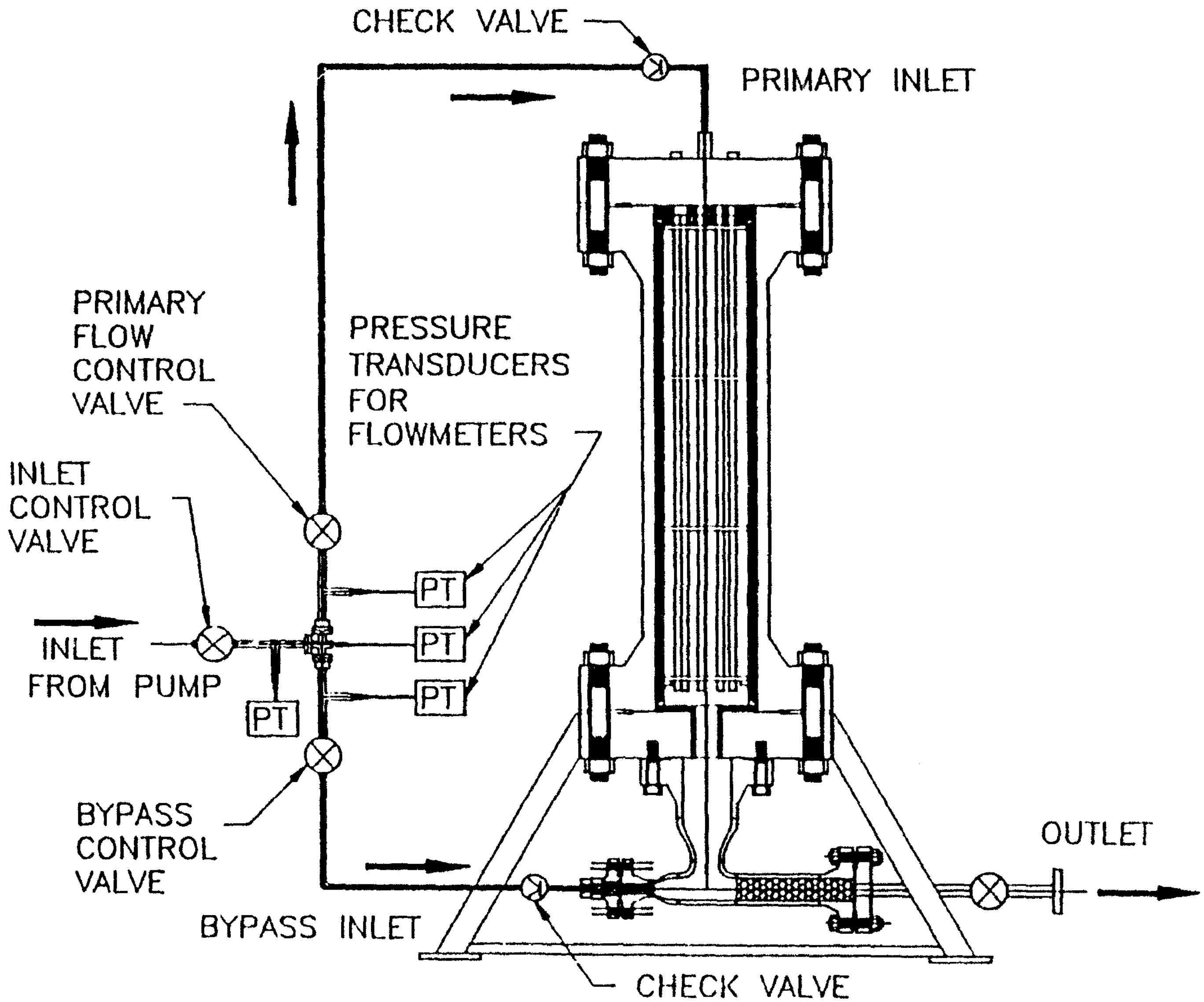

Figure 1. Pebble bed heater schematic.

2. GAS SUPPLY CONTROL SYSTEM DESCRIPTION

The control system analysis starts with a control system layout and performance characteristics of the specific valves used to direct the flow to the PBH and the bypass system.

2.1 Control System Layout

Liquid nitrogen is pumped from a tank through a series of pipes and valves to the Pebble Bed Heater. Numerous diagnostic measurements, exhaust valves, check valves and control valves are used to control the fluid flow as indicated in Figure 2 which is taken from Reference 3. The PBH control valves denoted as V7 and V8 are of specific interest to this study.

The PBH controls perform the functions of regulating the outlet temperature of the PBH mixer to a specified setpoint. The PBH operates by receiving LN from the high pressure pumping system and branching the LN flow into two subsystems, the primary pebble-bed and the bypass thermal mixer. Precise control of valves 7 and 8 in the primary and bypass lines is required to produce a stable outlet temperature of the PBH.

2.2 Control Valves

Globe valves have been selected for the PBH valves because of their rugged construction, cryogenic rating and high capacity. Valve position control is achieved by the use of a closed feedback control loop to the actuators using the outlet temperature of the mixer as the feedback sensor point. Valtek Mark One valves and Linear Spring actuators were chosen to develop valve performance characteristics and establish cost estimates (Reference 4).

TABLE 1 DRIVER GAS DESIGN CONDITIONS

CASE NUMBER	MAXIMUM BACK PRESSURE (MPa)	MAXIMUM BACK PRESSURE (ATM)	GAS TEMPERATURE (K)	GAS TEMPERATURE (R)
1	12.8	129	663	1193
2	7.8	79	468	842
3	2.9	29	361	650
4	0.98	10	288	518

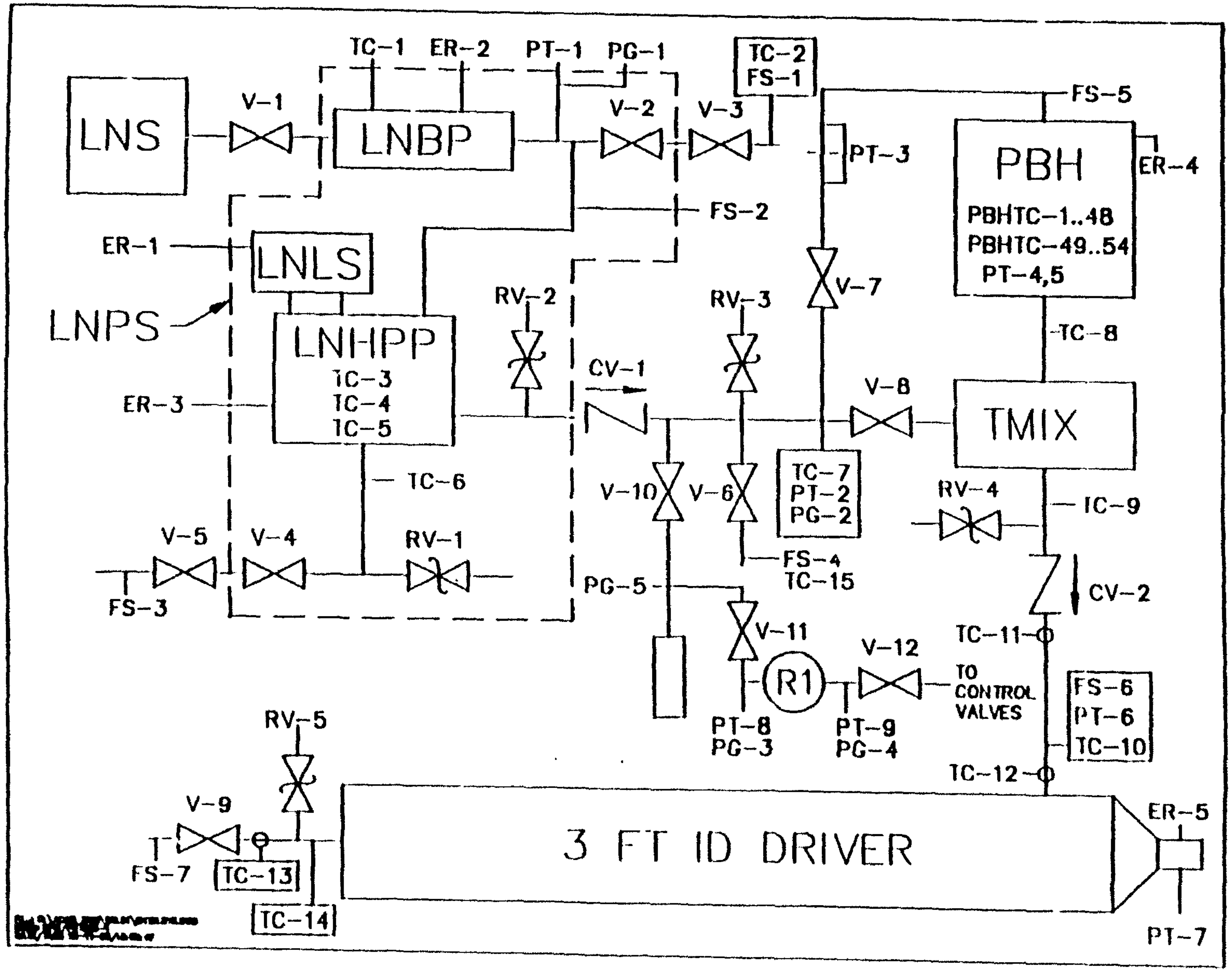

Figure 2. Gas supply system schematic.

3. THERMAL HYDRAULIC ANALYSIS

Engineering procedures were developed from analytical models based on conservation of fluid momentum and energy. All Pebble Bed Heater thermal hydraulic processes are relatively slow so transients are not important.

3.1 Model

The relationship defining the temperature of the nitrogen gas leaving the thermal mixer is

$$\dot{m}_T(C_p T + h_v) = \dot{m}_7(C_p T_{PB} + h_v) + \dot{m}_8 C_p T_{LN} \qquad \text{EQ (1)}$$

Conservation of mass gives

$$\dot{m}_T = \dot{m}_7 + \dot{m}_8 \qquad \text{EQ (2)}$$

Substituting (2) into (1) and solving for temperature gives

$$T = T_{PB} - \frac{\dot{m}_8}{\dot{m}_T}\left(T_{PB} - T_{LN} + \frac{h_v}{C_p} \right) \qquad \text{EQ (3)}$$

For convenience we define a reference temperature

$$T_R = T_{PB} - T_{LN} + \frac{h_v}{C_p} \qquad \text{EQ (4)}$$

Both $\dot{m}_7$ and $\dot{m}_8$ are a function of time during the operation of the PBH due to changing back pressure and, near the end of the run, changing PBH exit temperature. Control valves located on the primary PBH supply line (V7) and the mixer bypass supply line (V8) are assumed identical with respect to flow capability.

The mass flow rates are determined by equating the pressure drops in the primary and bypass legs. In the primary system the pressure drops are due to the pipes, valve 7, the elbows and the PBH; in the bypass system the pressure drops are due to the pipes and valve 8. Following Reference 5 we have for the primary leg

<u>Pipes</u>

$$DELP1 = \frac{\rho\, U_7^2}{2} f_p \frac{L}{D} = C1\, U_7^2 \qquad \text{EQ (5)}$$

Elbows

$$DELP2 = N \frac{\rho U_7^2}{2} f_{90} = C2 U_7^2 \qquad \text{EQ (6)}$$

Valve

$$DELP3 = \left[\frac{\rho U_7 A L_7}{CV x} \right]^2 = C3 \left(\frac{x}{L_7} \right)^{-2} U_7^2 \qquad \text{EQ (7)}$$

Pebble Bed Heater

$$DELP4 = \frac{\rho U_{PB}^2}{2} f_{PB} = C4 U_{PB}^2 \qquad \text{EQ (8)}$$

Here the pressure drop constant was selected such that the pressure drop equalled 20 psi based on BRL measurements on the existing PBH.

For the bypass leg

Pipes

$$DELP5 = \frac{\rho U_8^2}{2} f_P \frac{L_8}{D} = C1 U_8^2 \qquad \text{EQ (9)}$$

and

Valve

$$DELP6 = \left[\frac{\rho U_8 A L_8}{CV x} \right]^2 = C3 \left(\frac{x}{L_8} \right)^{-2} U_8^2 \qquad \text{EQ (10)}$$

Summing pressure drops

$$U_7^2 \left[C1 + C2 + C3 \left(\frac{x}{L_7} \right)^{-2} + C4 \right] = U_8^2 \left[C5 + C6 \left(\frac{x}{L_8} \right)^{-2} \right] \qquad \text{EQ (11)}$$

Equation 11 can be rewritten as

$$U_7^2 \; C7\,(x) = U_8^2 \; C8\,(x) \qquad \text{EQ (12)}$$

and therefore

$$\frac{U_8}{U_7} = \left(\frac{C7}{C8}\right)^{1/2} \qquad \text{EQ (13)}$$

where it is understood that the terms C7 and C8 are functions of x.

Since the liquid nitrogen is essentially incompressible, Equation 3 can be rewritten as

$$T = T_{PB} - \frac{U_8}{(U_7 + U_8)} T_R = T_{PB} - \left(1 + \left(\frac{C8}{C7}\right)^{1/2}\right)^{-1} T_R \qquad \text{EQ(14)}$$

which gives the output gas temperature as a function of valve position. Setting the output temperature at the desired or set point control temperature

$$T = T_c$$

and performing a bit of algebra, there results

$$\left(\frac{x}{L}\right)_7 = \left[\frac{C3}{\left(\frac{T_R}{T_{PB} - T_C} - 1\right)^2 \left(C5 + C6\left(\frac{x}{L}\right)^{-2}\right) - (C1 + C2 + C4)}\right]^{1/2} \qquad \text{EQ (15)}$$

3.2 Calculations

Sample calculations are made to indicate nominal valve settings and their sensitivities. The basic procedure is to set one valve (e.g., V7) at a single setting and control the PBH output temperature with the other valve (V8). It is desirable that the valves be operated in mid range, if possible, simply to avoid fine settings and/or slamming into the stops unnecessarily. The design test conditions are addressed first at their peak back pressures. Then the effect of back pressure is considered.

3.2.1 Design Test Conditions

A broad range of PBH output temperatures are achievable if the PBH is heated to 2000 °R (1110 °K). The peak design temperature of 1193 °R (663 °K) is achieved with a secondary valve relative opening of 0.2 to 0.5 as the primary valve relative opening ranges from 0.25 to 1.0 (Figure 3).

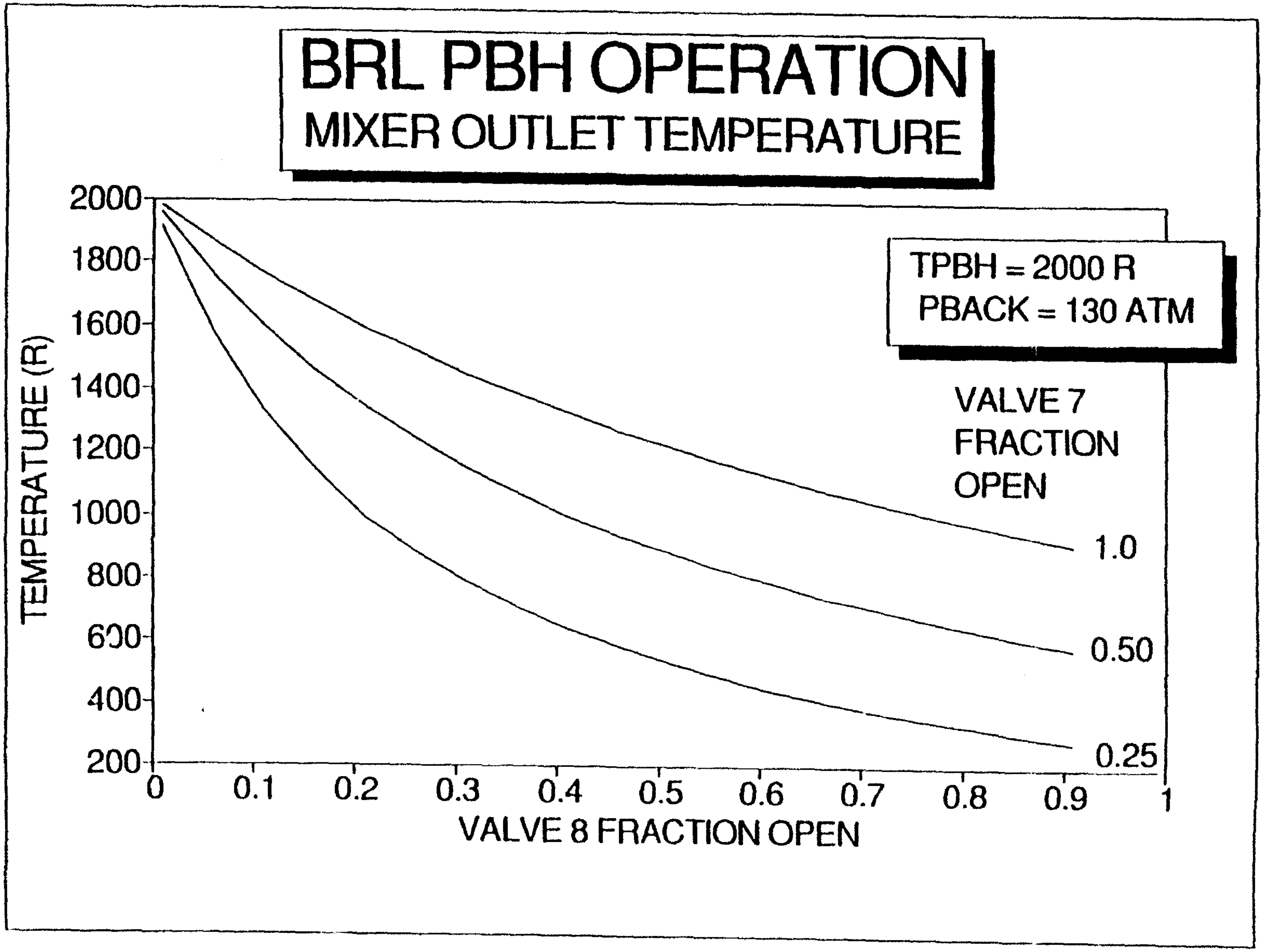

Figure 3. BRL PBH operation mixer outlet temperature.

Considering each design case individually, the sensitivity to outlet temperature is established by calculating the required valve settings for the nominal design condition and for the next lowest outlet design condition (Figures 4 to 7). Initial bed temperatures were picked based on enthalpy scaling from present test results (i.e., thermal energy required is proportional to the mass and temperature of gas required). However, while technically feasible to operate at PBH temperatures near the desired outlet temperature for the lower pressures, a minimum bed overheat of 500 °R was evolved by trial and error to insure robust valve control (see for example, Figure 8 compared to Figure 6 and Figure 9 compared to Figure 7).

3.2.2 Effect of Back Pressure

All of the pressure drop mechanisms considered except the PBH assumed that the nitrogen was liquid; therefore, only the PBH pressure drop will be a function of back pressure. We have

$$DELP4 = f\,(Re)\,\frac{\rho}{2}\,U_{PB}^{2} \qquad \text{EQ (16)}$$

The Reynolds number range considered is about 10 to 1000 and according to Reference 5, the pressure drop across a porous media is not a strong function of Reynolds number in this range. Further, the mass flow is constant and the nitrogen gas phase follows the perfect gas law which results in

$$DELP4 \sim \frac{T}{P} \qquad \text{EQ (17)}$$

Thus, at a given bed temperature, the pressure drop is inversely proportional to the back pressure. Figures 10 and 11 indicate valve setting combinations required at a lower back pressure for each of the elevated design temperature conditions. While there is some effect (e.g., the required V8 relative opening is lowered about 0.1 for a 70 percent V7 opening), the required valve positions are well within the operating capability of the gas supply system and the long pumping cycle (order of minutes) allows plenty of time for the automatic control system to adjust.

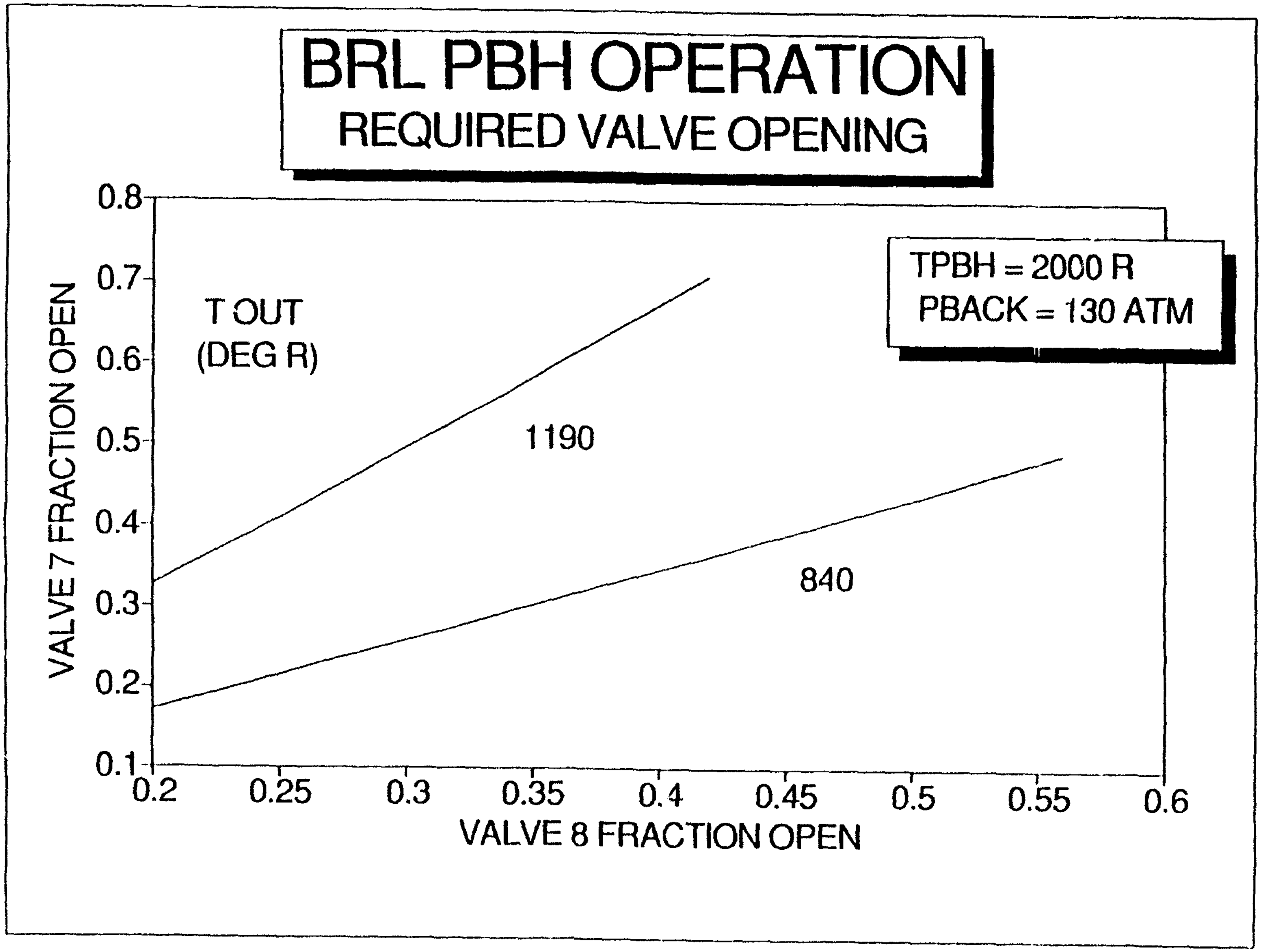

Figure 4. BRL PBH operation required valve opening, TPBH = 2000 R, PBACK = 130 ATM.

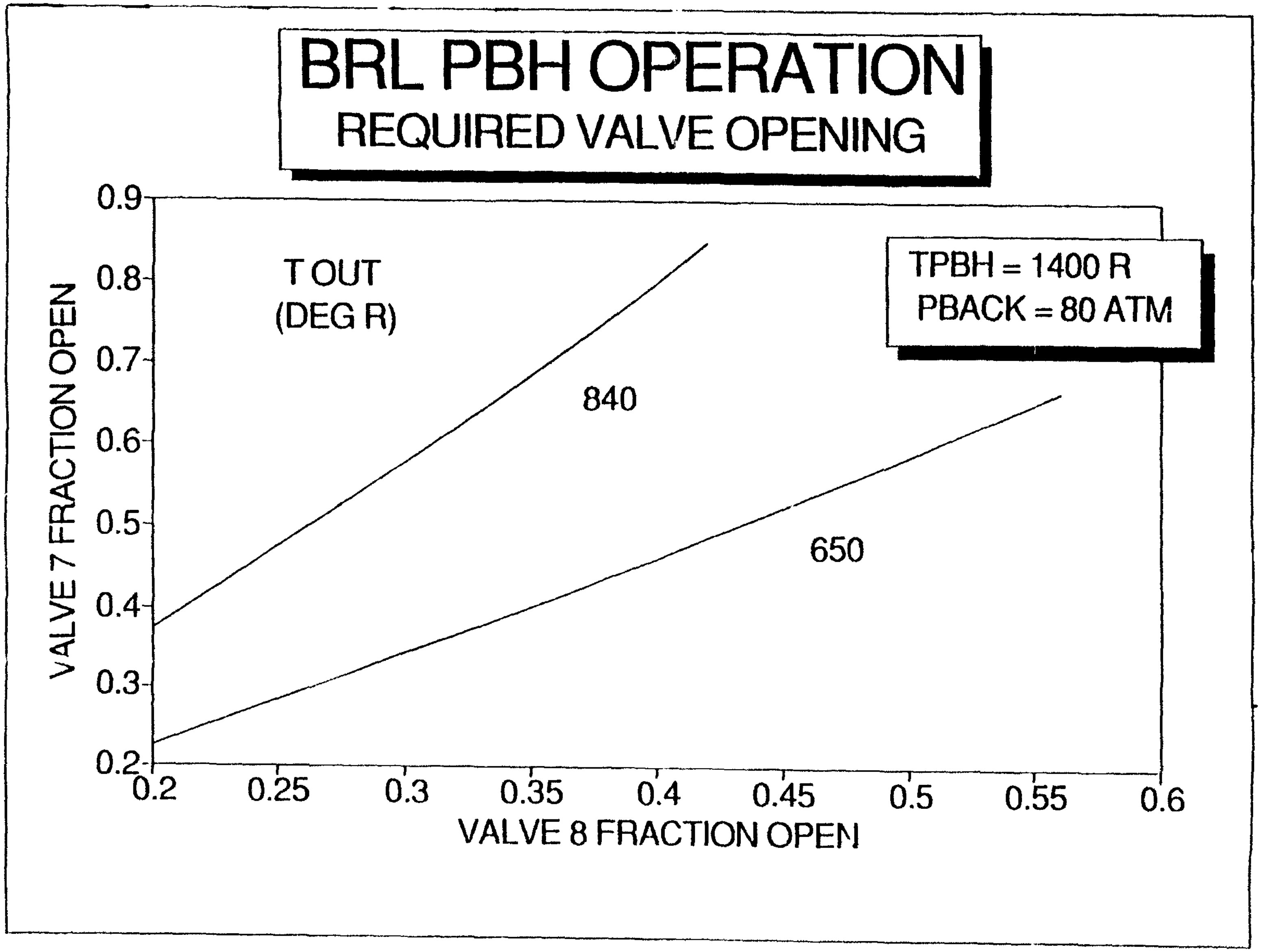

Figure 5. BRL PBH operation required valve opening, TPBH = 1400 R, PBACK = 80 ATM.

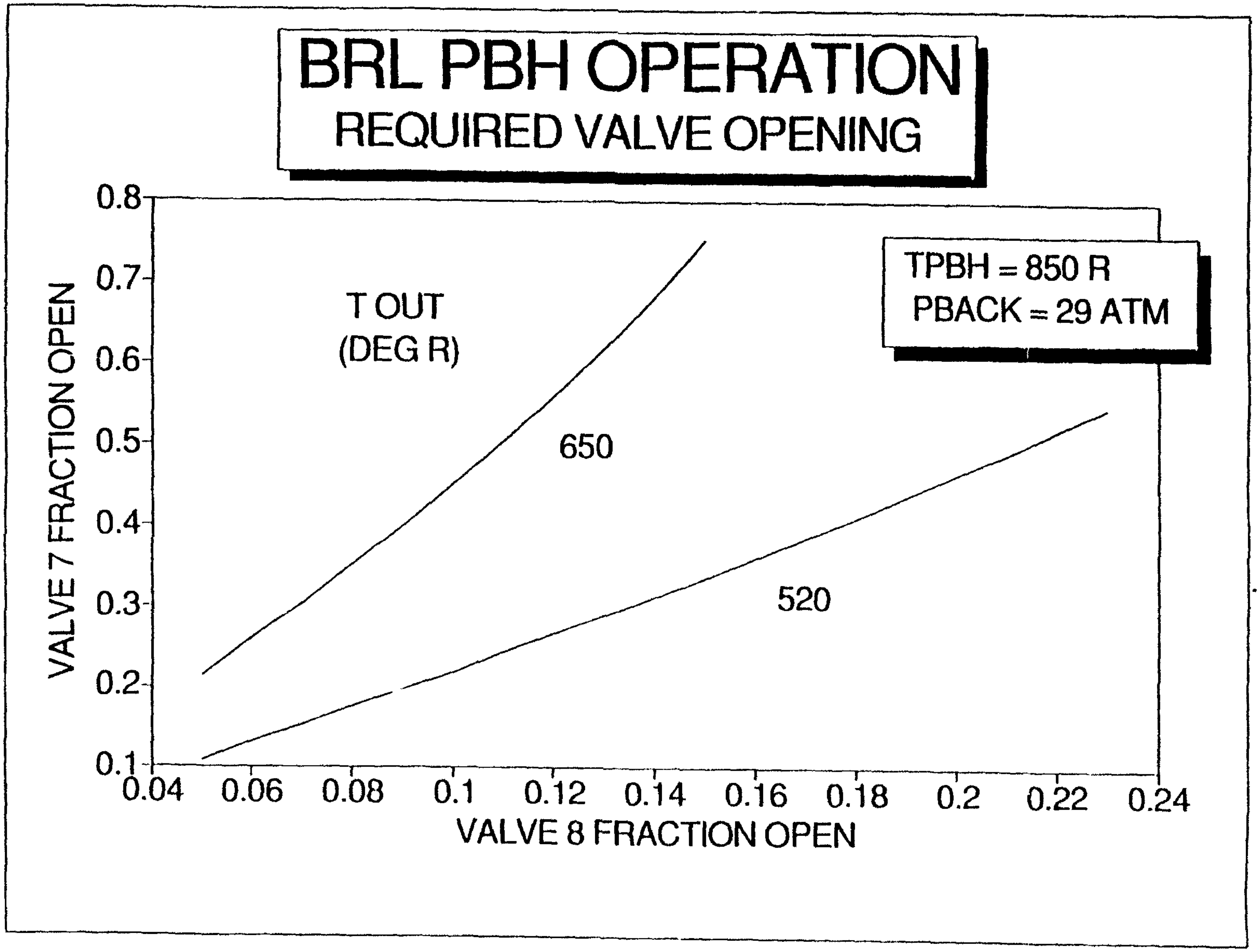

Figure 6. BRL PBH operation required valve opening, TPBH = 850 R, PBACK = 29 ATM.

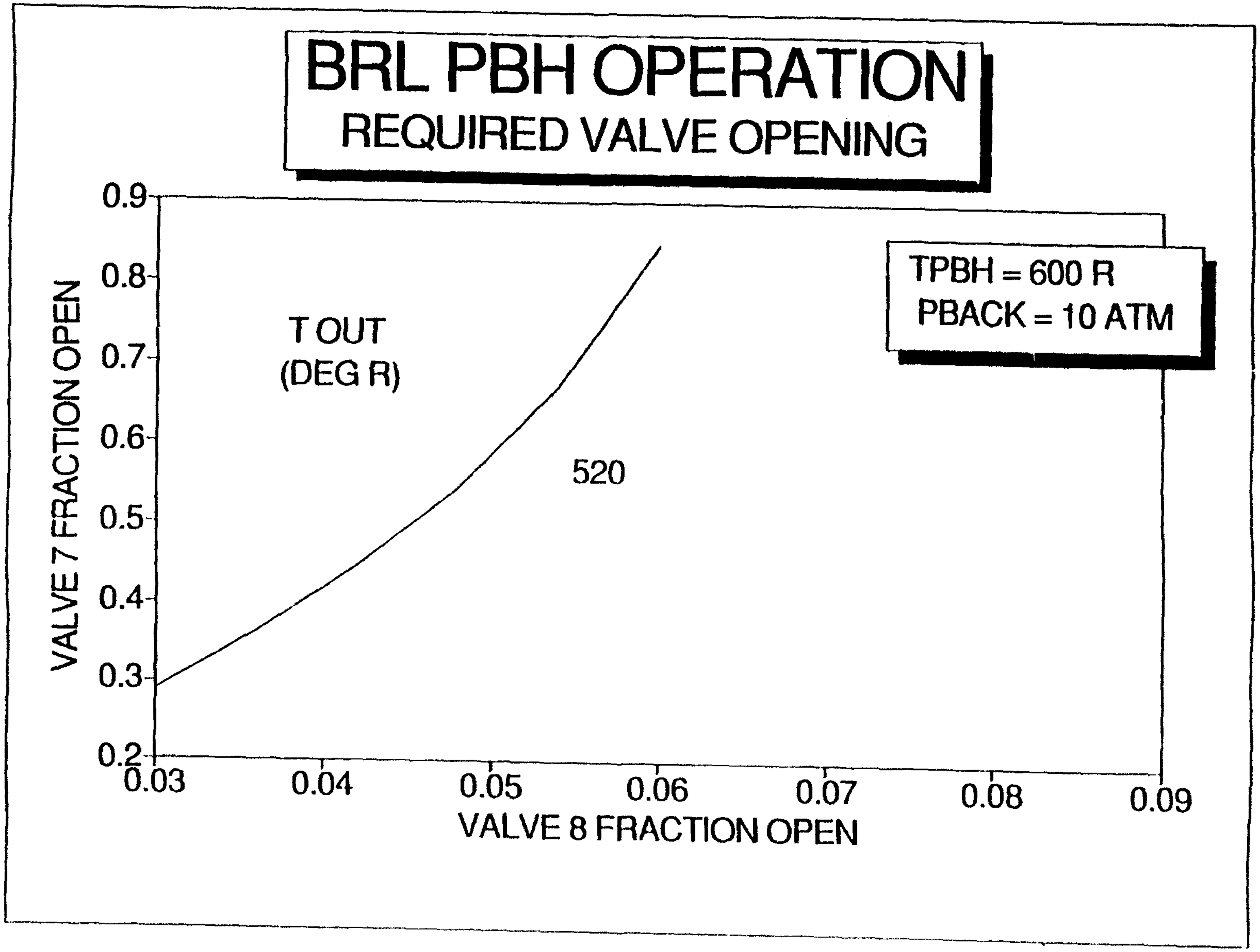

Figure 7. BRL PBH operation required valve opening, TPBH = 600 R, PBACK = 10 ATM.

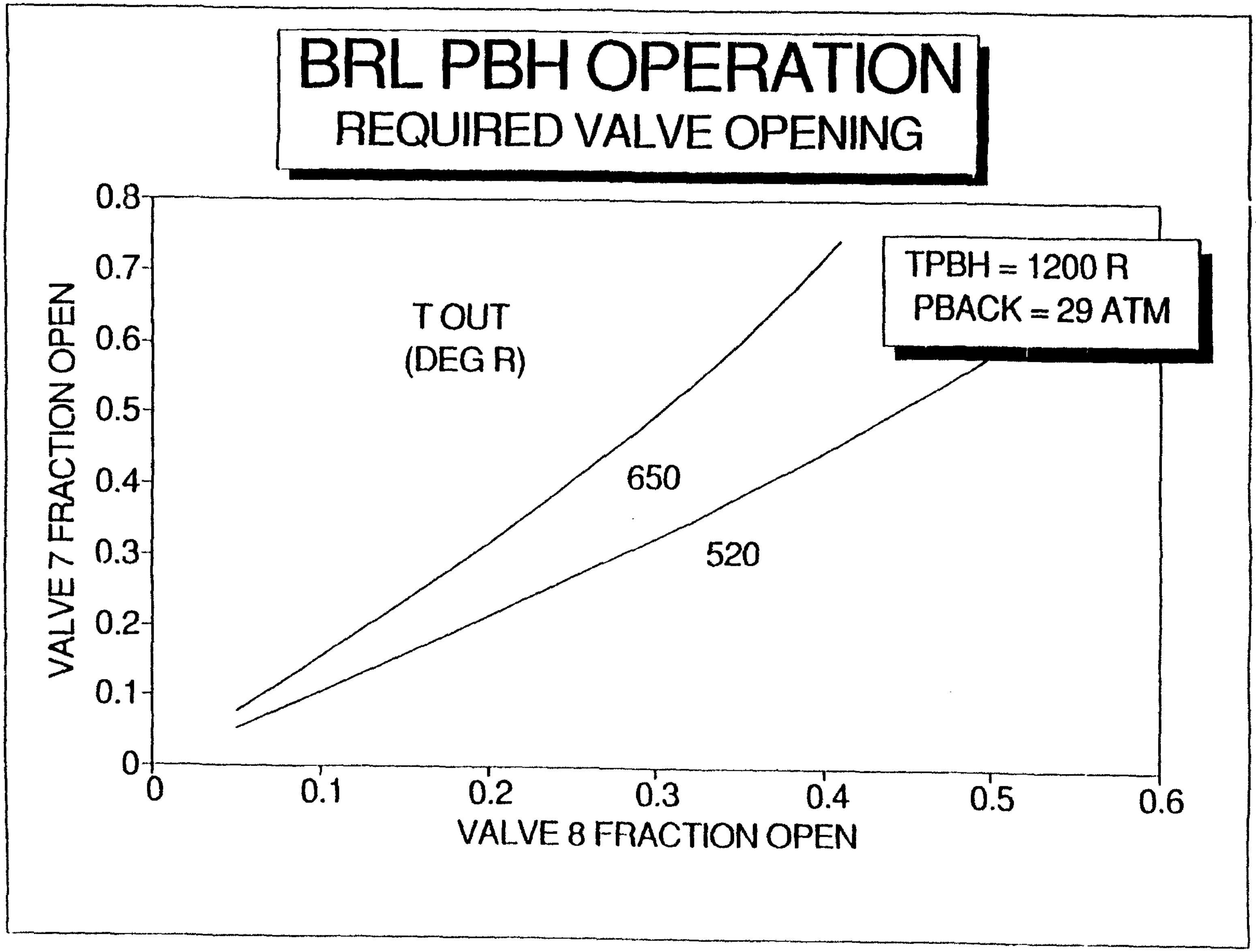

Figure 8. BRL PBH operation required valve opening, TPBH = 1200 R, PBACK = 29 ATM.

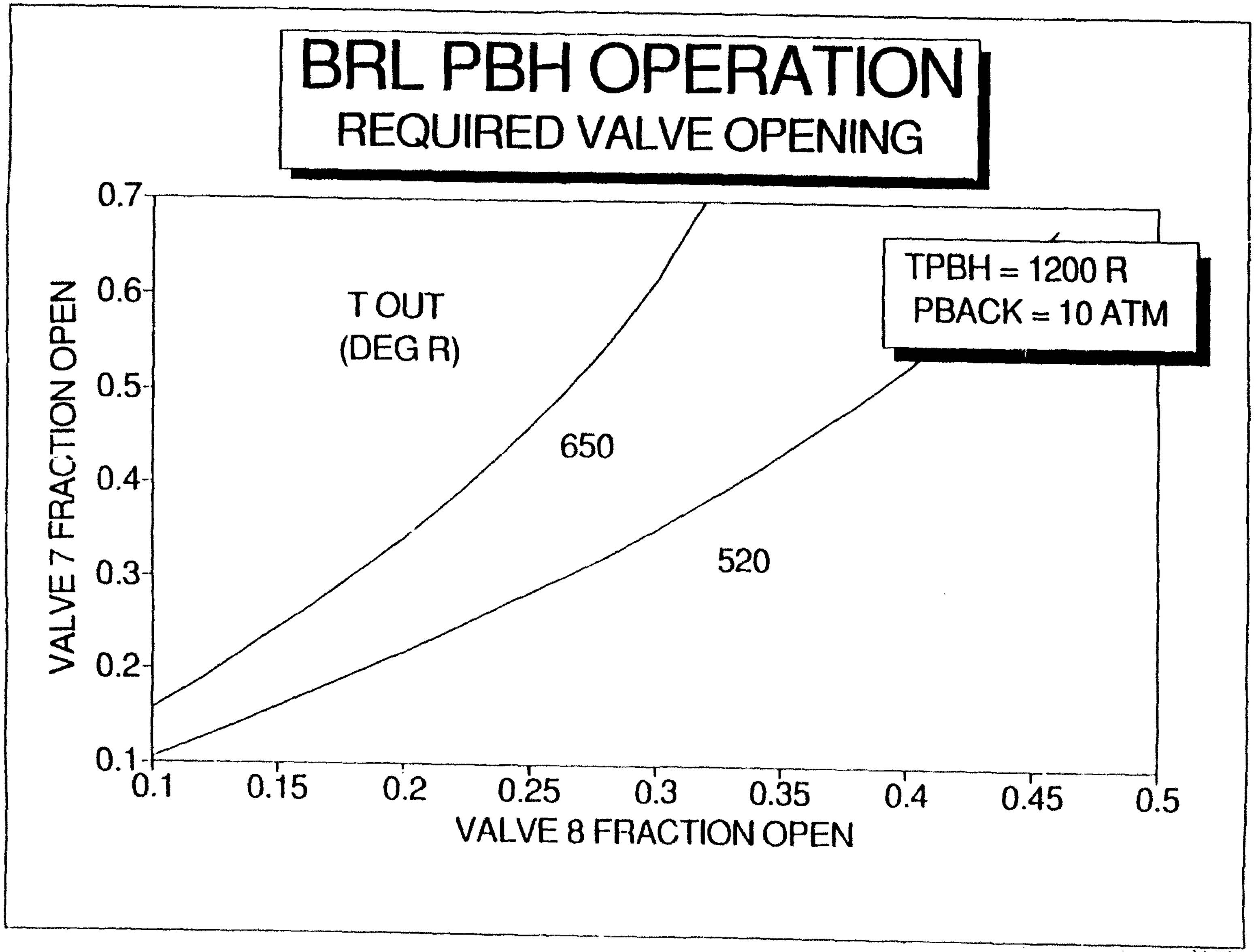

Figure 9. BRL PBH operation required valve opening, TPBH = 1200 R, PBACK = 10 ATM.

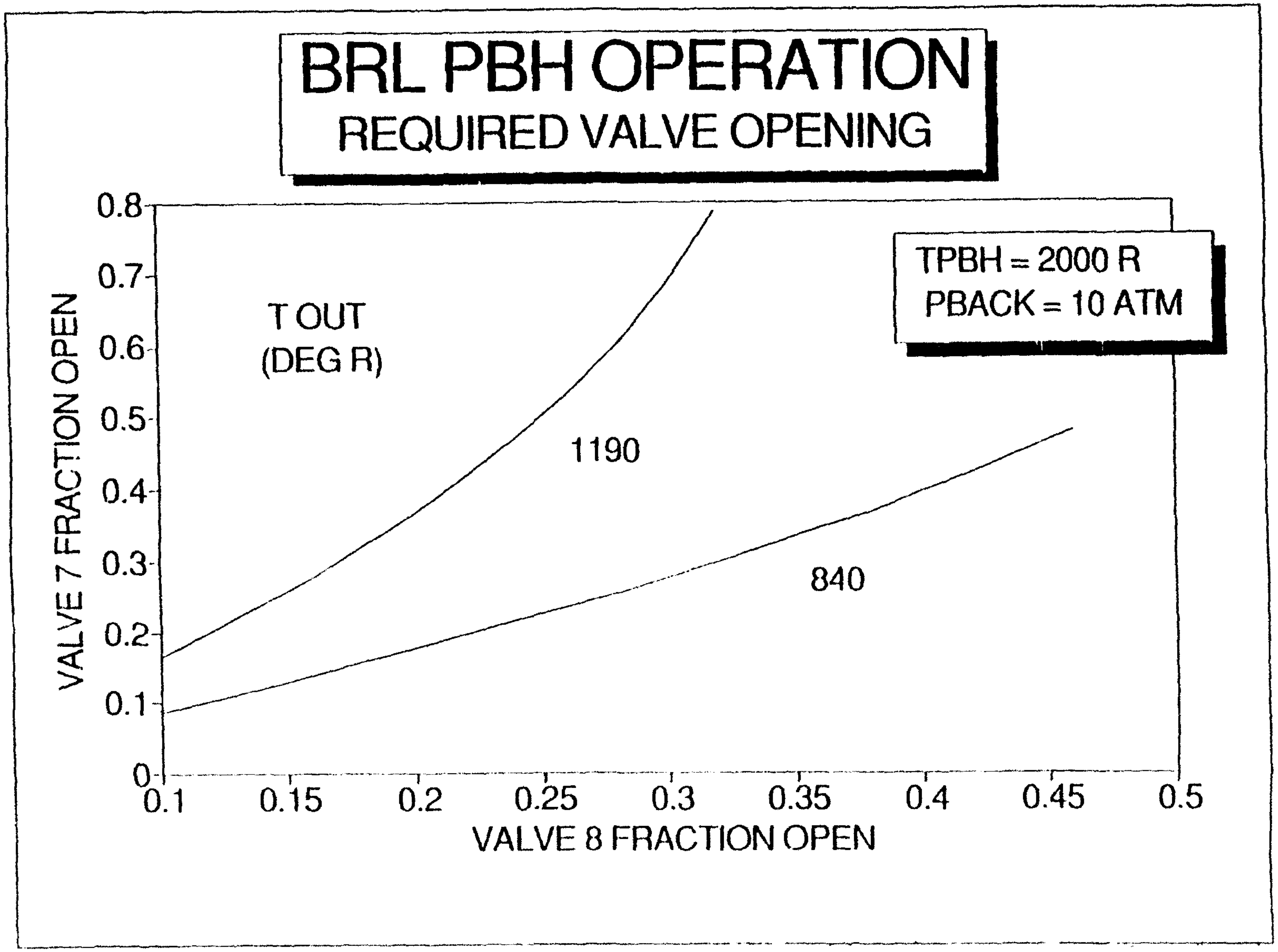

Figure 10. BRL PBH operation required valve opening, TPBH = 2000 R, PBACK = 10 ATM.

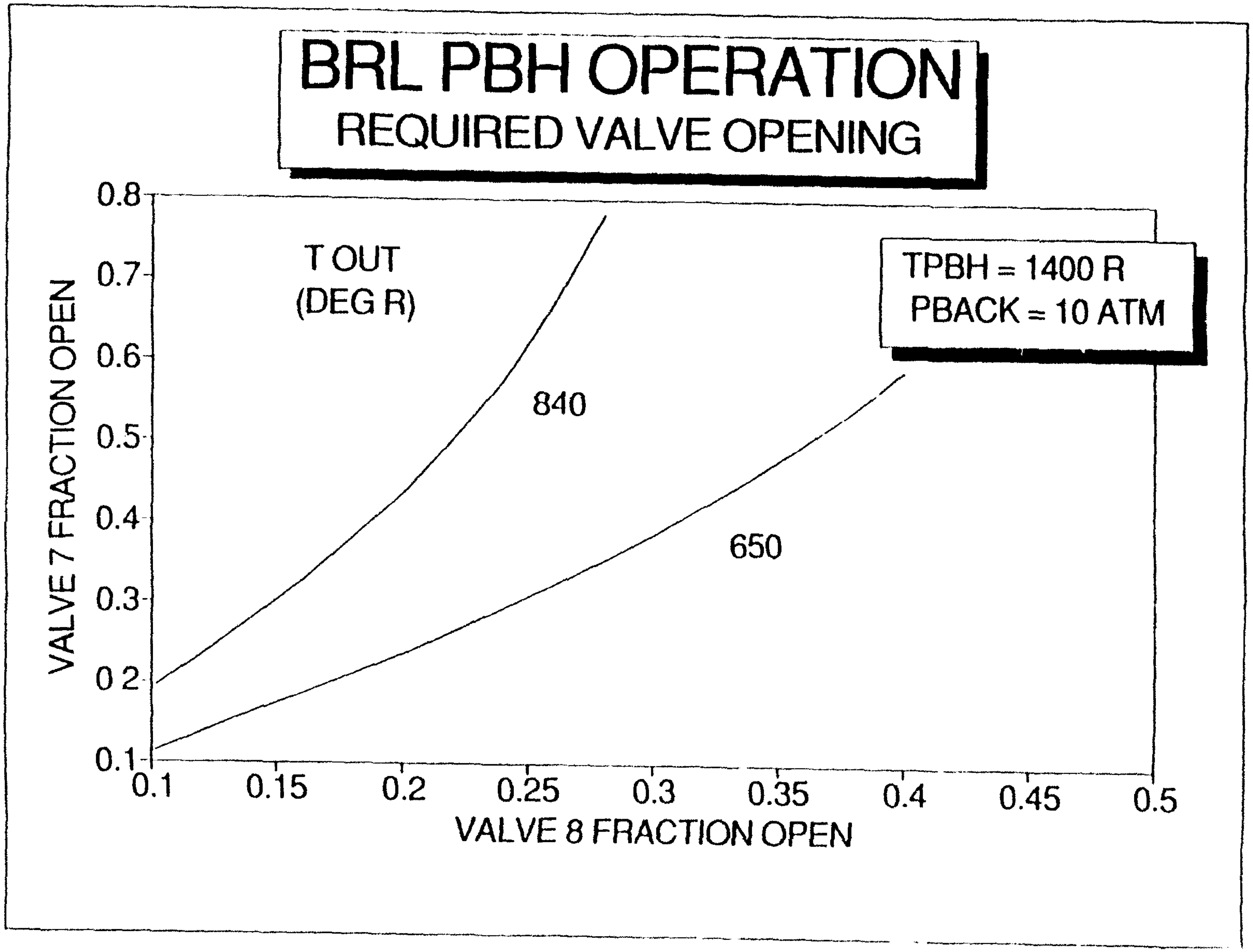

Figure 11. BRL PBH operation required valve opening, TPBH = 1400 R, PBACK = 10 ATM.

4. CONTROL SYSTEM DYNAMIC ANALYSIS

A dynamic model of the valve operation and control system was developed to assess automatic valve performance.

4.1 Model

Once the primary valve has been set, the mass flow rate through the bypass valve is

$$\dot{m}_8 = MFR \frac{x(t)}{L} \qquad \text{EQ (18)}$$

where MFR = mass flowrate with the valve fully open (back pressure dependent).

The valve seat is positioned by a spring loaded pneumatically actuated piston. Modern globe valves are fast acting and highly damped so the actuator is modeled as a damped spring mass system. The force balance equation for the pneumatic actuator is

$$m\ddot{x} + f\dot{x} + kx = F(t) \qquad \text{EQ (19)}$$

Defining a valve position forcing function as

$$X_f(t) = \frac{F(t)}{k} \qquad \text{EQ (20)}$$

and defining the following constants

$$\omega_n = \sqrt{\frac{k}{m}} \qquad \text{EQ (21)}$$

$$\zeta = \frac{f}{2\sqrt{km}} \qquad \text{EQ (22)}$$

Equation 19 becomes

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = X_f(t)\,\omega_n^2 \qquad \text{EQ (23)}$$

The Laplace transform of EQ 23 is

$$x(s) = \frac{X_f(s)\ \omega_n^2 + (s+2\zeta\omega_n)\,x(0)}{s^2+2\ \zeta\ \omega_n\ s+\omega_n^2} = \left(X_f(s) + \frac{(s+2\zeta\omega_n)x(0)}{\omega_n^{\ 2}}\right)G(s) \qquad \text{EQ (24)}$$

where $X_f(s)$ is the transformed valve position forcing function, x(0) is the valve actuator initial position determined from Figures 4 to 7 and

$$G(s) = \frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2} \qquad \text{EQ (25)}$$

Since pumping time (minutes) is long compared to the valve response time (~ seconds) and valve damping is high, a proportional control system was selected. Setting the actuator forcing function proportional to the difference between the measured output temperature and the control or setpoint temperature

$$X_f = K\ (T-T_c) \qquad \text{EQ (26)}$$

Substituting (EQ 18) into (EQ 3) gives

$$T = T_{PB} - \frac{MFR}{\dot{m}_T L}\ T_R\ x(t) \qquad \text{EQ (27)}$$

Taking the Laplace transforms of (EQ 26) and (EQ 27) and combining with (EQ 24) gives

$$T(s) = T_{PB}(s) - \left(\frac{MFR}{\dot{m}_T\ L}T_R\right)G(s)\left[K(T(s)-T_c(s)) + \frac{(s+2\zeta\omega_n)\,x(0)}{\omega_n^{\ 2}}\right] \qquad \text{EQ (28)}$$

or

$$T\ (s) = T_{PB}(s) + K_1\,G(s)\left[T_c(s) - T(s) - \frac{(s+2\zeta\omega_n)\,x(0)}{K\omega_n^{\ 2}}\right] \qquad \text{EQ (29)}$$

where the nondimensional

$$K_1 = K\,\frac{MFR}{\dot{m}_T\ L}\ T_R \qquad \text{EQ (30)}$$

Solving for T(s) in (EQ 29) gives

$$T(s) = \frac{T_{PB}(s) + K_1 G(s) T_c(s)}{1 + K_1 G(s)} - \frac{K_1 (s + 2\zeta\omega_n) x(0) G(s)}{K\omega_n^2 (1 + K_1 G(s))} \qquad \text{EQ (31)}$$

Because T_c (the setpoint temperature) is a constant value, the Laplace transform is

$$T_c(s) = \frac{T_c}{s} \qquad \text{EQ (32)}$$

The temperature of the outlet gas of the PBH (primary flow), T_{PB}, entering the thermal mixer can also be considered a constant because

1. This temperature will be maintained at a nearly constant value until the pebble-bed temperature at the end (bottom) of the pebble-bed starts dropping. This typically would occur when approximately 80 % of the process flow has been used.

2. During the last 20% of the flow period, the gas temperature at the outlet will decrease slowly compared to the response rate of the control valves.

Thus, the Laplace transform of T_{PB} is

$$T_{PB}(s) = \frac{T_{PB}}{s} \qquad \text{EQ (33)}$$

Substituting (EQ 32) and (EQ 33) into (EQ 31) gives

$$T(s) = \frac{1}{s}\left(\frac{T_{PB} + K_1 T_C G(s)}{1 + K_1 G(s)}\right) - \frac{K_1 (s + 2\zeta\omega_n) x(0) G(s)}{K\omega_n^2 (1 + K_1 G(s))} \qquad \text{EQ (34)}$$

and taking the inverse transform of (EQ 34) gives

$$T(t) = \frac{T_{PB} + K_1 T_c}{1 + K_1} + \left[\frac{K_1 (T_{PB} - T_c)}{1 + K_1} - \frac{K_1}{K} x(0)\right] * e^{-\omega_n \zeta t}\left(\cos(\omega_n t\sqrt{1 + K_1 - \zeta^2}) + \frac{\zeta}{\sqrt{1 + K_1 - \zeta^2}} \sin(\omega_n t\sqrt{1 + K_1 - \zeta^2})\right) \qquad \text{EQ (35)}$$

High gain ($K_1 >> 1$) is required to result in the steady state value of T approaching T_c. Inspection of EQ 35 indicates that for T_{PB} of the order of 2000°R and T_c of the order of 1000 °R, K_1 must be of the order of 50 to achieve controlled mixed gas temperatures within 5 percent of the desired temperature T_c.

The resulting solution for valve position (from EQ 27) becomes

$$\frac{x(t)}{L} = \frac{\dot{m}_T}{MFR\ T_R} \frac{K_1(T_{PB}-T_c)}{1+K_1} *$$

$$\left[1-\left(1-K_2\frac{x(0)}{L}\right)e^{-\omega_n\zeta t}\left(\cos(\omega_n t\sqrt{1+K_1-\zeta^2})+\frac{\zeta}{\sqrt{1+K_1-\zeta^2}}\sin(\omega_n t\sqrt{1+K_1-\zeta^2})\right)\right] \quad \text{EQ (36)}$$

where the nondimensional

$$K_2 = \frac{L}{K}\frac{1+K_1}{T_{PB}-T_c}$$

4.2 Calculations

Example calculations were made to demonstrate valve performance using the following characteristics from Valtek literature:

ω_n = spring cylinder actuator natural frequency ≈ 2.5 cps
ζ = damping ratio ≈ 0.7

Selecting an initial position of the primary valve as 70 percent open, the peak design condition of 2000 °R and 129 atm back pressure, an initial valve position of half open and a K_1 of 50, the setpoint temperature is achieved in less than a quarter of a second (Figure 13). Note that the valve motion is minimal due to the excellent choice of initial position; Figure 14 provides a better view of the motion by changing the scale of the ordinate.

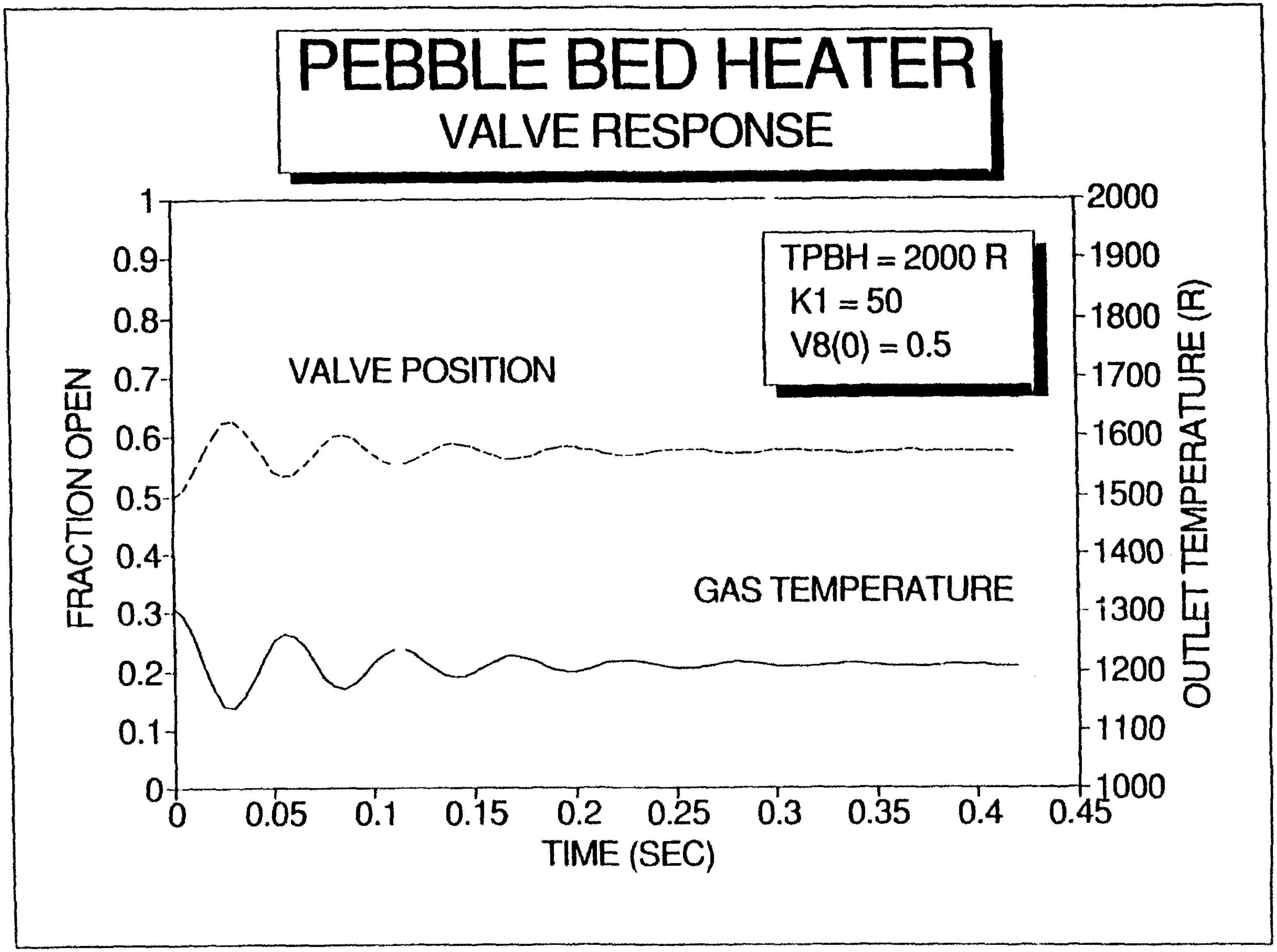

Figure 13. Pebble bed heater valve response.

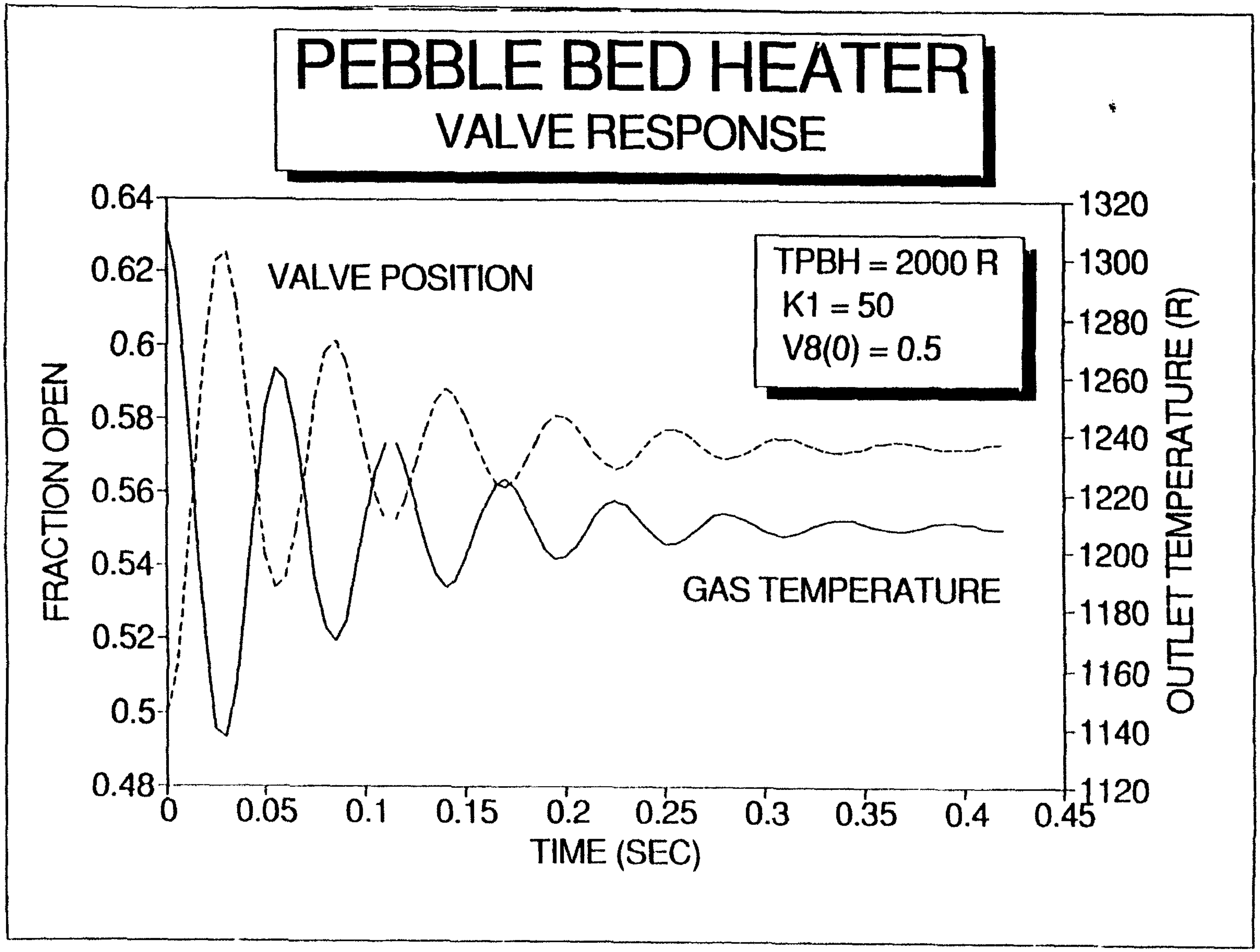

Figure 14. Pebble bed heater valve response.

5. Cost Estimate

Components of the control system are itemized in Table 2 along with a suggested vender and catalog prices. Unburdened hardware costs total $56,000. The estimated price to procure, assemble, program, install and checkout the system is $200,000. Including hardware purchases, the period of performance is expected to be six months.

BRL 1/6TH SCALE LBTS TESTBED CONTROL SYSTEM COSTS
DATA ACQUISITION/CONTROL AND PC COMPUTER COMPONENTS
COMPLETE SYSTEM WITH AUTOMATION ON ALL SYSTEMS

ITEM	QTY	UNIT	PART NUMBER MODEL NUMBER	DESCRIPTION/SPECIFICATION	UNIT COST	EXT COST	VENDER
1	1	EA	WH-CH-7	WORKHORSE INDUSTRIAL CONTROL AND DATA ACQUISITION CHASS	750	750	METRABYTE CAT 24
2	1	EA	WH-CIB-PAR	WORKHORSE PARALLEL INTERFACE CARD	399	399	METRABYTE CAT 24
3	1	EA	WH-PCDB-ISO	WORKHORSE PC INTERFACE CARD	675	675	METRABYTE CAT 24
4	1	EA	WH-AIN-16	WORKHORSE 16 CHANNEL ANALOG INPUT CARD	795	795	METRABYTE CAT 24
5	1	EA	WH-P-40	WORKHORSE I/0 TERMINAL FOR WH-AIN-16	50	50	METRABYTE CAT 24
6	3	EA	WH-TC-16	WORKHORSE 16 CHANNEL THERMOCOUPLE INPUT CARD	795	2385	METRABYTE CAT 24
7	3	EA	WH-P-40/CJC	WORKHORSE I/0 TERMINAL FOR WH-TC-16	95	285	METRABYTE CAT 24
8	1	EA	WH-DIB 32	WORKHORSE 32 POINT LOW-LEVEL DIGIGTAL I/O CARD	595	595	METRABYTE CAT 24
9	1	EA	WH-P 40	WORKHORSE I/0 TERMINAL FOR WH-DIB-32	50	50	METRABYTE CAT 24
10	1	EA	WH-PWR-100/110	WORKHORSE SYSTEM POWER SUPPLY, 100 WATT, 110 VAC	750	750	METRABYTE CAT 24
11	200	FT	WH-CRO-200	INTERFACE CABLE FOR PC TO WORKHORSE, 200 FEET	1.75	350	METRABYTE CAT 24
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30	1	EA	A-L30H2412LP	NEMA 4 ENCLOSURE, 30 X 24 X 12, FOR WORKHORSE SYSTEM	156	156	HOFFMAN ENCLOSURES CAT
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32	1	EA	D-L722524	NEMA 12 RACK MOUNT ENCLOSURE, 72 X 24 X 30, FOR PC	850	850	HOFFMAN ENCLOSURES CAT
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Table 2 Automatic Control System Components

BRL 1/6TH SCALE LBTS TESTBED CONTROL SYSTEM COSTS
CONTROL AND MANUAL VALVE COMPONENTS

ITEM	QTY	UNIT	PART NUMBER MODEL NUMBER	DESCRIPTION/SPECIFICATION	UNIT COST	EXT COST	VENDER
1	1	EA	V-1 MOD	CONVERT EXISTING VALVE FOR REMOTE ON/OFF CONTROL	750	750	AUTOMATED VALVE SYSTEMS
2	1	EA	V-3	LN GLOBE VALVE WITH ELECTRO PNEUMATIC ON/OFF CONTROL, 1"	2796	2796	MASONEII AN/DRESSER
3	1	EA	V-5	LN GLOBE VALVE WITH ELECTRO-PNEUMATIC ON/OFF CONTROL, 1"	2796	2796	MASONEII AN/DRESSER
4	1	EA	V-6	LN GLOBE VALVE WITH ELECTRO-PNEUMATIC PROPORTIONAL CONT	5463	5463	MASONEII AN/DRESSER
5	1	EA	V-7	LN GLOBE VALVE WITH ELECTRO-PNEUMATIC PROPORTIONAL CONT	5463	5463	MASONEII AN/DRESSER
6	1	EA	V-8	LN GLOBE VALVE WITH ELECTRO-PNEUMATIC PROPORTIONAL CONT	5463	5463	MASONEII AN/DRESSER
7	1	EA	V-10	AUX NITROGEN GAS VALVE, 3/4", MANUAL	375	375	CAPITAL WESTWARD
8	1	EA	V-11	CONTROL VALVE SUPPLY, HIGH PRESSURE, 3/4", MANUAL	375	375	CAPITAL WESTWARD
9	1	EA	V-12	CONTROL VALVE SUPPLY, LOW PRESSURE, 3/4", MANUAL	225	225	CAPITAL WESTWARD
10	1	EA	V-13	DRIVER DRAIN VALVE, 3/4", MANUAL	375	375	CAPITAL WESTWARD
11	2	EA	R-1	CONTROL VALVE PRESSURE REGULATOR, 3/4", MANUAL	570	1140	CIRCLE SEAL CONTROLS
12	250	FT	AUXNIT1	AUX NITROGEN SUPPLY TUBING, 3/8" OD	7.5	1875	TUBESALES
13	30	EA	AUXNIT2	AUX NITROGEN SUPPLY FITTINGS	7.5	225	LONG BEACH VALVE AND FITTING
14	6	EA	PGH-45L-100	PRESSURE GAGE FOR CONTROL VALVES, 0-100 PSIG	115	690	OMEGA CATALOG
15	0	EA			0	0	
16	0	EA			0	0	
17	0	EA			0	0	
18	0	EA			0	0	
19	0	EA			0	0	
20	0	EA			0	0	
				TOTAL CONTROL VALVE SYSTEM COST		28011	

Table 2 (Cont'd)

BRL 1/6TH SCALE LBTS TESTBED CONTROL SYSTEM COSTS
INSTRUMENTATION AND MISCELLANEOUS COMPONENTS

ITEM	QTY	UNIT	PART NUMBER MODEL NUMBER	DESCRIPTION/SPECIFICATION	UNIT COST	EXT COST	VENDER
1	1	EA	PANEL-ERX01	REMOTE ELECTRICAL RELAY STATUS DISPLAY PANEL	750	750	CUSTOM MADE
2	8	EA	CY7-SD7	LN TEMPERATURE SENSOR, 10 TO 425 K	85	680	OMEGA ENGINEERING
3	2	EA	PX700-300GI	LOW PRESSURE TRANSMITTER, 0-300 PSI	399	798	OMEGA ENGINEERING
4	2	EA	PX725-3KGI	HIGH PRESSURE TRANSMITTER, 0-3000 PSIG	495	990	OMEGA ENGINEERING
5	2	EA	PGT-60B-3000	AUX NITROGEN SUPPLY PRESSURE GAGE, 0 3000 PSIG	282	564	OMEGA ENGINEERING
6	2	EA	PSW-108	PRESSURE SWITCH, 10-100 PSI	60	120	OMEGA ENGINEERING
7	2	EA	PSW-133	PRESSURE SWITCH, 500-3000 PSI	111	222	OMEGA ENGINEERING
8	2	EA	FSW-112R	FLOW SWITCH, LOW PRESURE	126	252	OMEGA ENGINEERING
9	2	EA	FSW-108	FLOW SWITCH, HIGH PRESURE	524	1048	OMEGA ENGINEERING
10	12	EA	NB2-CASS-18U-12	TYPE K THERMOCOUPLE PROBES W/NEMA 4 ENCLOSURE, 1/8" DIA	44	528	OMEGA ENGINEERING
11	500	FT	EXPP-K-20-TWSH	TYPE K THERMOCOUPLE WIRE, SHIELDED, 20 AWG SOLID	0.32	160	OMEGA ENGINEERING
12	500	FT	87F3856WF	24 AWG 6 PAIR SHIELDED INSTRUMENTATION CABLE	1.35	675	NEWARK ELECTRONICS
13	8	EA	90F9606	NEMA 4 ENCLOSURE, 14 X 12 X 6	52	416	NEWARK ELECTRONICS
14	1	EA	MISCELCON1	MISC ELECTRICAL CONNECTOR HARDWARE	250	250	ENG ESTIMATE
15	1	EA	MISCELTRY1	MISC ELECTRICAL CABLE TRAYS AND FASTENERS	500	500	ENG ESTIMATE
16	1	EA	MISCHDWR1	MISC MECHANICAL HARDWARE	500	500	ENG ESTIMATE
17	0	EA			0	0	
18	0	EA			0	0	
19	0	EA			0	0	
20	0	EA			0	0	
				TOTAL INSTRUMENTATION AND MISC HARDWARE COST		8453	

Table 2 (Cont'd)

6. Summary

Conclusions and recommendations reached as result of this design study are summarized below.

6.1 Conclusions

* An automated control system for the BRL 1/6th scale shock tube is feasible and practical using off the shelf hardware.

* Globe valves of the type selected for valves 7 and 8 give positive control over the output gas temperature with reasonable valve actuator positions.

* Driver gas backpressure has a small effect on control valve position based on the Pebble Bed Heater pressure drop model developed here.

* The analytical models should be calibrated with test data for each design condition.

6.2 Recommendations

* Assembly, programming, installation and checkout of an automated control system should begin immediately.

* The time dependent driver gas filling model developed in Reference 2 should be coupled to the gas supply system quasi-steady and dynamic control models in a system simulation to develop detailed control strategies for each test condition. This simulation should be used to establish test procedures, train operators and analyze test data.

* Pebble Bed Heater and mixer nozzle pressure drop data should be obtained for a variety of flow conditions and a more detailed model developed for use in the control system model.

* A control system analysis should be performed for the existing valves which are being retrofitted for automatic control and the models should be calibrated with test data.

7. REFERENCES

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2. Hove, D., and Osofsky, I., "An Analytical Model for the BRL Heated Driver Gas Supply System," Twelfth International Symposium on Military Applications of Blast Simulation, Perpignon, France, October 1992.

3. Mason, G. M., "Procedures for the Operation of the Driver Gas Fill System for the BRL 1/6th Scale LB/TS Test Facility," LA91-21-TR, SPARTA, Inc., December 1991.

4. VALTEK Brochures: Mark One Body Assembly, Linear Spring Cylinder Actuators and Beta Control Valve Positioners.

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Nomenclature

A	area
CV	valve characteristic
C_p	specific heat at constant pressure
d	diameter
f	friction factor
F	force
G	transfer function
h_v	heat of vaporization
L	actuator full travel
k	spring constant
K	gain constant
m	mass
N	number of units
Re	Reynolds number
s	transform variable
t	time
T	temperature
U	fluid velocity
x	position

Greek

ω_n	natural frequency
ζ	damping
ρ	density

Superscripts

$\cdot$	derivative wrt time
$\cdot\cdot$	second derivative wrt time

Subscripts

7	valve 7 or primary line
8	valve 8 or bypass line
PB	pebble bed
p	pipe
T	total
90	elbow
LN	liquid nitrogen
R	reference
C	control

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