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Simulation of Pressure and Temperature Responses for the 20 Inch Supersonic Wind Tunnel

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for the
20 Inch Supersonic Wind Tunnel

Abstract

A simulation of the pressure and temperature responses of the 20 Inch Supersonic Wind Tunnel (SWT) is developed. The simulation models the tunnel system as a set of lumped-parameter volumes connected by flow regulating elements such as valves and nozzles. Simulated transient responses of temperature and pressure for the five boundary points of the 20 Inch Supersonic Wind Tunnel operating map are produced from their respective initial conditions, tunnel operating conditions, heater input power, and valve positions. Upon reaching steady state, a linearized model for each operating point is determined. Both simulated and actual tunnel responses are presented for comparison.

Nomenclature

A	area
D	diameter
E	energy
k	thermal conductivity
m	mass
MW	megawatts
P	pressure
Q	heat
JTC	Joule-Thompson coefficient
Re	Reynolds number
Pr	Prandtl number
T	temperature
v	volume
V	voltage
w	thermal mass
W	flow
C	flow coefficient
R	resistance
c_p	constant pressure specific heat (0.241 Btu/lbm- R)
c_v	constant volume specific heat (0.171 Btu/lbm- R)
γ	c_p/c_v (1.4)
R	gas constant (53.3 ft-lbf/lb- R)
g	acceleration due to gravity (32.2 ft/sec**2)
T_{ref}	reference temperature (460 R)

Subscripts:

cv	control volume
i	inlet
o	outlet
m	surrounding vessel

1.0 Introduction

A simulation which models the pressure and temperature responses of the 20 Inch Supersonic Wind Tunnel (SWT) has been developed. This simulation is intended to provide a basis for developing pressure and temperature control laws for the 20 Inch SWT.

The simulation is written in the Advanced Continuous Simulation Language (ACSL). ACSL provides the capability to simulate the response of systems represented by nonlinear, time-varying differential equations. Transient responses are simulated by supplying an appropriate set of initial conditions and time history of inputs. Run-time commands are invoked during the simulation execution to determine a linearized system model based on small perturbations about desired operating points. Eigenvalues of the linearized system are then determined for those particular operating conditions.

The major elements which comprise the tunnel system are shown in Figure 1. Six volumes, each describing a section of the tunnel system, represent the 20 Inch SWT:

Bottlefield
Heater Upstream
Heater Downstream
Mixing Tee
Settling Chamber
Vacuum Spheres

Flow between these volumes is calculated at seven points:

Valve 3162
Heater
Valve 3295
Valve 3170
Valve 3292
Valve 3296
Nozzle

Mass and energy are balanced for each volume. The rate of mass transfer is simulated by calculating the entering and exiting flow rates. The mass of air within a volume is determined by integrating the net rate of mass transfer. The rate of energy exchange is simulated by calculating the enthalpy of the entering and exiting air flows as well as the heat transfer to the surrounding vessel. Similarly, the energy of the air within a volume is determined by integrating the net rate of energy exchange. Consequently, the temperature of the air within a volume is determined from the ratio of energy to mass. The pressure is determined from the ideal gas equation of state.

Each volume and flow calculation is explicitly identified in the simulation source code. Pertinent parameters used to model each system element are shown in Figure 1. Inputs to the simulation are: initial conditions for temperature and pressure, valve positions, and heater input power. Alternately, heater input power may be specified by the tap position of a variable autotransformer. Outputs from the simulation are the temperature and pressure responses of each volume.

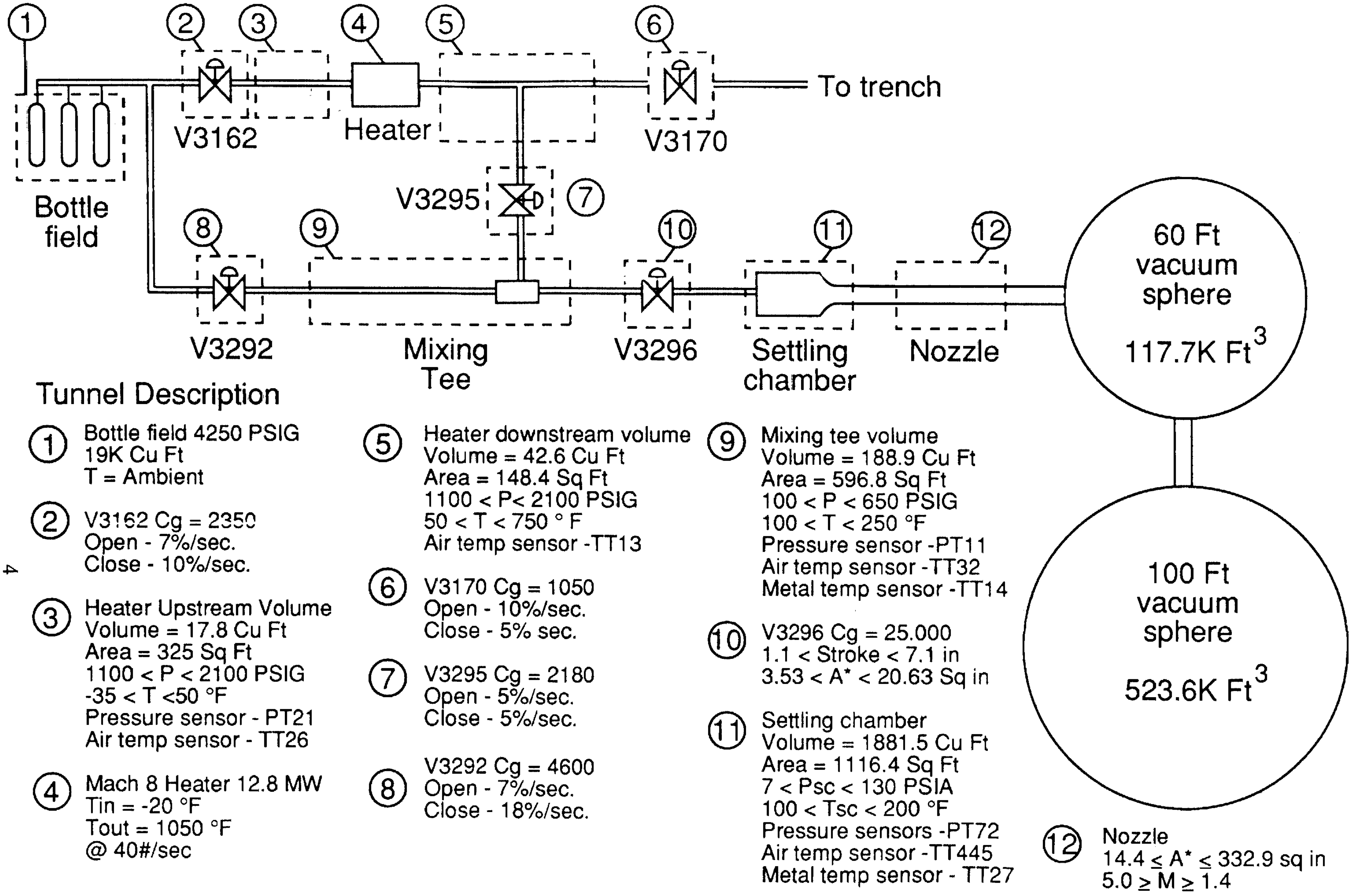
The settling chamber, nozzle, and valve 3296 are the simulation elements specific to the 20 Inch SWT. The remaining simulation elements are common to other test cells that use the Mach 8 Air Distribution System. Responses for the other test cells may be simulated by inserting equations to represent the specific test cell elements between the mixing tee and the vacuum spheres. Operating conditions that discharge to the atmosphere instead of to the vacuum spheres are also accommodated.

2.0 Governing Equations

Equations describing the fundamental relationships between the system elements shown in Figure 1 are based on mathematical models appropriate to the type of system element. Modeling techniques used for the general types of elements are: First Law control volume analysis for volumes, manufacturer's published flow equations for valves, and idealized flow characteristics for the heater and nozzle orifices.

2.1 Volume Models

For each of the volumes used to represent the 20 Inch SWT, a mass and energy balance is performed. The temperature and pressure are determined directly from the mass and energy within the volume.



Tunnel Description

① Bottle field 4250 PSIG
19K Cu Ft
T = Ambient

② V3162 Cg = 2350
Open - 7%/sec.
Close - 10%/sec.

③ Heater Upstream Volume
Volume = 17.8 Cu Ft
Area = 325 Sq Ft
$1100 < P < 2100$ PSIG
$-35 < T < 50$ °F
Pressure sensor - PT21
Air temp sensor - TT26

④ Mach 8 Heater 12.8 MW
Tin = -20 °F
Tout = 1050 °F
@ 40#/sec

⑤ Heater downstream volume
Volume = 42.6 Cu Ft
Area = 148.4 Sq Ft
$1100 < P < 2100$ PSIG
$50 < T < 750$ ° F
Air temp sensor -TT13

⑥ V3170 Cg = 1050
Open - 10%/sec.
Close - 5% sec.

⑦ V3295 Cg = 2180
Open - 5%/sec.
Close - 5%/sec.

⑧ V3292 Cg = 4600
Open - 7%/sec.
Close - 18%/sec.

⑨ Mixing tee volume
Volume = 188.9 Cu Ft
Area = 596.8 Sq Ft
$100 < P < 650$ PSIG
$100 < T < 250$ °F
Pressure sensor -PT11
Air temp sensor -TT32
Metal temp sensor -TT14

⑩ V3296 Cg = 25.000
$1.1 <$ Stroke < 7.1 in
$3.53 < A^* < 20.63$ Sq in

⑪ Settling chamber
Volume = 1881.5 Cu Ft
Area = 1116.4 Sq Ft
$7 < P_{sc} < 130$ PSIA
$100 < T_{sc} < 200$ °F
Pressure sensors -PT72
Air temp sensor -TT445
Metal temp sensor - TT27

⑫ Nozzle
$14.4 \leq A^* \leq 332.9$ sq in
$5.0 \geq M \geq 1.4$

Figure 1. System Diagram

Heat transfer to and from the surrounding vessel is considered to be by forced convection only. The vessel is assumed to be perfectly insulated. Figure 2 shows the representation of a typical volume.

Mass Balance.

$$\dot{m}_{cv} = \dot{m}_i - \dot{m}_o \tag{1}$$

$$m_{cv} = \int \dot{m}_{cv} \quad + m_{ic} \tag{2}$$

$$m_{ic} = P_{ic}v/(RT_{ic}) \tag{3}$$

Energy Balance.

$$\dot{E}_{cv} = c_p\left(\dot{m}_i T_i - \dot{m}_o T_o\right) - \dot{Q}_m \tag{4}$$

$$E_{cv} = \int \dot{E}_{cv} \quad + E_{ic} \tag{5}$$

$$E_{ic} = m_{ic}c_v(T_{ic} - T_{ref}) \tag{6}$$

Temperature.

Temperature is determined from the internal energy and the mass within the volume:

$$T_{cv} = E_{cv}/(c_v m_{cv}) \quad + T_{ref} \tag{7}$$

Pressure.

Pressure is determined using the Ideal gas equation:

$$P_{cv} = \frac{m_{cv}T_{cv}R}{v} \tag{8}$$

Heat Transfer.

Heat transfer to the surrounding vessel is based on flow through a round duct:

$$\dot{Q}_m = U \cdot A \cdot (T_{cv} - T_m) \tag{9}$$

where

$$U = .023\frac{k}{D}(Re)^{0.8}(Pr)^{0.4} \tag{10}$$

Metal Temperature.

The temperature of the surrounding vessel is determined by integrating the rate of heat flow into the respective thermal mass:

$$T_m = \frac{1}{w_m}\int \dot{Q}_m \quad + T_{mic} \tag{11}$$

2.2 Flow Models

Valves.

The flow through valves V3162, V3170, V3292, V3295, and V3296 is modeled using a published flow equation from Fisher Controls [4]:

$$W = K_v \delta C_v P_H/\sqrt{T_H} \tag{12}$$

where

$K_v = 4.84 \times 10^{-4}$
δ - valve stroke
P_H - upstream pressure
T_H - upstream temperature

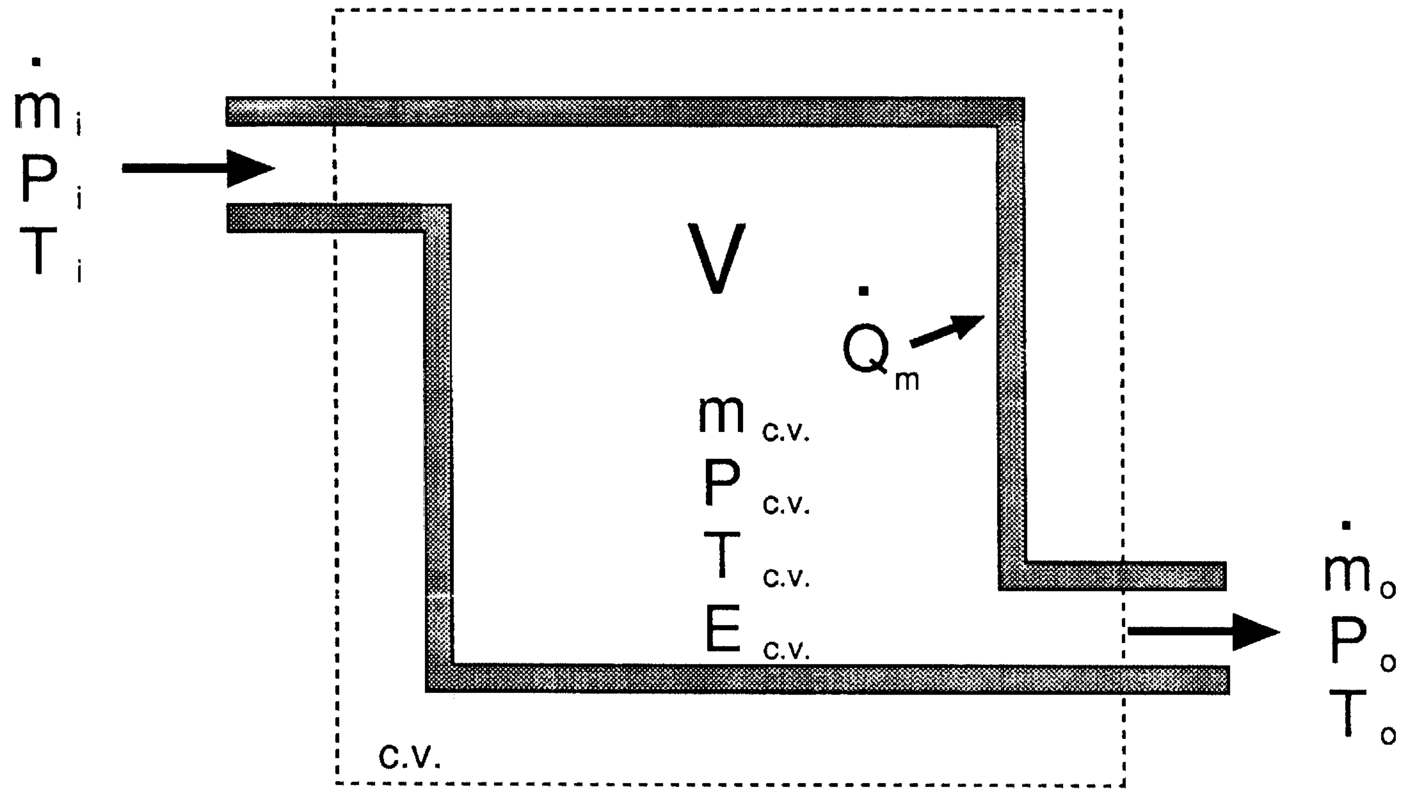


Figure 2. Typical volume

$$C_v - C_G(\delta)\sin\left[\frac{59.54}{C_1}\sqrt{1-\frac{P_L}{P_H}}\right]$$

where

$C_G(\delta)$ - flow factor based on valve stroke δ
C_1 - flow recovery factor from manufacturer's data
P_L - downstream pressure

Heater.

Flow through the heater is modeled by:

$$W = \sqrt{C_v P_H (P_H - P_L)/T_H} \tag{13}$$

where

$C_v = 25.17$ for M8 Heater
P_H upstream pressure
P_L downstream pressure
T_H upstream temperature

Nozzle.

The nozzle flow is determined by:

$$W = AP_H \left(\frac{P_L}{P_H}\right)^{1/\gamma} \sqrt{\frac{2g\gamma}{(\gamma-1)RT_H}\left[1-\left(\frac{P_L}{P_H}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{14}$$

when

$$\frac{P_L}{P_H} \leq 0.5283$$

and

$$W = AP_H \sqrt{\frac{g\gamma}{RT_H}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}} \tag{15}$$

when

$$\frac{P_L}{P_H} > 0.5283$$

where A - nozzle cross-sectional area

2.3 Heater Model

The heat input to the system by the Mach 8 Heater is determined from the electrical power input :

$$\text{HPOWER} = V_{TAP}^2/R_{HTR} \tag{16}$$

where

$$V_{TAP} = f(\text{TAP POSITION}) \tag{17}$$

and

$$R_{HTR} = R_{ko} + R_{k1}(T_{HTR} - 615) \tag{18}$$

The thermal equivalent of the electrical input power is transferred into the Heater Downstream volume through the thermal mass of the heater core. This provides a simulation of heater core temperature dependent on heater mass flow rate, heater input power, and heater outlet temperature. The electrical power input may be specified directly in MW or by the autotransformer tap position.

2.4 Throttling Process

The temperature drop associated with throttling across valves is determined using the Joule-Thompson coefficient and the associated pressure drop:

$$\Delta T = JTC \cdot (P_H - P_L) \tag{19}$$

3.0 Method of Solution

A computer model of the above equations was implemented using ACSL (Appendix B). ACSL provides a simple method of representing the mathematical equations on a digital computer. ACSL sorts the continuous model equations, in contrast to programming languages such as FORTRAN where program execution depends critically on statement order. The nonlinear, time dependent differential equations are solved directly by integrating from a given set of initial conditions to a final state determined by system inputs. The state variables for the 20 Inch SWT model are listed in Table 1.

Table 1. State Variables

State Variable	ACSL Variable Name
Bottlefield Energy	BFENRG
Bottlefield Mass	BFMAS
Heater Upstream Energy	HUENRG
Heater Upstream Mass	HUMAS
Heater Upstream Metal Temperature	HUTPIP
Heater Downstream Energy	HDENRG
Heater Downstream Mass	HDMAS
Heater Downstream Metal Temperature	HDTPIP
Heater Core Temperature	TCORER
Mixing Tee Energy	MTENRG
Mixing Tee Mass	MTMAS
Mixing Tee Metal Temperature	MTTPIP
Piping Energy	PPENRG
Piping Metal Temperature	PPTPIP
Settling Chamber Energy	SCENRG
Settling Chamber Mass	SCMAS
Settling Chamber Metal Temperature	SCTPIP
Vacuum Sphere Energy	VSENRG
Vacuum Sphere Mass	VSMAS

4.0 Results

The model was exercised for the five boundary points that establish the 20 Inch SWT operating map shown in Figure 3. The simulation was driven by values of valve positions and heater power read directly from files of data logged during actual tunnel runs. Initial mass and energy states for each volume were determined from pressure and temperature conditions at the beginning of the run. Initial

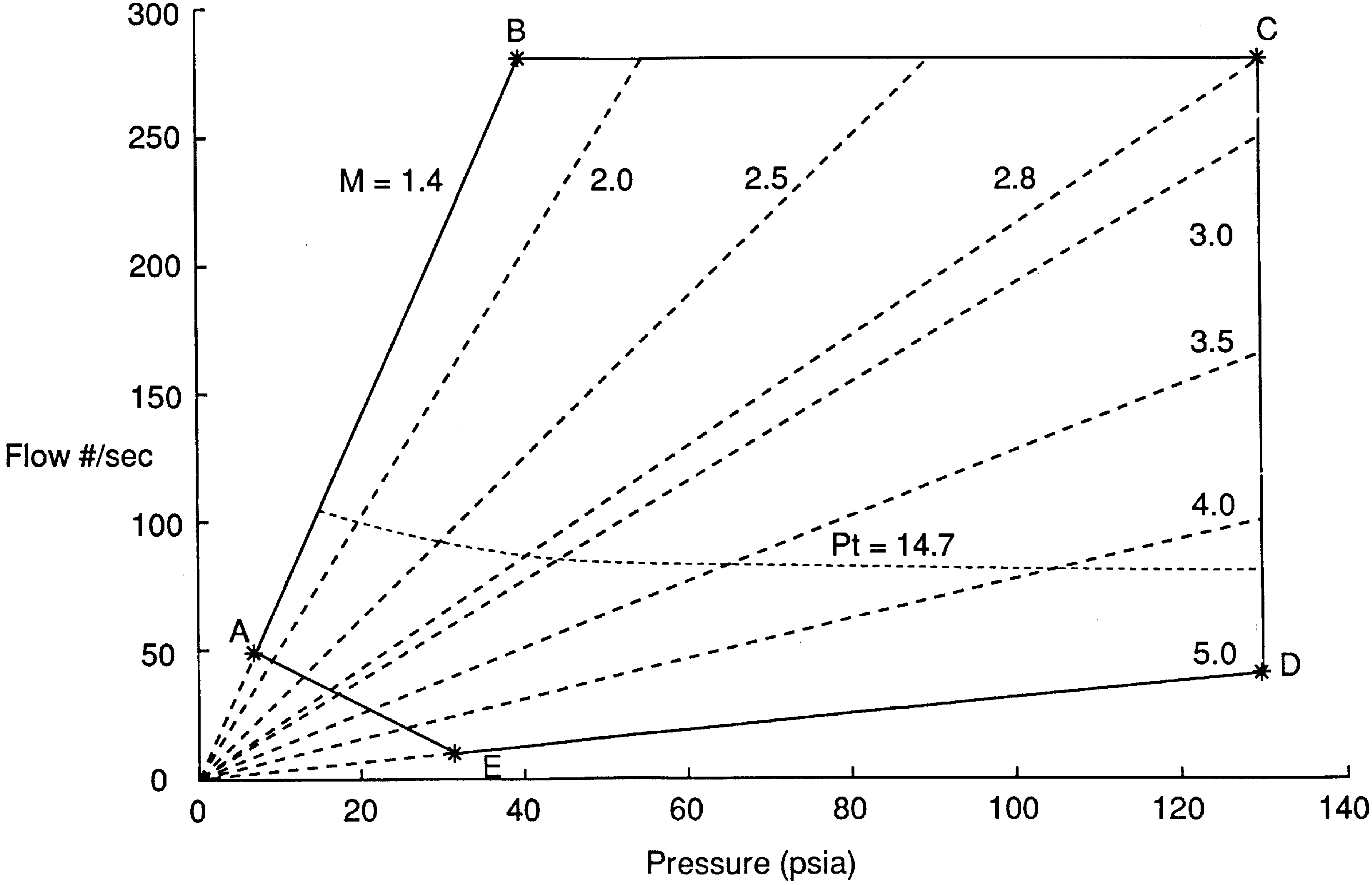


Figure 3. 20 Inch SWT Operating Map

values for piping and pressure vessel temperatures were set according to either the available sensor readings or the assumption of thermal equilibrium within the volume.

Figure 4 shows the results of a simulation run at operating condition 'A'. The first plot compares the simulated settling chamber pressure to the actual pressure logged during a tunnel run. The second plot similarly compares the simulated and actual settling chamber temperatures. The third plot shows the actual valve positions logged during the tunnel run. These valve positions were used as part of the dynamic input to the simulation. Similarly, the last plot shows the actual heater power logged during the run. This data was also used as dynamic input to the simulation. Thus, the simulation output, in terms of settling chamber pressure and temperature, may be compared to the actual tunnel response for an identical set of inputs. The position commands to valves V3295 and V3292 were specified by a human operator during the tunnel run. Similarly, the heater electrical power was controlled manually by selecting the autotransformer tap position during the run.

Referring to Figure 3, operating point 'A' is characterized by a settling chamber absolute pressure of seven pounds per square inch, corresponding to a mass flow rate of fifty pounds per second. The desired settling chamber temperature is 100 degrees Fahrenheit. A complete listing of operating point parameters is provided in Appendix A.

Figure 5 shows the same data for a simulation of operating condition 'B'. Point 'B' is characterized by a settling chamber absolute pressure of 40 pounds per square inch, corresponding to a mass flow rate of 280 pounds per second. The desired settling chamber temperature is 100 degrees Fahrenheit.

Figures 6–8 provide a more comprehensive view of the simulation capability. These figures show the results of a run at operating point 'C'. Figure 6 shows the same results as for points 'A' and 'B'. Figure 7 shows the simulated and actual tunnel responses for heater outlet air temperature, mixing tee air temperature, mixing tee metal temperature, and settling chamber metal temperature. Figure 8 illustrates the correspondence between simulated and actual responses for the mixing tee pressure and regulator station pressure. Figure 8 also shows the position of valve V3162 logged during the run, which is used as part of the dynamic input to the simulation.

Referring again to Figure 3, operating point 'C' is characterized by a settling chamber absolute pressure of 130 pounds per square inch, corresponding to a mass flow rate of 280 pounds per second. The desired settling chamber temperature is 100 degrees Fahrenheit.

Figures 9 and 10 show data for simulations of operating conditions 'D' and 'E', respectively. Valve 3292 is not used for these runs due to their low mass flow rate requirements. Point 'D' is characterized by a settling chamber absolute pressure of 130 pounds per square inch, corresponding to a mass flow rate of 40 pounds per second. The desired settling chamber temperature is 200 degrees Fahrenheit. Point 'E' is characterized by a settling chamber absolute pressure of 32 pounds per square inch, corresponding to a mass flow rate of 10 pounds per second. Similarly, the desired settling chamber temperature is 200 degrees Fahrenheit.

The simulation was also used to provide the expected tunnel responses to a 3.5% step change in position of valve V3292 as well as a single autotransformer tap change at operating point 'C'. These test conditions were not provided during any of the actual tunnel tests. Therefore, no comparison to actual tunnel data is provided. Figure 11 shows the simulated settling chamber and mixing tee pressure responses to a 3.5% step change of valve V3292. Figure 12 shows the corresponding simulated air temperature responses. Figure 13 shows the simulated settling chamber and mixing tee air temperature responses to a single tap change. Figure 14 shows the corresponding simulated pressure responses.

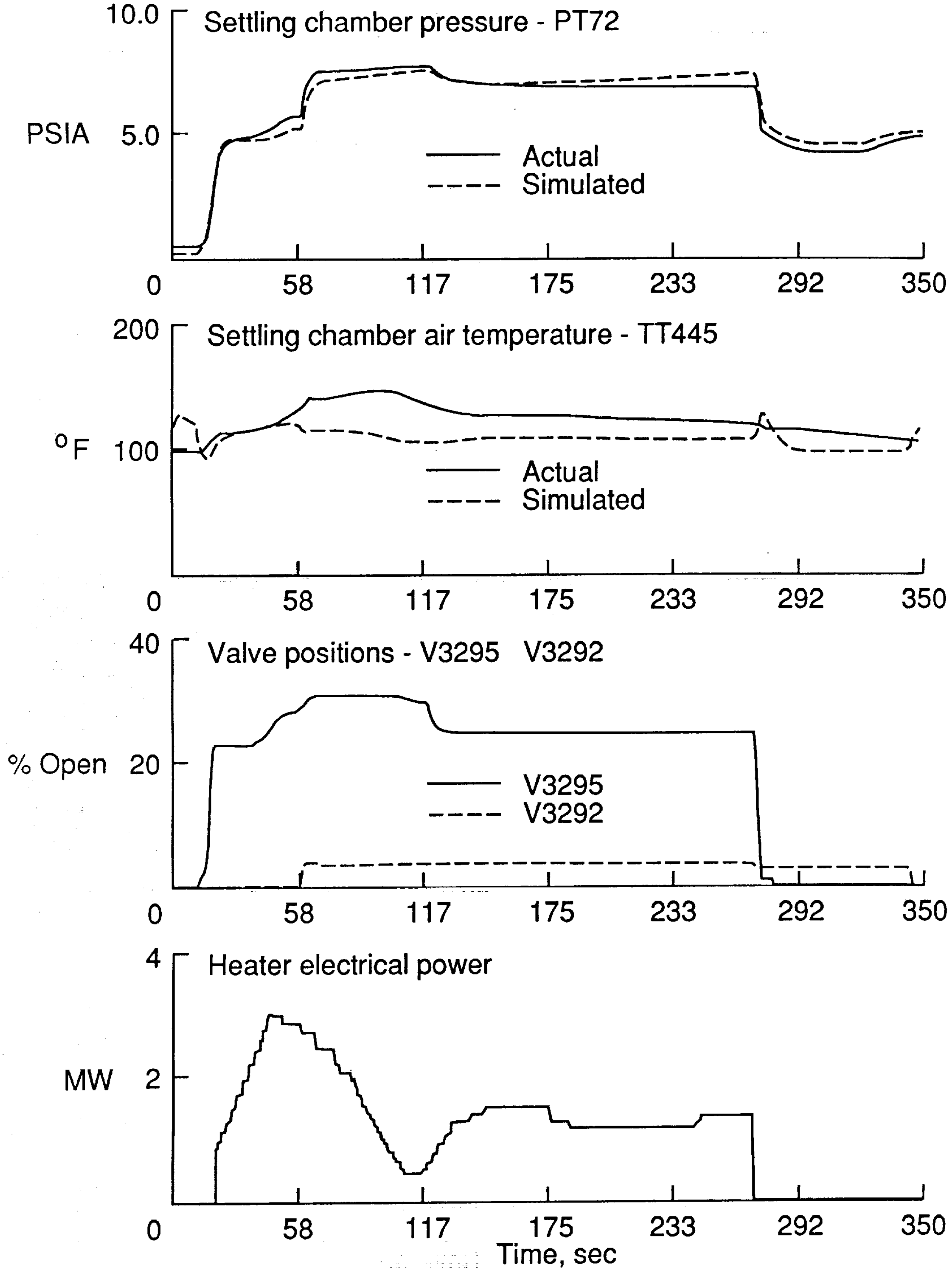


Figure 4. Simulated and Actual Responses - Pt A

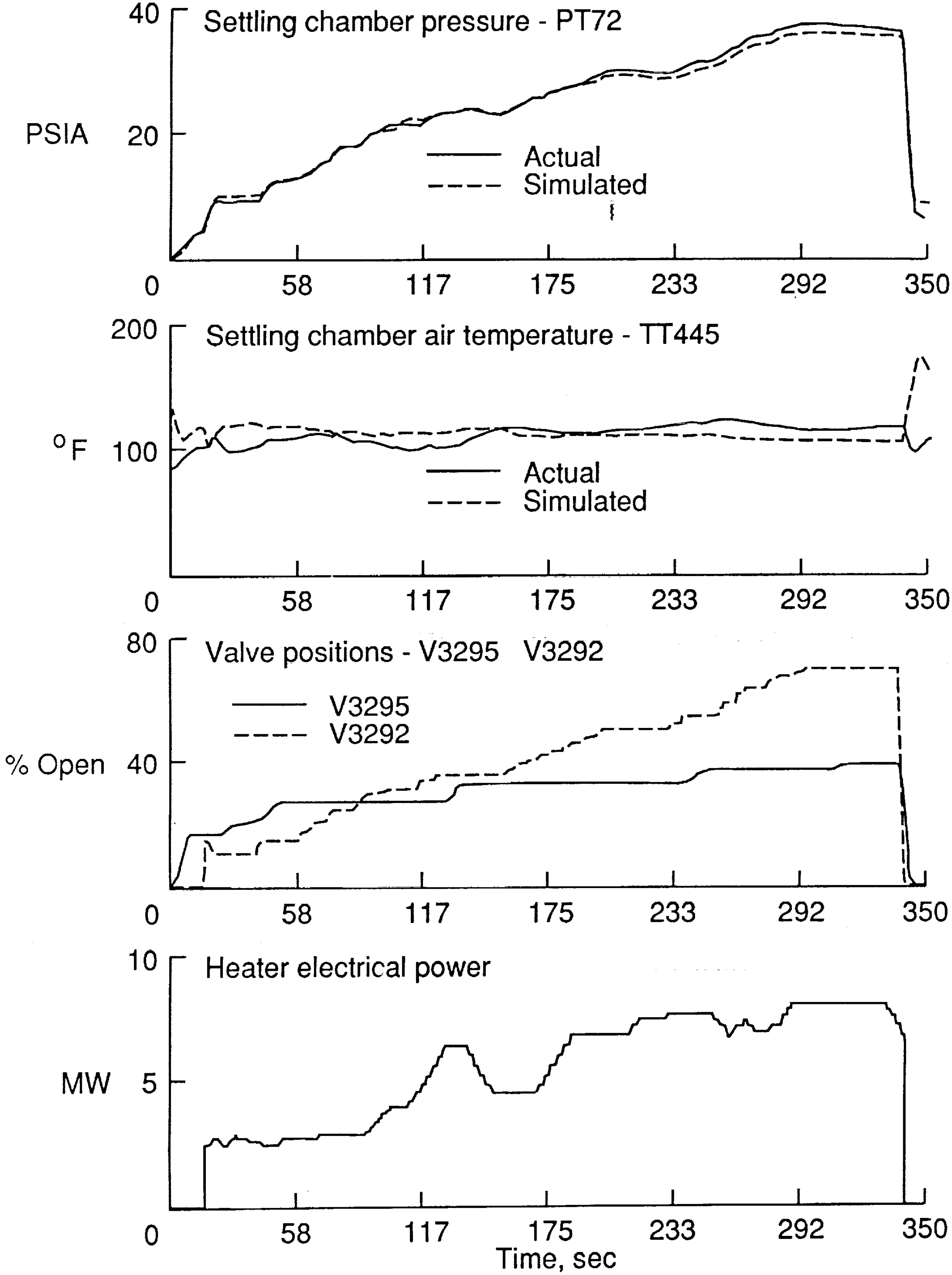
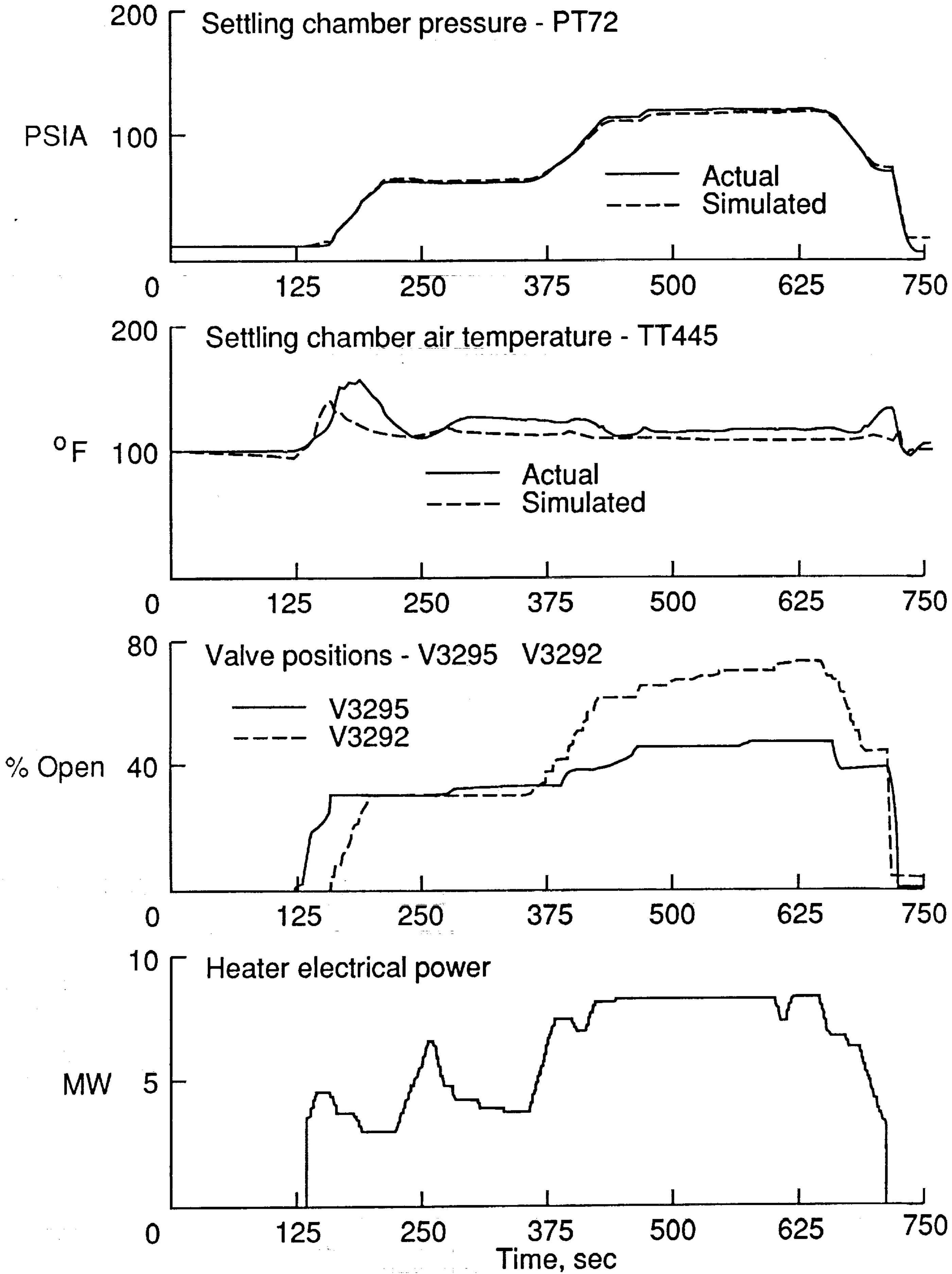


Figure 5. Simulated and Actual Responses - Pt B


Settling chamber pressure - PT72

Settling chamber air temperature - TT445

Valve positions - V3295 V3292

Heater electrical power

Figure 6. Simulated and Actual Responses - Pt C

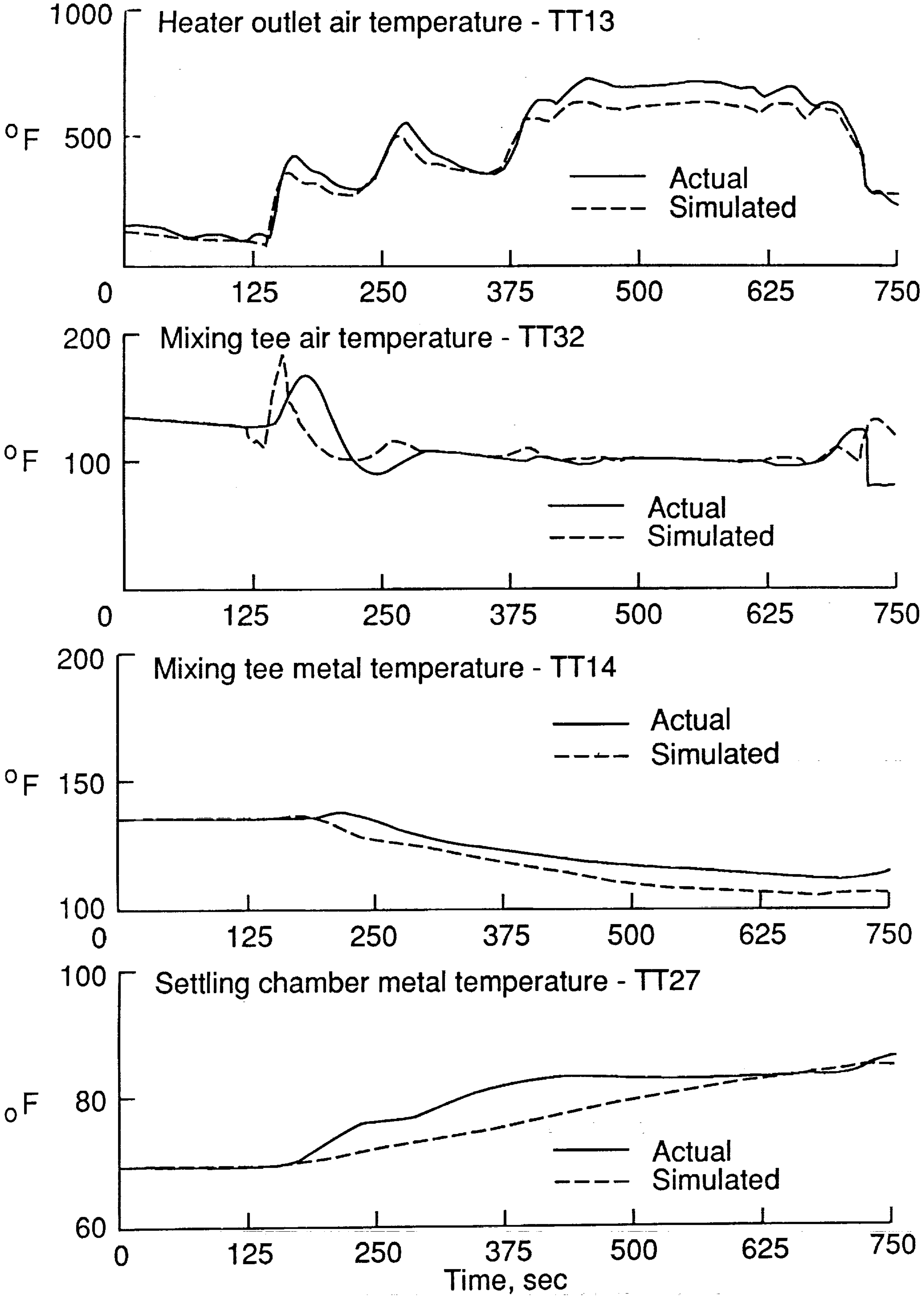


Figure 7. Simulated and Actual Responses - Pt C

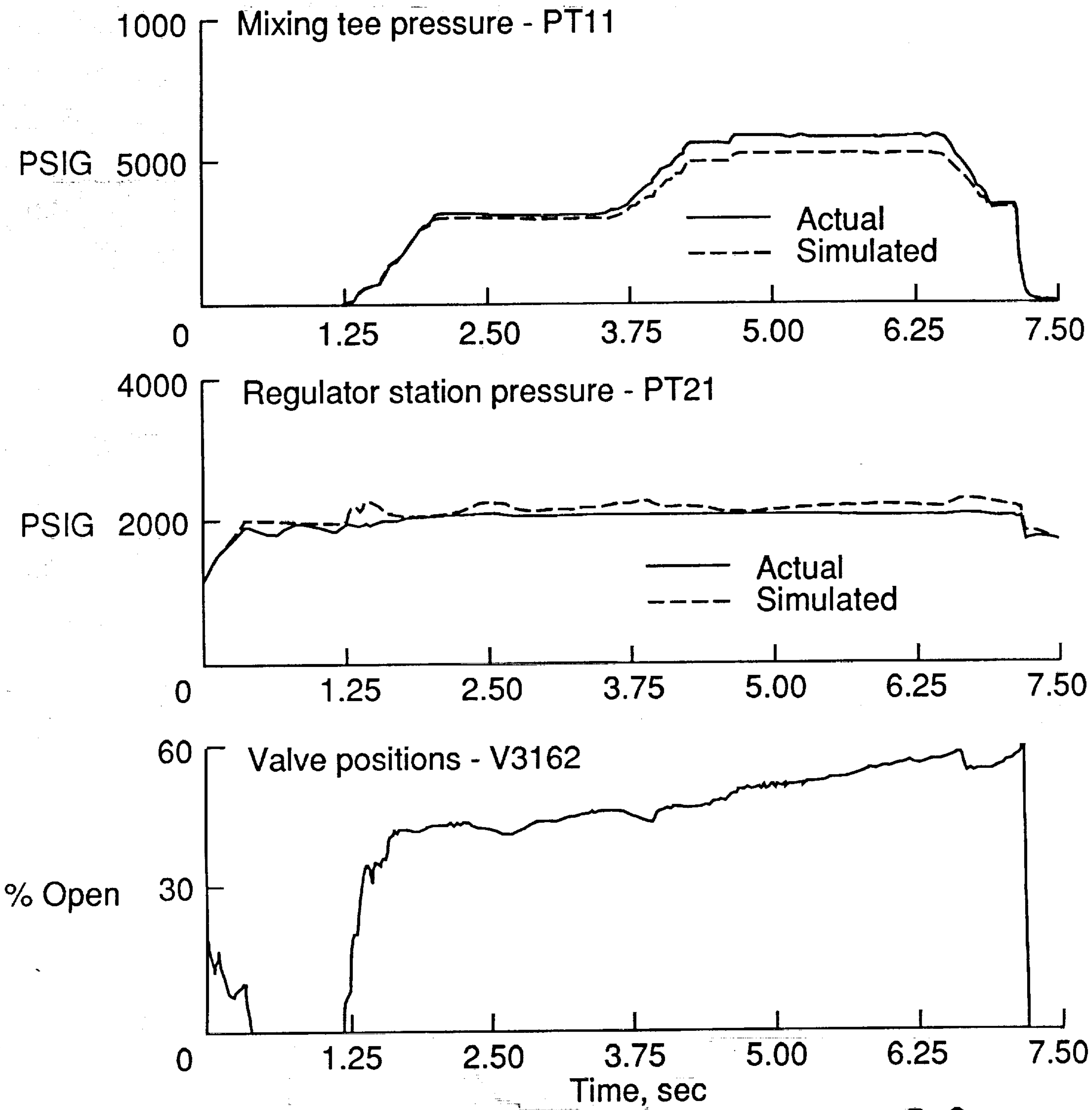


Figure 8. Simulated and Actual Responses - Pt C

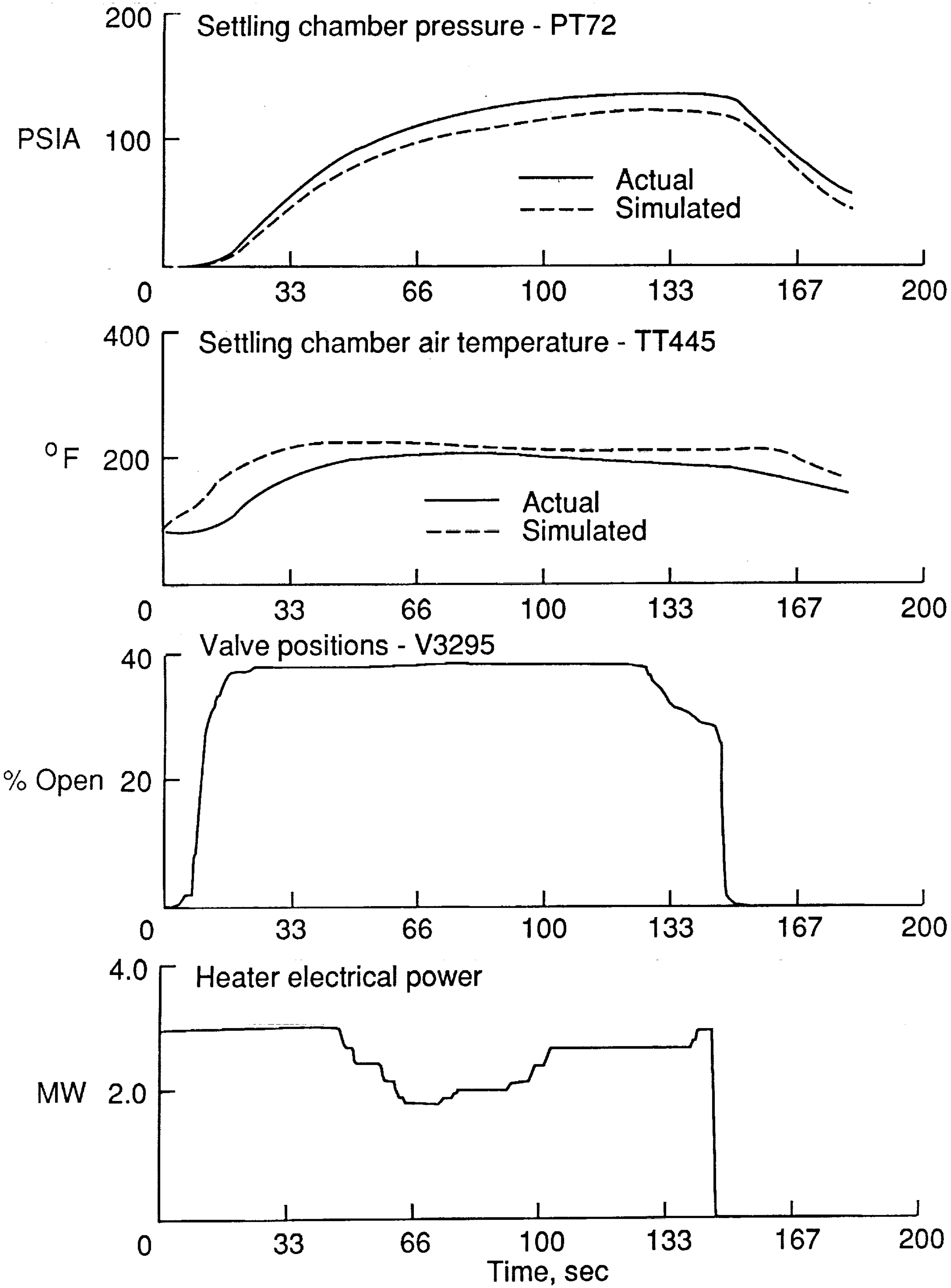


Figure 9. Simulated and Actual Responses - Pt D

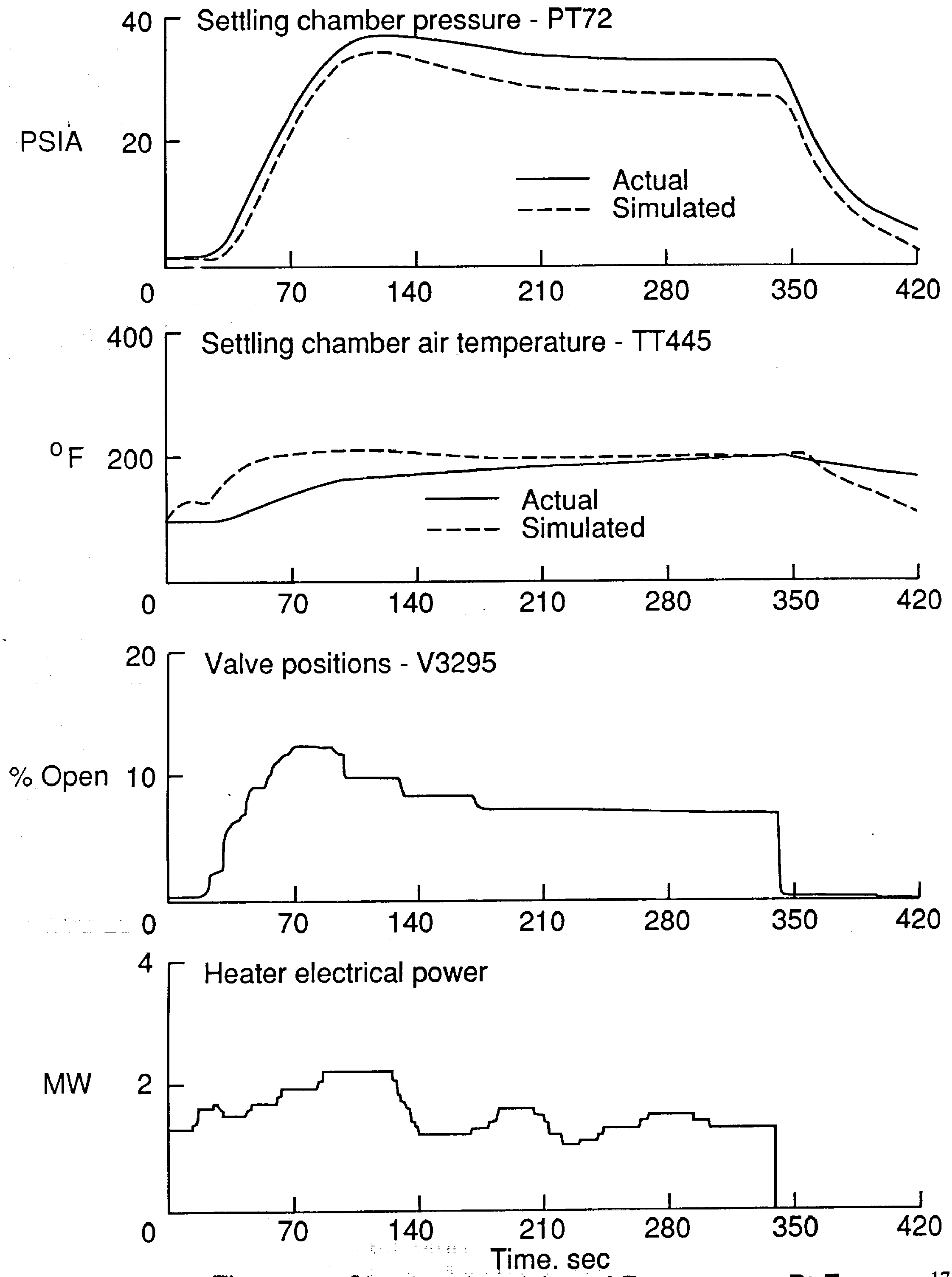


Figure 10. Simulated and Actual Responses - Pt E

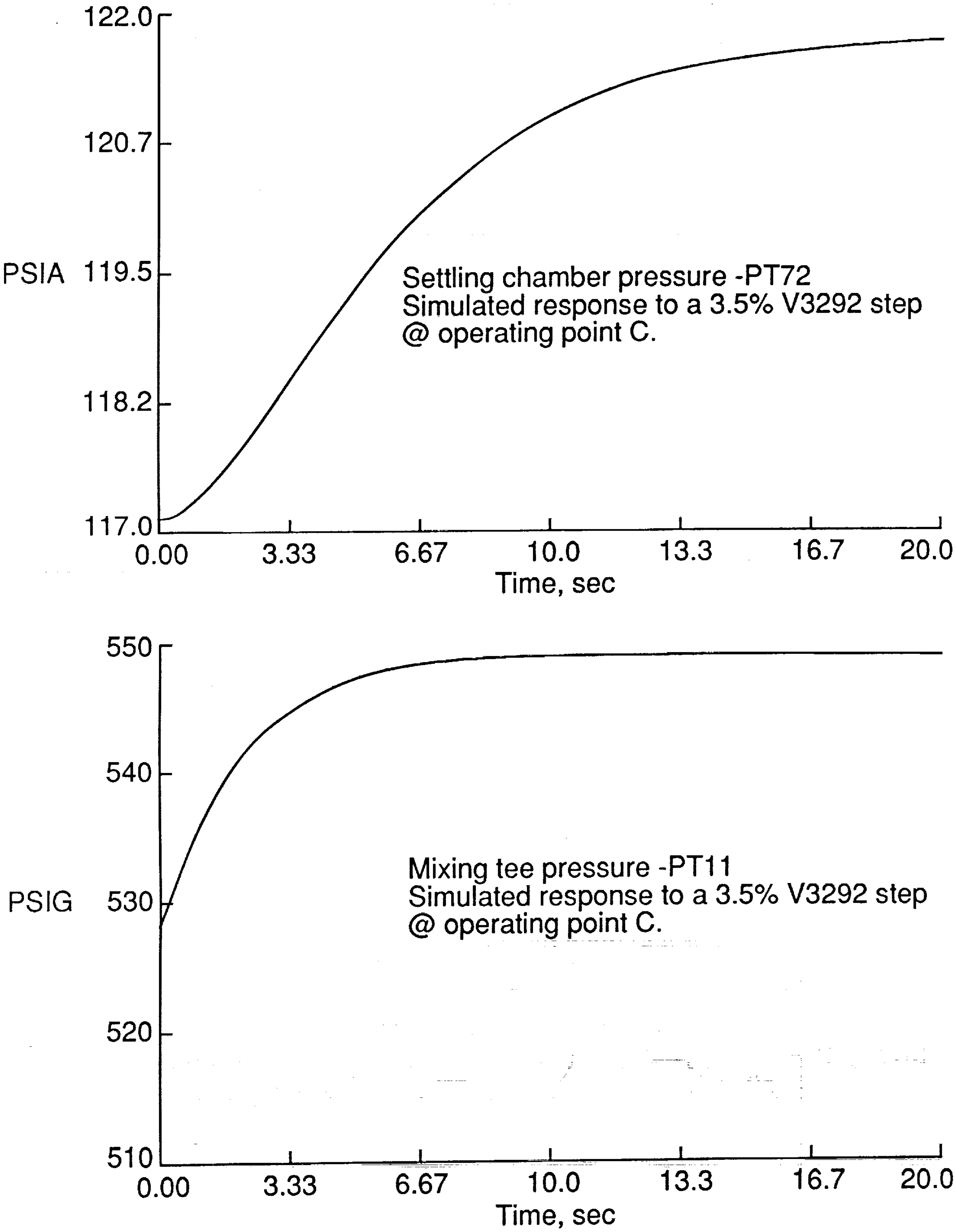


Figure 11. Simulated Pressure Responses - Pt C

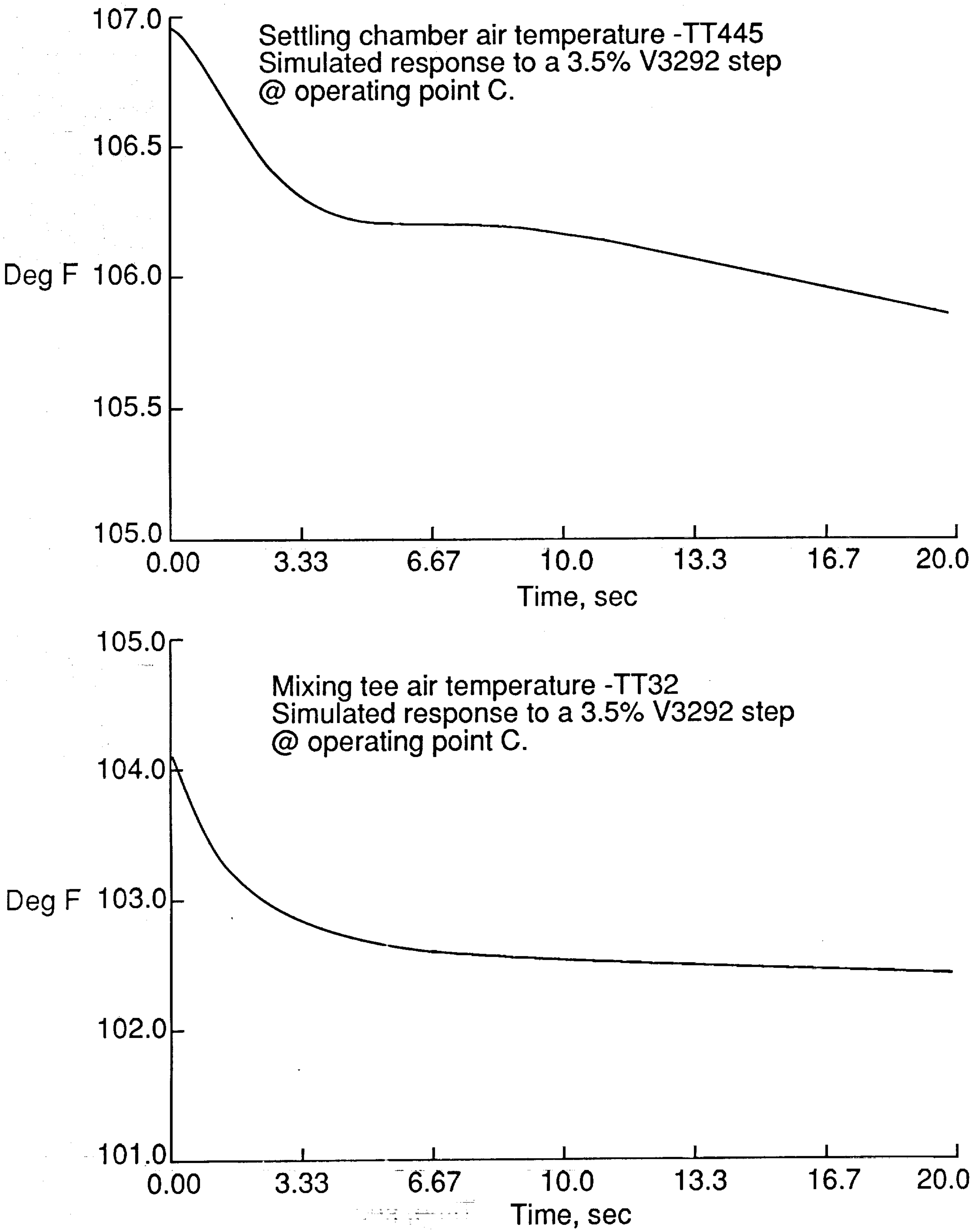


Figure 12. Simulated Temperature Responses - Pt C

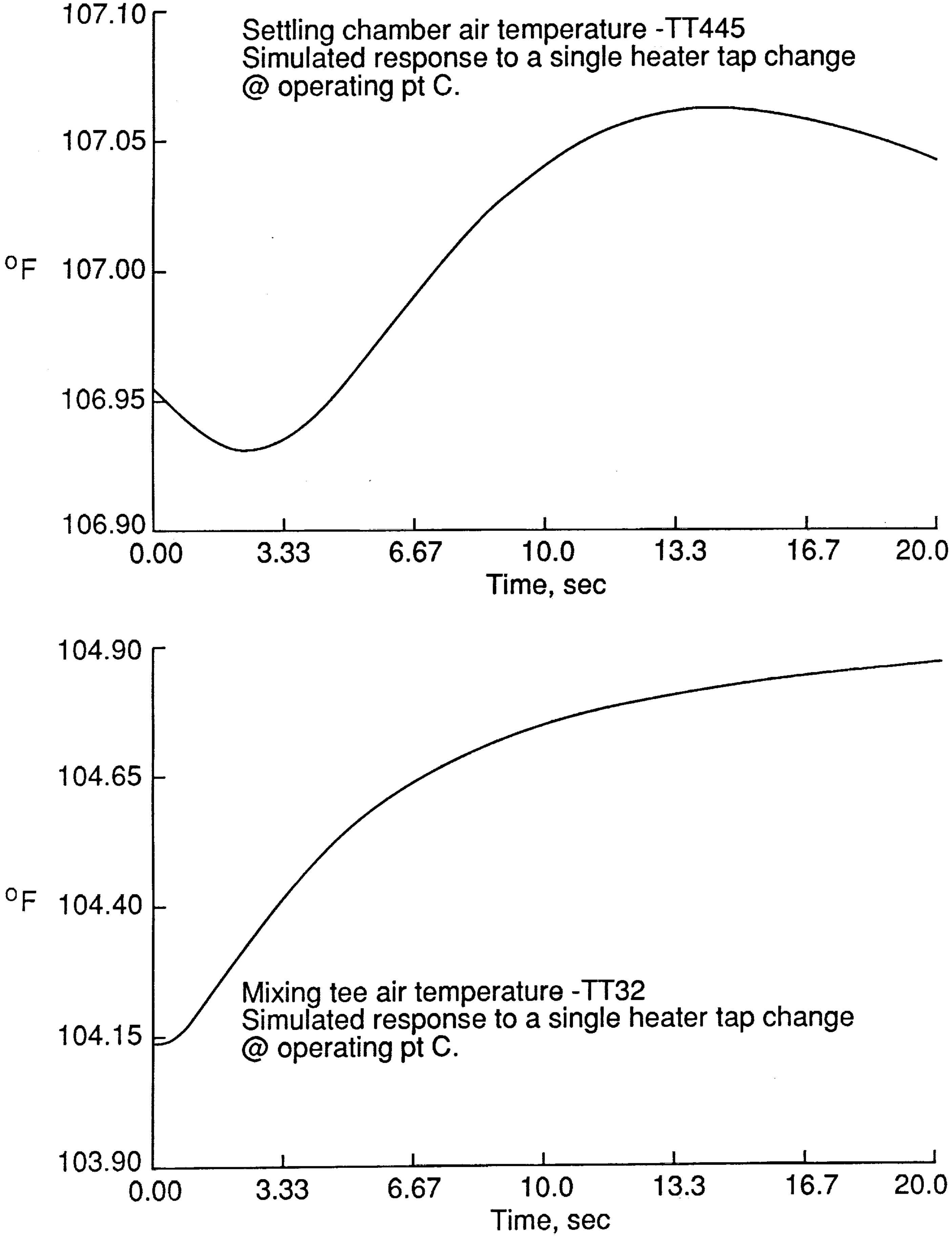


Figure 13. Simulated Temperature Responses - Pt C

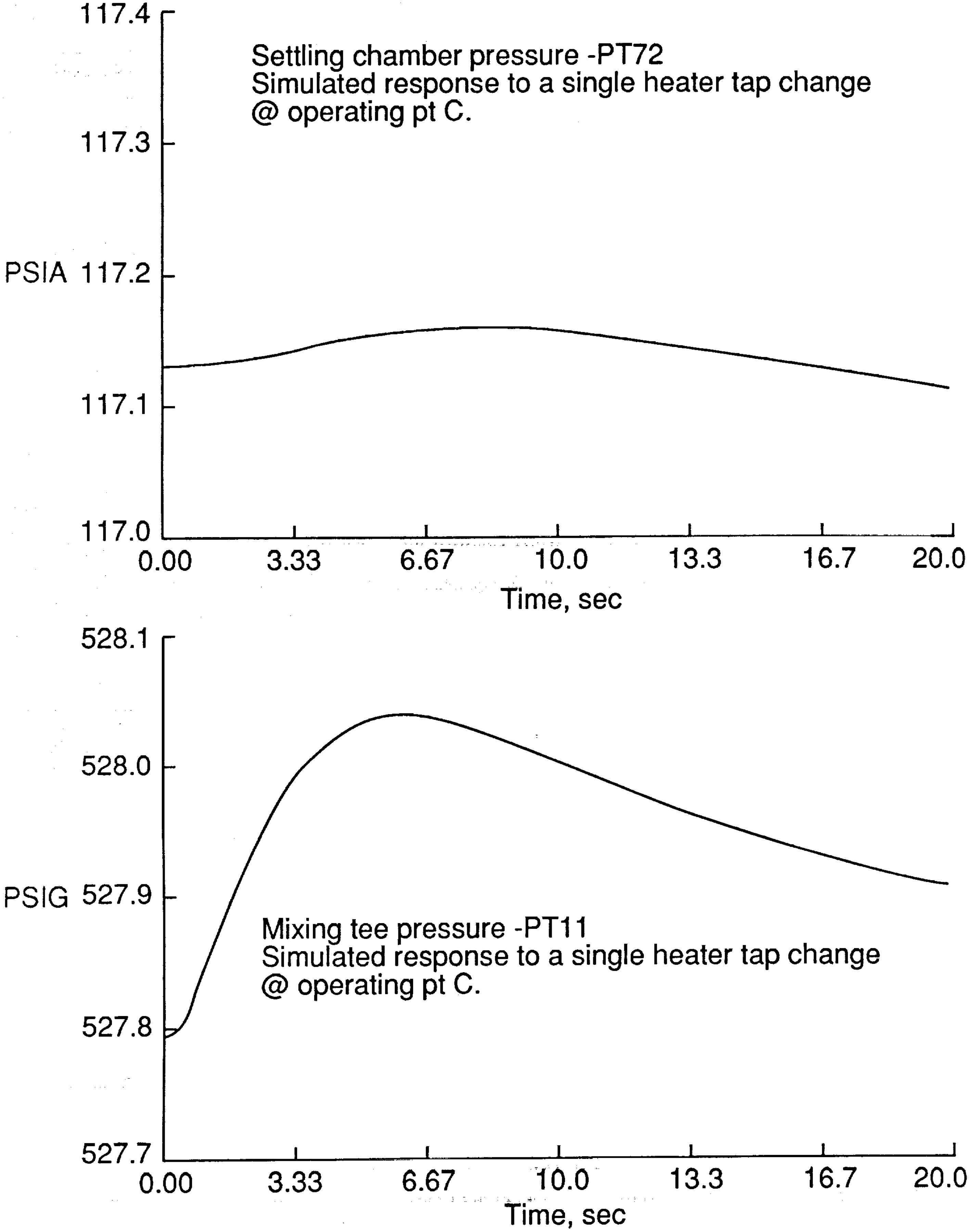


Figure 14. Simulated Pressure Responses - Pt C

Upon reaching steady state at each operating point, a linearized model and associated eigenvalues were evaluated using the ACSL 'ANALYZ' command. The 'FREEZE' command was used to eliminate the following variables from the state vector during the linearization:

BFENRG - Bottlefield Energy
BFMAS - Bottlefield Mass

VSENRG - Vacuum Sphere Energy
VSMAS - Vacuum Sphere Mass

These states were associated with eigenvalues that were either zero or very close to the origin. The input vector was defined by the 'CONTRL' command as:

VP3162 - V3162 Valve Position
VP3170 - V3170 Valve Position
VP3295 - V3295 Valve Position
VP3292 - V3292 Valve Position
HPOWER - M8 Heater Electrical Power

The output vector was defined by the 'OBSERV' command as:

PT21 - Heater Upstream Pressure
PT11 - Mixing Tee Pressure
PT72 - Settling Chamber Pressure
TT13 - Heater Downstream Temperature
TT32 - Mixing Tee Air Temperature
TT445 - Settling Chamber Pressure

Appendix A lists the operating point parameters, the ABC matrices for the linearized model, and the corresponding eigenvalues.

5.0 Conclusion

The development of a simulation of the pressure and temperature responses of the 20 Inch SWT has been presented. The simulation models the temperature and pressure responses based on initial conditions, valve positions, heater input power, and nozzle area. Results of typical simulation runs have been presented, illustrating the correspondence of simulated and actual tunnel responses. Deviations of the simulated temperature transient response from the actual temperature transients are attributed to the lumped-parameter characterization and the assumption of simple convective heat transfer between the air and surrounding vessels and piping. The simulated pressure transient responses follow the actual pressure transients quite well, with relatively small steady-state error.

The simulation has been used to determine a linearized model and corresponding eigenvalues for the five boundary points of the 20 Inch SWT operating map. The simulation contains elements common to other test cells using the Mach 8 Air Distribution System. Similar results for other test cells may be obtained by modification of the code describing the test cell elements.

6.0 References

1. Mitchell and Gauthier Associates: Advanced Continuous Simulation Language, Edition 4.1, Concord, Massachusetts, 1987.
2. Phillips, J.; and Owen-Jones, J. B.: Concise Applied Thermodynamics, D. Van Nostrand Company Ltd, London, 1966.
3. Potter, M. C.; and Foss, J. F.: Fluid Mechanics, Great Lakes Press, Inc., Okemos, Michigan, 1982.
4. Van Wylen, G. J.; and Sonntag, R. E.: Fundamentals of Classical Thermodynamics, Second Edition, John Wiley & Sons, New York, NY, 1978.
5. Fisher Controls: Control Valve Handbook, Fisher Controls International, Inc., Marshalltown, Iowa, 1977.

Appendix A

This appendix contains the numerical data pertinent to the linearized models determined for the five boundary points of the 20 Inch SWT operating map. For each operating point, the A, B, and C matrices a e provided for the linear model:

$$\dot{x} = Ax + Bu;$$

$$y = Cx;$$

where

x - state vector;

u - input vector;

y - output vector.

Table A-1. Model States, Inputs and Outputs

STATE VECTOR	INPUT VECTOR	OUTPUT VECTOR
HDENRG	VP3162	PT21
HDMAS	VP3170	PT11
HDTPIP	VP3295	PT72
HUENRG	VP3292	TT13
HUMAS	HPOWER	TT32
HUTPIP		TT445
MTENRG		
MTMAS		
MTTPIP		
PPENRG		
PPTPIP		
SCENRG		
SCMAS		
SCTPIP		
TCORER		

The eigenvalues corresponding to the respective A matrix for each model are listed in Table A-2.

Operating Point 'A'

Mach	1.4	Valve 3162	46.9 %
Flow	50 #/sec	Heater Upstream	2060 PSIG
Psc	7 PSIA	Valve 3295	24.7 %
Tsc	100 degF	Valve 3292	3.5 %
A*	322.9 in**2	Mixing Tee	99 PSIG
Valve 3296	7.1 in	Heater Power	1.2 MW
Valve 3170	0.0 %		

PT 'A' B MATRIX ELEMENTS - ROWS ACROSS, COLUMNS DOWN

	1	2	3	4	5
1	0.	0.	−2777.0800	0.	0.
2	0.	0.	−79.097700	0.	0.
3	0.	0.	0.	0.	0.
4	732.27800	0.	0.	0.	0.
5	162.37300	0.	0.	0.	0.
6	−0.1050810	0.	0.	0.	0.
7	0.	0.	2189.1500	3344.1400	0.
8	0.	0.	79.097700	305.36700	0.
9	0.	0.	−0.0308547	−0.0771601	0.
10	0.	0.	102.31000	255.89000	0.
11	0.	0.	−0.0127871	−0.0319863	0.
12	0.	0.	0.	0.	0.
13	0.	0.	0.	0.	0.
14	0.	0.	0.	0.	0.
15	0.	0.	0.	0.	16.374600

PT 'A' C MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

	1	2	3	4	5
1	0.	0.	0.	0.1216600	9.5752200
2	0.	0.	0.	0.	0.
3	0.	0.	0.	0.	0.
4	0.0143952	−0.3601020	0.	0.	0.
5	0.	0.	0.	0.	0.
6	0.	0.	0.	0.	0.

	6	7	8	9	10
1	0.	0.	0.	0.	0.
2	0.	0.0114850	0.9023410	0.	0.
3	0.	0.	0.	0.	0.
4	0.	0.	0.	0.	0.
5	0.	0.0608321	−1.0683800	0.	0.
6	0.	0.	0.	0.	0.

	11	12	13	14	15
1	0.	0.	0.	0.	0.
2	0.	0.	0.	0.	0.
3	0.	0.0011533	0.0905492	0.	0.
4	0.	0.	0.	0.	0.
5	0.	0.	0.	0.	0.
6	0.	0.0713649	−1.3018600	0.	0.

PT 'A' A MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

	1	2	3	4	5
1	−39.143500	608.50500	5.5600700	8.8942100	665.12600
2	−0.1251930	−9.8946400	0.	0.2984480	23.580700
3	2.769E-04	0.0087502	−0.0055601	−5.277E-04	−0.0248051
4	0.5475780	41.474900	0.	−2.3625600	−94.493100
5	0.1247360	9.8113400	0.	−0.2991810	−23.639200
6	2.759E-05	0.0028404	0.	2.793E-04	−0.0079257
7	0.0745869	0.2510310	0.	0.	0.
8	4.583E-04	0.0833065	0.	0.	0.
9	−1.871E-07	−3.407E-05	0.	0.	0.
10	6.198E-04	0.1131430	0.	0.	0.
11	−7.750E-08	−1.414E-05	0.	0.	0.
12	0.	0.	0.	0.	0.
13	0.	0.	0.	0.	0.
14	0.	0.	0.	0.	0.
15	0.6589010	−11.500900	0.	−0.1149440	−9.0828800

	6	7	8	9	10
1	0.	0.	0.	0.	0.
2	0.	0.	0.	0.	0.
3	0.	0.	0.	0.	0.
4	24.471200	0.	0.	0.	0.
5	0.	0.	0.	0.	0.
6	−0.0102751	0.	0.	0.	0.
7	0.	−1.3078300	10.507000	14.559600	0.
8	0.	−0.0026625	−0.4644460	0.	0.
9	0.	1.314E-04	−0.0023075	−0.0021715	0.
10	0.	0.7135500	16.943000	0.	−0.8080470
11	0.	0.	−0.0021093	0.	5.616E-05
12	0.	0.0684784	−1.5275100	0.	0.3587340
13	0.	0.0026625	0.4644460	0.	0.
14	0.	4.242E-07	7.377E-05	0.	0.
15	0.	0.	0.	0.	0.

	11	12	13	14	15
1	0.	0.	0.	0.	2452.7100
2	0.	0.	0.	0.	0.
3	0.	0.	0.	0.	0.
4	0.	0.	0.	0.	0.
5	0.	0.	0.	0.	0.
6	0.	0.	0.	0.	0.
7	0.	0.	0.	0.	0.
8	0.	0.	0.	0.	0.
9	0.	0.	0.	0.	0.
10	14.823000	0.	0.	0.	0.
11	−0.0018529	0.	0.	0.	0.
12	0.	−1.3538600	−24.294500	1.2228700	0.
13	0.	−0.0167117	−1.6088100	0.	0.
14	0.	2.202E-05	−4.016E-04	−3.054E-04	0.
15	0.	0.	0.	0.	−42.412400

Operating Point ‘B’

Mach	1.4	Valve 3162	52.5 %
Flow	280 #/sec	Heater Upstream	2220 PSIG
Psc	40 PSIA	Valve 3295	39.1 %
Tsc	100 degF	Valve 3292	69.5 %
A*	322.9 in**2	Mixing Tee	600 PSIG
Valve 3296	7.1 in	Heater Power	8.1 MW
Valve 3170	0.0 %		

PT ‘B’ B MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

	1	2	3	4	5
1	0.	0.	−15804.500	0.	0.
2	0.	0.	−105.82000	0.	0.
3	0.	0.	0.	0.	0.
4	944.45400	0.	0.	0.	0.
5	226.19200	0.	0.	0.	0.
6	−0.1096730	0.	0.	0.	0.
7	0.	0.	8782.7100	2897.7100	0.
8	0.	0.	105.82000	307.84600	0.
9	0.	0.	0.	0.	0.
10	0.	0.	0.	0.	0.
11	0.	0.	0.	0.	0.
12	0.	0.	0.	0.	0.
13	0.	0.	0.	0.	0.
14	0.	0.	0.	0.	0.
15	0.	0.	0.	0.	16.326900

PT ‘B’ C MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

	1	2	3	4	5
1	0.	0.	0.	0.1216520	9.5793400
2	0.	0.	0.	0.	0.
3	0.	0.	0.	0.	0.
4	0.0223339	−2.3813100	0.	0.	0.
5	0.	0.	0.	0.	0.
6	0.	0.	0.	0.	0.

	6	7	8	9	10
1	0.	0.	0.	0.	0.
2	0.	0.0114440	0.9020020	0.	0.
3	0.	0.	0.	0.	0.
4	0.	0.	0.	0.	0.
5	0.	0.0114086	−0 1918390	0.	0.
6	0.	0.	0.	0.	0.

	11	12	13	14	15
1	0.	0.	0.	0.	0.
2	0.	0.	0.	0.	0.
3	0.	0.0011508	0.0905721	0.	0.
4	0.	0.	0.	0.	0.
5	0.	0.	0.	0.	0.
6	0.	0.0180486	−0.3269550	0.	0.

PT ‘B’ A MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

	1	2	3	4	5
1	−59.389200	3650.7200	9.5251800	34.356100	2811.7800
2	−0.1195710	−9.4999500	0.	0.2849060	22.530400
3	−0.0022929	−0.2305860	−0.0095247	0.0063100	0.3826790
4	0.4951250	39.792100	0.	−2.1883000	−86.558300
5	0.1190920	9.3735800	0.	−0.2863780	−22.646000
6	1.623E-05	9.321E-04	0.	2.824E-04	−0.0049001
7	0.1587990	−3.3078700	0.	0.	0.
8	4.794E-04	0.1263830	0.	0.	0.
9	0.	0.	0.	0.	0.
10	0.	0.	0.	0.	0.
11	0.	0.	0.	0.	0.
12	0.	0.	0.	0.	0.
13	0.	0.	0.	0.	0.
14	0.	0.	0.	0.	0.
15	1.0518500	−59.735400	0.	−0.6764980	−53.507000

	6	7	8	9	10
1	0.	0.	0.	0.	0.
2	0.	0.	0.	0.	0.
3	0.	0.	0.	0.	0.
4	28.591500	0.	0.	0.	0.
5	0.	0.	0.	0.	0.
6	−0.0120052	0.	0.	0.	0.
7	0.	−1.1435300	8.3894900	64.298700	0.
8	0.	−0.0026573	−0.4641080	0.	0.
9	0.	9.367E-05	−0.0016851	−0.0082949	0.
10	0.	0.7126540	12.440800	0.	−0.6710530
11	0.	−5.752E-07	−0.0015464	0.	3.936E-05
12	0.	0.0685044	−1.1350300	0.	0.3561730
13	0.	0.0026573	0.4641080	0.	0.
14	0.	0.	3.782E-06	0.	0.
15	0.	0.	0.	0.	0.

	11	12	13	14	15
1	0.	0.	0.	0.	1987.1400
2	0.	0.	0.	0.	0.
3	0.	0.	0.	0.	0.
4	0.	0.	0.	0.	0.
5	0.	0.	0.	0.	1987.1400
6	0.	0.	0.	0.	0.
7	0.	0.	0.	0.	0.
8	0.	0.	0.	0.	0.
9	0.	0.	0.	0.	0.
10	55.552000	0.	0.	0.	0.
11	−0.0069440	0.	0.	0.	0.
12	0.	−1.3179600	3.2130300	4.4906600	0.
13	0.	−0.0041539	−0.7294570	0.	0.
14	0.	2.067E-05	−3.236E-04	−0.0011214	0.
15	0.	0.	0.	0.	−34.361700

Operating Point ‘C’

Mach	2.8	Valve 3162	55.9 %
Flow	280 #/sec	Heater Upstream	2090 PSIG
Psc	130 PSIA	Valve 3295	47.5 %
Tsc	100 degF	Valve 3292	71.4 %
A^*	95.8 in^{**2}	Mixing Tee	575 PSIG
Valve 3296	7.1 in	Heater Power	8.3 MW

PT ‘C’ B MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

	1	2	3	4	5
1	0.	0.	−16769.200	0.	0.
2	0.	0.	−105.74300	0.	0.
3	0.	0.	0.6820260	0.	0.
4	483.04800	0.	0.	0.	0.
5	208.14900	0.	0.	0.	0.
6	−0.0060565	0.	0.	0.	0.
7	0.	0.	9008.0700	2759.5700	0.
8	0.	0.	105.74300	281.29600	0.
9	0.	0.	−0.0059791	−0.0159163	0.
10	0.	0.	98.114000	261.07800	0.
11	0.	0.	−0.0122562	−0.0326335	0.
12	0.	0.	0.	0.	0.
13	0.	0.	0.	0.	0.
14	0.	0.	0.	0.	0.
15	0.	0.	0.	0.	16.403200

PT ‘C’ C MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

	1	2	3	4	5
1	0.	0.	0.	0.1224640	9.5744800
2	0.	0.	0.	0.	0.
3	0.	0.	0.	0.	0.
4	0.0251598	−2.7272300	0.	0.	0.
5	0.	0.	0.	0.	0.
6	0.	0.	0.	0.	0.

	6	7	8	9	10
1	0.	0.	0.	0.	0.
2	0.	0.0114912	0.9021570	0.	0.
3	0.	0.	0.	0.	0.
4	0.	0.	0.	0.	0.
5	0.	0.0120183	−0.2151880	0.	0.
6	0.	0.	0.	0.	0.

	11	12	13	14	15
1	0.	0.	0.	0.	0.
2	0.	0.	0.	0.	0.
3	0.	0.0011524	0.0906312	0.	0.
4	0.	0.	0.	0.	0.
5	0.	0.	0.	0.	0.
6	0.	0.0056342	−0.1034530	0.	0.

PT ‘C’ A MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

	1	2	3	4	5
1	−66.157300	4747.1300	8.7401100	31.864500	2417.3600
2	−0.1020200	−8.1409700	0.	0.2443230	19.210300
3	−1.148E-04	−0.0498852	−0.0087400	2.006E-05	0.0650455
4	0.2338170	18.417900	0.	−1.6362800	−40.308800
5	0.1014430	7.9875000	0.	−0.2459560	−19.340600
6	1.435E-06	1.098E-04	0.	3.281E-04	−8.267E-04
7	0.1950750	−3.9513900	0.	0.	0.
8	5.772E-04	0.1535380	0.	0.	0.
9	−3.255E-08	−8.700E-06	0.	0.	0.
10	5.333E-04	0.1418790	0.	0.	0.
11	−6.657E-08	−1.772E-05	0.	0.	0.
12	0.	0.	0.	0.	0.
13	0.	0.	0.	0.	0.
14	0.	0.	0.	0.	0.
15	1.1351200	−81.383500	0.	−0.5359790	−42.157900

	6	7	8	9	10
1	0.	0.	0.	0.	0.
2	0.	0.	0.	0.	0.
3	0.	0.	0.	0.	0.
4	30.315000	0.	0.	0.	0.
5	0.	0.	0.	0.	0.
6	−0.0127288	0.	0.	0.	0.
7	0.	−1.1710000	8.8387500	62.697100	0.
8	0.	−0.0026619	−0.4644100	0.	0.
9	0.	9.839E-05	−0.0017616	−0.0081914	0.
10	0.	0.7151690	12.227700	0.	−0.6872380
11	0.	0.	−0.0015243	0.	4.096E-05
12	0.	0.0686162	−1.4085900	0.	0.3595510
13	0.	0.0026619	0.4644100	0.	0.
14	0.	2.252E-07	3.904E-05	0.	0.
15	0.	0.	0.	0.	0.

	11	12	13	14	15
1	0.	0.	0.	0.	2092.6200
2	0.	0.	0.	0.	0.
3	0.	0.	0.	0.	0.
4	0.	0.	0.	0.	0.
5	0.	0.	0.	0.	0.
6	0.	0.	0.	0.	0.
7	0.	0.	0.	0.	0.
8	0.	0.	0.	0.	0.
9	0.	0.	0.	0.	0.
10	54.589200	0.	0.	0.	0.
11	−0.0068236	0.	0.	0.	0.
12	0.	−0.3923630	1.0391900	4.3711100	0.
13	0.	−0.0012334	−0.2165930	0.	0.
14	0.	6.202E-06	−1.139E-04	−0.0010916	0.
15	0.	0.	0.	0.	−36.185700

Operating Point ‘D’

Mach	5.0	Valve 3162	41.4 %
Flow	40 #/sec	Heater Upstream	1864 PSIG
Psc	130 PSIA	Valve 3295	30.9 %
Tsc	200 degF	Valve 3292	0.0 %
A*	14.4 in^{**2}	Mixing Tee	610 PSIG
Valve 3296	1.1 in	Heater Power	2.8 MW
Valve 3170	0.0 %		

PT ‘D’ B MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

	1	2	3	4	5
1	0.	0.	−4998.4700	0.	0.
2	0.	0.	−86.307500	0.	0.
3	0.	0.	0.	0.	0.
4	−263.55700	0.	0.	0.	0.
5	190.33400	0.	0.	0.	0.
6	0.	0.	0.	0.	0.
7	0.	0.	4493.7900	0.	0.
8	0.	0.	86.307500	0.	0.
9	0.	0.	0.	0.	0.
10	0.	0.	0.	0.	0.
11	0.	0.	0.	0.	0.
12	0.	0.	0.	0.	0.
13	0.	0.	0.	0.	0.
14	0.	0.	0.	0.	0.
15	0.	0.	0.	0.	16.365100

PT ‘D’ C MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

	1	2	3	4	5
1	0.	0.	0.	0.1221430	9.5816600
2	0.	0.	0.	0.	0.
3	0.	0.	0.	0.	0.
4	0.0220652	−0.9105040	0.	0.	0.
5	0.	0.	0.	0.	0.
6	0.	0.	0.	0.	0.

	6	7	8	9	10
1	0.	0.	0.	0.	0.
2	0.	0.0114606	0.9023500	0.	0.
3	0.	0.	0.	0.	0.
4	0.	0.	0.	0.	0.
5	0.	0.0162818	−0.5899490	0.	0.
6	0.	0.	0.	0.	0.

	11	12	13	14	15
1	0.	0.	0.	0.	0.
2	0.	0.	0.	0.	0.
3	0.	0.0011503	0.0906466	0.	0.
4	0.	0.	0.	0.	0.
5	0.	0.	0.	0.	0.
6	0.	0.0062491	−0.2202930	0.	0.

PT 'D' A MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

	1	2	3	4	5
1	-51.248600	1456.3500	5.8692600	13.305600	1026.0600
2	−0.1080210	−8.5679700	0.	0.2579560	20.339700
3	−2.957E-04	−0.0389259	−0.0058692	0.0010232	0.0806849
4	−0.0747402	−2.3153500	0.	−0.8626810	2.8108300
5	0.1074500	8.4546200	0.	−0.2581310	−20.352000
6	1.128E-04	0.0073820	0.	5.357E-05	−0.0157330
7	0.1030180	1.3139600	0.	0.	0.
8	4.829E-04	0.0960792	0.	0.	0.
9	0.	0.	0.	0.	0.
10	0.	0.	0.	0.	0.
11	0.	0.	0.	0.	0.
12	0.	0.	0.	0.	0.
13	0.	0.	0.	0.	0.
14	0.	0.	0.	0.	0.
15	0.8840600	−24.750600	0.	−0.2347000	−18.509400

	6	7	8	9	10
1	0.	0.	0.	0.	0.
2	0.	0.	0.	0.	0.
3	0.	0.	0.	0.	0.
4	22.268400	0.	0.	0.	0.
5	0.	0.	0.	0.	0.
6	−0.0093502	0.	0.	0.	0.
7	0.	−0.2661280	4.9632400	10.579000	0.
8	0.	−4.150E-04	−0.0804379	0.	0.
9	0.	2.798E-05	−0.0010322	−0.0017270	0.
10	0.	0.1318150	7.3023200	0.	−0.1648080
11	0.	1.307E-07	−9.076E-04	0.	1.223E-05
12	0.	0.0222233	−0.8058670	0.	0.0670078
13	0.	4.150E-04	0.0804379	0.	0.
14	0.	0.	0.	0.	0.
15	0.	0.	0.	0.	0.

	11	12	13	14	15
1	0.	0.	0.	0.	2058.9300
2	0.	0.	0.	0.	0.
3	0.	0.	0.	0.	0.
4	0.	0.	0.	0.	0.
5	0.	0.	0.	0.	0.
6	0.	0.	0.	0.	0.
7	0.	0.	0.	0.	0.
8	0.	0.	0.	0.	0.
9	0.	0.	0.	0.	0.
10	11.972600	0.	0.	0.	0.
11	−0.0014966	0.	0.	0.	0.
12	0.	−0.0704947	0.4812590	1.1187200	0.
13	0.	−1.707E-04	−0.0329318	0.	0.
14	0.	1.855E-06	−4.634E-05	−2.794E-04	0.
15	0.	0.	0.	0.	−35.603100

Operating Point 'E'

Mach	5.0	Valve 3162	24.0 %
Flow	10 #/sec	Heater Upstream	1103 PSIG
Psc	32 PSIA	Valve 3295	10.0 %
Tsc	200 degF	Valve 3292	0.0 %
A*	14.4 in^{**2}	Mixing Tee	147 PSIG
Valve 3296	1.1 in	Heater Power	2.2 MW
Valve 3170	11.9 %		

PT 'E' B MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

	1	2	3	4	5
1	0.	−4023.8500	−5896.3000	0.	0.
2	0.	−41.408500	−60.677500	0.	0.
3	0.	0.	0.	0.	0.
4	110.71000	0.	0.	0.	0.
5	81.076600	0.	0.	0.	0.
6	−0.1744370	0.	0.	0.	0.
7	0.	0.	4293.3400	0.	0.
8	0.	0.	60.677500	0.	0.
9	0.	0.	0.	0.	0.
10	0.	0.	0.	0.	0.
11	0.	0.	0.	0.	0.
12	0.	0.	0.	0.	0.
13	0.	0.	0.	0.	0.
14	0.	0.	0.	0.	0.
15	0.	0.	0.	0.	16.365100

PT 'E' C MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.	0.	0.	0.1218830	9.5785800	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
2	0.	0.	0.	0.	0.	0.	0.0114619	0.9028180	0.	0.	0.	0.	0.	0.	0.
3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.0011530	0.0905970	0.	0.
4	0.0373288	−2.5845200	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
5	0.	0.	0.	0.	0.	0.	0.0560671	−2.3460100	0.	0.	0.	0.	0.	0.	0.
6	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.0225549	−0.8012540	0.	0.

PT 'E' A MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

	1	2	3	4	5
1	−49.114900	1296.4600	4.0050300	34.101300	2672.1700
2	−0.1781320	−14.076000	0.	0.4262190	33.569800
3	−0.0052256	−0.4338660	−0.0040050	0.0128898	1.0152200
4	0.0869982	6.3051200	0.	−1.8584200	−8.9053900
5	0.1778030	14.001300	0.	−0.4262140	−33.569800
6	1.641E-04	0.0131515	0.	2.294E-04	−0.0336915
7	0.0587260	0.2415530	0.	0.	0.
8	2.147E-04	0.0486974	0.	0.	0.
9	0.	0.	0.	0.	0.
10	0.	0.	0.	0.	0.
11	0.	0.	0.	0.	0.
12	0.	0.	0.	0.	0.
13	0.	0.	0.	0.	0.
14	0.	0.	0.	0.	0.
15	0.9284760	−15.528500	0.	−0.7897580	−62.208600

	6	7	8	9	10
1	0.	0.	0.	0.	0.
2	0.	0.	0.	0.	0.
3	0.	0.	0.	0.	0.
4	11.352300	0.	0.	0.	0.
5	0.	0.	0.	0.	0.
6	−0.0047667	0.	0.	0.	0.
7	0.	−0.3288400	7.2087200	4.0953800	0.
8	0.	−4.058E-04	−0.0808637	0.	0.
9	0.	4.204E-05	−0.0015492	−7.270E-04	0.
10	0.	0.1369760	9.2562600	0.	−0.1989430
11	0.	3.097E-07	−0.0011681	0.	1.629E-05
12	0.	0.0203134	−1.1380400	0.	0.0686673
13	0.	4.058E-04	0.0808637	0.	0.
14	0.	2.980E-07	5.935E-05	0.	0.
15	0.	0.	0.	0.	0.

	11	12	13	14	15
1	0.	0.	0.	0.	926.88000
2	0.	0.	0.	0.	0.
3	0.	0.	0.	0.	0.
4	0.	0.	0.	0.	0.
5	0.	0.	0.	0.	0.
6	0.	0.	0.	0.	0.
7	0.	0.	0.	0.	0.
8	0.	0.	0.	0.	0.
9	0.	0.	0.	0.	0.
10	4.6158300	0.	0.	0.	0.
11	−5.770E-04	0.	0.	0.	0.
12	0.	−0.0727939	0.6418340	0.4164470	0.
13	0.	−1.711E-04	−0.0329319	0.	0.
14	0.	2.380E-06	−8.454E-05	−1.040E-04	0.
15	0.	0.	0.	0.	−16.027700

Table A-2 Eigenvalues
PT ‘A’ COMPLEX EIGENVALUES IN ASCENDING ORDER

	REAL
1	−2.7630E-04
2	−6.3167E-04
3	−8.2154E-04
4	−0.00232002
5	−0.00267969
6	−0.07930920
7	−0.15291600
8	−0.49909500
9	−0.80907900
10	−0.83155300
11	−1.11525000
12	−1.27472000
13	−2.13115000
14	−35.1432000
15	−80.9724000

PT ‘B’ COMPLEX EIGENVALUES IN ASCENDING ORDER

	REAL	IMAGINARY	FREQUENCY	DAMPING
1	−0.00104569			
2	−0.00270519			
3	−0.00280500			
4	−0.00366776			
5	−0.00634853			
6	−0.13960600	+/−0.08697920	0.164485	0.848748
8	−0.49894000			
9	−0.67433000			
10	−0.75309400			
11	−1.02034000			
12	−1.11429000			
13	−1.29440000			
14	−33.5545000			
15	−93.2435000			

PT ‘C’ COMPLEX EIGENVALUES IN ASCENDING ORDER

	REAL
1	−0.00101619
2	−0.00261037
3	−0.00355310
4	−0.00363841
5	−0.00461733
6	--0.16323700
7	--0.22422700
8	−0.24605300
9	−0.38480500
10	−0.49969000
11	−0.69050900
12	−1.09308000
13	−1.14130000
14	−31.0387000
15	−98.9331000

PT ‘D’ COMPLEX EIGEN VALUES IN ASCENDING ORDER

	REAL
1	−2.4714E-04
2	−5.1650E-04
3	−6.0521E-04
4	−0.00248492
5	−0.00393938
6	−0.03526640
7	−0.06819240
8	−0.08323000
9	−0.09235360
10	−0.16569900
11	−0.16647600
12	−0.25542300
13	−0.92102400
14	−29.4508000
15	−86.0216000

OPERATING POINT 'E' COMPLEX EIGENVALUES IN ASCENDING ORDER

	REAL
1	−8.8553E-05
2	−1.6777E-04
3	−1.9877E-04
4	−4.8855E-04
5	−0.00185111
6	−0.03591100
7	−0.05460000
8	−0.06983020
9	−0.09330200
10	−0.10376900
11	−0.19932200
12	−0.31696100
13	−1.71268000
14	−36.3505000
15	−76.4317000

APPENDIX B
Simulation Source Code Listing

```
Program 20IN
Initial
Macro QNRG(X,TGdegR,TMdegR,FLO)
   ' This macro calculates the rate of heat energy transfered out '
   ' of a volume to the surrounding pipe mass'
       X_TFLM  = (TGdegR + TMdegR) * 0.5
       X_CPG = .23777 - 4.75178E-8 * TGdegR
       X_MUG = .00692 + 7.78859E-5 * TGdegR
       X_KG  = .00075 + 2.91114E-5 * TGdegR
       X_MUF = .00692 + 7.78859E-5 * X_TFLM
       X_PR  = X_CPG * X_MUG/X_KG
       X_FLOW  = ABS(FLO)
       X_RE  = XK2/X_DIA * X_FLOW/X_MUF * TGdegR/X_TFLM
       X_U   = XK1/X_DIA * X_KG * X_PR**TEXP * X_RE**QEXP
       X_QNRG  = X_U * X_AREA * (TGdegR-TMdegR)
Macro end
Macro M8HETR(X,TGdegR,TMdegR,FLO)
' This macro calculates the rate of heat energy delivered'
'by the M8 Heater'
       X_TFLM  = (TGdegR + TMdegR) * 0.5
       X_CPG = .23777 - 4.75178E-8 * TGdegR
       X_MUG = .00692 + 7.78859E-5 * TGdegR
       X_KG = .00075 + 2.91114E-5 * TGdegR
       X_MUF = .00692 + 7.78859E-5 * X_TFLM
       X_PR  = X_CPG * X_MUG/X_KG
       X_FLOW  = ABS(FLO)
       X_RE  = XK2/X_DIA * 0.00463 * X_FLOW/X_MUF * TGdegR/X_TFLM
       X_U   = XK1/X_DIA * 216.0 * * X_KG * X_PR**TEXP * X_RE**QEXP
       X_DELT  = (TGdegR-TMdegR)
       X_QNRG  = X_U * X_AREA * (TGdegR-TMdegR)
Macro end
                '************External Data Reading Capability****************'
Logical REXDAT
Constant REXDAT=.FALSE.
'Set REXDAT to .TRUE. to read external data'
'Variables from the gaslab logging file'
ARRAY EXDATA(31)
EQUIVALENCE (EXDATA(1),TIMEX),(EXDATA(2),PT33X),...
            (EXDATA(3),PT21X),...
            (EXDATA(4),PT42X),(EXDATA(5),PT45X),...
            (EXDATA(6),PT11X),...
            (EXDATA(7),PT66X),(EXDATA(8),PT72X),...
            (EXDATA(9),PT73X),...
            (EXDATA(10),PT38X),(EXDATA(11),PT82X),...
            (EXDATA(12),TT13X),...
```

```
          (EXDATA(13),TT14X),(EXDATA(14),TT24X),...
          (EXDATA(15),TT25X),...
          (EXDATA(16),TT26X),(EXDATA(17),TT27X),...
          (EXDATA(18),TT29X),...
          (EXDATA(19),TT32X),(EXDATA(20),TT33X),...
          (EXDATA(21),TT43X),...
          (EXDATA(22),TT445X),(EXDATA(23),VP162X),...
          (EXDATA(24),VP170X),...
          (EXDATA(25),VP295X),(EXDATA(26),VP292X),...
          (EXDATA(27),WA2X),...
          (EXDATA(28),WA3X),(EXDATA(29),PD3X),...
          (EXDATA(30),ULTCPX),...
          (EXDATA(31),HPOWRX)
constant exdata=31*0.
'File ID number'
INTEGER RFILE
CONSTANT RFILE=20

LOGICAL DATFLG
CONSTANT DATFLG = .TRUE.

IF(.NOT.REXDAT)GO TO RDEND
'OPEN EXTERNAL DATA FILE'
call Ofile

CALL RDATA(RFILE,DATFLG,EXDATA)

    vp3162 = 0.01*VP162X
    vp3170 = 0.01*VP170X
    vp3295 = 0.01*VP295X
    vp3292 = 0.01*VP292X

    BFPRic = pt33x + Patm $'pt33x in psig, BFPric in psia'
    HUPRic = pt21x + Patm $'pt21x in psig, HUPric in psia'
    HDPRic = pt21x - PD3x $'Delta p across heater'
    MTPRic = pt11x + Patm $'pt11x in psig, MTPRic in psia'
    SCPRic = pt72x        $'pt72x in psia, SCPRic in psia'
    VSPRic = PT73x* (0.0193368) $'Convert from mmHg to PSiA'

    HUdRic = TT26x + FtoR $'Heater inlet temperature in degR'

    HUTPic = HUdRic       $'Metal temp assumed in equilibrium'

    HDdRic = TT13x + FtoR $'Heater outlet temperature in degR'
    HDTPic = HDdRic       $'Metal temp assumed in equilibrium'
    TCORic = HDdRic       $'Heater core temp also in equilib'

    MTdRic = TT32x + FtoR $'Mixing Tee air temp in degR'
    MTdrix = MTdric
    MTTPic = TT14x + FtoR $'Mixing Tee metal temp in degR'
    PPTpic = MTTPic       $' Piping volume metal temp'

    SCdRic = TT445x + FtoR $'Settling chamber air temp'
```

```
      SCdaic = SCdRic

      SCTPic =  TT27x  + FtoR  $'Settling chamber metal temp'
      ULTAP = ULTCPX

      SCHEDULE NWDATA .AT. TIMEX
RDEND..CONTINUE

                   '********** General Constants for Air ***************'
Constant CVair = 0.171 $'CV for air in [BTU/(LBM R)]'
Constant CPair = 0.240 $'CP for air in [BTU/(LBM R)]'
Constant R     = 53.36 $'R  for air in [ft-lbf/(LBM R)]'
Constant FtoR  = 460.  $'Conversion from degF to degR'
Constant Gamma = 1.4   $'CPair/CVair'
Constant JTC   = 0.021 $'Joule-Thompson coefficient'
Constant Tref  = 460.  $'Reference Temperature'

Alpha = 2.0/Gamma              $ '1.4286'
Beta  = (Gamma+1.)/Gamma              $ '1.7143'
Prcrit  = (2.0/(Gamma+1.0))**(Gamma/(Gamma-1.0)) $ '0.5283'
Maxang = asin(1.0)       $'Fisher valve equation constant'
Constant Patm   = 14.7       $'Atmospheric Pressure'
Constant ATdegF  = 65.      $'Ambient Temperature degF'
ATdegR  = ATdegF + FtoR   $'Ambient Temperature degR'

'*********** Constants for Heat Transfer calculations  *********'
Constant XK1 = 7.666E-5, XK2 = 55004.0  $'Combined constants'
Constant TEXP = 0.4, QEXP = 0.8         $'Reynolds & Prandtl expnts'

'********************* Misc variables  *************************'
constant Tend = 0.
INTEGER LSW

'******** Calculate initial conditions  ******************'
'***   Bottlefield  IC  ***'
Logical BFv1,BFv2
BFdegR = 45 + FtoR    $'Initial Temperature'
BFdRic = BFdegR
BFmic = (BFPRic*BFvol*144)/(R*BFdegR) $'Initial mass'
BFenic = BFmic*CVair*(BFdegR-Tref)    $'Initial energy'

'*** Upstream Heater volume IC  ***'
HUmic = (HUPRic*HUvol*144)/(R*HUdRic) $'Initial mass'
HUenic = CVair*(HUdRic-Tref)*HUmic$'Initial energy'

'*** Downstream Heater volume IC  ***'
HDmic = (HDpric*HDvol*144)/(R*HDdRic)    $'Initial mass'
HDenic = CVair*(HDdRic-Tref)*HDmic        $'Initial energy'

'***  Mixing Tee volume IC  ***'
MTmic = (MTPRic*MTvol*144)/(R*MTdRic)    $'Initial mass'
MTdegR = MTdRic
MTenic = MTmic*CVair*(MTdRic-Tref)       $'Initial energy'
```

```
'***  Piping volume IC  ***'
PPdegR = MTdRic
PPenic = 2*MTmic*CVair*(MTdRic-Tref)   $'Initial energy'

'***  Settling chamber volume IC  ***'
SCmic = (SCPRic*SCvol*144)/(R*SCdRic)   $'Initial mass'
SCenic = SCmic*CVair*(SCdRic-Tref)      $'Initial energy'

'*** Vacuum sphere volume IC  ***'
Logical Atmos                          $'Discharge to atmosphere'
VSdegR = ATdegR                        $'Initial Temperature'
VSmic = (VSpric*VSvol*144)/(R*VSdegR)   $'Initial mass'
VSenic = VSmic*CVair*(VSdegR-Tref)      $'Initial energy'

End $ ' of Initial '

Dynamic
       Cinterval Cint = 0.5
       Constant  Tstp = 100.

       IF(.NOT.DATFLG)TSTP=T
       Tplot = T - Tend
       Termt(T .ge. Tstp)
Derivative
       Algorithm Ialg = 4
       Nsteps   Nstp = 1
Maxterval Maxt = .01
       Minterval Mint = 1.0E-08

'*****************   4.2K PSI Bottlefield   *************'
Constant BFvol  = 19000.   $'Volume in ft**3'
Constant BFarea=76000. $'Surface area in ft**2'
Constant BFcmwm=549312.$ 'Specific heat*thermal mass'
Constant BFdia=12. $'Diameter in inches'
Constant BFv1 = .true.
Constant BFv2 = .true.

'*************  Bottlefield Calculations  ****************'
       'Calculate Outflow = flow thru V3162 and V3292'
         BFmdot = -(F3162 + WA3)
       'Integrate BFmdot'
         BFmas = Modint(BFmdot,BFmic,BFv1,BFv2)
       'Calculate Energy '
       'Heat Transfer through the Bottlefield Mass not included'
         BFendt = -CPair*(F3162*(TH3162-Tref) + WA3*(TH3292-Tref))
       BFenrg = Modint(BFendt,0.,BFv1,BFv2) $'Integrate BFendt'
       'Temperature'
         BFdegR = BFenrg/(Cvair*BFmas) + BFdRic
         BFdegF = BFdegR - FtoR
       'Calculate Pressure'
         BFPres = BFmas*R*BFdegR/(BFvol*144.) $'Ideal gas'
         PT33   = BFPres - Patm $'PT33 in psig"
```

```
'*********************  Valve 3162  *************************'
'Constant Cg3162 = 1190.0'      $'Valve Cg'
'Table look-up for v3162 Cg based on valve data p. 1-18'
'of the Fisher catalog - includes minimum flow characteristic'
'based on 8% equivalent opening from 0.5% to 8% opening'
Table CGF162, 1, 14...
    /0.0,0.005,0.0051,0.08,0.1,0.2,0.3,0.4,0.5,...
      0.6,0.7,0.8,0.9,1.0,...
    0.0,0.0,65.,65.,81.8,137.,230.,376.,599.,928.,...
      1340.,1740.,2170.,2350./

Constant SF3162  =    1.0       $'Valve 3162 Cg scaling factor'
Constant C13162 =   31.6        $'Valve C1'
Constant w3162  = 0.667         $'Omega for valve linear response'
Constant R8v162 = .10           $'Maximum valve rate in (% x100)/sec'
Constant CMD162 = 0.            $'Valve position command'
Constant V162IC = 0.            $'Valve position IC'

'**************  V3162 Calculations  ***********************'
      'Valve Position'
       'Err162 = w3162*(CMD162 - VP3162)'
       'V162DT = Bound(-R8v162,R8v162,Err162)'
       'VP3162 = Integ(V162DT,v162IC)'

      'Determine flow direction'
      DP3162 = BFPres - HUPres $'(BF - Hu) pressure drop'
       SGN162 = LSW(DP3162 .GE. 0.,1,-1)
      PH3162 = RSW(DP3162 .GE. 0.,BFPres,HUPres)
       PL3162 = RSW(DP3162 .GE. 0.,HUPres,BFPres)
      TH3162 = RSW(DP3162 .GE. 0.,BFdegR,HUdegR)

      'Fisher Valve calculation'
       PF3162 = 1.0 - PL3162/PH3162
      ANG162 = AMIN1(Maxang,(59.54/C13162*SQRT(PF3162) ) )
      CG3162 = CGF162(VP3162)*SIN(ANG162)*SGN162*SF3162
      F3162  = 4.84e-04 * CG3162 * PH3162/SQRT(TH3162)

'************  Upstream Heater volume  ************'
Constant HUvol  =   17.8        $'Volume in ft**3'
'Constant HUPRic =   14.7'      $'Initial pressure in psia'

Constant HUarea=  325.          $'Surface area in ft**2'
Constant HUcmwm = 2381.6        $'Specific Heat .117 vs. .241'

Constant HUdia=     5.  $'Diameter in inches'

'**************  Upstream Heater Calculations  *******************'

      'Calculate mdot = (flow from 3162) - flow thru Heater orifice'
        HUmdot = F3162 - FHEATR
      'Integrate HUmdot'
        HUmas = Integ(HUmdot,HUmic)
```

```
       'Calculate Energy '

       'Invoke Heat transfer macro'
         'Macro QNRG(X,TGdegR,TMdegR,INFLO)'
       QNRG('HU',HUdegR,HUTpip,amax1(F3162,FHEATR))

       DT3162 = JTC*(BFpres - HUPres)
          HUendt = CPair*(F3162*(TH3162-DT3162-Tref) -...
                FHEATR*(THHETR-Tref))...
            - HUQNRG

       'Integrate HUendt'
         HUenrg = Integ(HUendt,HUenic)

       'AIR Temperature'
         HUdegR = HUenrg/(Cvair*HUmas) + Tref
         TT26   = HUdegR - FtoR

       'Pipe Temperature'
         HUTpip = Integ(HUQNRG/HUcmwm,HUTPic)
         HUpipF = HUTpip - FtoR

       'Calculate Pressure'
         HUPres = HUmas*R*HUdegR/(HUvol*144.) $'Ideal gas'
         PT21 = HUPres - Patm $'PT21 in psig'

'******************  Heater Flow  ************************'
Constant CfHETR = 42.319

'********  Heater Flow Calculations  ********************'
       'Determine flow Direction'
         DPHETR = HUPres - HDpres $'(HU - HD) pressure drop'
          SGNHTR = LSW(DPHETR .GE. 0.,1,-1)
         PHHETR = RSW(DPHETR .GE. 0.,HUPres,HDpres)
          PLHETR = RSW(DPHETR .GE. 0.,HDpres,HUPres)
         THHETR = RSW(DPHETR .GE. 0.,HUdegR,HDdegR)

         FLOWSQ = CfHETR * PHHETR * (PHHETR-PLHETR)/THHETR
          FHEATR = SQRT(FLOWSQ)*SGNHTR

' *********  Downstream Heater Volume  **********'
Constant HDvol   =   42.6        $'Volume in ft**3'
'Constant HDpric =   14.7'       $'Initial pressure in psia'

'Constant HDarea =  148.4'       $'Surface area in ft**2'
Constant HDarea  = 100.          $'Effective surface area'

'Constant HDcmwm = 3676.4' $'Specific heat*thermal mass'
'Constant HDcmwm = 1784.8'
Constant HDcmwm  = 1000.

Constant HDdia   =    6.  $'Diameter in inches'
```

```
'************** Downstream Heater Calculations ******************'

       'Calculate mdot = (flow thru heater) - flow thru 3295 and 3170'
         HDmdot = FHEATR - (F3295 + F3170)
       'Integrate HDmdot'
         HDmas = Integ(HDmdot,HDmic)
       'Calculate Energy '
         'Invoke Heat transfer macro'
         'Macro QNRG(X,TGdegR,TMdegR,FLO)'

       QNRG('HD',HDdegR,HDTpip,amax1(FHEATR,F3295,F3170))

           HDendt = CPair*(FHEATR*(THHETR-Tref)-...
              F3295*(TH3295-Tref)...
              -F3170*(TH3170-Tref))...
              - HDQNRG - M8QNRG

         HDenrg = Integ(HDendt,HDenic) $'Integrate HDendt'

       'Air Temperature'

         HDdegR = HDenrg/(Cvair*HDmas) + Tref
         TT13 = HDdegR - FtoR

       'Pipe Temperature'

         HDTpip = Integ(HDQNRG/HDcmwm,HDTPic)
         HDpipF = HDTpip - FtoR

       'Calculate Pressure'
         HDpres = HDmas*R*HDdegR/(HDvol*144.) $'Ideal gas'

'********************** M8 Heater ******************************'
       Constant M8vol  =    0.71        $'Volume in ft**3'

       Constant M8area =    342.9       $'Surface area in ft**2'
       Constant M8cmwm =    57.83       $'Specific heat*thermal mass'
         'CPMTL * WEMCOR'
       Constant M8dia  =     0.3675     $'Diameter in inches'
       Constant RK0    =     0.3711     $'Fixed heater resistance term'
       Constant RK1    =     2.0E-05    $'Temperature dependent resistance'
       Constant MW2BTU =     947.244    $'Conversion from MW to BTU/sec'

       'Tap changer voltages'
       ARRAY NLT1(3)
       CONSTANT NLT1   =     164.0, 880.0, 1596.0
       CONSTANT VPTAP  =     24.0
   Constant INLT = 1                     $'No-load tap position'
   Constant KHTR=1,UZ1=0.

             'Invoke M8 Heat Transfer Macro'
             'Macro M8HETR(X,TGdegR,TMdegR,FLO)'
             M8HETR('M8',HDdegR,TCOREr,FHEATR)
```

```
          'Compute input power to heater'
        NLTAP = NLT1(INLT)
        VTAP = NLTAP + ULTAP * VPTAP
          RHTR = RK0 + (TCOREr - 615.0) * RK1
        HPOWRi  = RSW(HPOWRX .GT. 0.1,...
                   (VTAP * VTAP / RHTR * 1.18)*1e-06,0.)

        HPOWER = KHTR*HPOWRi + UZ1

        'Power in MW converted to BTUS'
        QELECT  = HPOWER * MW2BTU

        'M8 Heater Core Temperature in degR'
        TCOREr =  Integ((M8QNRG+QELECT)/M8cmwm,TCORic)
        TCOREf = TCOREr - FtoR

"*********************  Valve 3170  ***************************'
'Constant Cg3170  = 1050.0' $'Valve Cg'
'Table look-up for v3170 Cg based on valve data p. 1-18'
'of the Fisher catalog - includes minimum flow characteristic'
'based on 8% equivalent opening from 0.5% to 8% opening'
Table CGF170, 1, 14...
     /0.0,0.005,0.0051,0.08,0.1,0.2,0.3,0.4,0.5,...
       0.6,0.7,0.8,0.9,1.0,...
     0.0,0.0,156.,156.,195.,373.,530.,667.,787.,...
       889.,976.,1040.,1050.,1050./

Constant SF3170  =  1.2     $'Valve 3170 Cg scaling factor'
Constant C13170  = 27.3     $'Valve C1'
Constant w3170   =  0.667   $'Omega for valve linear response'
Constant R8v170  =  0.1     $'Maximum valve rate in (% x100)/sec'
Constant CMD170  =  0.      $'Valve position command'
Constant V170IC  =  0.      $'Valve position IC'

'***********  V3170 Calculations  *********************'
        'Valve Position'
        'Err170 = w3170*(CMD170 - VP3170)'
        'V170DT = Bound(-R8v170,R8v170,Err170)'
        'VP3170 = Integ(V170DT,v170IC)'

        'Determine flow direction'
        DP3170 = HDpres - Patm $'(HD - Patm) pressure drop'
          SGN170 = LSW(DP3170 .GE. 0.,1,-1)
        PH3170 = RSW(DP3170 .GE. 0.,HDpres,Patm)
          PL3170 = RSW(DP3170 .GE. 0.,Patm,HDpres)
        TH3170 = RSW(DP3170 .GE. 0.,HDdegR,ATdegR)

        'Fisher Valve calculation'
          PF3170 = 1.0 - PL3170/PH3170
          ANG170 = AMIN1(Maxang,(59.54/C13170*SQRT(PF3170) ) )
          Cg3170 = CGF170(VP3170)*SIN(ANG170)*SGN170*SF3170
          F3170  = 4.84e-04 * Cg3170 * PH3170/SQRT(TH3170)
```

```
'************************  Valve 3295  **************************'

Constant Cg3295  = 3627.0       $'Valve Cg - determined from Matlab'
                                 ' analysis of data'
'Table look-up for v3295 Cg based on valve data p. 1-18'
'of the Fisher catalog - includes minimum flow characteristic'
'based on 8% equivalent opening from 0.5% to 8% opening'
Table CGF295, 1, 9 ...
     /0.0,0.005,0.0051,0.1,0.2,0.3,0.4,0.5,1.0,...
      0.0,0.0,20.,513.,826.,1014.,1306.,1633.,2180./

     ' 0.0,0.0,20.,261.,326.,653.,980.,1306.,1633.,...
         1960.,2286.,2613.,2940.,3627./'

Constant SF3295 =  3.0        $'Valve 3295 Cg scaling factor'
Constant C13295 = 20.9        $'Valve C1'
Constant w3295  =  0.652      $'Omega for valve linear response'
Constant R8v295 =  0.1        $'Maximum valve rate in (% x100)/sec'
Constant CMD295 =  0.         $'Valve position command'
Constant V295IC =  0.         $'Valve position IC'

'************  V3295 Calculations  **********************'
       'Valve Position'
         'Err295 = w3295*(CMD295 - VP3295)'
         'V295DT = Bound(-R8v295,R8v295,Err295)'
         'VP3295 = Integ(V295DT,v295IC)'

       'USED FOR READING EXTERNAL DATA'
       VP295i = RSW(VP3295 .LT. 0.005,0.,VP3295)

       'Determine flow direction'
         DP3295 = HDpres - MTPres $'(HD - MT) pressure drop'
          SGN295 = LSW(DP3295 .GE. 0.,1,-1)
         PH3295 = RSW(DP3295 .GE. 0.,HDpres,MTPres)
          PL3295 = RSW(DP3295 .GE. 0.,MTPres,HDpres)
         TH3295 = RSW(DP3295 .GE. 0.,HDdegR,MTdegR)

       'Fisher Valve calculation'
         PF3295 = 1.0 - PL3295/PH3295
         ANG295 = AMIN1(Maxang,(59.54/C13295*SQRT(PF3295) ) )
         Cv3295 = CGF295(vp3295)
         F3295  = 4.84e-04 * Cv3295 * PH3295/SQRT(TH3295)

'***********************  Valve 3292  ***************************'
Constant Cg3292 = 3910.0       $'Valve Cg'
Constant C13292 =   28.9       $'Valve C1'
Constant w3292  =    0.261     $'Omega for valve linear response'
Constant R8v292 =    0.1       $'Maximum valve rate in (% x100)/sec'
Constant CMD292 =    0.        $'Valve position command'
Constant V292IC =    0.        $'Valve position IC'

'************  V3292 Calculations  **********************'
       'Valve Position'
         'Err292 = w3292*(CMD292 - VP3292)'
         'V292DT = Bound(-R8v292,R8v292,Err292)'
         'VP3292 = Integ(V292DT,v292IC)'
```

```
       'USED FOR READING EXTERNAL DATA'
       VP292i = RSW(VP3292 .LT. 0.005,0.,VP3292)

       'Determine flow direction'
         DP3292 = BFPres - MTPres $'(BF - MT) pressure drop'
          SGN292 = LSW(DP3292 .GE. 0.,1,-1)
         PH3292 = RSW(DP3292 .GE. 0.,BFPres,MTPres)
          PL3292 = RSW(DP3292 .GE. 0.,MTPres,BFPres)
         TH3292 = RSW(DP3292 .GE. 0.,BFdegR,MTdegR)

       'Fisher Valve calculation'
         PWA3 = 1.0 - PL3292/PH3292
         ANG292 = AMIN1(Maxang,(59.54/C13292*SQRT(PWA3) ) )
         Cv3292 = Cg3292*SIN(ANG292)*SGN292
         WA3  = 4.84e-04 * VP292i * Cv3292 * PH3292/SQRT(TH3292)

'****************  Mixing Tee volume   ************************* '
Constant MTvol    =  188.9       $'Volume in ft**3'
'Constant MTPRic =   14.7'       $'Initial pressure in psia'

Constant MTarea   =  596.8            $'Surface area in ft**2'
'Constant MTcmwm = 2177.2'            $'Specific heat*thermal mass '
Constant MTcmwm   = 4000.             $'Specific heat*thermal mass '
Constant MTdia    =   14.0            $'Diameter in inches'
Constant MThc     = 2.0e-04           $'Fixed convective coefficient'

' ***** Mixing Tee  Calculations  **********'
       'Calculate mdot = (flow thru 3295 and 3292) - flow thru 3296'
         MTmdot = (F3295 + WA3) - F3296
       'Integrate MTmdot'
         MTmas = Integ(MTmdot,MTmic)
       'Calculate Energy '
         'Invoke Heat transfer macro'
         'Macro QNRG(X,TGdegR,TMdegR,INFLO)'

       QNRG('MT',MTdegR,MTTPip,amax1((F3295+WA3),F3296))

       MTcnrg = ((TH3292-DT3292) - MTTpip)*...
                MTarea*ABS(WA3)*MThc
       MThnrg = ((TH3295-DT3295) - MTTpip)*...
                MTarea*ABS(F3295)*MThc

         DT3292  = JTC*(BFPres - MTPres)
         DT3295  = JTC*(HDPres - MTPres)

       MTendt = CPair*(F3295*(TH3295-DT3295-Tref)...
                + WA3*(TH3292-DT3292-Tref)...
                - F3296*(TH3296-Tref))...
                - MTQNRG -MTcnrg - MThnrg

       MTenrg = Integ(MTendt,MTenic) $'Integrate MTendt'
```

```
       'Temperature'
         MTdegR = MTenrg/(Cvair*MTmas)  + Tref
         TT32 = MTdegR - FtoR
       'Pipe Temperature'
         MTTPip = Integ(MTQNRG/MTcmwm,MTTPic)
         TT14   = MTTPip - FtoR
       'Calculate Pressure'
         MTPres = MTmas*R*MTdegR/(MTvol*144.) $'Ideal gas'
         PT11   = MTPres - Patm  $'PT11 in psig'

'********************* Piping Volume ***************************'
' This volume represents the piping between MT and V3296'
' This volume is considered to be part of mixing tee volume'

Constant PParea = 1000.         $'Surface area in ft**2'
Constant PPcmwm = 8000.         $'Specific heat*thermal mass '
Constant PPdia  =   14.0        $'Diameter in inches'

       PPendt = CPair*F3296*(MTdegR - PPdegR) - PPqnrg
       PPenrg = Integ(PPendt,PPenic)
       PPdegR = PPenrg/(CVair * 2*MTmas) + Tref
       TT999  = PPdegR - FtoR
       QNRG('PP',PPdegR,PPTPip,amax1((F3295+WA3),F3296))

          'Pipe Temperature'
           PPTPip = Integ(PPQNRG/PPcmwm,PPTPic)
           TT998 = PPTpip - FtoR

'************************  Valve 3296  ***************************'
Constant Cg3296 = 1.0       $'Valve Cg - not used for 3296'
Constant C13296 = 1.0       $'Valve C1 - not used for 3296'
Constant w3296  = 0.783     $'Omega for valve linear response'
                            'Omega not used for 3296'
Table CGF296, 1, 2 ...
    /1.1,  7.1,...
    3.53, 20.636/
    Constant vp3296 = 1.1     $'Valve 3296 setting in inches'
Cf3296 = CGF296(vp3296)

'************   V3296 Calculations   **********************'
       'Determine flow direction'
         DP3296 = MTPres - SCPres $'(MT - SC) pressure drop'
          SGN296 = LSW(DP3296 .GE. 0.,1,-1)
         PH3296 = RSW(DP3296 .GE. 0.,MTPres,SCPres)
          PL3296 = RSW(DP3296 .GE. 0.,SCPres,MTPres)
         TH3296 = RSW(DP3296 .GE. 0.,MTdegR,SCdegR)

         'Orifice flow calculation'
          PF3296 = BOUND(Prcrit,1.0,PL3296/PH3296)
          'bottom bound is Prcrit, upper bound not restrictive'
           XPR296 = PF3296**Alpha - PF3296**Beta
           F3296 = 2.056*Cf3296*PH3296*SQRT(XPR296/TH3296)*SGN296
```

```
'************  Settling Chamber   *******************************'
Constant SCvol  = 1881.5         $'Volume in ft**3'
'Constant SCPRic =   14.7'       $'Initial pressure in psia'

Constant SCarea = 1116.4 $'Surface area in ft**2'
Constant SCcmwm = 4004.4 $'Specific heat*thermal mass'
Constant SCdia  =   63.0 $'Diameter in inches'

' ***** Settling Chamber Calculations  **********'
      'Calculate mdot = (flow thru 3296) - flow thru nozzle'
        SCmdot = F3296 - FNOZL
      'Integrate SCmdot'
        SCmas = Integ(SCmdot,SCmic)
      'Calculate Energy '
        'Invoke Heat transfer macro'
        'Macro QNRG(X,TGdegR,TMdegR,INFLO)'
        'Heat transfer based on INFLOW'

      QNRG('SC',SCdegR,SCTPip,amax1(F3296,FNOZL))

      SCendt = CPair*(F3296*(PPdegR-Tref)...
                - FNOZL*(THNOZL-Tref))...
                - SCQNRG

      SCenrg = Integ(SCendt,SCenic) $'Integrate SCendt'

      'Temperature'
        SCdegR = SCenrg/(Cvair*SCmas) + Tref
        TT445 = SCdegR - FtoR
    'Pipe Temperature'
        SCTPip= Integ(SCQNRG/SCcmwm,SCTPic)
        TT27  = SCTPip - FtoR

    'Flow and Flow Energy'
        SCPres = SCmas*R*SCdegR/(SCvol*144.) $'Ideal gas'
        PT72   = SCPres

'*********************  Nozzle  ******************************'
Constant ANOZL = 14.4

'************   Nozzle flow Calculations  **********************'
      'Determine flow direction'
        DPNOZL = SCPres - VSPres $'(SC - VS) pressure drop'
         SGNNZL = LSW(DPNOZL .GE. 0.,1,-1)
        PHNOZL = RSW(DPNOZL .GE. 0.,SCPres,VSpres)
         PLNOZL = RSW(DPNOZL .GE. 0.,VSpres,SCPres)
        THNOZL = RSW(DPNOZL .GE. 0.,SCdegR,VSdegR)

      'Orifice flow calculation'
        PFNOZL = BOUND(Prcrit,1.0,PLNOZL/PHNOZL)
         'bottom bound is Prcrit, upper bound not restrictive'
         XPRNZL = PFNOZL**Alpha - PFNOZL**Beta
         FNOZL = 2.056*ANOZL*PHNOZL*SQRT(XPRNZL/THNOZL)*SGNNZL
```

```
'************  Vacuum Sphere   *******************************'
'Constant VSvol = 117755.0'   $'60  ft sphere volume in ft**3'
Constant  VSvol = 523600.0    $'100 ft sphere volume in ft**3 '

Constant VSarea =  14816.0    $'Surface area in ft**2'
Constant VScmwm = 256535.0    $'Specific heat*thermal mass'
Constant VSdia  =     72.0    $'Diameter in inches'
Constant Atmos  = .False.

       'Calculate mdot =  flow thru nozzle'
         VSmdot = FNOZL
       'Integrate VSmdot'
         VSmas = Integ(VSmdot,VSmic)
       'Calculate Energy '
         VSendt = CVair*(FNOZL*THNOZL)
         VSenrg = Integ(VSendt,VSenic) $'Integrate VSendt'
       'Temperature'
         VSdegR = VSenrg/(Cvair*VSmas) + Tref
         VSdegF = VSdegR - FtoR
       'Flow and Flow Energy'
         VSpres = RSW(Atmos,Patm,VSmas*R*VSdegR/(VSvol*144.))
                  'Ideal gas'

End $ ' of Derivative '

Discrete NWDATA
     IF(.NOT.REXDAT)GO TO REXEND
       vp3162 = 0.01*VP162X
     vp3170 = 0.01*VP170X
     vp3295 = 0.01*VP295X
     vp3292 = 0.01*VP292X
       'HPOWER = HPOWRX'
       VSprsX = PT73x* (0.0193368)
       ULTAP = int(ULTCPX)

     PROCEDURAL
       IF(.NOT.DATFLG) GO TO DATEND
         CALL RDATA(20,DATFLG,EXDATA)
         SCHEDULE NWDATA .AT. TIMEX
       DATEND..CONTINUE
       END$'OF PROCEDURAL'
       REXEND..CONTINUE

End$'of Discrete NWDATA'
End $ ' of Dynamic '

Terminal
tstart = tend
tend = t
End $ ' of Terminal '
End $ ' of Program '
```

```
      subroutine Ofile
      character*16 fname
      write(*,10)
10    format(' Enter three digit data file id: '\)
      read(*,*)id
      fname = 'A   .DAT'
      WRITE(fname(2:4),'(I3.3)')ID
      OPEN(UNIT=20,FILE=fname,STATUS='OLD',FORM='UNFORMATTED')
      return
      end

      SUBROUTINE RDATA(XLUNIT,FLG,XOUT)
      REAL XOUT(31),X(31)
      LOGICAL FLG
      INTEGER XLUNIT,TLUNIT
      READ(XLUNIT,ERR=1,END=1)(X(I),I=1,31)
      DO 10 I=1,31
10    XOUT(I) = X(I)
      GO TO 2

1     FLG  = .FALSE.
      CLOSE(XLUNIT)

2     CONTINUE
      RETURN
      END
```

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16. Abstract

A simulation of the pressure and temperature responses of the 20-Inch Supersonic Wind Tunnel (SWT) is developed. The simulation models the tunnel system as a set of lumped-parameter volumes connected by flow regulating elements such as valves and nozzles. Simulated transient responses of temperature and pressure for the five boundary points of the 20-Inch Supersonic Wind Tunnel operating map are produced from their respective initial conditions, tunnel operating conditions, heater input power, and valve positions. Upon reaching steady state, a linearized model for each operating point is determined. Both simulated and actual tunnel responses are presented for comparison.

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