A COMPUTER SIMULATION OF A NAVAL BOILER

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

A COMPUTER SIMULATION OF A
NAVAL BOILER

by

Wallace Paul Fini

September 1978

Thesis Advisor: T. Houlihan

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T186183

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A Computer Simulation of a Naval Boiler		5. TYPE OF REPORT & PERIOD COVERED Engineer's Thesis; September 1978
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Wallace Paul Fini		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		12. REPORT DATE September 1978
		13. NUMBER OF PAGES 101
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Navy D-Type Boiler
Computer Simulation
Naval Boiler
Combustion Engineering Type V-2M Boiler

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601 |

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(20. ABSTRACT Continued)

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A Computer Simulation of a Naval Boiler

by

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B.S.E.E., Worcester Polytechnic Institute, 1967

Submitted in partial fulfillment of the
requirements for the degrees of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

and

MECHANICAL ENGINEER

from the

NAVAL POSTGRADUATE SCHOOL
September 1978

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A non-linear computer model of a U.S. Navy D-Type boiler was developed using lumped parameters. The program was coded in IBM CSMP-III simulation language. A companion routine was also coded to permit the user to implement the model for a particular boiler using only readily accessible data. The model was adapted for a Combustion Engineering Type V-2M boiler for analysis.

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NOMENCLATURE

English Symbols

A	-	Area (ft^2)
A_{dr}	-	Drum Downcomer Total Cross Sectional Area (ft^2)
A_{ds}	-	Header Downcomer Total Cross Sectional Area (ft^2)
AMB	-	Main Bank Heat Transfer Surface Area (ft^2)
A_r	-	Main Bank Riser Total Cross Sectional Area (ft^2)
A_s	-	Screen Riser Total Cross Sectional Area (ft^2)
Be	-	Becker's Factor
C	-	A General Constant
C_ℓ	-	Specific Heat of Liquid (Btu/lbm/°F)
C_m	-	Specific Heat of Tube Metal (Btu/lbm/°F)
C_p	-	Specific Heat (Btu/lbm/°F)
C_{R1}	-	Specific Heat of Flue Gas in the Furnace (Btu/lbm/°F)
C_{R1a}	-	Specific Heat of Flue Gas at the Furnace Exit (Btu/lbm/°F)
C_{R2}	-	Specific Heat of Flue Gas at Superheater Exit (Btu/lbm/°F)
C_{R3}	-	Specific Heat of Flue Gas at Main Bank Exit (Btu/lbm/°F)
C_{st}	-	Constant used in Rohsenow Correlation
C_3-C_{11}	-	Constants Used in Various Equations
d	-	Diameter (ft)
D_{dr}	-	Sum of the Diameters of the Drum Downcomers (ft)
D_{ds}	-	Sum of the Diameters of the Screen Downcomers (ft)

D_r - Sum of the Diameters of the Main Bank Tubes (ft)

D_s - Sum of the Diameters of the Screen Tubes (ft)

EB - Total Heat Input to the Furnace (Btu/sec)

ED1 - Heat Transferred from the Desuperheated Steam to the Tubes (Btu/sec)

ED2 - Heat Transferred from the Superheater Tubes to the Steam (Btu/sec)

ER1 - Heat Transfer Rate from the Flue Gas to the Screen Tubes (Btu/sec)

ER2 - Heat Transfer Rate from the Flue Gas to the Superheater (Btu/sec)

ER3 - Heat Transfer Rate from the Flue Gas to the Main Bank (Btu/sec)

ER4 - Heat Transfer Rate from the Flue Gas to the Economizer (Btu/sec)

E_{wr} - Heat Transfer Rate to the Riser Liquid (Btu/sec)

EW1 - Heat Transfer Rate from the Economizer Tubes to the Feed Water (Btu/sec)

EW2 - Heat Transfer Rate from the Desuperheater Tubes to the Drum (Btu/sec)

EW3 - Heat Transfer Rate to the Screen Riser Liquid (Btu/sec)

EW4 - Heat Transfer Rate to the Main Bank Riser Liquid (Btu/sec)

f - Friction Factor

F_{dr} - Drum Downcomer Friction Factor

F_{ds} - Heater Downcomer Friction Factor

F_r - Main Bank Riser Friction Factor

F_s - Screen Riser Friction Factor

g - Acceleration of Gravity - 32.2 ft/sec^2

G - Mass Flow Rate (lbm/sec)

GB	-	Fuel Flow Rate (lbm/sec)
GD1	-	Total Steam Flow Rate from Boiler (lbm/sec)
GD2	-	Desuperheated Steam Flow Rate (lbm/sec)
GD3	-	Steam Condensing from Vapor to Liquid in the Steam Drum (lbm/sec)
GD4	-	Superheated Steam Flow (lbm/sec)
GL	-	Air Mass Flow Rate (lbm/sec)
GR	-	Total Flue Gas Flow Rate (lbm/sec)
GS	-	Screen Riser Circulation Flow Rate (lbm/sec)
Gr	-	Riser Circulation Flow Rate (lbm/sec)
Gw	-	Downcomer Circulation Flow Rate (lbm/sec)
GØ	-	Main Bank Riser Mass Flow Rate (lbm/sec)
Gwr	-	Drum Downcomer Circulation Flow Rate (lbm/sec)
Gws	-	Header Downcomer Circulation Flow Rate (lbm/sec)
HD1	-	Enthalpy of Saturated Steam (Btu/lbm)
Hfg	-	Heat of Vaporization (Btu/lbm)
Ho	-	Heating Value of Fuel Oil (Btu/lbm)
HNB	-	Non-boiling Height (ft)
HNBR	-	Main Bank Riser Non-boiling Height (ft)
HNBS	-	Screen Riser Non-boiling height (ft)
HW1	-	Enthalpy of Saturated Water (Btu/lbm)
HW2	-	Enthalpy of Downcomer Liquid (Btu/lbm)
HW3	-	Enthalpy of Feed at Economizer Inlet (Btu/lbm)
HW4	-	Enthalpy of Feed at Economizer Outlet (Btu/lbm)
HW6	-	Enthalpy of Water in Lower Drum (Btu/lbm)

Hxr	-	Effective Height of Main Bank/Drum Downcomer Circuit (ft)
Hxs	-	Effective Height of Screen/Header Downcomer Circuit (ft)
k	-	Thermal Conductivity (Btu/hr-ft-°F)
K	-	a general constant
Ks	-	Equivalent Sand Roughness (in)
KR1-KR4	-	Constants Used in the Gas Heat Transfer Equations
ℓ	-	Length (ft)
L	-	Tube Length (ft)
LB	-	Boiling Length (ft)
Ldr	-	Total Length of Drum Downcomer Tubes (ft)
Lds	-	Total Length of Header Downcomer Tubes (ft)
Ldlr	-	Avg. Length of Drum Downcomer Tubes (ft)
Ldls	-	Avg. Length of Header Downcomer Tubes (ft)
Lr	-	Total Length of Main Bank Tubes (ft)
Lrl	-	Avg. Length of Main Bank Tubes (ft)
Ls	-	Total Length of Screen Tubes (ft)
Lsl	-	Avg. Length of Screen Tubes (ft)
LMTD	-	Log Mean Temperature Difference (°F)
M	-	Mass (lbm)
MM1	-	Mass of Screen Tube Metal (lbm)
MM2	-	Mass of Superheater Tube Metal (lbm)
MM3	-	Mass of Riser Tube Metal (lbm)
MM4	-	Mass of Economizer Tube Metal (lbm)
MM5	-	Mass of Desuperheater Tube Metal (lbm)
MR1	-	Mass of Flue Gas in Furnace (lbm)
MW1	-	Mass of Water in Steam Drum (lbm)

P	-	Pressure (psia)
PD	-	Pressure of Steam Volume in Steam Drum (psi)
PD1	-	Saturation Pressure Corresponding to Enthalpy of Water in the Steam Drum (psi)
PD2	-	Pressure at Superheater Outlet (psia)
PD2	-	Pressure at Desuperheater Outlet (psia)
Pr	-	Prandtl Number
Psat	-	Saturation Pressure (psia)
PW1	-	Pressure in Water Drum (psi)
PW2	-	Pressure in Screen Header (psi)
q	-	Heat Transfer Rate (Btu/sec)
R	-	Tube Radius (in)
Ra1	-	Average Density in the Main Bank Risers (lbm/ft^3)
Ra2	-	Average Density in the Screen Risers (lbm/ft^3)
RD1	-	Density of Saturated Steam (lbm/ft^3)
Re	-	Reynolds Number
RW	-	Density of Saturated Water (lbm/ft^3)
RS	-	Density of Two-Phase Mixture at Screen Outlet (lbm/ft^3)
RØ	-	Density of Two-Phase Mixture at Main Bank Outlet (lbm/ft^3)
t	-	Time (sec)
T	-	Temperature (°F)
Tsat	-	Saturation Temperature (°F)
TD	-	Temperature of Steam Drum Vapor (°F)
TD1	-	Temperature of Saturated Steam Corresponding to Drum Enthalpy (°F)
TD2	-	Superheater Outlet Temperature (°F)

TD3 - Desuperheater Outlet Temperature (°F)

TM1 - Screen Metal Temperature (°F)

TM2 - Superheater Metal Temperature (°F)

TM3 - Main Bank Metal Temperature (°F)

TM4 - Economizer Metal Temperature (°F)

TM5 - Desuperheater Metal Temperature (°F)

TR1 - Temperature of Flue Gas in Furnace (°F)

TR2 - Temperature of Flue Gas Leaving Furnace (°F)

TR3 - Temperature of Flue Gas Leaving Superheater (°F)

TR4 - Temperature of Flue Gas Leaving Main Bank (°F)

TR5 - Temperature of Flue Gas Leaving Economizer (°F)

TRa2 - Average Flue Gas Temperature Across the Superheater (°F)

TRa3 - Average Flue Gas Temperature Across the Main Bank (°F)

TRa4 - Average Flue Gas Temperature Across the Economizer (°F)

TW3 - Feed Inlet Temperature (°F)

TW4 - Feed Outlet Temperature (°F)

To - Ambient Temperature

U_b - Bubble Rise Velocity (ft/sec)

U_m - Mean Velocity (ft/sec)

V - Volume (ft^3)

VB - Boiling Volume (ft^3)

VD1 - Volume of Steam in Steam Drum (ft^3)

VENT - Percent Throttle Valve Opening

VNDR - Water Drum Volume (ft^3)

VR - Main Riser Bank Fluid Volume (ft^3)

VS - Screen Riser Bank Fluid Volume (ft^3)

v	-	Specific Volume (ft^3/lbm)
X	-	Quality (percent)
XØ	-	Quality at Main Bank Riser Outlet (percent)
Xs	-	Quality at Screen Riser Outlet (percent)
Xe	-	Quality at Riser Exit (percent)
Z1	-	Drum Downcomer Bend Loss Factor
Z2	-	Drum Downcomer Exit Loss Factor
Z3	-	Main Bank Riser Bend Loss Factor
Z4	-	Main Bank Riser Exit Loss Factor
Z5	-	Screen Riser Bend Loss Factor
Z6	-	Screen Riser Exit Loss Factor
Z7	-	Header Downcomer Bend Loss Factor
Z8	-	Header Downcomer Exit Loss Factor

Greek Letters

μ	-	Viscosity (lbm/ft-sec)
ρ	-	Density (lbm/ft^3)
σ	-	Surface Tension (lbf/ft)
ρ_{Da1}	-	Average Density in Superheater (lbm/ft^3)
ρ_{Da2}	-	Average Density in Desuperheater (lbm/ft^3)

Subscripts

a	-	Average
ℓ,f	-	Liquid
g	-	Vapor
M,m	-	Metal

∞	-	Far Field Average
r	-	Main Bank
s	-	Screen
dr	-	Drum Downcomer
ds	-	Header Downcomer
D	-	Steam
R	-	Flue Gas
W	-	Water

I. INTRODUCTION

The increasing attractiveness and efficiency of computer-aided design techniques have established a need for reasonably accurate computer models of all types of engineering systems. The design of multivariable controllers, in particular, requires the availability of state information about a system which is not available from conventional transfer function simulations. A number of computer models of marine boilers have been proposed [1,2,3,4]. All of these efforts share one or more of the following features:

a. Lumped parameters are used.

b. Bubble formation effects with respect to shrink and swell are not modeled.

c. The furnace screen and main riser bank are lumped together as are their respective downcomers [1,3,4].

d. The model is linearized using a Taylor expansion or perturbation technique [3].

Use of lumped parameters is dictated by the need to maintain computational efficiency, particularly when the model is used in control system design and optimization schemes. In the past, effects due to vapor formation in the drum have not been included due to the lack of a suitable model. A simple model based on the Rohsenow correlation [5] was developed for use in the current simulation. However, its contribution to shrink and swell effects was negligible and

it was eliminated from the equation set. Regarding the tube banks, Haraguchi and Akasara [2] split out the various riser and downcomer loops, including intermediate headers. Considering the general level of uncertainty inherent in the correlations used in this model, this appears to be an excessive degree of complication. A compromise position was taken in the present effort in that the screen and main riser bank and their associated downcomers were modeled separately, but intermediate headers within the screen circuit were not addressed individually since their configuration varies widely from one boiler to another.

The objective of this thesis was to develop a general, non-linear model of a Navy boiler for use in simulations covering the full operating range of the propulsion plant. However, since a linearized version is normally needed for multivariable controller design, CENTRL, a computer code developed locally for use with CSMP models, could be used to generate linearized state space representations described by the matrix equations:

$$\{\dot{x}\} = [A]\{\Delta x\} + [B]\{\Delta u\}$$

$$\{\Delta y\} = [C]\{\Delta x\} + [D]\{\Delta u\}$$

This approach would produce linearized representations covering the entire boiler operating range in a piecewise

fashion, rather than attempting to extend the range of applicability of a single state space or linear model.

Since this author found the notation used in Reference [1] particularly readable, it was adopted for use in this document.

II. DESIGN CONSIDERATIONS

A. D-TYPE BOILER

The single furnace (D-Type), uncontrolled-superheat boiler was chosen as the basis for the model since it is the predominant design in the current U.S. Navy inventory. The nominal operating pressures range from 600 to 1200 psi, and all designs are conceptually similar. A basic schematic is shown in Figure 1. These boilers are typified by relatively fast response times for use in high speed maneuvering vessels. This puts heavy emphasis on properly designed control systems. Manual control of these boilers is essentially infeasible except under the most favorable circumstances, e.g. steady steaming at low speeds. Current conventional control systems used by the Navy are of the same generic type with relatively minor customization except in hardware from one installation to the next. These designs have been based on analog models intended to provide reasonable dynamic responses for pressure, water level, and steam flow which are the only state parameters measured by conventional controllers. Although these control systems have in general proven satisfactory, there is some indication [6] that multivariable control systems can effect significant improvement in both response time and demands on auxiliary equipment.

A typical boiler of this type, the Combustion Engineering Type V-2M is shown in Figure 2. The main components of the boiler are the furnace which is surrounded on all sides except the floor by screen tubes, the superheater, main riser banks, economizer, water drum, steam drum, desuperheater, downcomers, and screen headers. Navy boilers do not include air heaters and the only air preheating which occurs is accomplished by passing the incoming air over the exhaust stack liner. This procedure generally produces an air temperature of about 100-130°F for an ambient of 70°F. In contrast to the boilers used as the basis for previous models, the desuperheater is located in the water drum rather than in the steam drum. All of the steam generated passes through the superheater prior to being split out as main superheated steam and auxiliary desuperheated steam.

All of these boilers are of the natural circulation type. The "throttle valve" was considered to be in the superheated main steam line.

B. MODEL FLEXIBILITY

The model was designed to be as flexible as possible to permit its relatively simple adaptation to a particular boiler. Since the boiler technical manual or equivalent, the steam and gas tables, and standard engineering handbooks may be presumed to be available, the model was designed to utilize data only from these sources for implementation.

To convert this input data into the form required by the model, an interface program was developed to adjust parameters and determine initial conditions at the operating point for which the input data were extracted. This approach was taken to avoid the necessity of redesigning the model for each operating range or specific boiler design being considered.

C. ASSUMPTIONS

To permit tractable computation, a number of simplifying assumptions were made in the formulation of the model:

1. Feed water entering the drum mixes thoroughly with the drum liquid.
2. No steam generation occurs in the steam drum except through mass transfer at the water-vapor interface.
3. There is a uniform distribution of heat flux in the generating tubes.
4. The mixture of steam and water in the generating tubes is homogeneous.
5. Quality varies linearly in the generating tubes.
6. Heat losses to the ambient except through the exhaust gases are neglected.
7. All downcomers and risers in a particular circuit have the same length as the average length, and the shapes and diameters are equal. Also the number of tubes is the same as in the actual boiler.
8. The slip ratio is 1.0 (no slip).

Since the feed enters through a long, horizontal feed pipe, and the drum liquid is in a state of turbulence, the first assumption is well justified. Although the second assumption is not strictly correct during transients when there is a significant change in drum pressure, and hence saturation temperature, the effect of steam generated at the drum wall-liquid interface appears to be negligible based on an analysis of this factor in connection with this study. The assumption of uniform heat flux is recommended by Reference [7] as a reasonable alternative to a stepwise integration over the tube height. The assumption of a linear change in quality is a consequence of the assumption of a linear heat load. For a well designed boiler, heat losses through the casing are small compared to the total energy generated. The effects of any such losses will be reflected in small errors in the computed heat capacities of the gas and in the heat transfer coefficients. The assumptions regarding tube geometry are made primarily for computational simplification. The last assumption regarding slip is not an essential one, and higher slip ratios could easily be considered if necessary to the analysis of a particular boiler design. In addition to these explicitly stated assumptions, those inherent in the correlations employed in the model formulation are also considered to have been made.

III. MODEL ANALYSIS

A. GENERAL

The model was envisioned as an assemblage of control volumes for which the rates of energy transfer are described by appropriate equations to obtain the rate of change of energy storage. The resulting differential equations were integrated to obtain the "state" of the system. In this way, the states can be chosen to have specific physical interpretations. The system is shown diagrammatically in Figure 3.

The following control volumes were considered in the model formulation:

1. Riser tube walls
2. Superheater tube walls
3. Economizer mass
4. Desuperheater tube walls
5. Riser fluid (kinetic energy)
6. Riser fluid (thermal energy)
7. Steam drum water volume
8. Steam drum steam volume
9. Water drum
10. Furnace

B. FLUE GAS AND COMBUSTION SYSTEM

The flue gas and combustion system is shown schematically in Figure 4. Heat is carried into the furnace through the

sensible heat of the air and fuel, and the heat released in combustion. Since the fuel-air ratio is relatively constant, and the fuel and air have relatively constant inlet temperatures, the sensible heats were lumped with the heating value of the fuel. The mass flow rate into the furnace is given by

$$G_R = G_B + G_L$$

and the total heat input is

$$E_B = G_B \times H_O \, .$$

The heat transfer to the furnace screen is primarily through radiation, i.e.,

$$E_{R1} = K_{R1} \left\{ \left(\frac{T_{R1} + 460}{100} \right)^4 - \left(\frac{T_{M1} + 460}{100} \right)^4 \right\} .$$

The heat balance for the mass of flue gas in the furnace is

$$\frac{d}{dt} \left(M_{R1} C_{R1} T_{R1} \right) = E_B - E_{R1} - G_R C_{R1} T_{R1}$$

where the last term represents the heat carried off by the flue gas. Heat transfer to the remaining tube banks is primarily through convection. The heat given up by the flue gas is given by the general relation

$$q_{gas} = \dot{M} C_p \Delta T$$

and the heat transfer to the tubes may be estimated with the Grimson Correlation [8]

$$q_{tube} = C\, Re^{n}\, Pr^{1/3} A\, (T_g - T_m) \quad .$$

Since the physical properties in the above equation do not change significantly over the expected range of temperature variations, the correlation is used in the form

$$q_{tube} = K\, G_R^{n}\, (T_g - T_m) \quad .$$

Since the tube geometry is not known in advance, an n = 0.6 was used as a reasonable average for most geometries found in practice. The equations for the tube banks were:

1. <u>Superheater</u>

$$ER_2 = G_R\, C_{R1a}\, (T_{R2} - T_{R1})$$
$$ER_2 = K_{R2}\, G_R^{.6}\, (T_{Ra2} - T_{M2})$$
$$T_{Ra2} = (T_{R2} + T_{R3}) / 2.0$$

2. Main Bank

$$E_{R3} = G_R C_{R2} (T_{R3} - T_{R4})$$
$$E_{R3} = K_{R3} G_R^{.6} (T_{Ra3} - T_{M3})$$
$$T_{Ra3} = (T_{R3} + T_{R4}) / 2.0$$

3. Economizer

$$E_{R4} = G_R C_{R3} (T_{R4} - T_{R5})$$
$$E_{R4} = K_{R4} G_R^{.6} (T_{Ra4} - T_{M4})$$
$$T_{Ra4} = (T_{R4} + T_{R5}) / 2.0$$

The arithmetic average temperature for the gas was used in the driving potential ΔT rather than the log mean temperature differences (LMTD), because a comparison of the results obtained for the two methods indicated the differences were slight for the temperatures involved and the simpler average was more computationally efficient.

C. WATER-STEAM CIRCULATION SYSTEM

As is shown in Figure 5, the basic circulation system consists of the steam drum, water drum or header, and the riser and downcomer tubes. The driving force for circulation

is the difference in density between the riser and downcomer loops. The pressure loss around the circuit balances this driving force. For the downcomers, the force balance is

$$P_{w1} - P_{D1} = R_w g H_{xr} - \left(F_{dr}\frac{L_{dr}}{D_{dr}} + Z_1 + Z_2 + 1\right)\frac{G_{wr}^2}{2A_{dr}^2 R_w}$$

for the drum downcomers, and

$$P_{w2} - P_{D1} = R_w g H_{xs} - \left(F_{ds}\frac{L_{ds}}{D_{ds}} + Z_7 + Z_8 + 1\right)\frac{G_{ws}^2}{2A_{ds}^2 R_w}$$

for the screen downcomer.

For the risers, the equations are:

$$P_{w1} - P_{D1} = \left(F_r\frac{L_r}{D_r} + 1\right)\frac{G_o^2 R_{a1}}{2A_r^2 R_o^2} + Z_3\frac{G_{wr}^2}{2A_r^2 R_w} + Z_4\frac{G_o^2}{2A_r^2 R_o}$$
$$+ R_{a1} g H_{xr} + R_{a1}\frac{L_{r1}}{A_r}\frac{d}{dt}\left(\frac{G_o}{R_o}\right)$$

$$P_{w2} - P_{D1} = \left(F_s\frac{L_s}{D_s} + 1\right)\frac{G_s^2 R_{a2}}{2A_s^2 R_s^2} + Z_5\frac{G_{ws}^2}{2A_s^2 R_w} + Z_6\frac{G_s^2}{2A_s^2 R_s}$$
$$+ R_{a2} g H_{xs} + R_{a2}\frac{L_{s1}}{A_s}\frac{d}{dt}\left(\frac{G_s}{R_s}\right)$$

for the screen and main bank, respectively. The friction factors are calculated from [9]

$$f = \left[\frac{1}{(1.74 - 2\log R/K_s)}\right] .$$

The friction factors for the risers are multiplied by Becker's factor [10] to account for two-phase effects

$$B_e = 1 + 16078.58\left(\frac{X}{P_{D1}}\right)^{.96} .$$

The relationship between riser and downcomer mass flow rates is given by the continuity equation

$$\frac{d}{dt}\rho_{av} = \frac{G_w - G_r}{V} .$$

The average density in the risers is found from

$$\rho_{av} = \frac{1}{L}\left[\int_{H_{NB}}^{L} \rho(l)\,dl + \rho_w H_{NB}\right] .$$

From the assumption that the quality varies linearly, the density may be obtained as a function of l from

$$\rho(l) = \frac{1}{V_f + \frac{X_e}{L_B}(l - H_{NB})V_{fg}} \qquad H_{NB} \leq l \leq L .$$

Regrouping the terms we get

$$\rho(l) = \frac{1}{\left(V_f - \frac{X_e}{L_B}H_{NB}V_{fg}\right) + \frac{X_e}{L_B}V_{fg}\,l} .$$

This expression can be integrated in closed form to yield

$$\int_{H_{NB}}^{L} \rho(l)\,dl = \frac{L_B}{X_e V_{fg}} \ln \left[\frac{\frac{X_e L}{L_B} V_{fg} + V_f - \frac{X_e}{L_B} H_{NB} V_{fg}}{\frac{X_e H_{NB}}{L_B} V_{fg} + V_f - \frac{X_e}{L_B} H_{NB} V_{fg}} \right] .$$

Combining terms and simplifying finally yields

$$\int_{H_{NB}}^{L} \rho(l)\,dl = \frac{L_B}{X_e V_{fg}} \ln \left[\frac{X_e V_{fg}}{V_f} + 1 \right] .$$

From this result, ρ_{av} is obtained as

$$\rho_{av} = \frac{1}{L} \left[\frac{L_B}{X_e V_{fg}} \ln \left[\frac{X_e V_{fg}}{V_f} + 1 \right] + \rho_w H_{NB} \right] .$$

An energy balance on the riser tube banks yields the quality

$$\frac{d}{dt} \left\{ \rho_{av} \left(H_{w1} + \frac{X_e}{2} H_{fg} \right) \right\} V_B$$

$$= G_w H_{w1} - G_r (H_{w1} + X_e H_{fg}) + E_{wr} - G_w (H_{w1} - H_{wr}) .$$

where VB is the boiling volume, and the last term on the right accounts for heat added in the non-boiling height to raise the enthalpy to saturated conditions.

The non-boiling height is obtained from

$$H_{NB} = L \frac{q_s}{q_t}$$

where q_s is the sensible heat added to the liquid in the non-boiling height, and q_t is the total heat input. The ratio q_s/q_t is given by

$$\frac{H_{wl} - H_{wr}}{(H_{wl} + X_e H_{fg}) - H_{wr}} .$$

The boiling volume is related to the non-boiling height by

$$V_B = \frac{L - H_{NB}}{L} V .$$

With substitution of the appropriate parameters, the above equations were applied to both circulation loops.

The mass balance of the water in the steam drum is

$$\frac{dM_{wl}}{dt} = G_o(1-X_o) + G_s(1-X_s) + G_{D3} + G_{W2} - G_{wr} - G_{ws}$$

and the energy balance is given by

$$\frac{d}{dt}\left(H_{W1} M_{W1}\right) = G_O (1-X_O) H_{W1} + G_S (1-X_S) H_{W1} + G_{D3} H_{fg} + G_{W2} H_{W4} - G_{Wr} H_{W2} - G_{WS} H_{W2} .$$

Since all the incoming feed must be passed through the riser tubes to be heated, an energy balance on the downcomers gives

$$G_{W2} H_{W4} + (G_{Wr} + G_{WS} - G_{W2}) H_{W1} = (G_{Wr} + G_{WS}) H_{W2}$$

$$G_{W2} (H_{W4} - H_{W1}) + (G_{Wr} + G_{WS}) H_{W1} = (G_{Wr} + G_{WS}) H_{W2} .$$

Solving for HW2, the downcomer enthalpy, we obtain

$$H_{W2} = \frac{G_{W2}}{G_{Wr} + G_{WS}} (H_{W4} - H_{W1}) + H_{W1} .$$

D. WATER-STEAM HEAT TRANSFER

1. Risers

The heat transferred to the riser tubers is used to bring the incoming flow to saturation conditions in the non-boiling height, and then generate steam in the remaining portion of the tube. To permit a tractable equation set, however, the tube walls were assumed to be at a uniform temperature, and all the heat was assumed to have been transferred under fully developed flow boiling conditions. Since the non-boiling height for the main bank was found to be small, the assumption was reasonable for that circuit. The non-boiling heights were higher in the screen circuit; however, the error in temperature introduced was less than three percent which was deemed an acceptable level. For fully developed flow boiling, Tong [11] recommends

$$q = \frac{A \, P_{sat}^{4/3}}{1.782 \times 10^{6}} \Delta T_{sat}^{3} \quad .$$

Therefore the heat transfer to the risers was given by

$$E_{w3} = K_{w3} \, P_{D1}^{4/3} \left(T_{m1} - T_{D1}\right)^{3}$$
$$E_{w4} = K_{w4} \, P_{D1}^{4/3} \left(T_{m3} - T_{D1}\right)^{3} \quad .$$

The tube metal temperatures were obtained from an energy balance,

$$M_{M1} C_M \frac{dT_{M1}}{dt} = E_{R1} - E_{W3}$$

for the screen, and for the main bank

$$M_{M3} C_M \frac{dT_{M3}}{dt} = E_{R3} - E_{W4} \quad .$$

2. <u>Desuperheater</u>

The Dittus-Boelter correlation [12] was used to determine the heat transfer from the steam to the tubes , i.e.,

$$E_{D2} = K_{D2} G_{D2}^{\,.8} (LMTD) \quad .$$

The log mean temperature difference was

$$LMTD = \frac{(T_{D2} - T_{D3})}{\ln\left[\frac{(T_{D2} - T_{MS})}{(T_{D3} - T_{MS})}\right]} \quad .$$

The energy given up by the steam was obtained from

$$E_{D2} = C_{D2} G_{D2} (T_{D2} - T_{D3}) \quad .$$

The heat transfer to the water in the drum was

$$E_{W2} = K_{W2} (T_{MS} - T_{W1}) \quad .$$

The metal temperature was obtained from the energy balance

$$M_{MS} C_M \frac{dT_{MS}}{dt} = E_{D2} - E_{W2} \quad .$$

3. Economizer

The Dittus-Boelter correlation gives the heat transfer from the tubes to the water as

$$E_{W1} = K_{W1} \, G_{W2}^{\,.8} \, LMTD$$

$$LMTD = \frac{T_{W4} - T_{W3}}{\ln\left\{\dfrac{T_{M4} - T_{W3}}{T_{M4} - T_{W4}}\right\}} \quad .$$

The heat absorbed by the water was

$$E_{W1} = G_{W2} \, C_W \, (T_{W4} - T_{W3}) \quad .$$

4. Superheater

The heat transfer to the steam was given by

$$E_{D1} = K_{D1} \, G_{D1}^{\,.8} \, (T_{D2} - T_{D1})$$

and the heat transferred from the metal in the tubes was

$$E_{D1} = K_{D1} G_{D1}^{.8} \, LMTD$$

$$LMTD = \frac{T_{D2} - T_{D1}}{\ln\left[\dfrac{T_{M2} - T_{D1}}{T_{M2} - T_{D2}}\right]} .$$

The metal temperature was found from

$$M_{M2} C_m \frac{dT_{M2}}{dt} = E_{R2} - E_{D1} .$$

E. PRESSURE DROP CALCULATIONS

For turbulent tube flow, the pressure drop is given by

$$\Delta P = f \, {}^L/_D \, \rho_{av} \frac{U_m^2}{2 g_c} .$$

Now

$$U_m = \frac{G}{A \rho_{av}} ,$$

so

$$\Delta P = f \, {}^L/_D \frac{G^2}{A^2 \rho_{av}} .$$

Lumping the constants we get

$$\Delta P = C \frac{G^2}{\rho_{av}} \quad .$$

Therefore the pressure drops in the superheater and desuperheater were given by

$$P_{D1} - P_{D2} = C_7 \frac{G_{D1}^2}{\rho_{Da1}}$$

and

$$P_{D2} - P_{D3} = C_9 \frac{G_{D2}^2}{\rho_{Da2}} \quad .$$

The average densities were found from the ideal gas law under the assumption that the temperature variation can be neglected, i.e., density is a function of pressure only. This assumption is motivated solely by the need for computational efficiency. It is reasonable for the desuperheater since the temperature excursions there are small. Although errors are larger for the superheater density values, they are still within accuracy overall limits for the model. The flow through the throttle value was given by

$$G_{D4} = C_3 P_{D2} V_{ENT} \quad .$$

F. EQUATIONS OF STATE

The following equations, obtained from Reference [13], were used to determine state properties. Within the range of pressures for which the model is valid (300-1500 psi), the results were within a few percent of tabular values in the worst case.

$$P_{sat} = \mathrm{EXP}\{(\ln H_{sat} - 4.46708)/.26452\}$$

$$T_{sat} = \mathrm{EXP}\{.22151 \ln P_{sat} + 4.77123\}$$

$$\rho_f = 63.8 - 0.01781\,T_{sat} + 1.132\mathrm{E}{-5}\,T_{sat}^2 - 6.786\mathrm{E}{-8}\,T_{sat}^3$$

$$v_{fg} = 524/P_{sat} - 0.1$$

$$h_{fg} = 922.13 - .40516\,P_{sat} + 1.717\mathrm{E}{-4}\,P_{sat}^2 - 4.219\mathrm{E}{-8}\,P_{sat}^3$$

IV. DETERMINATION OF CONSTANTS AND INITIAL CONDITIONS

A. GENERAL

For the model to be useful, it should be possible to obtain the necessary constants and initial conditions from the data supplied in the boiler Technical Manual augmented with reasonable engineering estimates and tabular data from standard handbooks.

The primary items of interest are heat transfer coefficients and initial conditions such as steam flow rates, inlet and outlet temperatures, circulation rates, etc. While some of these were directly obtainable from the boiler Technical Manual, others such as tube wall temperatures and riser exit quality were not. Therefore, a program was developed to permit the user to enter known data elements from the Technical Manual and other sources, and to obtain as an output the necessary values for the constants and initial conditions to ensure static balance at the specified operating point.

The basic premise under which the program operates is that the model equations with all derivatives set to zero form a determinant set with the addition of several relations which apply under equilibrium conditions. These relations are:

a. Riser and downcomer mass flow rates in each circuit are equal.

b. Total steam flow from the boiler equals the incoming feed flow rate.

c. Total heat transfer to the incoming feed equals the heat transfer to the screen and the main bank, and the heat removed from the steam passing through the desuperheater.

d. The net mass transfer at the steam liquid interface in the drum is zero.

B. PROGRAM EQUATIONS

The total heat input to the boiler was given by

$$E_B = \text{Heat Release } (\text{Btu/sec-ft}^3) \times \text{Furnace Volume } (\text{ft}^3) \ .$$

If the sensible heats of the oil and air are lumped with the heating value of the fuel, the heating value is

$$H_O = E_B / G_B \ .$$

The heat absorbed by the furnace screen at steady state was calculated from

$$\begin{aligned} ER1 = {} & \text{Furnace Heat Absorption } (\text{Btu/sec-ft}^2) \\ & \times \text{Radiant Heat Absorbing Surface } (\text{ft}^2) \ . \end{aligned}$$

Since the flue gas temperature and the screen tube wall temperatures were provided, the heat transfer coefficient for radiant heat transfer to the screen could be determined from

$$K_{R1} = E_{R1} \Big/ \left\{ \left(\frac{T_{R1}+460}{100}\right)^4 - \left(\frac{T_{M1}+460}{100}\right)^4 \right\} .$$

This result holds for the conditions reported in the manufacturers technical manual. Degredation due to age or fouling must be accounted for through the use of appropriate correlations.

With the enthalpy of the feed water at the economizer outlet and the enthalpy of the steam leaving the dry pipe, and the change in enthalpy of the steam flowing through the desuperheater, the heat transfer to the main bank was calculated from

$$E_{R3} = G_{D1}\,(H_{D1} - H_{W4}) - E_{R1} - G_{D2}\,(H_{SH_{OUT}} - H_{DS_{OUT}}) .$$

The metal temperature of the main bank risers were obtained by calculating the constant

$$K_{W4} = \frac{A_{MB}}{1.782 \times 10^6}$$

and solving the heat transfer equation

$$T_{M3} = \left\{ E_{R3} / K_{W4} P_{D1}^{4/3} \right\}^{1/3} + T_{D1} .$$

The specific heat of the flue gas passing the main bank was

$$C_{R2} = E_{R3} / G_R (T_{R3} - T_{R4})$$

and the unknown constant in the gas side heat transfer relation was determined from

$$K_{R3} = E_{R3} / G_R^{.6} (T_{Ra3} - T_{M3}) .$$

In a similar manner, the specific heat of the furnace flue gas is

$$C_{R1} = (E_B - E_{R1}) / G_R T_{R1}$$

and the water side heat transfer coefficient is

$$K_{W3} = E_{R1} / P_{D1}^{4/3} (T_{M1} - T_{D1})^3 .$$

The heat transferred in the desuperheater was:

$$E_{D2} = G_{D2} (H_{SH_{OUT}} - H_{DS_{OUT}}) .$$

With this value and the temperature difference the specific heat of the steam was computed from

$$C_{D2} = E_{D2} / G_{D2} (T_{D2} - T_{D3}) .$$

The heat transfer coefficient was calculated from the Dittus-Boelter correlation [11]

$$K_{D2} = \frac{k}{d} (.023) \left(\frac{4.0}{\pi \mu d} \right)^{.8} P_r^{.3} A .$$

The log mean temperature difference was

$$LMTD = E_{D2} / K_{D2} G_{D2}^{.8}$$

and the metal temperature was determined by

$$T_{MS} = (T_{D2} - Q T_{D3}) / (1 - Q)$$

where:

$$Q = \operatorname{Exp} \{ LMTD / (T_{D2} - T_{D3}) \} .$$

With the metal temperature, the water side heat transfer constant was obtained from

$$K_{W2} = E_{D2} / (T_{MS} - T_{W1}) .$$

Analysis of the Economizer is more complicated since it is a multipass heat exchanger with finned tubes. Additionally, since we are concerned with energy storage within the metal of the economizer, the internal and external heat transfer must be considered separately.

The heat transferred was given by the change in enthalpy of the feed water, i.e.,

$$E_{w1} = G_{D1} \left(H_{w4} - H_{w3} \right) .$$

The specific heat of the water was

$$C_w = E_{w1} / G_{D1} \left(T_{w4} - T_{w3} \right) .$$

As in the case of the desuperheater, the inside heat transfer coefficient was calculated from the Dittus-Boelter correlation as

$$K_{w1} = \frac{k}{d} (.023) \left(\frac{4}{\pi \mu d} \right)^{.8} Pr^{.4} A .$$

From this the LMTD was obtained as

$$LMTD = E_{w1} / K_{w1} G_{D1}^{.8} .$$

Finally the metal temperature was determined from

$$T_{M4} = (T_{W4} - \beta T_{W3}) / (1-\beta)$$
$$\beta = \exp\{LMTD / (T_{W4} - T_{W3})\}$$

The outside heat transfer constant was

$$K_{R4} = E_{W1} / G_R^{.6} (T_{Ra3} - T_{M4})$$

where

$$T_{Ra3} = \frac{T_{R4} + T_{R5}}{2}$$

The specific heat of the flue gas passing the economizer was

$$C_{R3} = E_{W1} / G_R (T_{R4} - T_{R5})$$

The superheater heat transfer was obtained from the change in enthalpy of the steam, i.e.,

$$E_{D1} = G_{D1} (H_{SH\,out} - H_{D1})$$

With this value and the known metal and gas temperatures, the specific heat of steam, the specific heat of the flue

gas passing the superheater, and the inside and outside heat transfer constants were determined as

$$C_{D1} = E_{D1} / G_{D1} (T_{D2} - T_{D1})$$

$$C_{R1a} = E_{D1} / G_R (T_{R2} - T_{R3})$$

$$K_{D1} = E_{D1} / G_{D1}^{.8} \, LMTD$$

$$K_{R2} = E_{D1} / G_R^{.6} (T_{Ra1} - T_{m2})$$

where:

$$LMTD = \frac{T_{D2} - T_{D1}}{\ln\left\{\dfrac{T_{M2} - T_{D1}}{T_{M2} - T_{D2}}\right\}}$$

and

$$T_{Ra1} = (T_{R2} + T_{R3}) / 2.0 \quad .$$

The superheater and desuperheater pressure drop constants were evaluated from the known equilibrium pressures as

$$C_7 = (P_{D1} - P_{D2}) \rho_{Da1} / G_{D1}^2$$

$$C_9 = (P_{D2} - P_{D3}) \rho_{Da2} / G_{D2}^2 \quad .$$

Similarly, the constants used in the calculation of the average steam densities were obtained from:

$$C_8 = (P_{D1} + P_{D2}) / (\rho_{D1} + \rho_{D2})$$

and

$$C_{10} = (P_{D2} + P_{D3}) / (\rho_{D2} + \rho_{D3}) .$$

Finally the steam value flow constant was computed from

$$C_3 = G_{D4} / (P_{D2} V_{ENT}) .$$

C. CIRCULATION BALANCE

Since they are not normally provided by the manufacturer, values for the friction factors, and bend and entrance loss coefficients must be assumed. The values do not appear to be particularly critical, and tables found in engineering handbooks may be used to determine reasonable values for these parameters.

An iterative procedure must be used to adjust the various flow values involved to achieve a steady state balance. Since the riser exit quality for boilers of this type generally lies in the range of .02 to .04, a starting trial value for the circulation flow rate may be obtained from:

$$E_r = X_e G_r H_{fg}$$

where X_E is the exit quality, E_r' is the heat transfer to the riser, G_r is the flow rate, and HFG is the heat of vaporization. With this trial value, the following balancing procedure is used:

1. Set HW2 (Downcomer Enthalpy) = HW1

2. Calculate HWG = HW2 + ED2/GØ

3. Calculate the riser exit quality:

$$X_o = E_{R3} / (H_{fg} + H_{w1} - H_{w6})\, G_o$$

4. Determine the non-boiling height:

$$H_{NBR} = H_{XR} (H_{w1} - H_{w6}) / (H_{w1} + X_o H_{fg} - H_{w6})$$

5. Compute the average riser density:

$$\rho_{a1} = \frac{1}{H_{XR}} \left\{ \frac{H_{XR} - H_{NBR}}{X_o V_{fg}} \ln\left(\frac{X_o V_{fg}}{V_f} + 1\right) + \rho_w H_{NBR} \right\}$$

6. Obtain the outlet density:

$$\rho_o = 1.0 / (V_f + X_o V_{fg})$$

7. Compute the friction factor:

$$F_R = \left\{ \frac{1}{1.74 - 2\log(R/K_s)} \right\}^2 \left\{ 1 + 16078.58 \left(\frac{X_o}{P_{D1}}\right)^{.96} \right\}$$

8. Next the riser loss factor is computed:

$$\psi_1 = (F_R \frac{L_R}{D_R} + 1)\, R_{a1}/2A_r^2 R_o^2 + Z_3/2A_r^2 R_w + Z_4/2A_r^2 R_o$$

9. Finally we may calculate GØ':

$$G_o' = \left\{ (R_w - R_{a1}) H_{xr}\, g \,/\, (C_{100} + \psi_1) \right\}^{1/2}$$

where C100 is the downcomer loss factor.

10. Compare GØ and GØ' if equal go on, otherwise update GØ:

$$G_o = \frac{G_o' - G_o}{2} + G_o$$

and return to step 2.

11. Assume a trial value for Gs (first pass only).

12. Compute Xs:

$$X_s = (G_{D1} - G_o X_o)/G_s$$

13-19 Same as for the main bank risers. Return to 12 if reiteration necessary.

20. Obtain HW2' from:

$$H_{W2}' = \frac{G_{W2}}{G_S + G_O} (H_{W4} - H_{W1}) + H_{W1}$$

21. If HW2' = HW2 go on, otherwise update HW2:

$$H_{W2} = \frac{H_{W2}' - H_{W2}}{2} + H_{W2}$$

and return to step 2.

Upon exit from the iteration loop, equilibrium values of the flow parameters will have been established. With these and the previously calculated heat transfer parameters, the program generates the list of constants and integration initial conditions required by the dynamic model. The program listing and a sample output is given in Appendix B.

V. RESULTS AND CONCLUSIONS

A. OPEN LOOP RESPONSES

The output curves for 10% increases and decreases in throttle valve opening and fuel flow are given in Figures 6-33. Ramp inputs of approximately 1.5% per second were used to simulate flexibility test conditions. Only one input parameter was varied for each run with all others held constant. The results were similar to those presented in [3] and [4] insofar as general trends were concerned. Since the boilers involved were of widely different geometries and sizes, a quantitative comparison was not possible. Since CSMP uses only single precision arithmetic packages and integration algorithms, the high frequency noise in the outputs is attributable to the roundoff error inherent in the wide variations in magnitudes of numbers used in the model, e.g., quality (order of 0.01) and riser mass flow rate (order of 1000). In common with the results of [3] and [4], the "swell effect" in response to an increase in throttle opening is negligible. It should be noted that the swell exhibited in the data of Whalley [3] is more apparent than real, inasmuch as the scales in his graphs are very magnified and the rise is actually only 0.01 inches. The sudden increase in riser mass flow rate shown in [3] is also not present in the current model.

Since "shrink" and "swell" effects are of some concern to controls designers, an attempt was made to model for such effects. Four possible causes for the phenomenon were considered.

1. Homogeneous Nucleation in the Steam Drum Liquid

This effect is caused by a difference between the saturation temperature corresponding to the actual drum pressure, and the actual liquid temperature. The superheat required for such nucleation is quite high however and nucleation will occur at the heating surfaces at much lower superheats. Therefore this was considered to be an unlikely cause for the effect.

2. Nucleate Boiling at the Drum Wall-liquid Interface

The driving force for this phenomenon is also the temperature difference between the drum surface and the saturation temperature. Since the temperature difference will be slight except under large drum pressure excursions, the impact of this factor should be slight. The Rohsenow correlation [5] may be solved in terms of a rate of vapor generation to yield

$$q/h_{fg} = \left\{ \frac{C_\ell \, \Delta T}{C_{sf} \, h_{fg} \, Pr_\ell^{1.7}} \right\}^3 \sqrt{\frac{g(\rho_\ell - \rho_v)}{g_c \, \sigma}} \; \mu_\ell A \, .$$

It was assumed that the vapor formed would be uniformly distributed bubbles which would rise to the surface with a

velocity given by [14]

$$U_b = \frac{1}{3}\sqrt{2 g D}$$

which is a conservative estimate since interaction effects tend to increase the rise velocity. The bubble diameter is given by [14]

$$D = .242\ P^{-.5}$$

This gives U_b as .25 ft/sec. The average liquid depth is 15 inches, so the transit time is ≈ 5 seconds. The effect was modeled crudely by assuming the entrained bubble mass was 5.0(q/hfg) lbm. The impact of this model on shrink and swell values was negligible, since no large pressure excursions were developed.

3. <u>Expansion and Contraction of Varpor Bubbles Entrained in the Riser Fluid</u>

An attempt was made to model this effect by including the riser tubes in the control volume used as the basis for liquid level determination. The equation used was

$$V_{OL} = M_{W1}/R_W + \left(\frac{R_{a1}}{R_{a1x}} - 1\right) V_{RB} + \left(\frac{R_{a2}}{R_{a2x}} - 1\right) V_{SB}$$

where Ra1x and Ra2x are the average riser densities computed using the specific volume for the saturated vapor corresponding

to drum pressure, while Ra1 and Ra2 were computed from the liquid temperature saturation conditions. The effects were insignificant.

4. Transient Deviation of Riser and Downcomer Mass Flow Rates

The small swell effect obtained by Whalley [3] can be attributed to the temporary increase of riser mass flow rate over downcomer mass flow rate. The period over which this imbalance could be sustained is short and would fail to account for the longer duration of "shrink" and "swell" effects observed in practice. It may, however trigger one of the two phase flow instabilities common to natural circulation loops e.g., flow oscillations [10,13]. The analysis of these effects was not exhaustive, and the modeling attempts were crude. In the case of the first two, however, the contribution to swell is probably not significant. Modeling difficulties with the latter two effects precluded any specific conclusions.

B. CONCLUSIONS

As with all simulations, the information available from the model is extensive. Notably, in this study, main bank and water-screen circulation values can be separately evaluated. Hence, the contribution of each of these elements to overall boiler operational response and efficiency can be determined.

The model simulates the responses of a Naval boiler quite well. Unfortunately, open loop data is unavailable

for the actual boiler and insufficient information was available to develop a model of the existing LHA-1 control system as a basis for comparison studies. As such, however, the model forms a basis upon which future studies involving modern control system designs can be established. Moreover, while considerable refinement of the model is possible, the advantages of greater accuracy must always be weighed against increased computation costs. In this regard, the implementation of more efficient integration algorithms would be particularly beneficial.

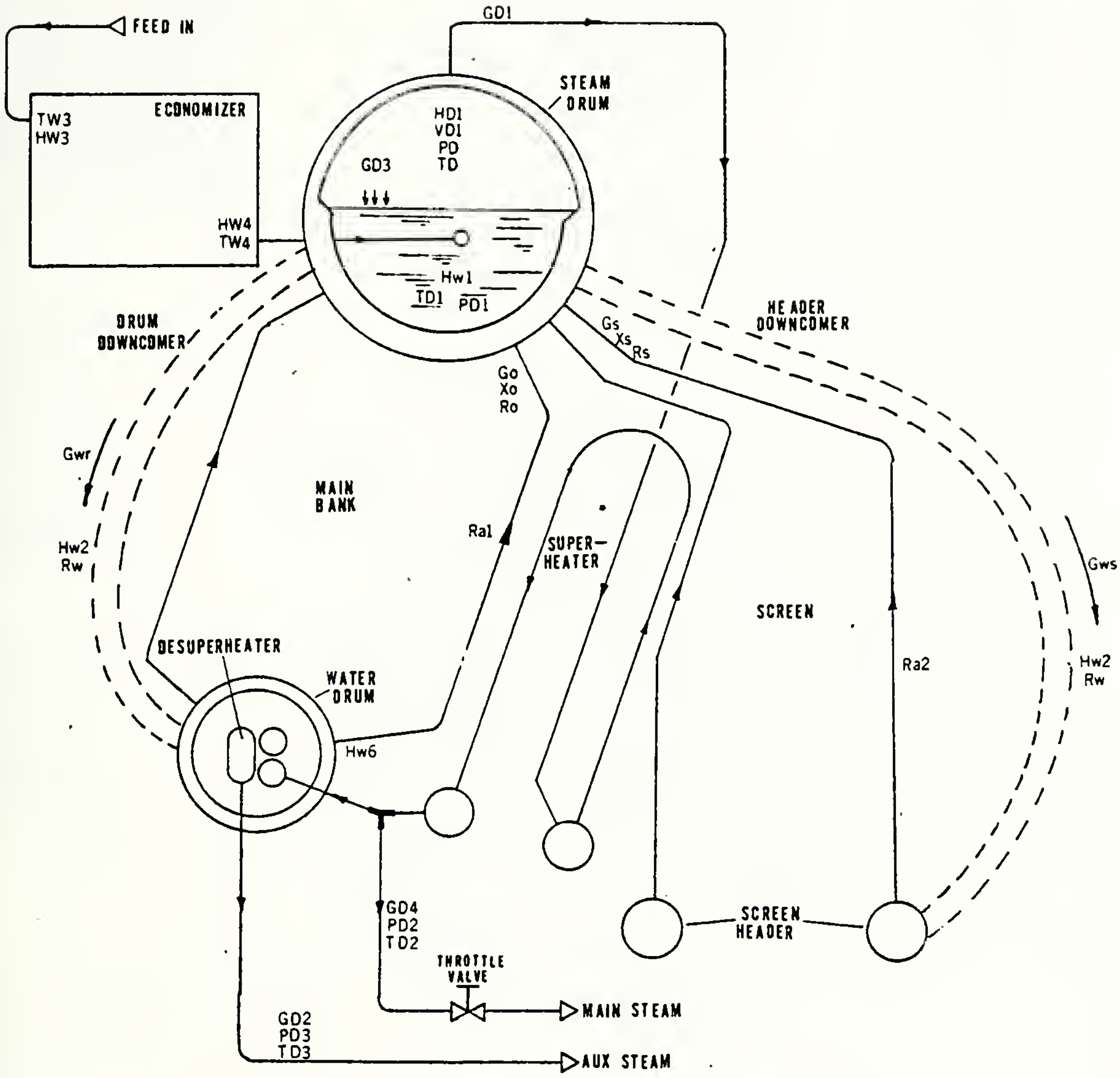

FIGURE 1. SIMPLIFIED BOILER SCHEMATIC

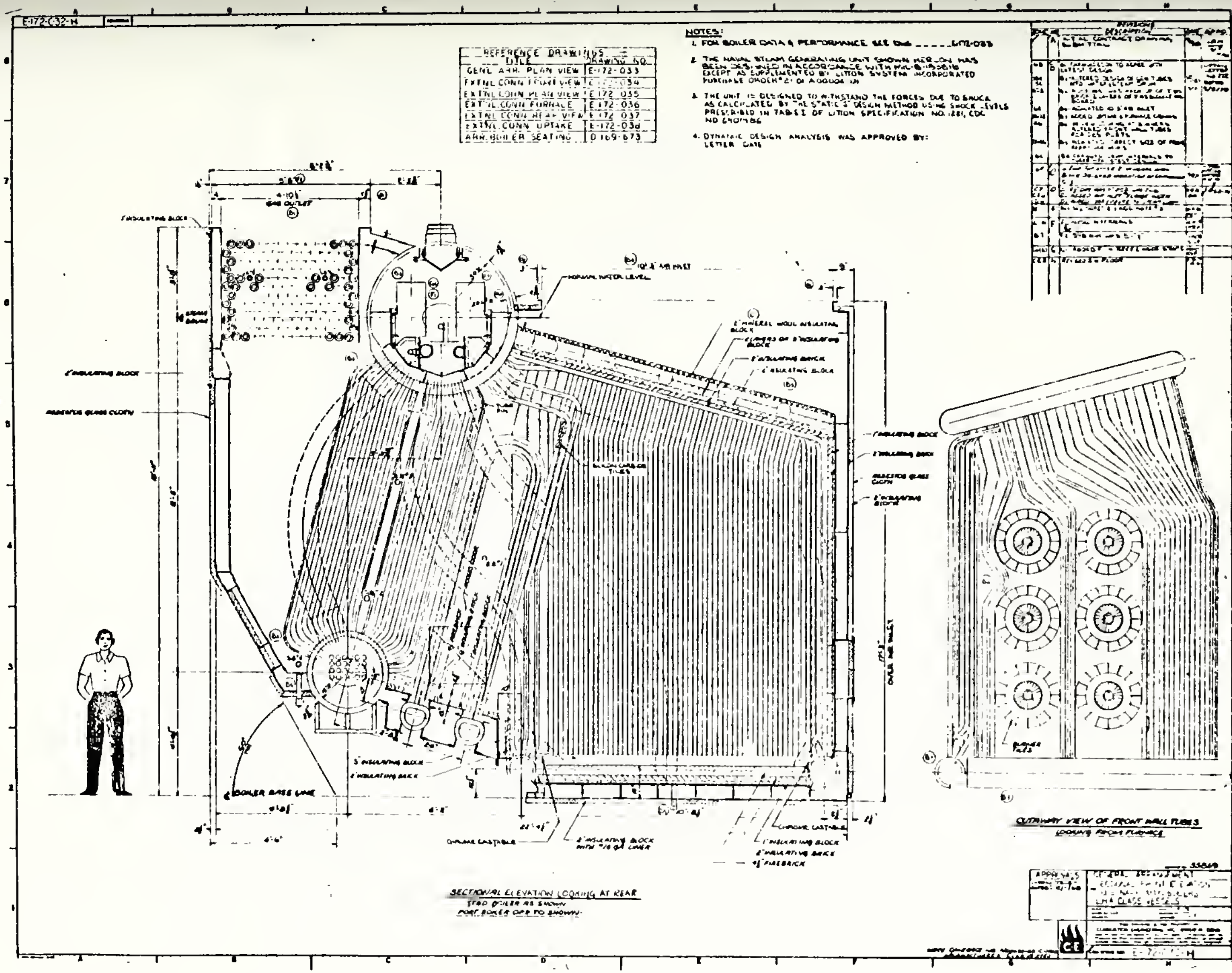

FIGURE 2. COMBUSTION ENGINEERING TYPE V-2M BOILER

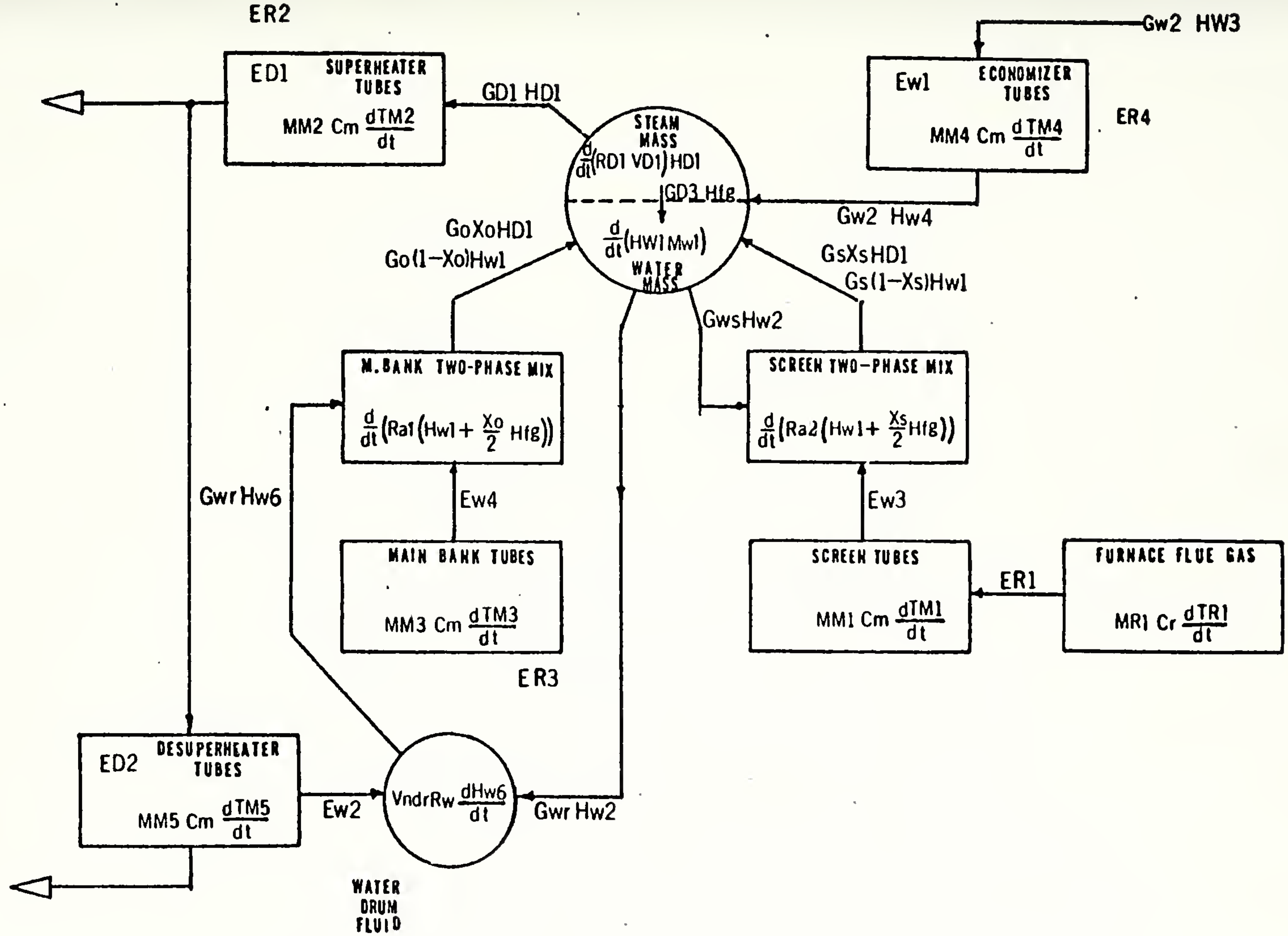

FIGURE 3. CONTROL VOLUME ARRANGEMENT

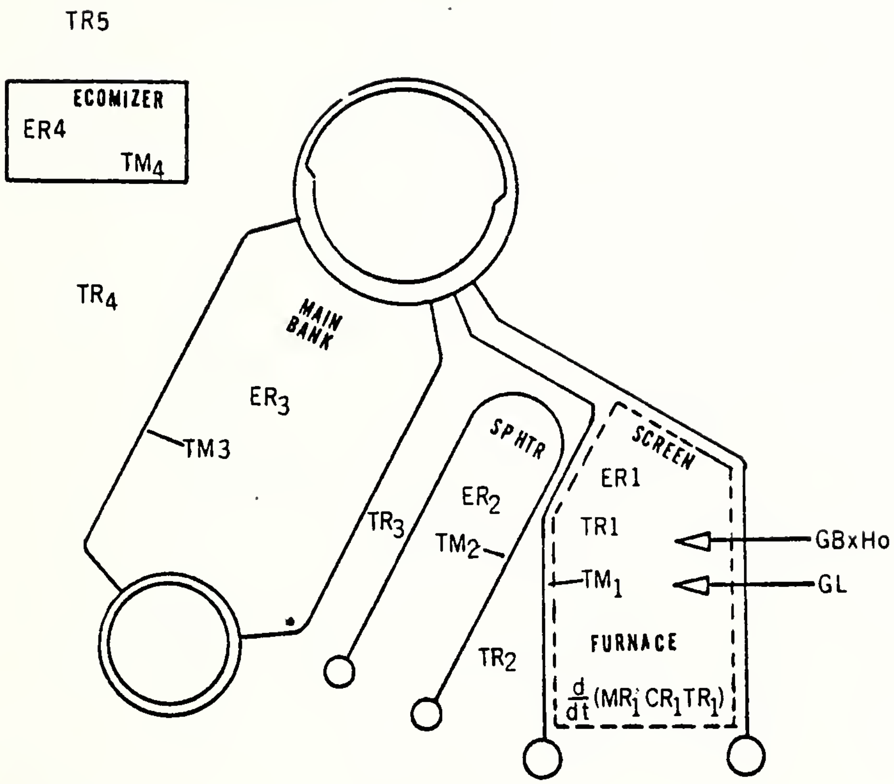

FIGURE 4. FLUE GAS AND COMBUSTION SCHEMATIC

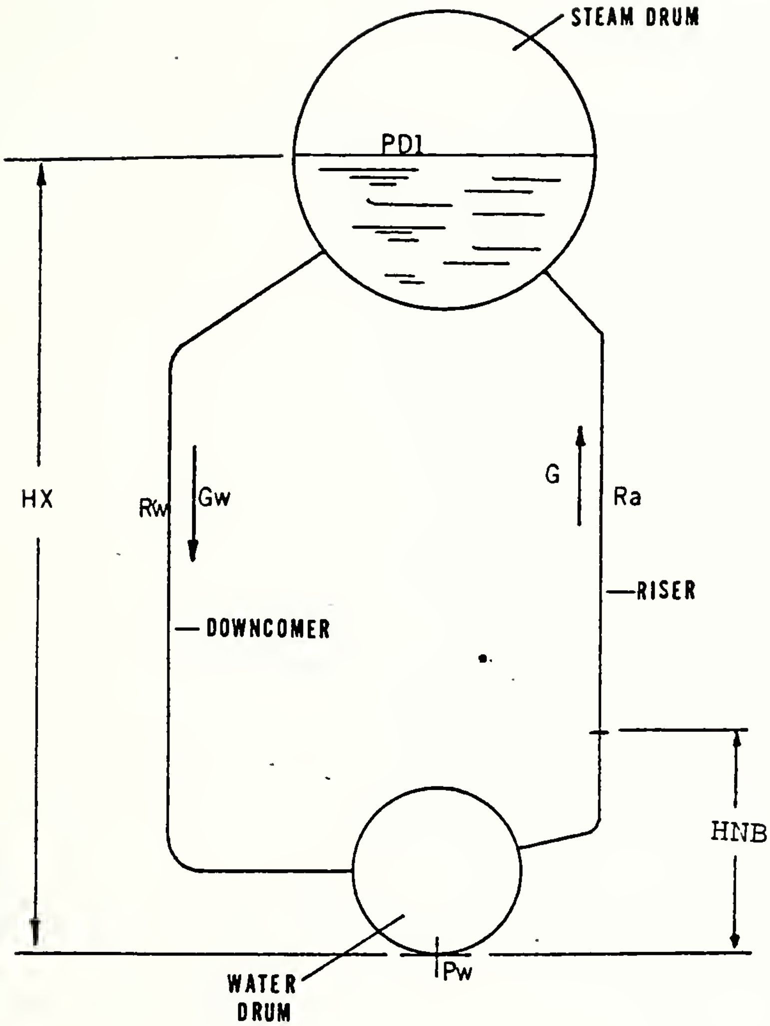

FIGURE 5. BASIC CIRCULATION SYSTEM

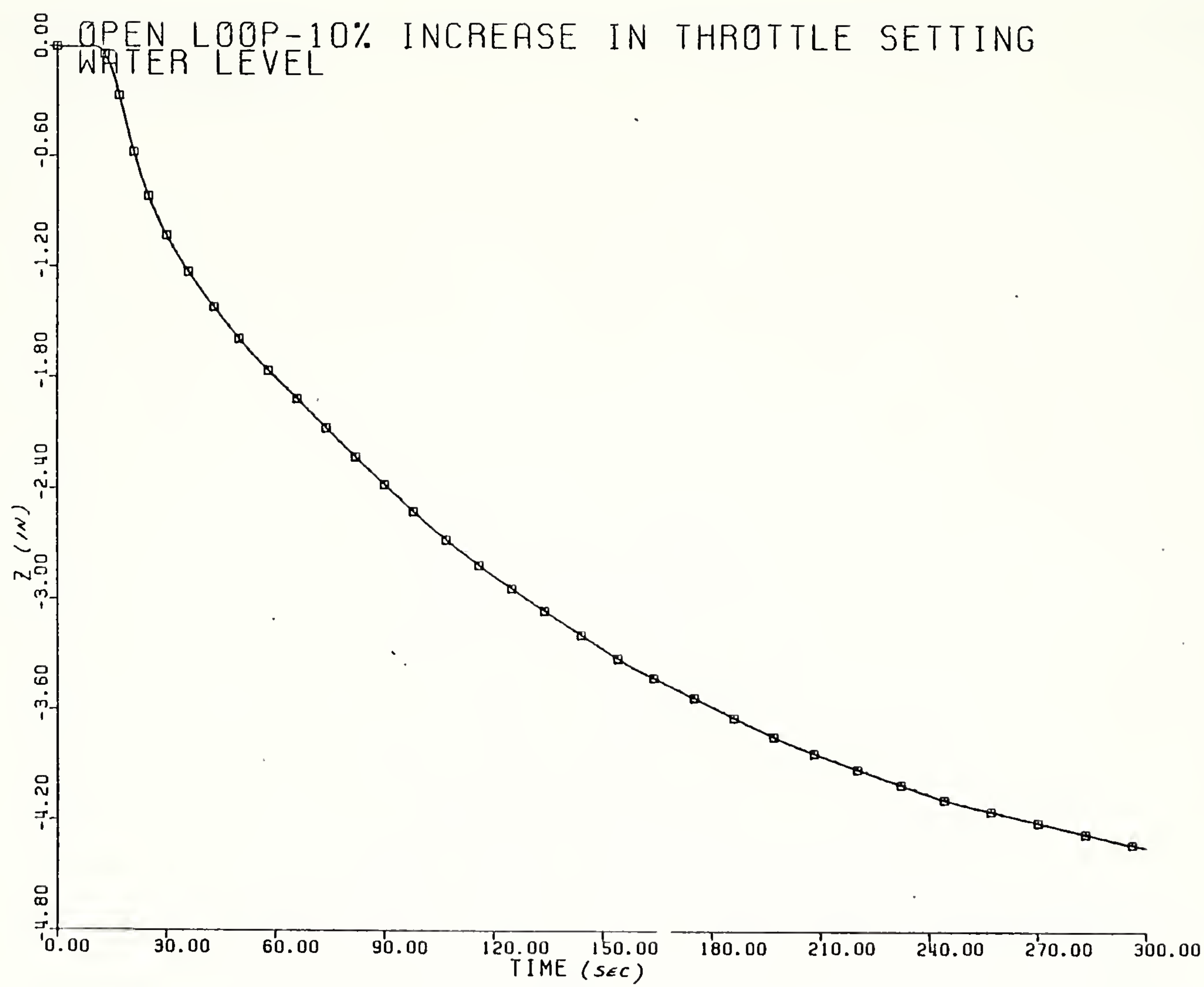

FIGURE 6. WATER LEVEL RESPONSE TO A 10% INCREASE IN THROTTLE SETTING

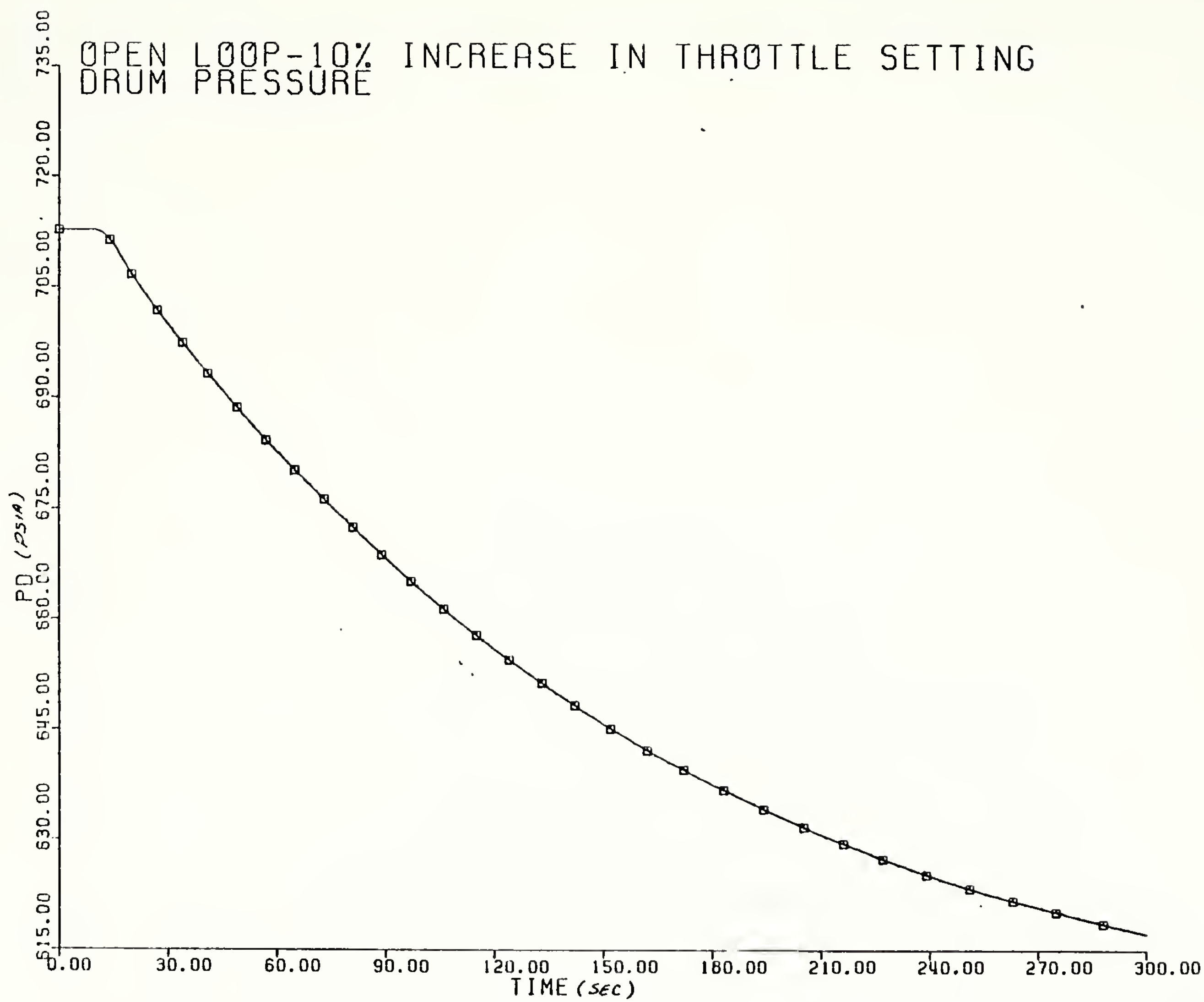

FIGURE 7. DRUM PRESSURE RESPONSE TO A 10% INCREASE IN THROTTLE SETTING

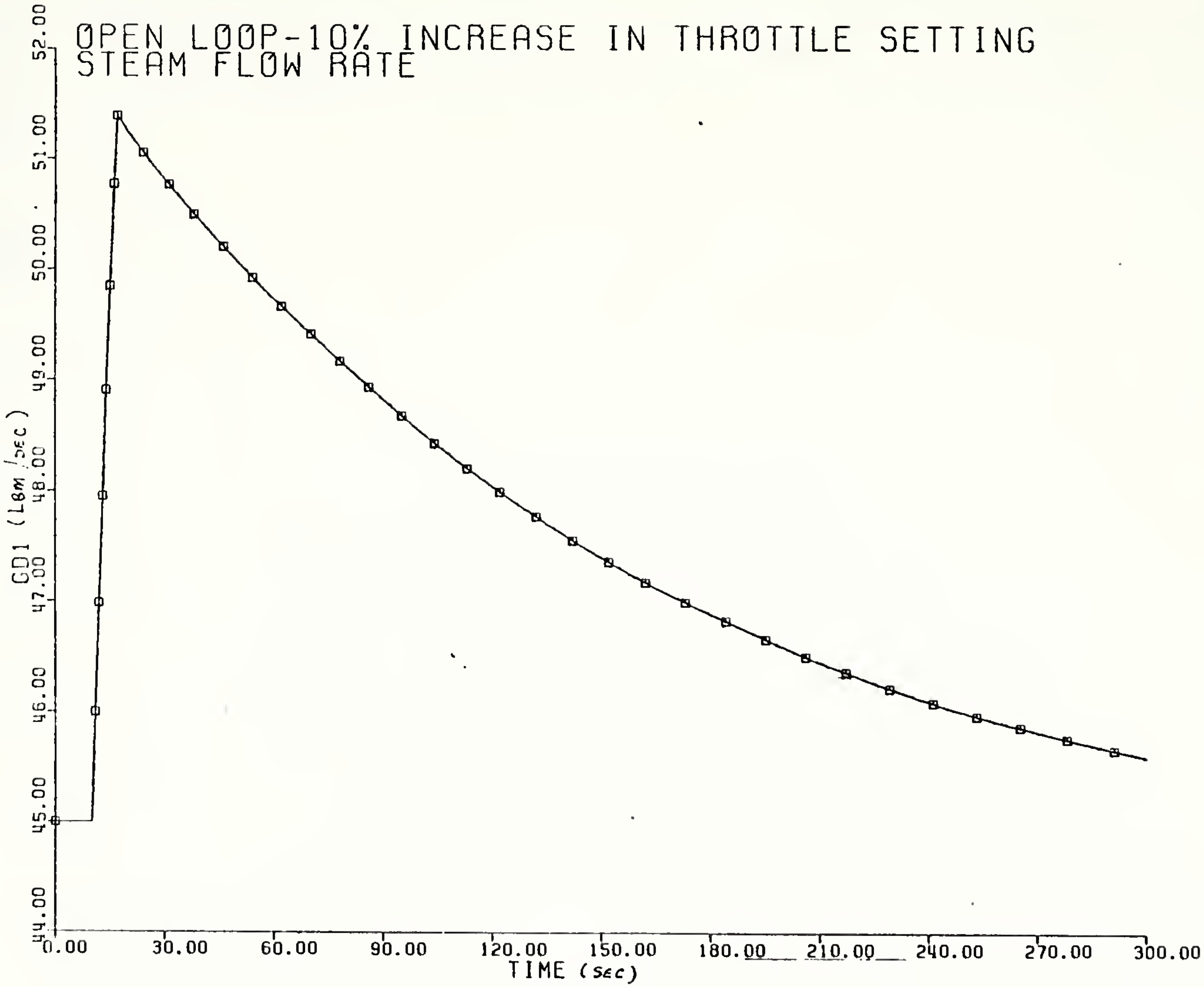

FIGURE 8. STEAM FLOW RATE RESPONSE TO A 10% INCREASE IN THROTTLE SETTING

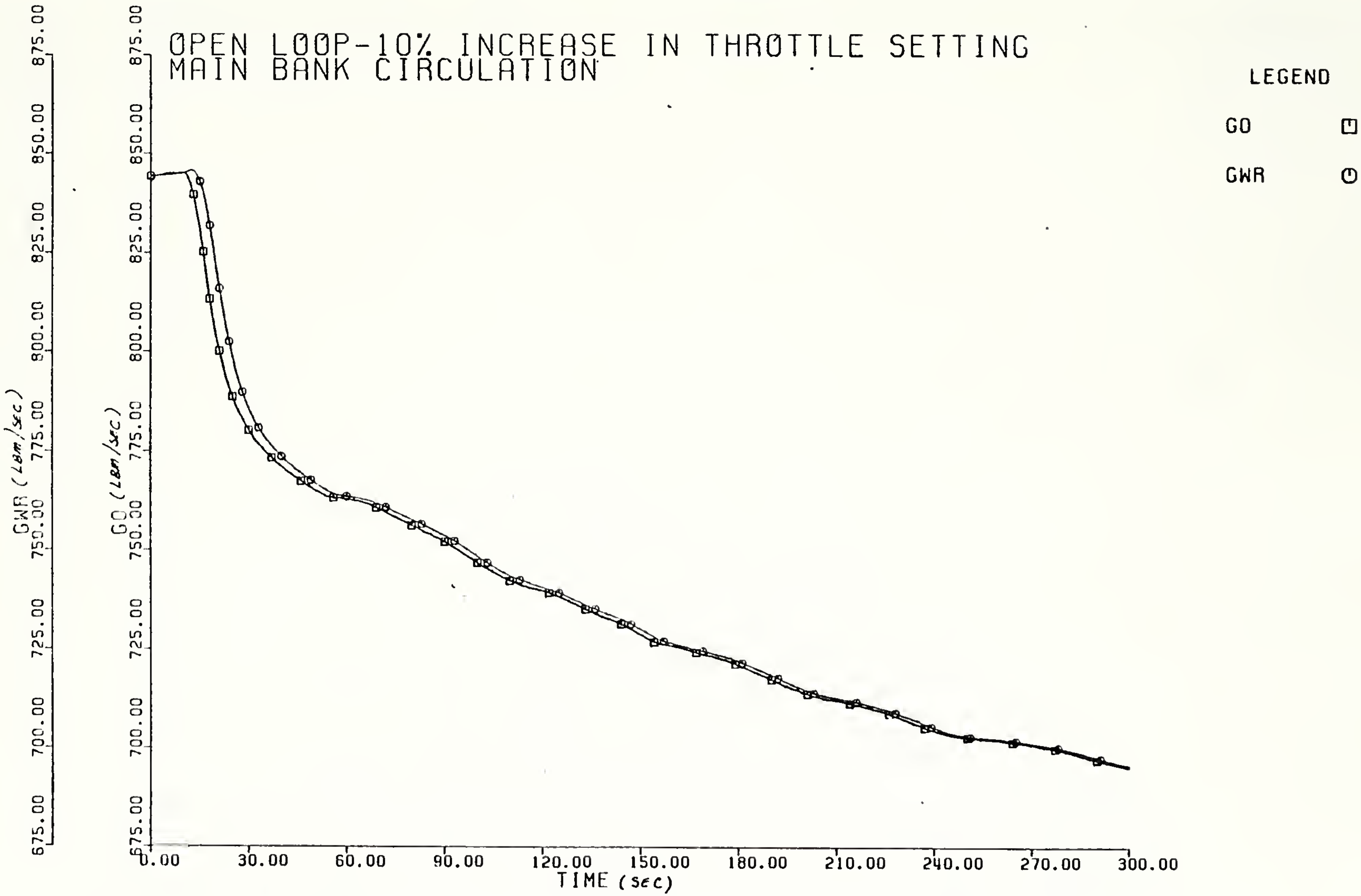

FIGURE 9. MAIN BANK CIRCULATION RESPONSE TO A 10% INCREASE IN THROTTLE SETTING

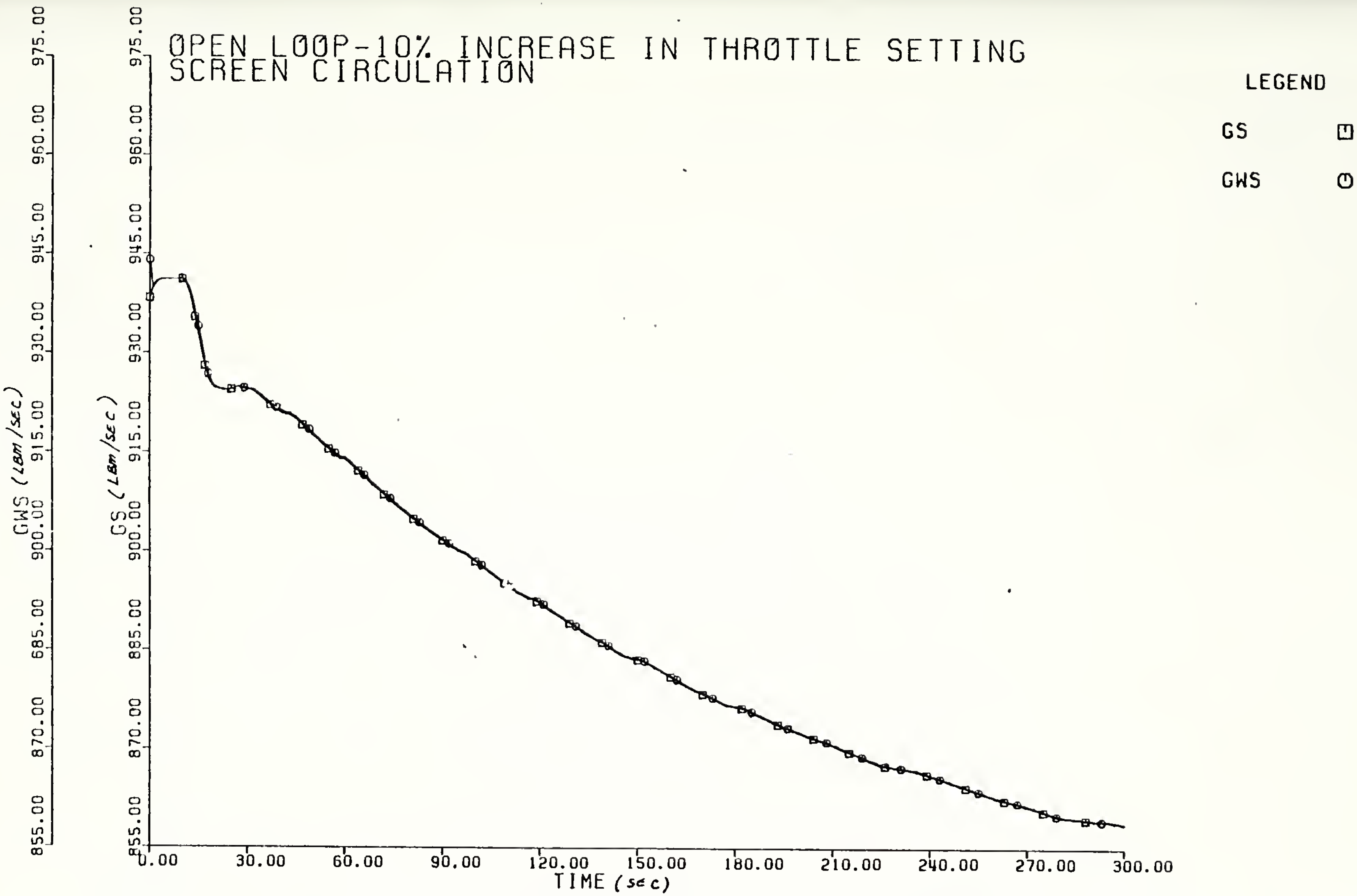

FIGURE 10. SCREEN CIRCULATION RESPONSE TO A 10% INCREASE IN THROTTLE SETTING

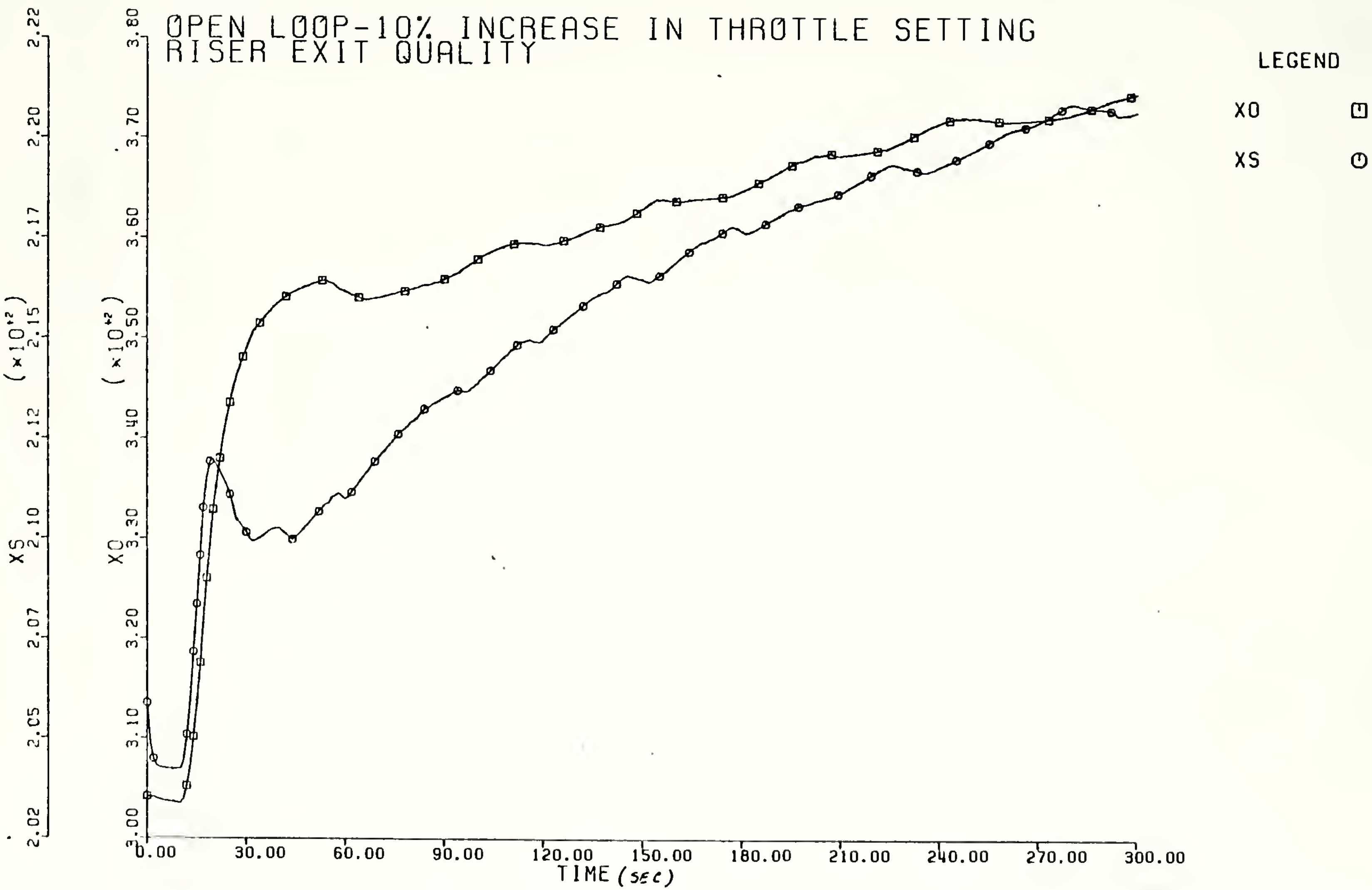

FIGURE 11. RISER EXIT QUALITY RESPONSE TO A 10% INCREASE IN THROTTLE SETTING

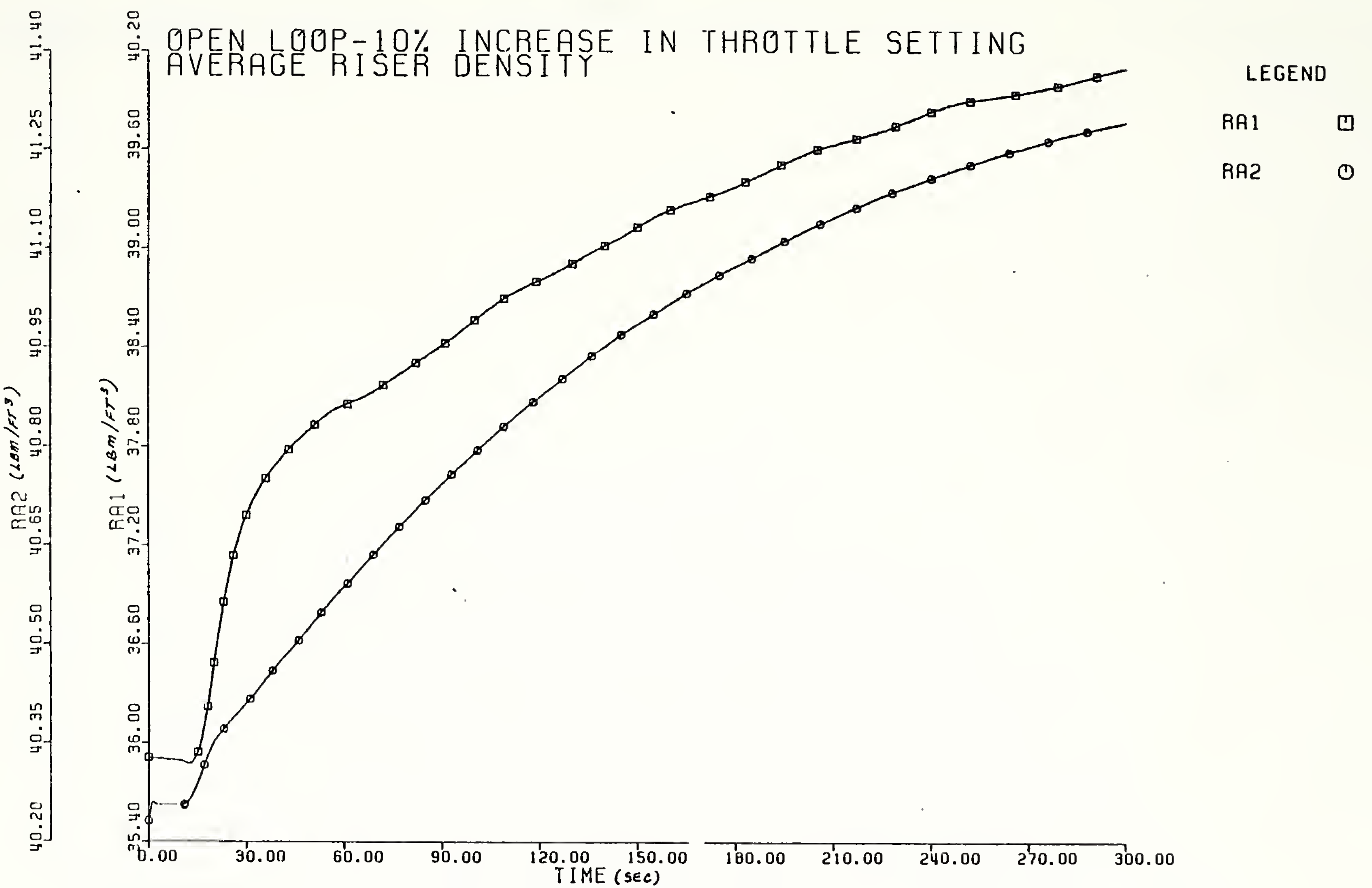

FIGURE 12. AVERAGE RISER DENSITY RESPONSE TO A 10% INCREASE IN THROTTLE SETTING

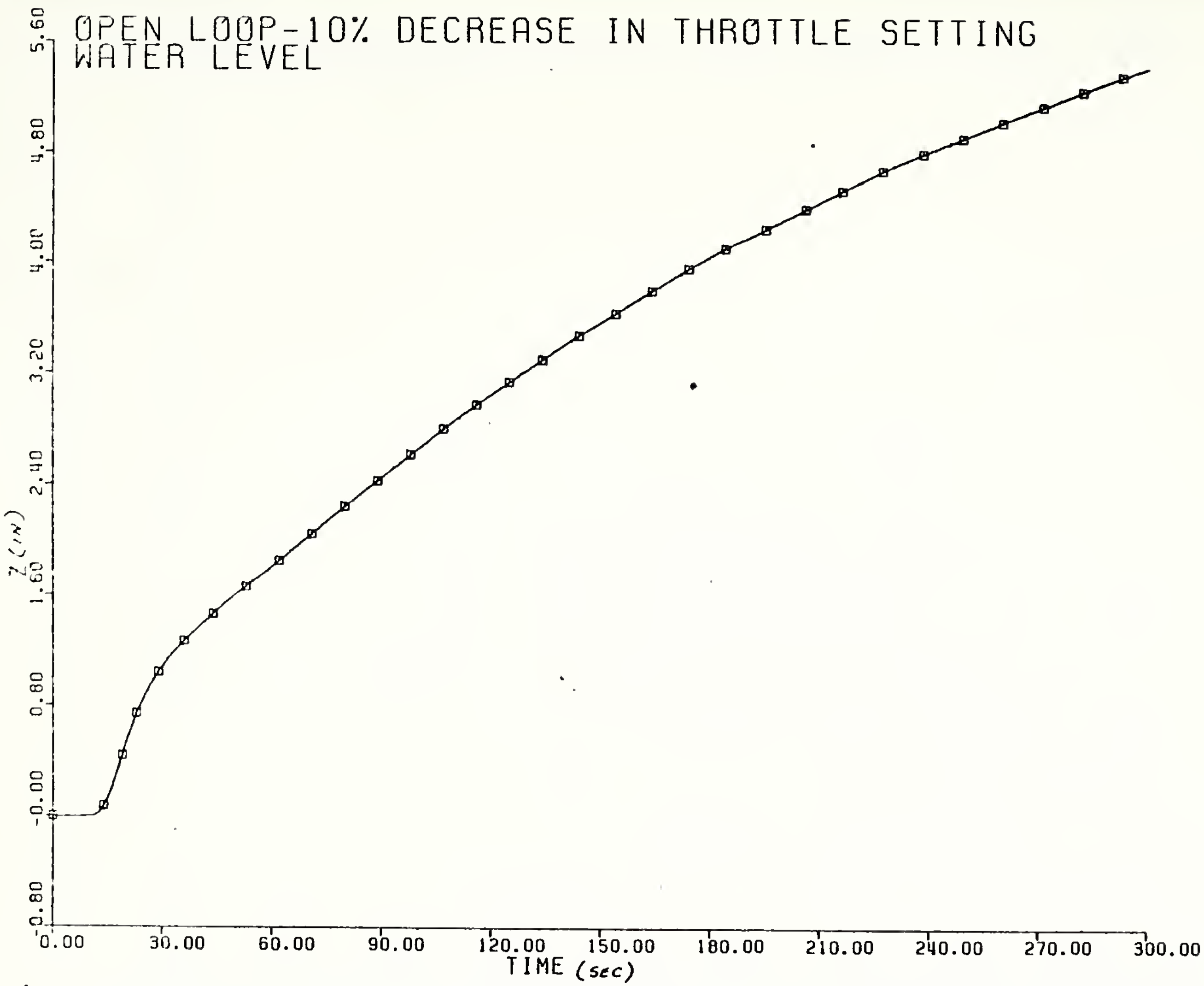

FIGURE 13. WATER LEVEL RESPONSE TO A 10% DECREASE IN THROTTLE SETTING

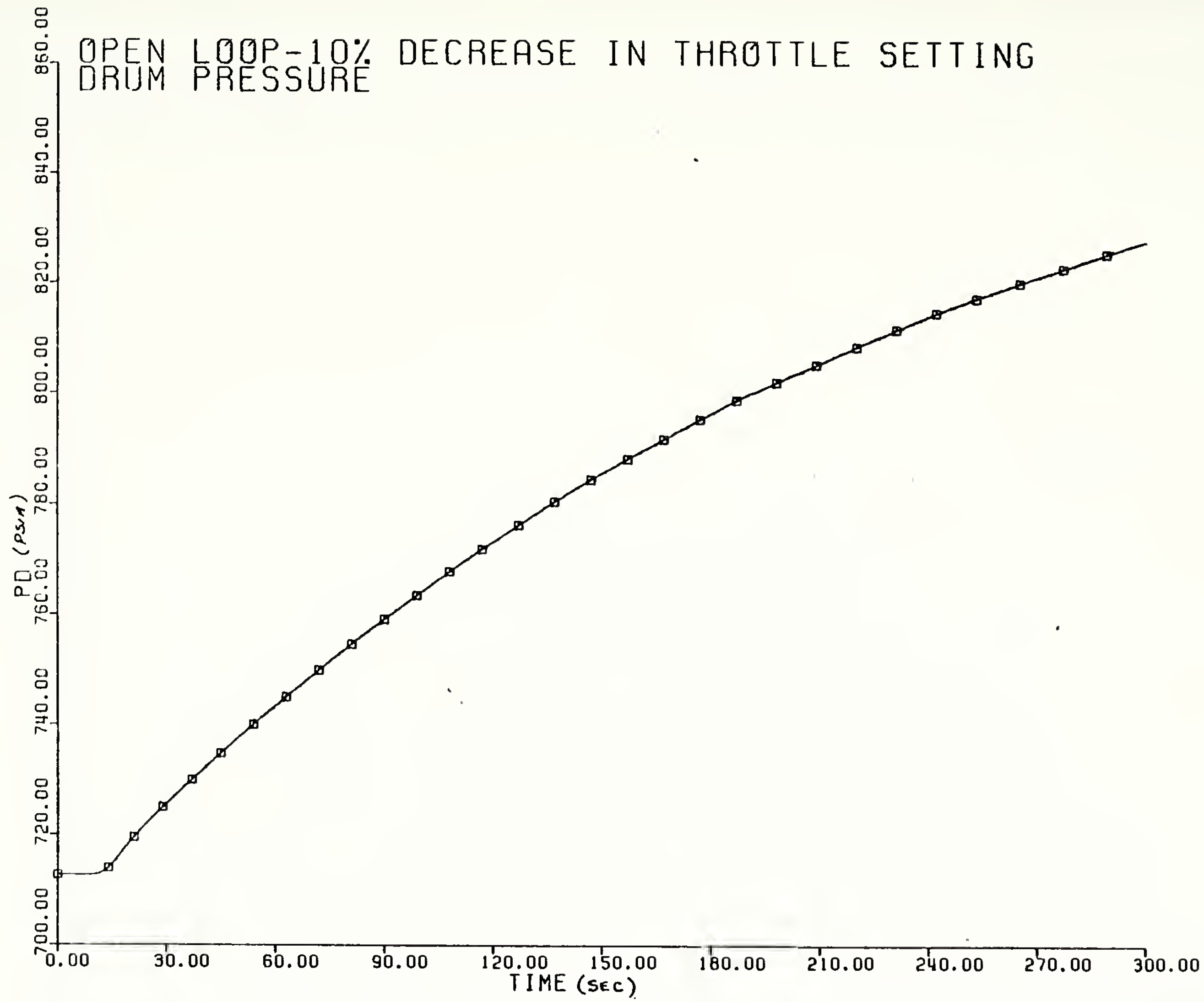

FIGURE 14. DRUM PRESSURE RESPONSE TO A 10% DECREASE IN THROTTLE SETTING

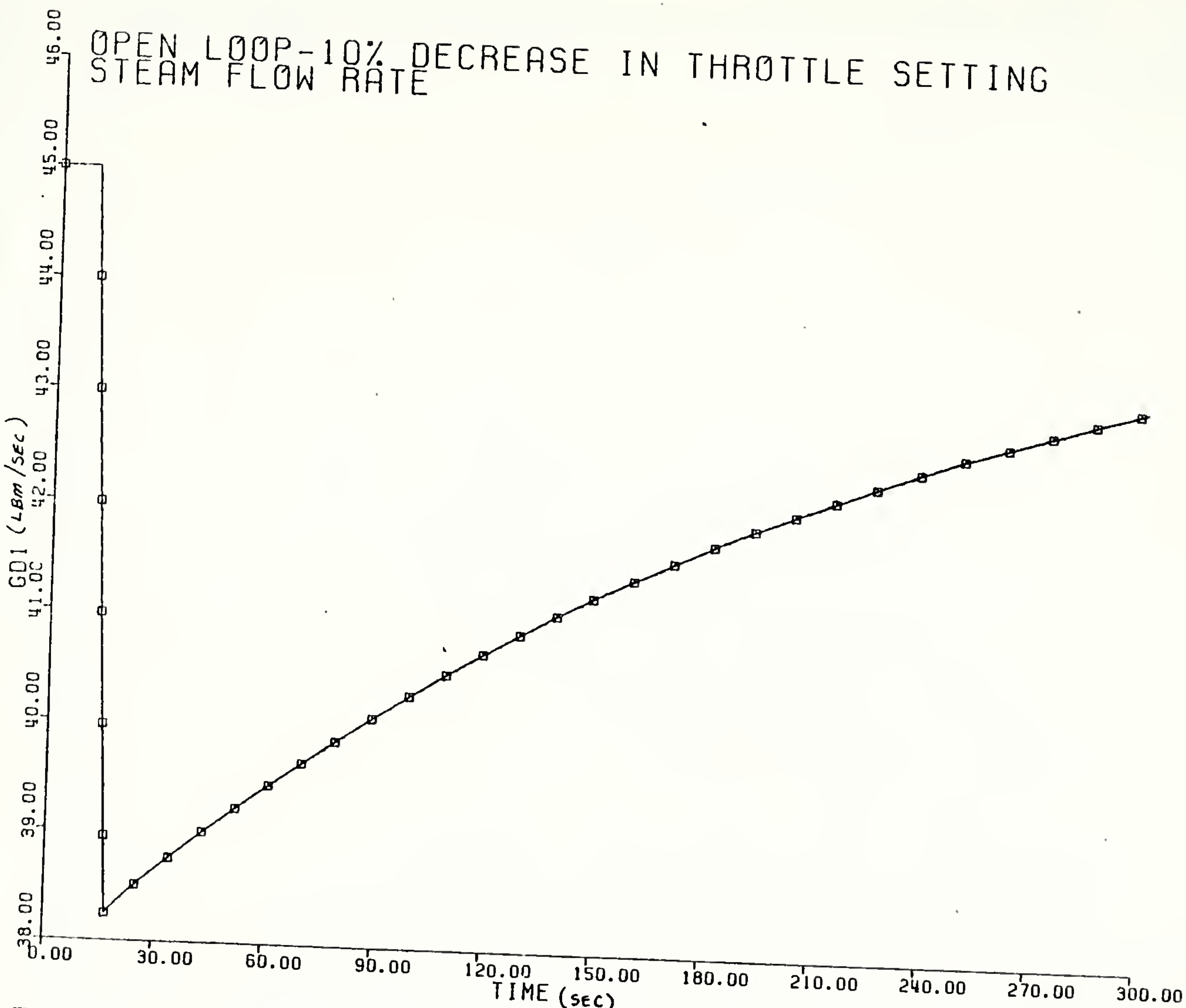

FIGURE 15. STEAM FLOW RATE RESPONSE TO A 10% DECREASE IN THROTTLE SETTING

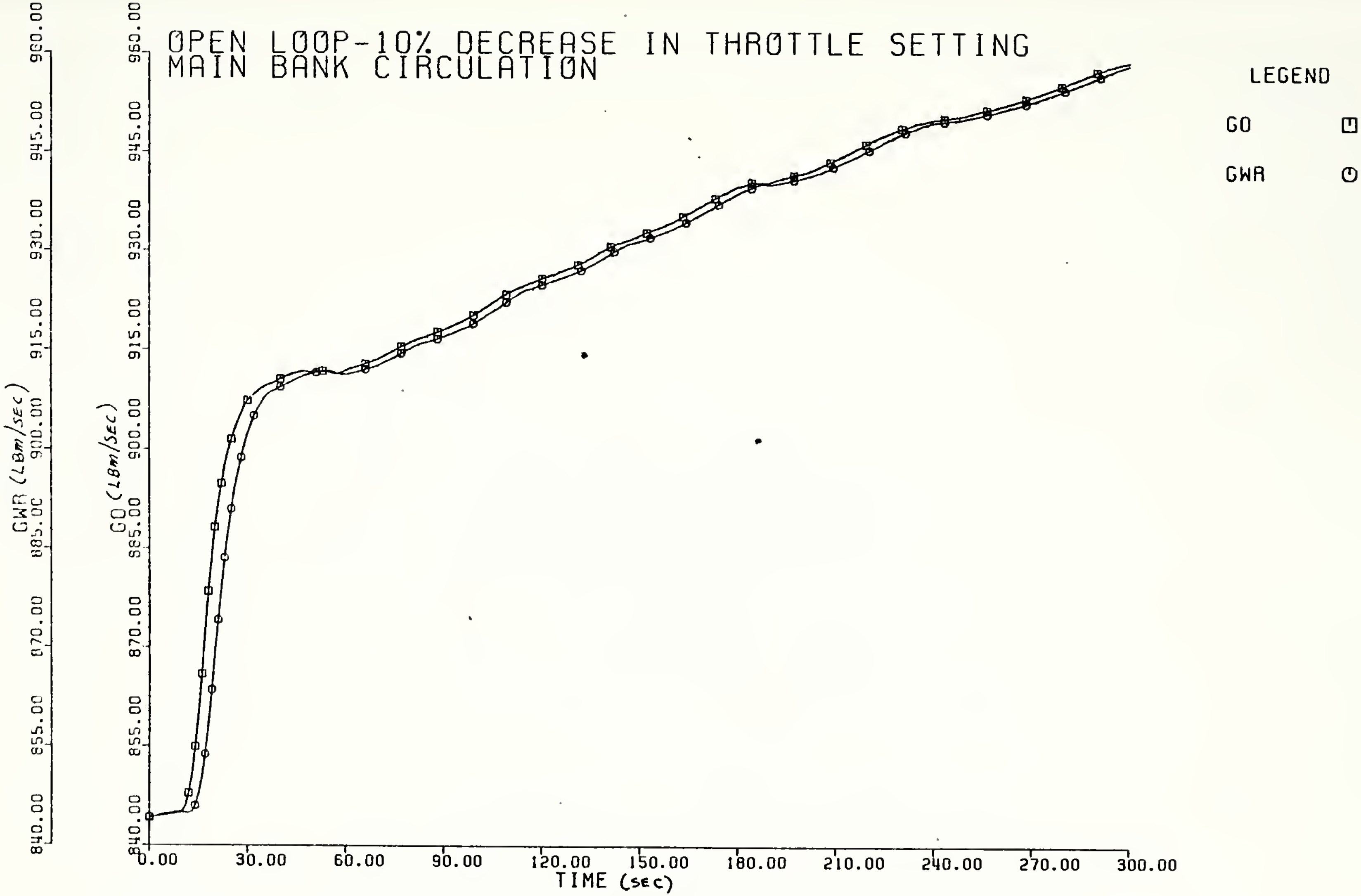

FIGURE 16. MAIN BANK CIRCULATION RESPONSE TO A 10% DECREASE IN THROTTLE SETTING

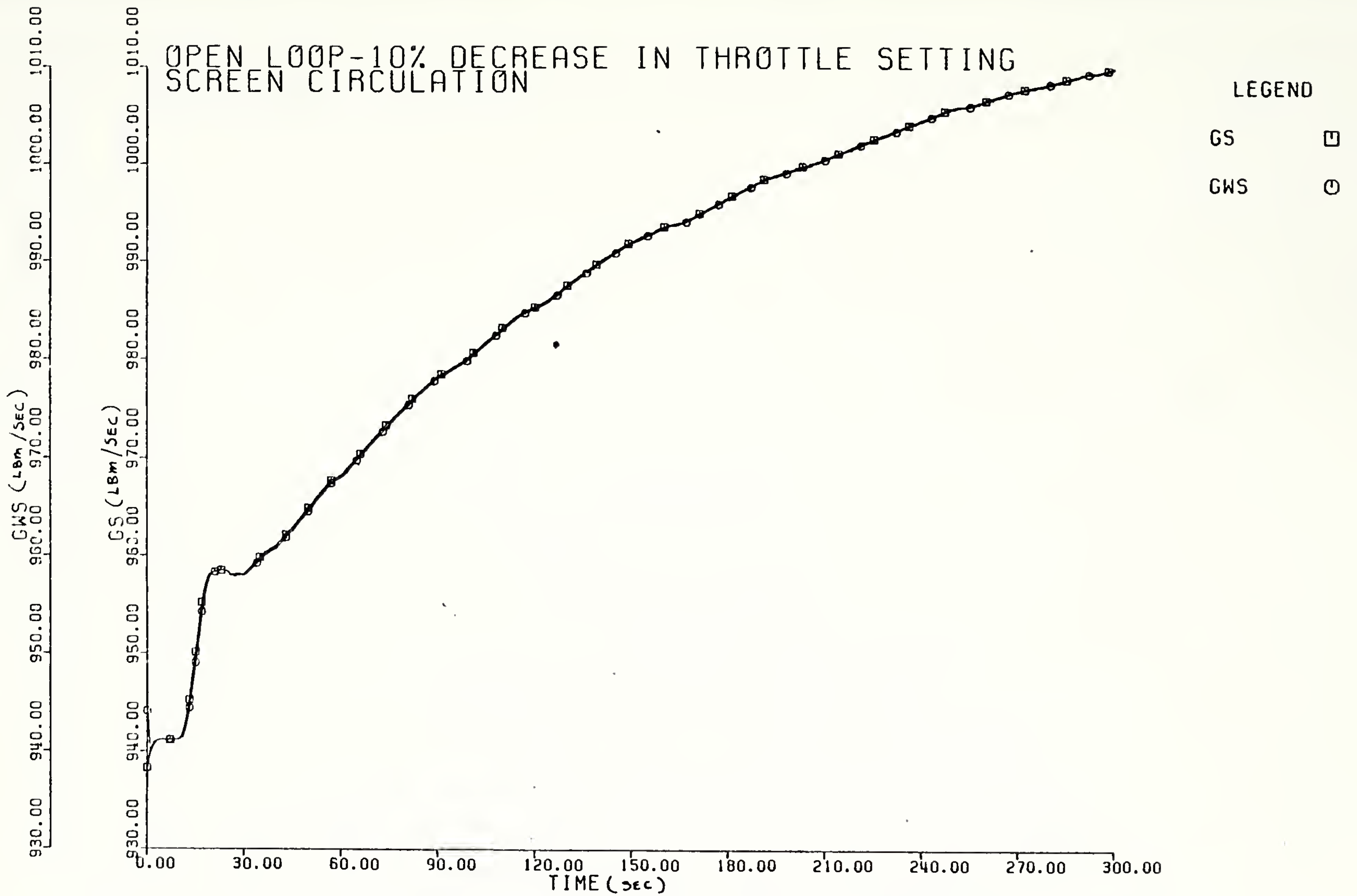

FIGURE 17. SCREEN CIRCULATION RESPONSE TO A 10% DECREASE IN THROTTLE SETTING

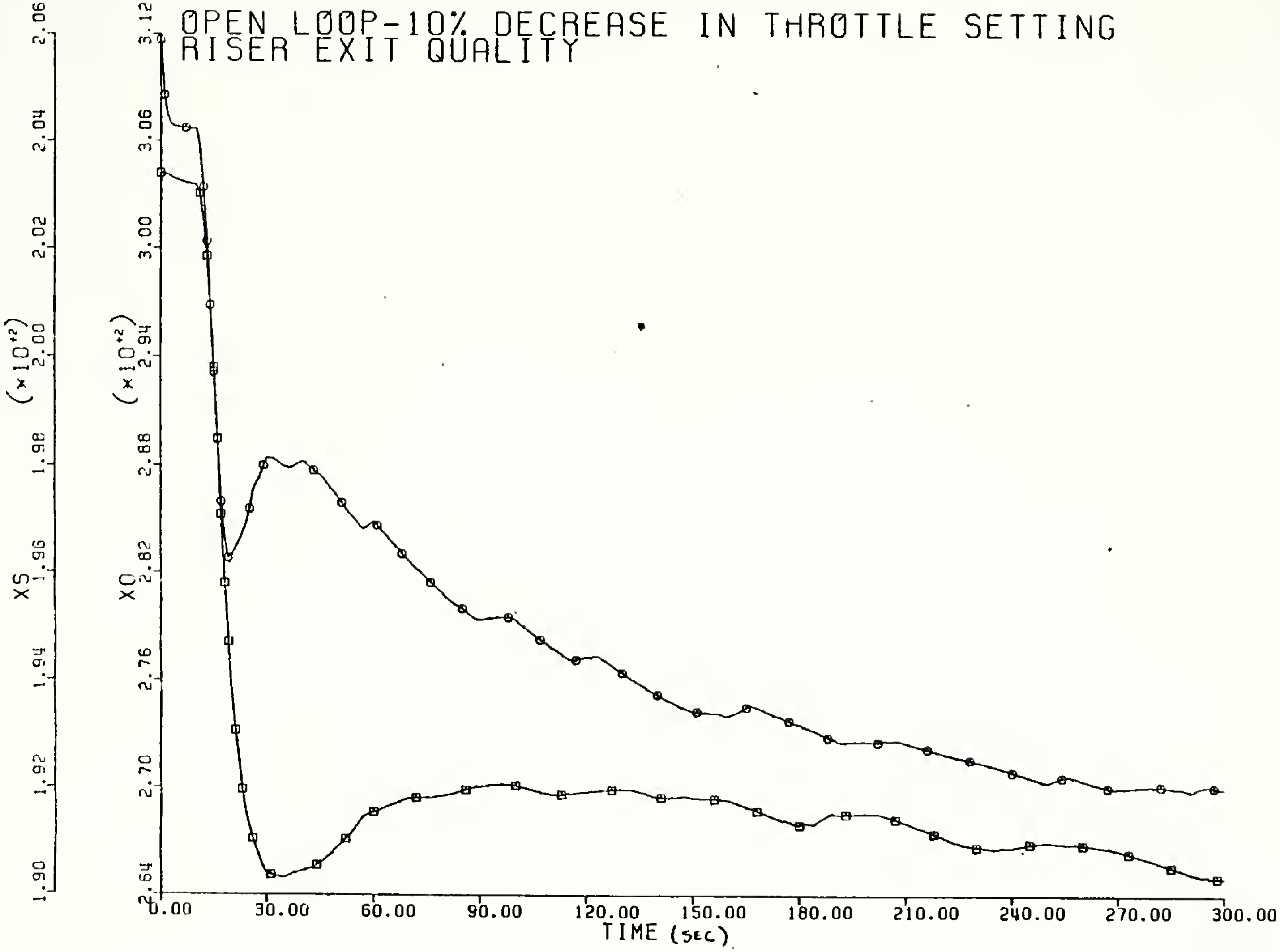

FIGURE 18. RISER EXIT QUALITY RESPONSE TO A 10% DECREASE IN THROTTLE SETTING

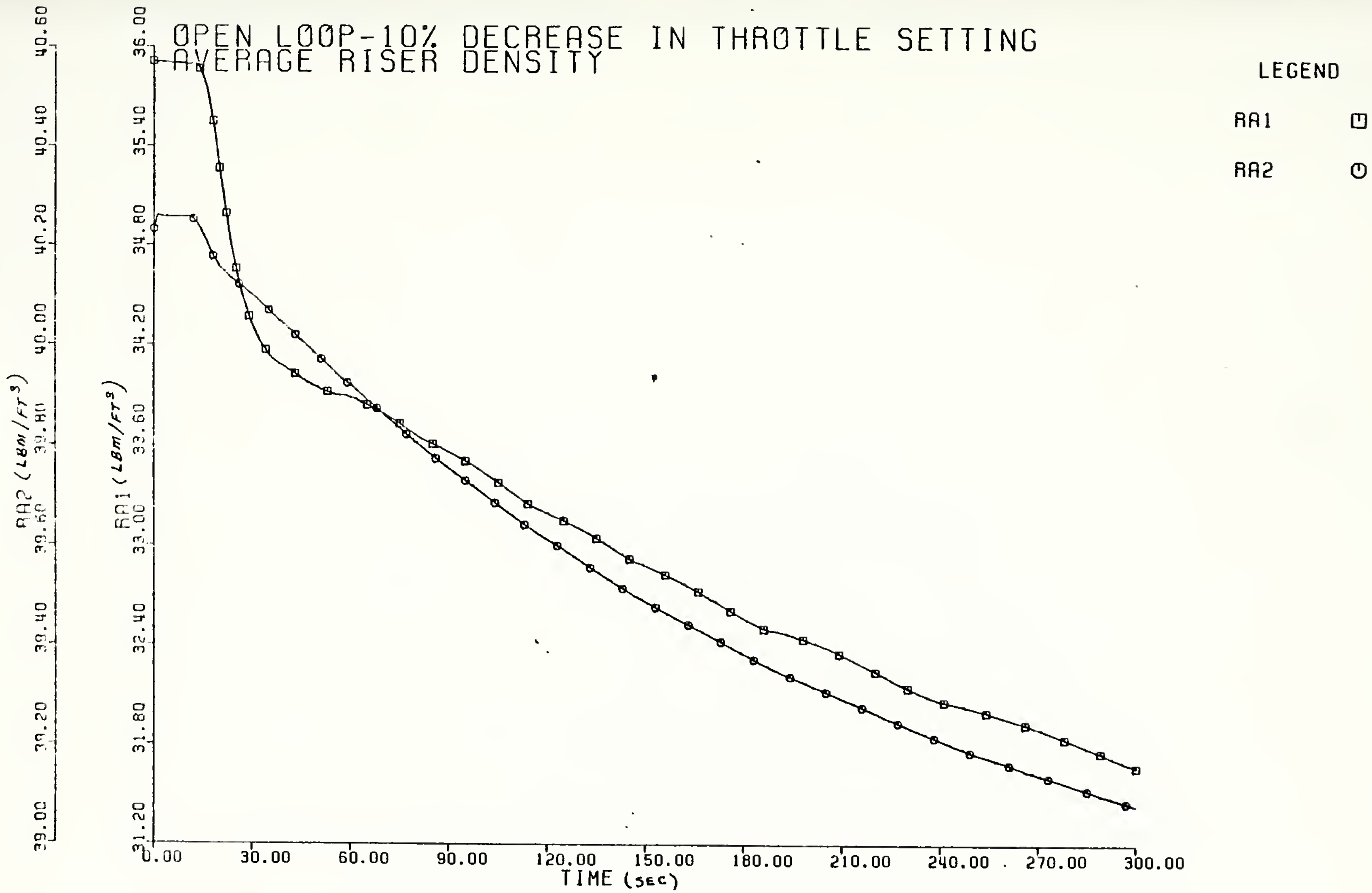

FIGURE 19. AVERAGE RISER DENSITY RESPONSE TO A 10% DECREASE IN THROTTLE SETTING

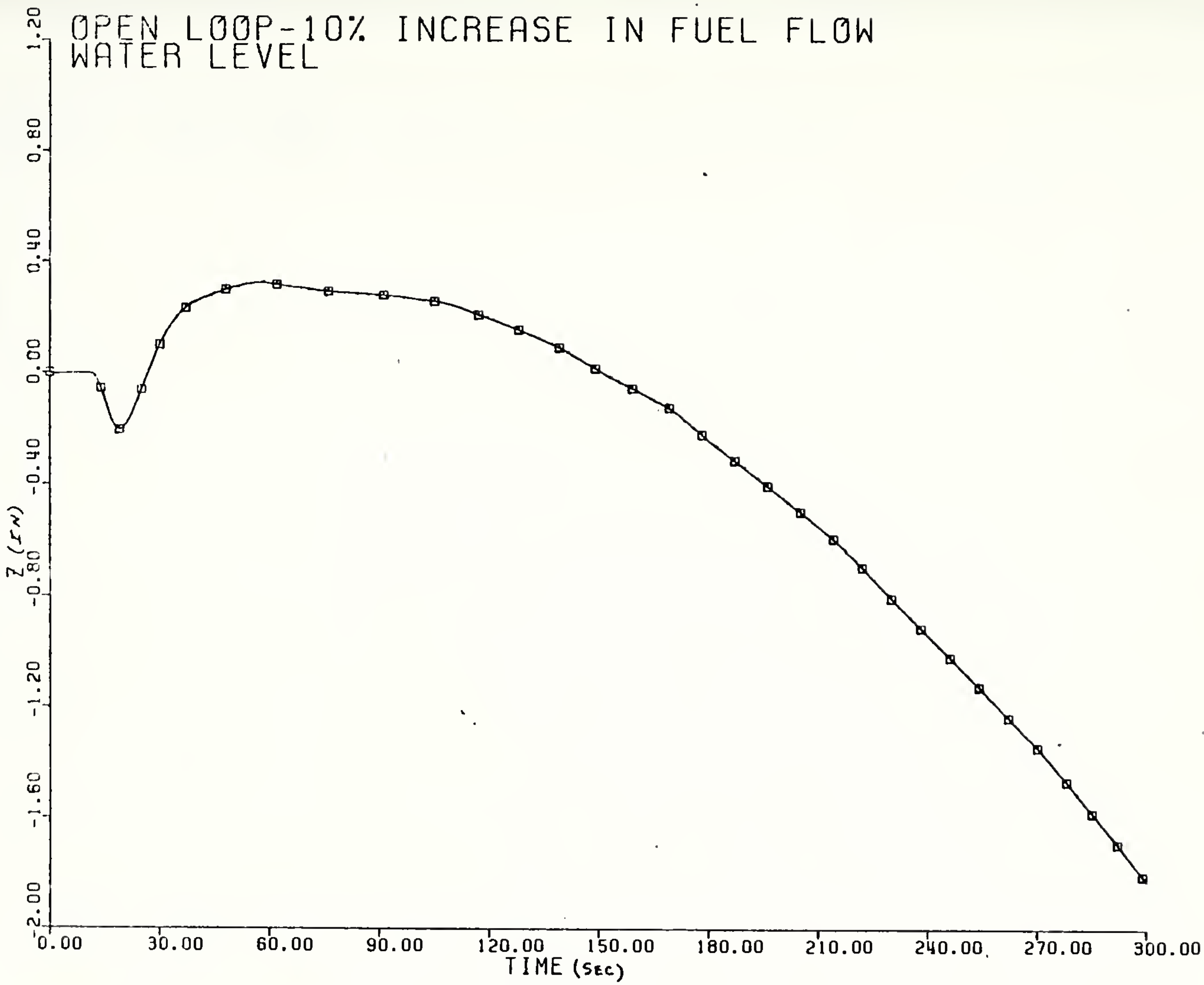

FIGURE 20. WATER LEVEL RESPONSE TO A 10% INCREASE IN FUEL FLOW

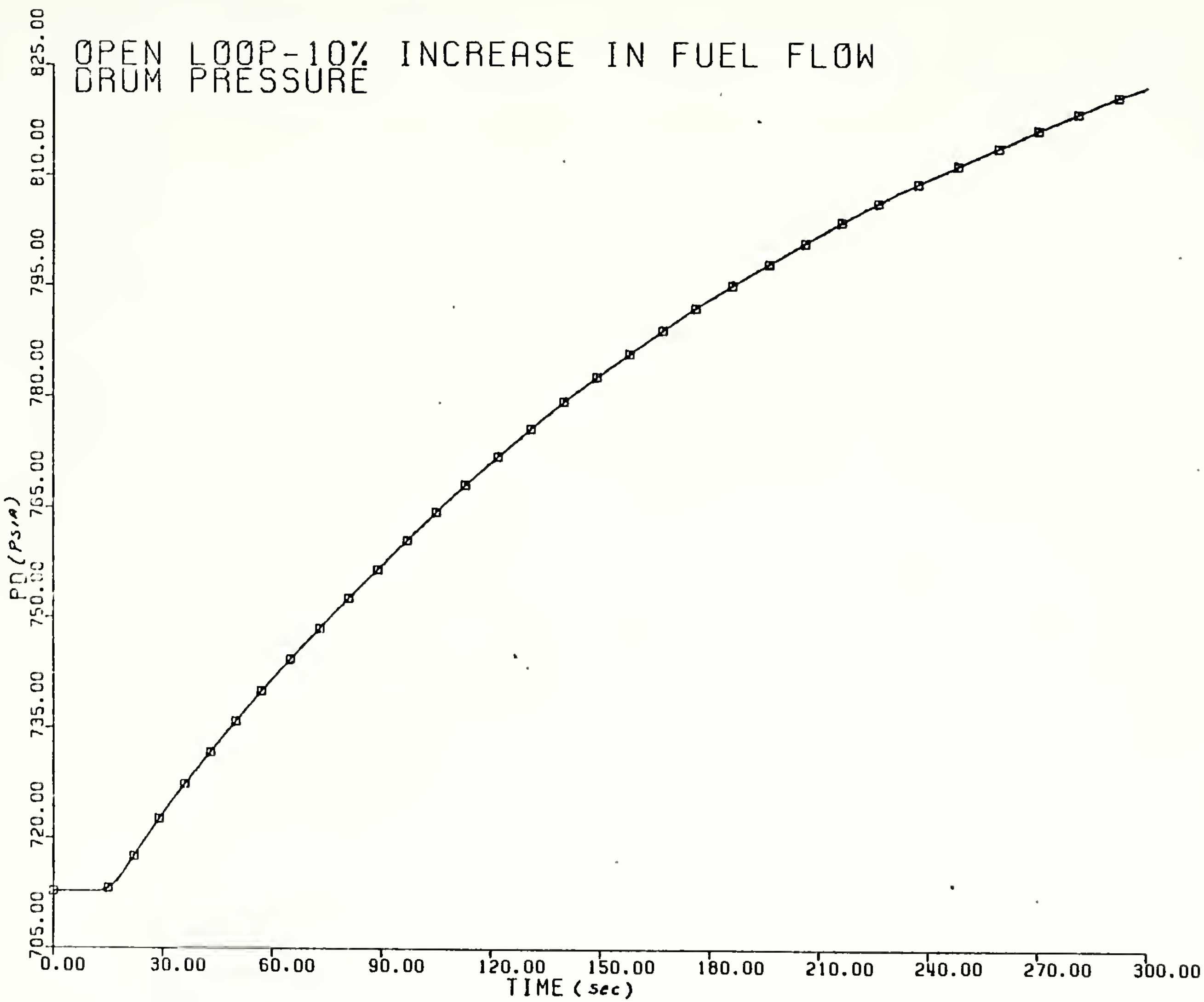

FIGURE 21. DRUM PRESSURE RESPONSE TO A 10% INCREASE IN FUEL FLOW

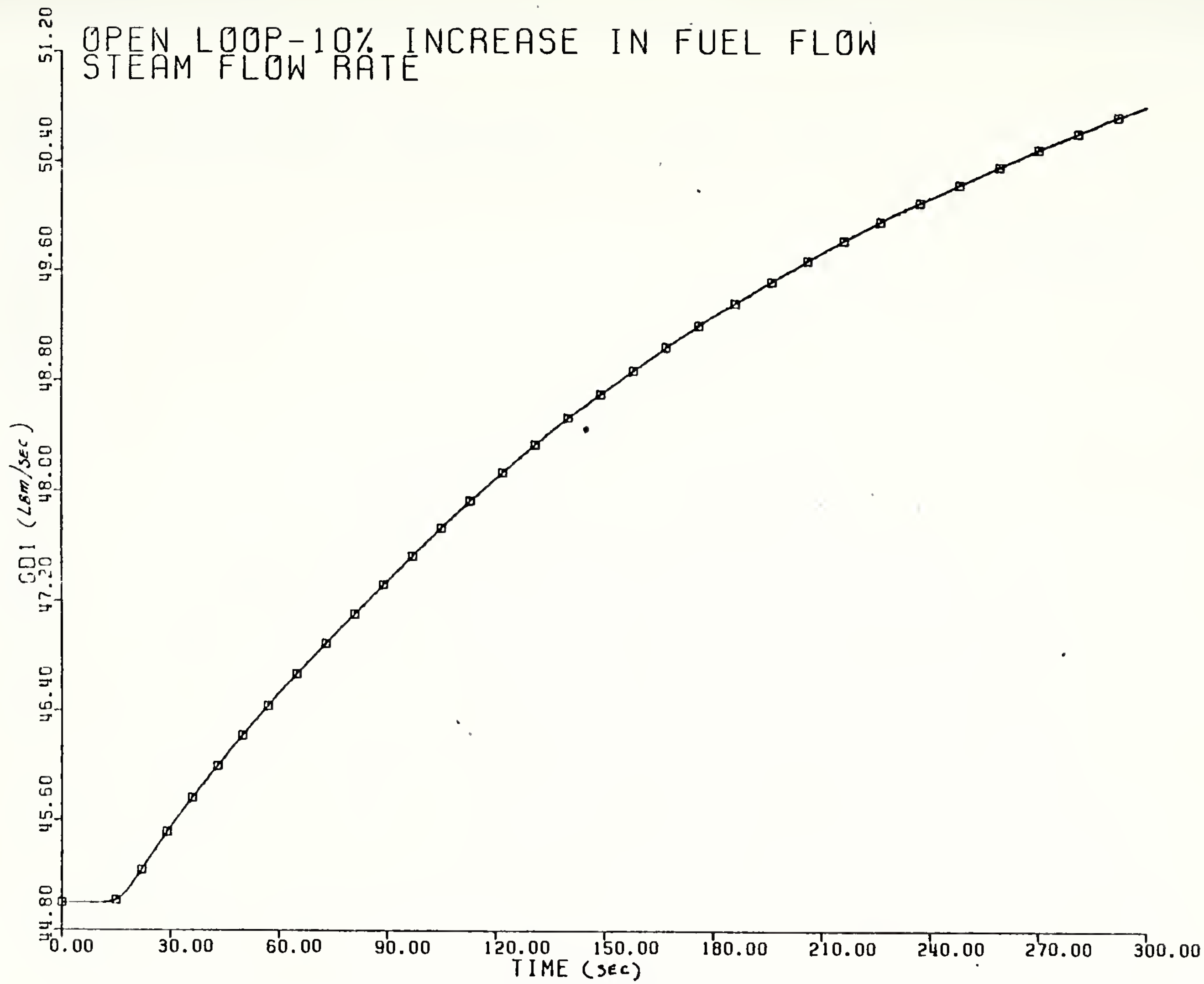

FIGURE 22. STEAM FLOW RATE RESPONSE TO A 10% INCREASE IN FUEL FLOW

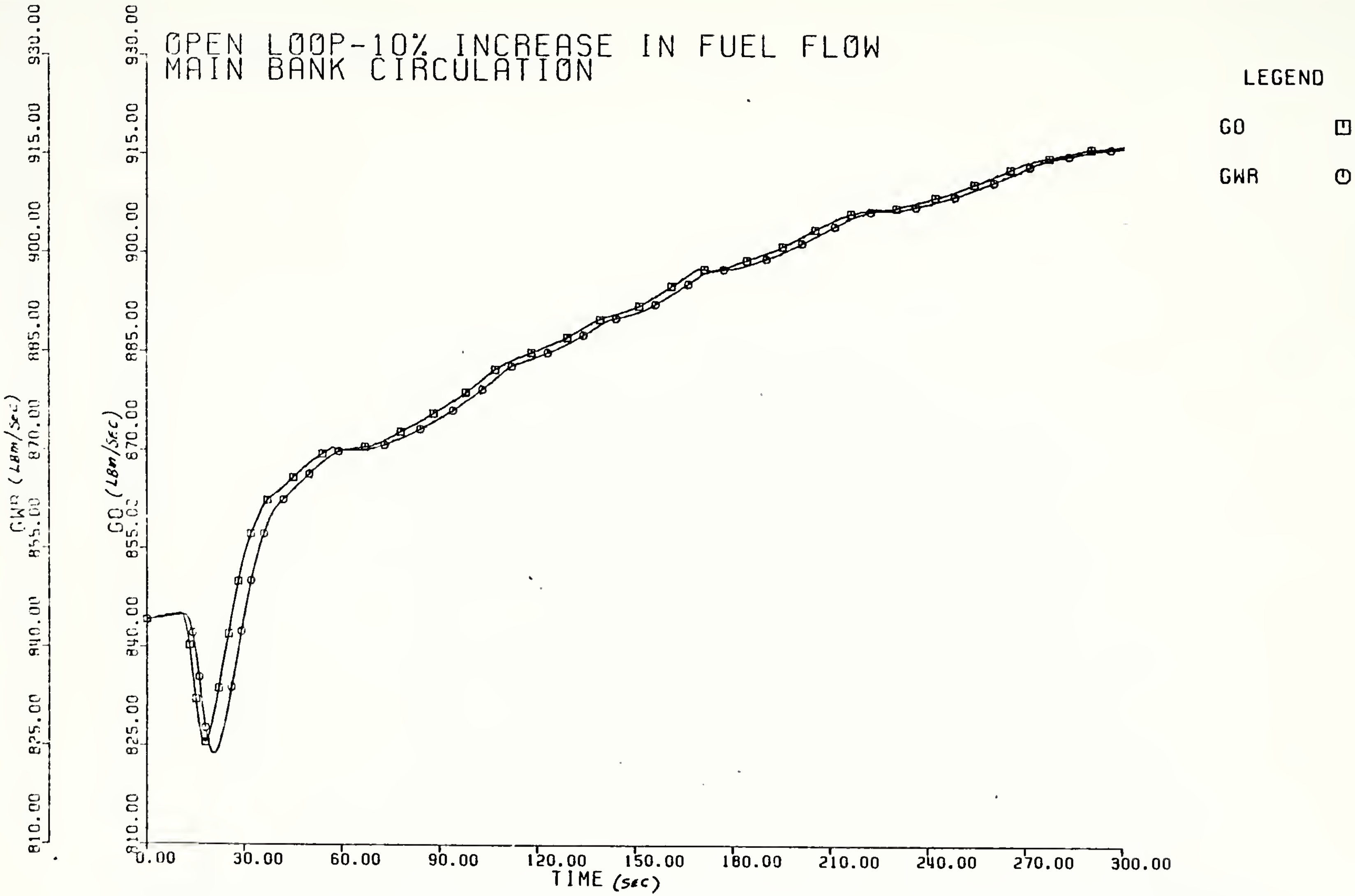

FIGURE 23. MAIN BANK CIRCULATION RESPONSE TO A 10% INCREASE IN FUEL FLOW

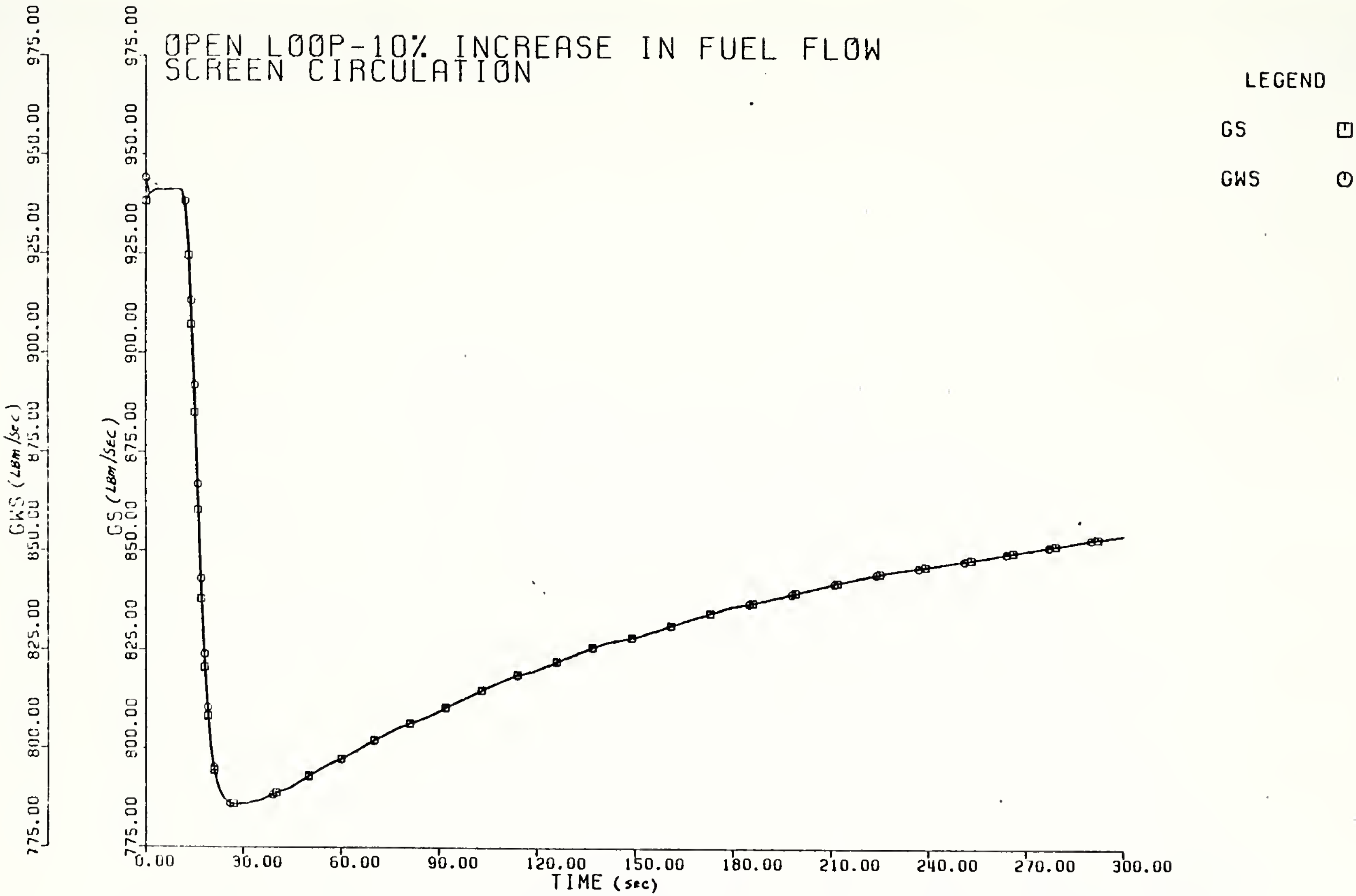

FIGURE 24. SCREEN CIRCULATION RESPONSE TO A 10% INCREASE IN FUEL FLOW

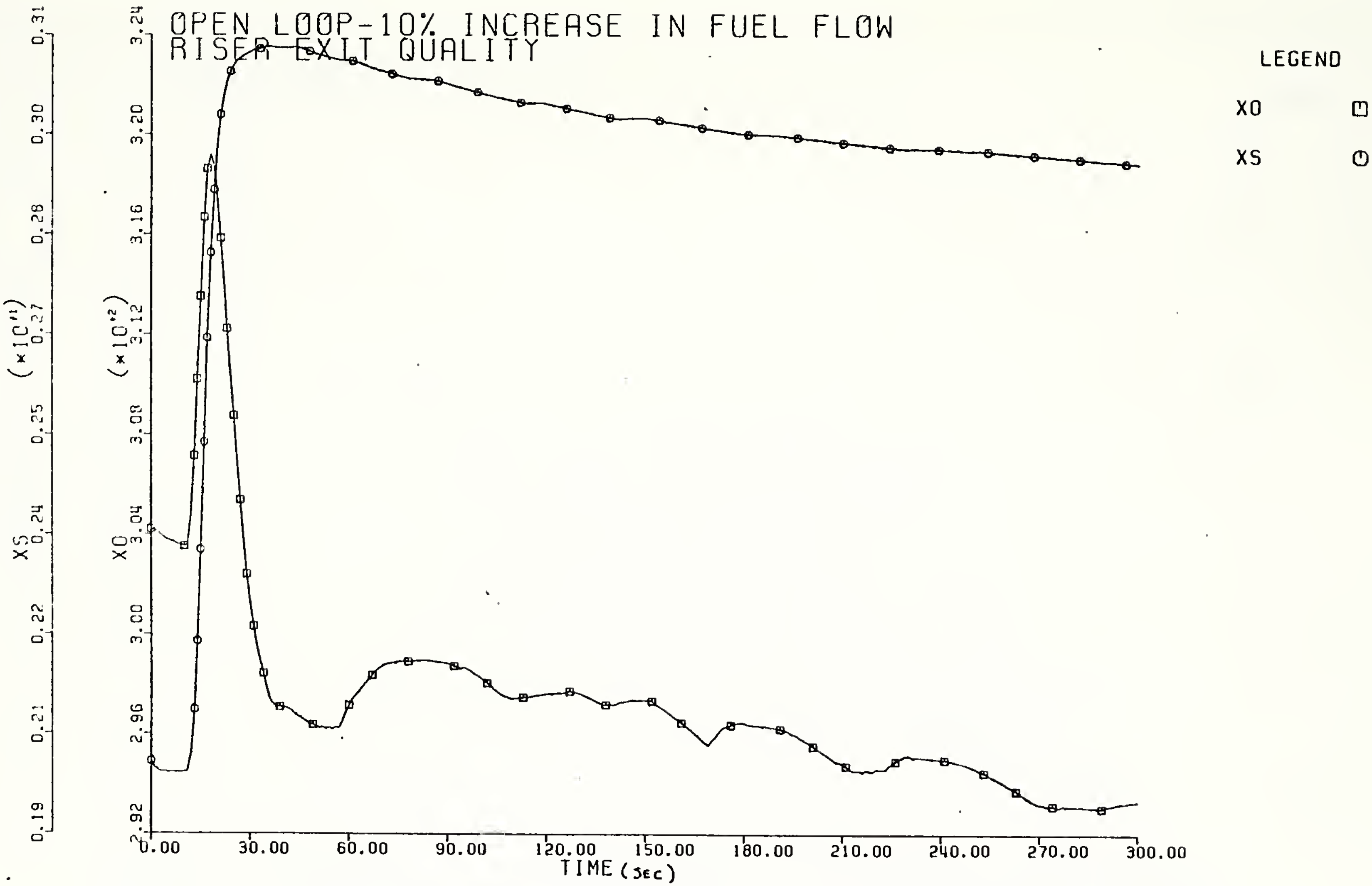

FIGURE 25. RISER EXIT QUALITY RESPONSE TO A 10% INCREASE IN FUEL FLOW

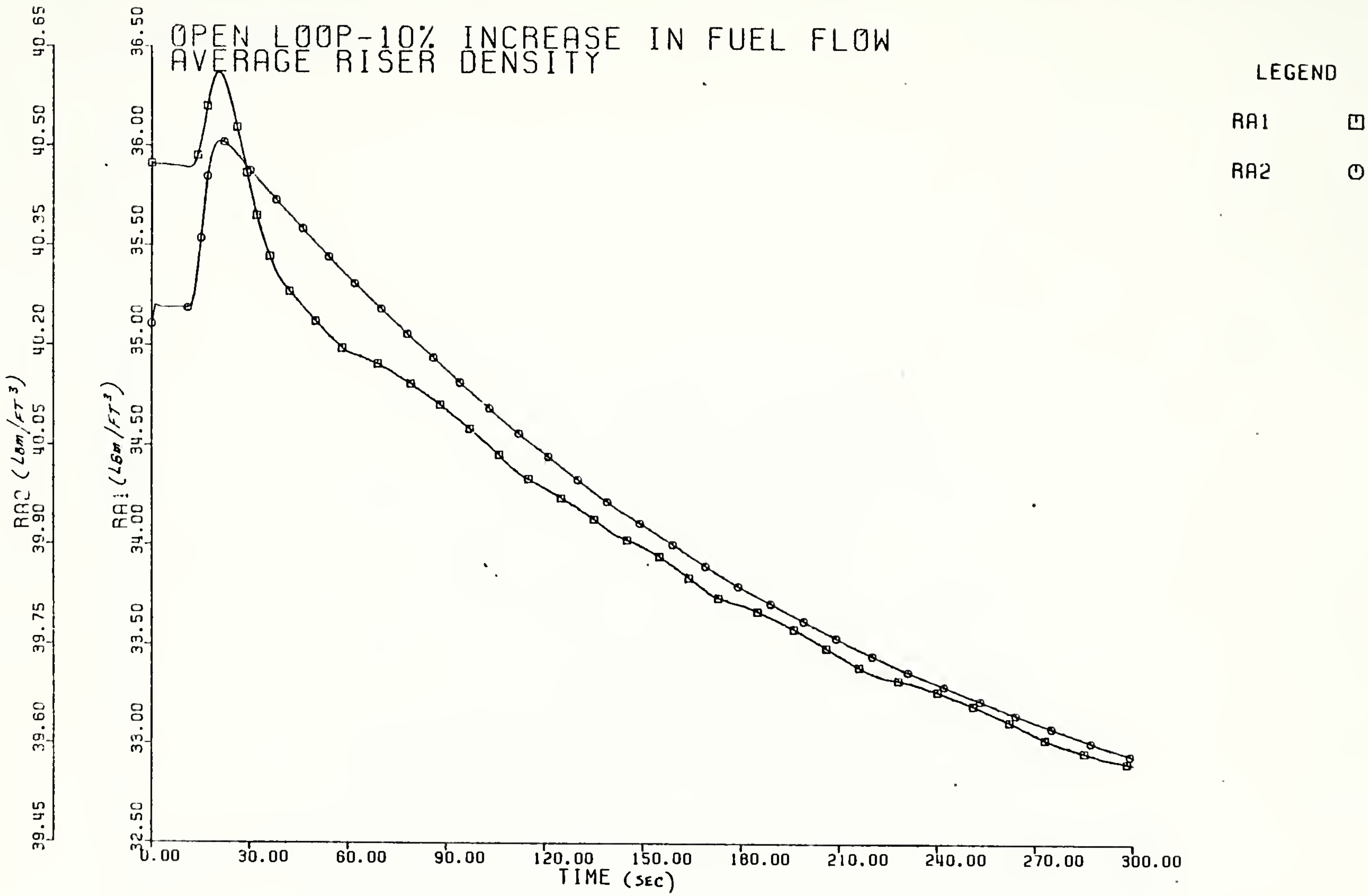

FIGURE 26. AVERAGE RISER DENSITY RESPONSE TO A 10% INCREASE IN FUEL FLOW

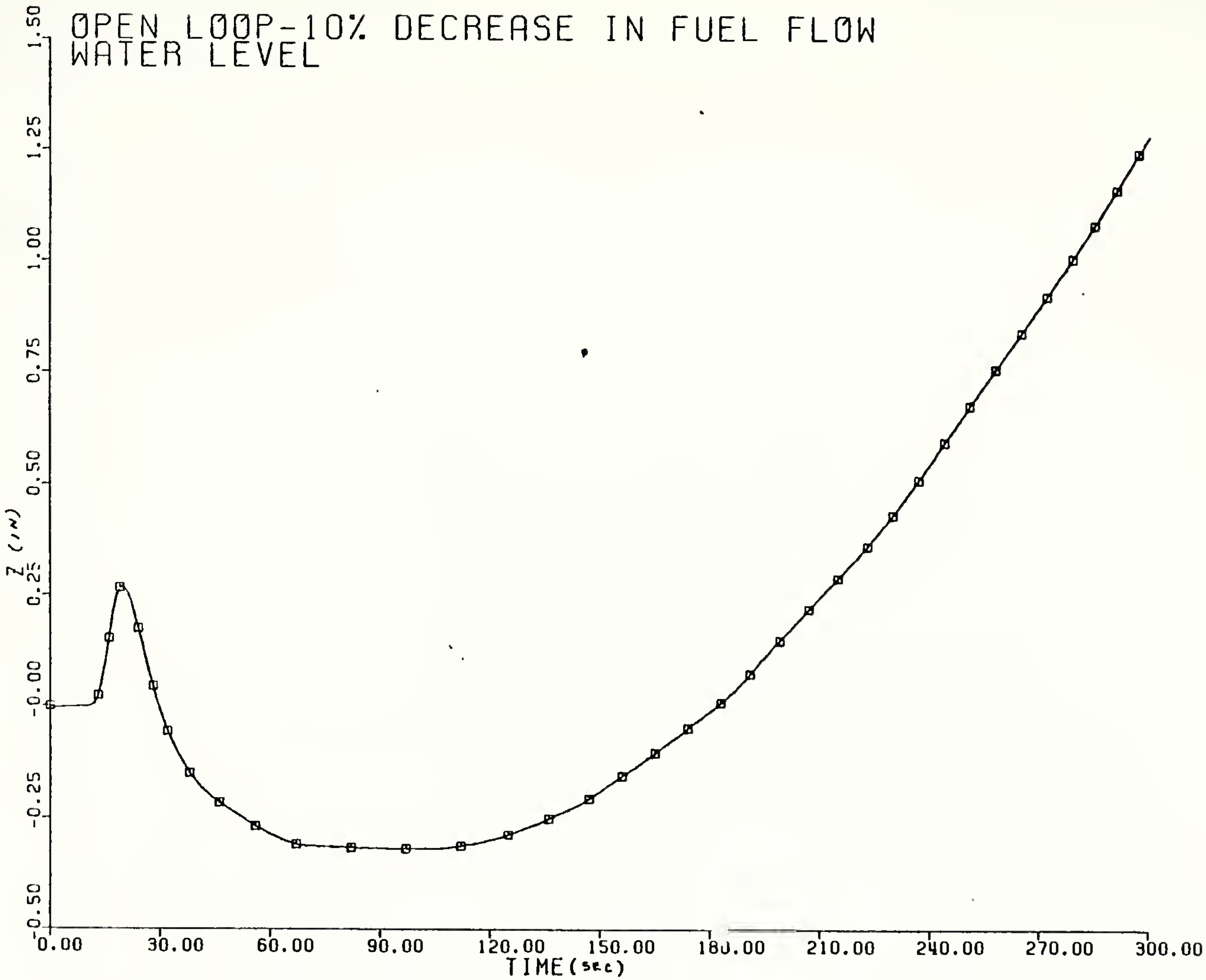

FIGURE 27. WATER LEVEL RESPONSE TO A 10% DECREASE IN FUEL FLOW

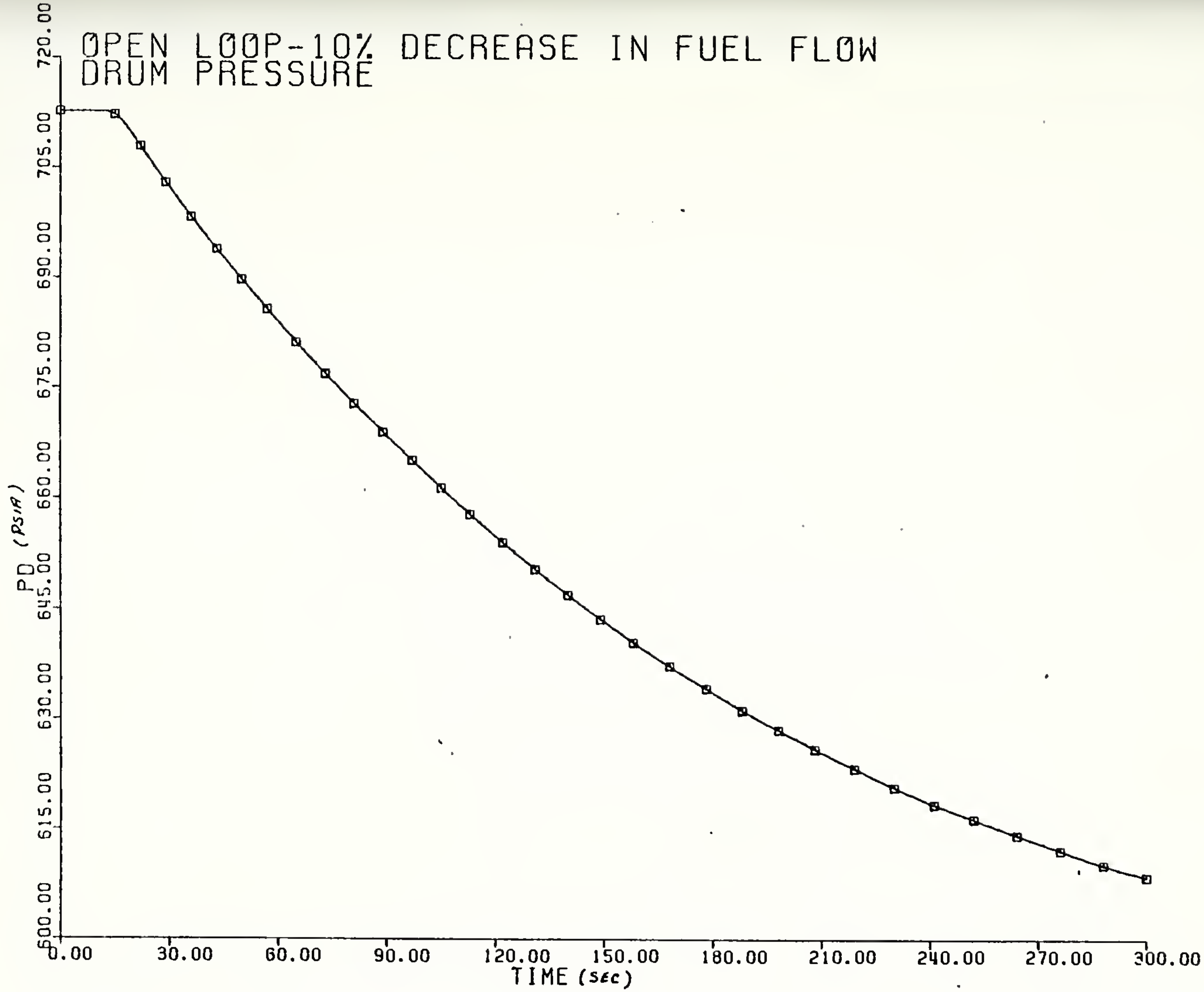

FIGURE 28. DRUM PRESSURE RESPONSE TO A 10% DECREASE IN FUEL FLOW

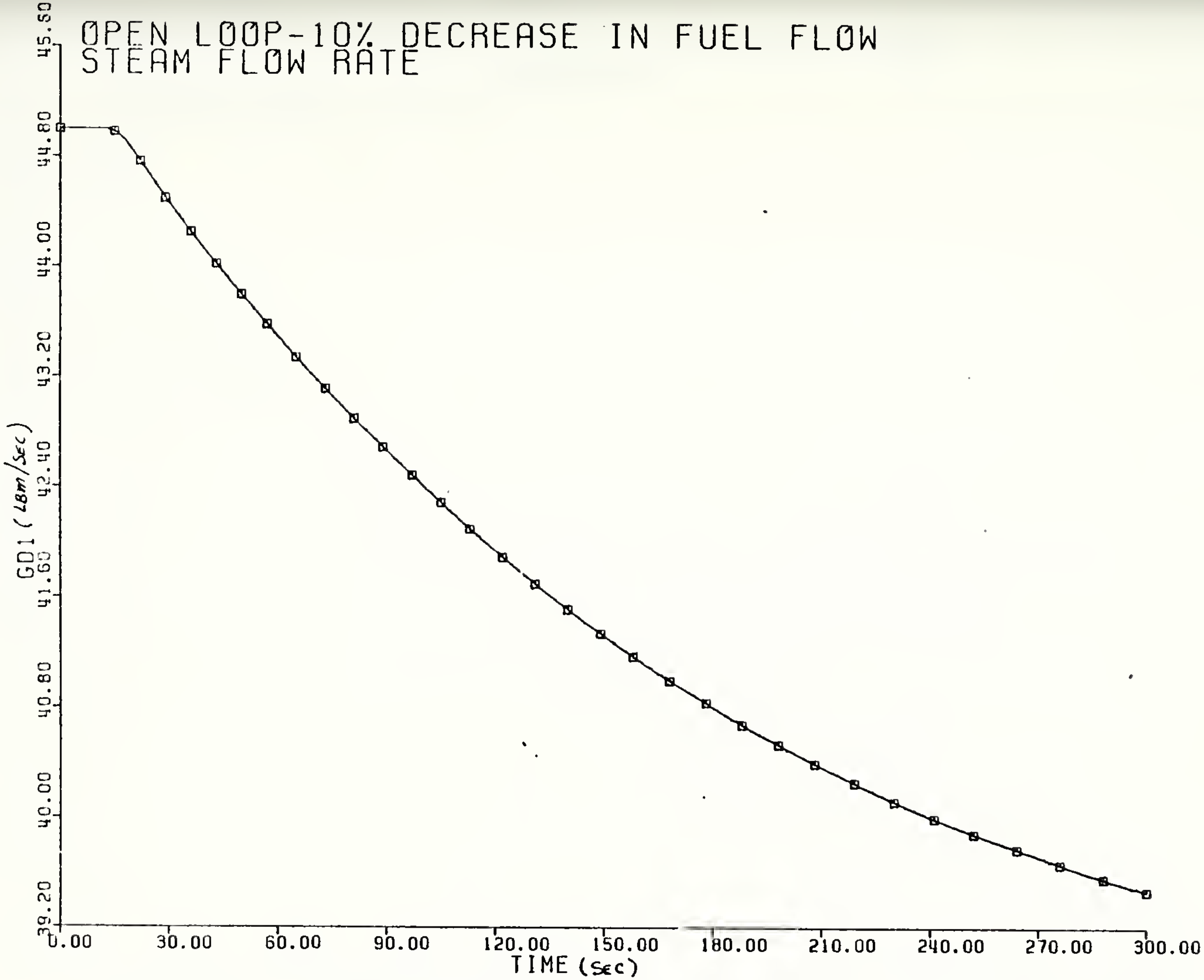

FIGURE 29. STEAM FLOW RATE RESPONSE TO A 10% DECREASE IN FUEL FLOW

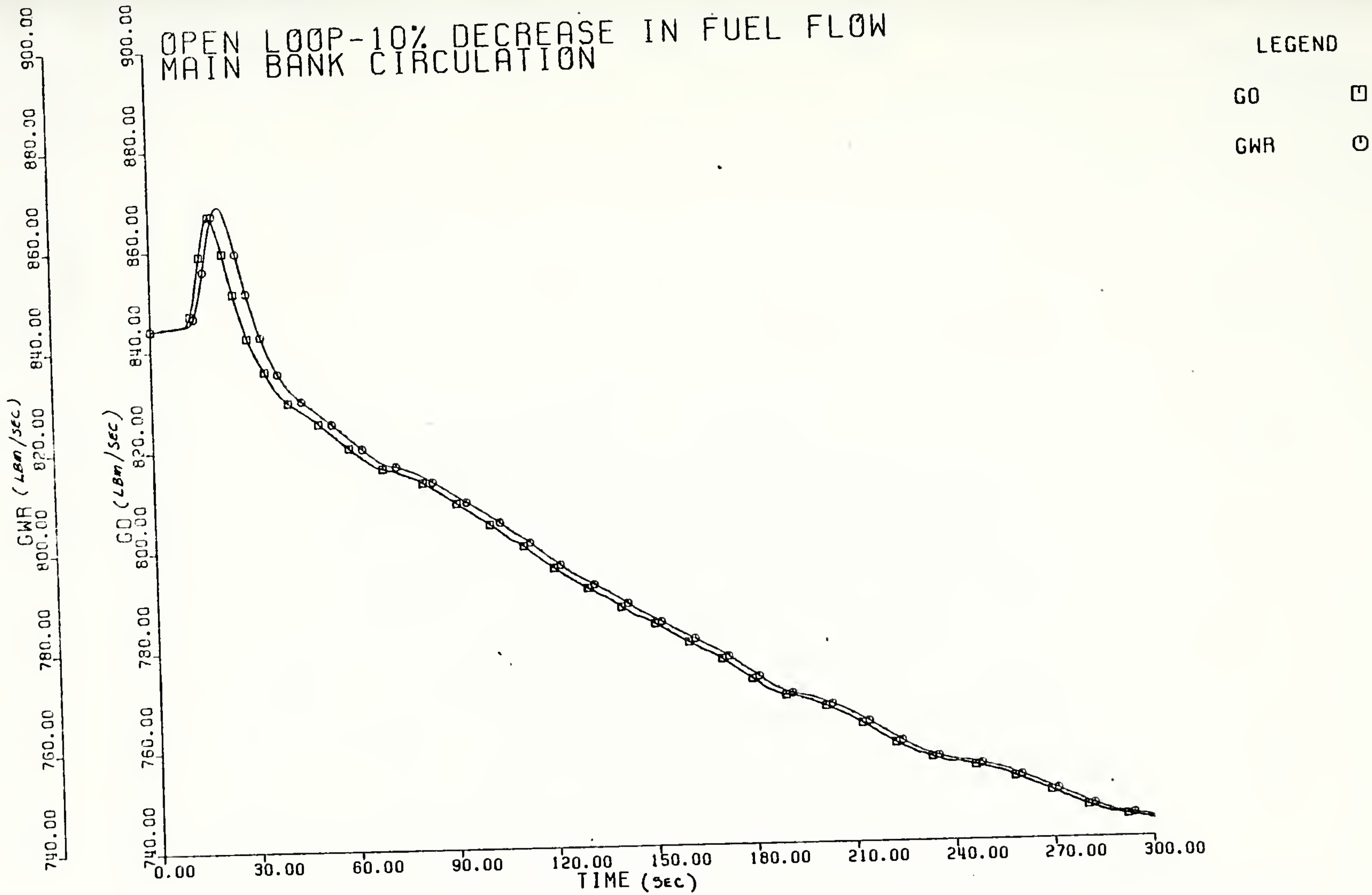

FIGURE 30. MAIN BANK CIRCULATION RESPONSE TO A 10% DECREASE IN FUEL FLOW

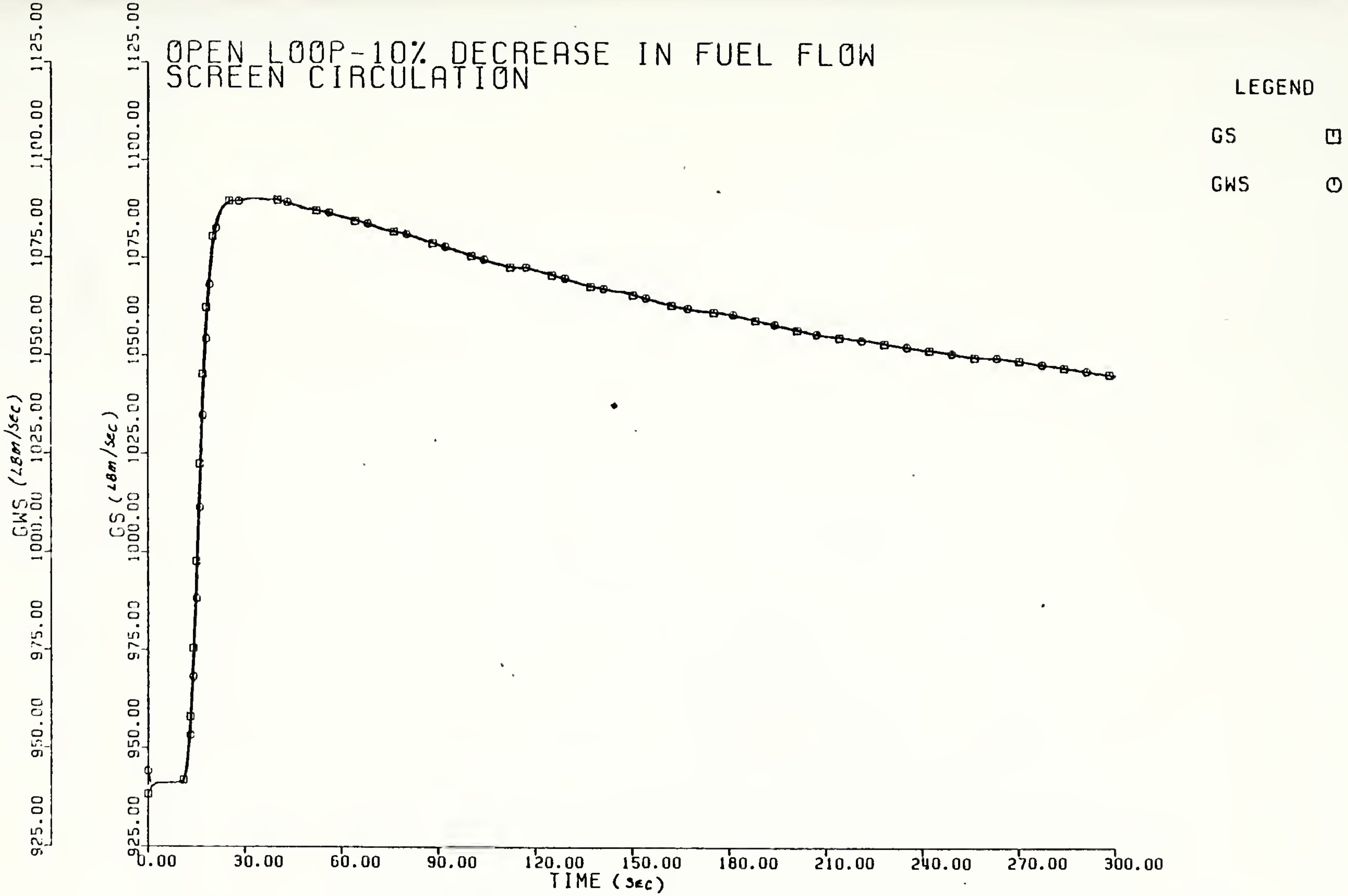

FIGURE 31. SCREEN CIRCULATION RESPONSE TO A 10% DECREASE IN FUEL FLOW

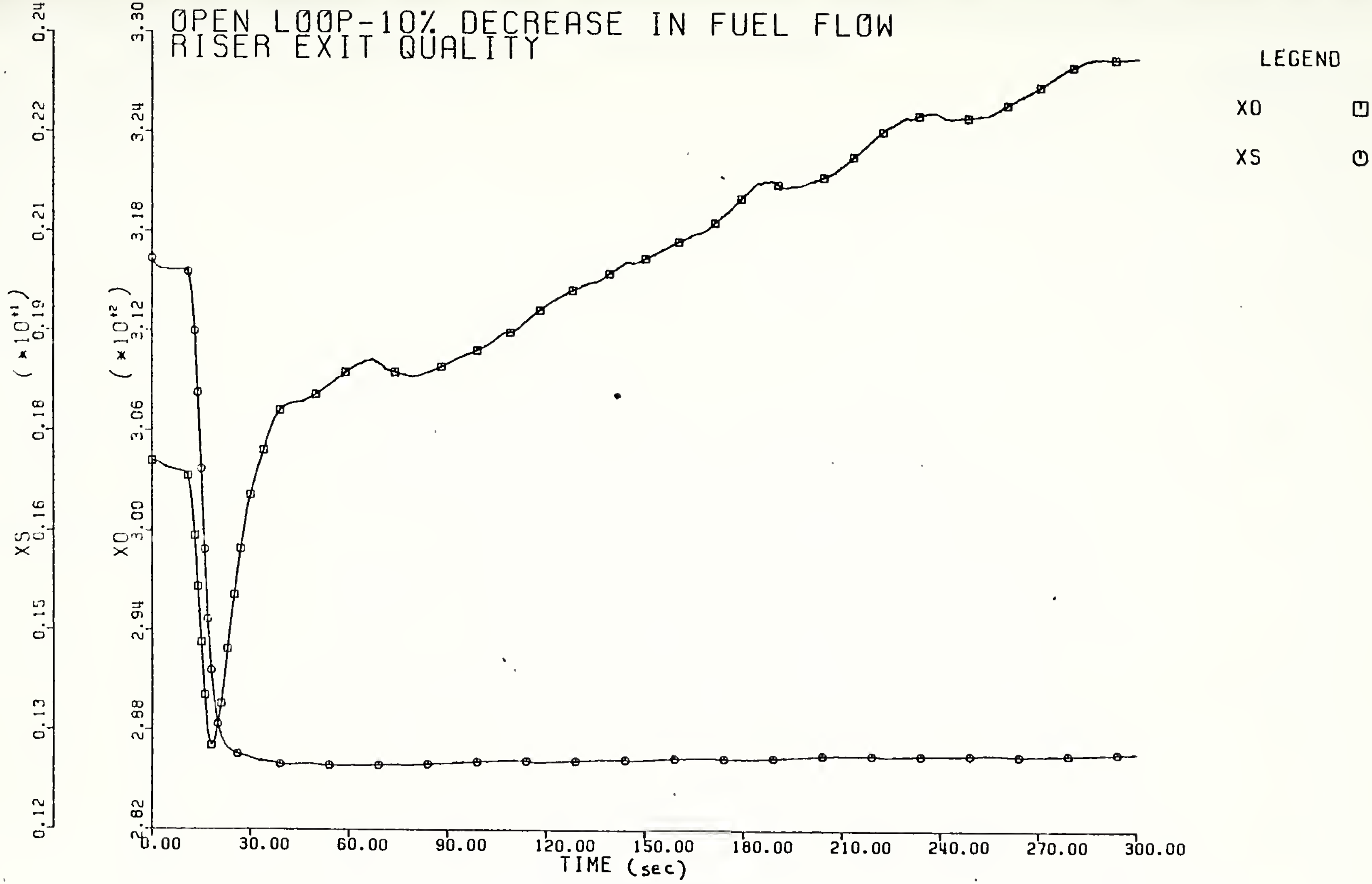

FIGURE 32. RISER EXIT QUALITY RESPONSE TO A 10% DECREASE IN FUEL FLOW

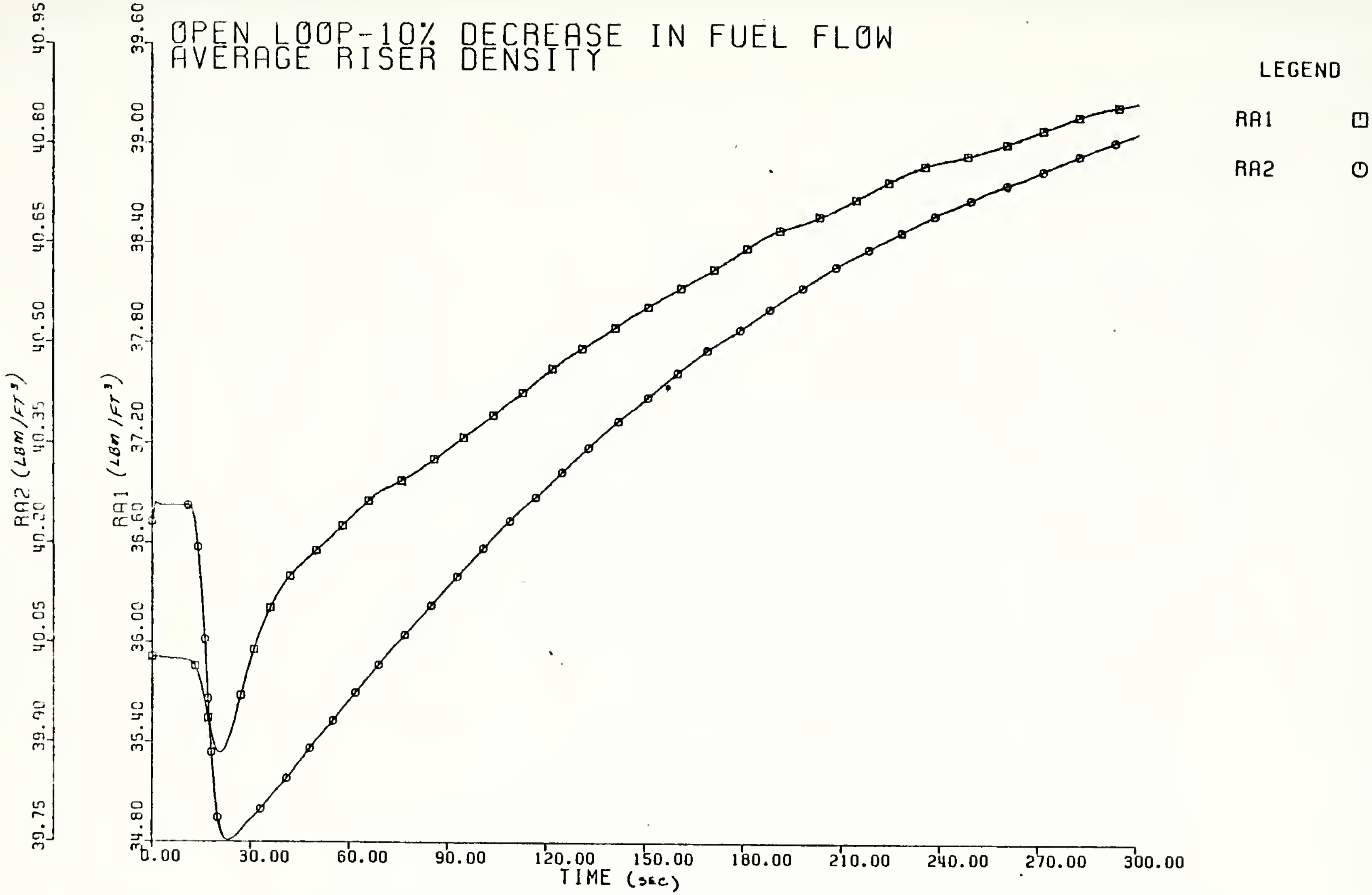

FIGURE 33. AVERAGE RISER DENSITY RESPONSE TO A 10% DECREASE IN FUEL FLOW

APPENDIX A

```
C     THIS PROGRAM CALCULATES THE CONSTANTS AND INITIAL CONDITIONS
C     FOR A US NAVY D-TYPE BOILER GIVEN THE INPUT DATA OBTAINED FROM
C     THE BOILER TECHNICAL MANUAL, STEAM TABLES, AND STANDARD ENGINEE--
C     ING HANDBOOKS.  THE INPUT DATA ARE ENTERED IN NAME LIST FORMAT.
C     NAMELIST DESIGNATIONS AND INPUT NEMONICS FOLLOW
C
C
C     INCON1:
C
C          OPPNT    OPERATING POINT(PERCENT)   *
C          TOTSTM   TOTAL STEAM FLOW(LB/HR)
C          SPHSTM   SUPERHEATED STEAM FLOW (LB/HR)
C          DSHSTM   DESUPERHEATED STEAM FLOW (LB/HR)
C          PDRUM    DRUM PRESSURE (PSIG)
C          SHOT     SUPERHEATER OUTLET TEMPERATURE (DEG-F)
C          SHOP     SUPERHEATER OUTLET PRESSURE (PSIG)
C          DSHOT    DESUPERHEATER OUTLET TEMPERATURE (DEG-F)
C          DSHOP    DESUPERHEATER OUTLET PRESSURE (PSIG)
C          ECONIT   ECONOMIZER FEED INLET TEMPERATURE (DEG-F)
C          ECONOT   ECONOMIZER FEED OUTLET TEMPERATURE (DEG-F)
C          AIRTMP   AIR INLET TEMPERATURE TO REGISTERS (DEG-F)
C          OILTMP   OIL TEMPERATURE AT BURNER INLET (DEG-F)
C          AIRFLO   AIRFLOW RATE (LB/HR)
C          OILFLO   OIL FLOW RATE (LB/HR)
C          XCSAIR   EXCESS AIR (PERCENT)   *
C          DRAFT    DRAFT LOSS (IN-H2O)
C          TGASSC   FLUE GAS TEMPERATURE LEAVING SCREEN (DEG-F)
C          TGASSH   FLUE GAS TEMPERATURE LEAVING SUPERHEATER (DEG-F)
C          TGASMB   FLUE GAS TEMPERATURE LEAVING MAIN BANK (DEG-F)
C          TGASEC   FLUE GAS TEMPERATURE LEAVING ECONOMIZER (DEG-F)
C          TSCRN    SCREEN TUBE WALL TEMPERATURE (DEG-F)
C          TSPHTR   SUPERHEATER TUBE WALL TEMPERATURE (DEG-F)
C          HRFVOL   HEAT RELEASE (KBTU/HR/CU FT FURNACE VOLUME)
C          FHAS     FURNACE HEAT ABSORBTION (KBTU/HR/SQ FT RADIANT HEAT
C                   ABSORBING AREA)
C
C          NOTE: "PERCENT" VALUES ARE TO BE LOGGED AS DECIMALS.
C
C     $SCREEN
C
C          DTUBSC   AVERAGE INSIDE DIAMETER OF SCREEN TUBES (IN)
C          LAVSC    AVERAGE LENGTH OF SCREEN TUBE (FT)
C          NTUBSC   NUMBER OF SCREEN TUBES
C          RHASSC   RADIANT HEAT ABSORBING AREA OF FURNACE SCREEN (SQ FT)
C          MASSSC   TOTAL WEIGHT OF SCREEN TUBES (LB)
C
C
C     $SPHTR
C
C          AREASH   TOTAL SUPERHEATER HEAT TRANSFER AREA (SQ FT)
C          MASSSH   TOTAL WEIGHT OF SUPERHEATER TUBES
C
C
C     $MNBANK
C
C
C          DTUBMB   AVERAGE INSIDE DIAMETER OF MAIN BANK TUBES (IN)
C          LAVMB    AVERAGE LENGTH OF MAIN BANK TUBE (IN)
C          NTUBMB   NUMBER OG MAIN BANK TUBES
C          MASSMB   TOTAL WEIGHT OG MAIN BANK TUBES (LB)
C          AREAMB   TOTAL HEAT TRANSFER AREA (SQ FT)
C
C
C     $ECON
C
C          DTUBEC   INSIDE DIAMETER OF ECONOMIZER TUBES(IN)
C          NPASSE   NUMBER OF  TUBE PASSES
C          NTUBEC   NUMBER OF TUBES PER PASS
C          LTUBEC   AVERAGE LENGTH OF ECONOMIZER TUBE (FT)
C          MASSEC   TOTAL WEIGHT OF ECONOMIZER (LB)
C
C
C     $DESPH
```

```
C
C       DTUBDS   INSIDE DIAMETER OF DESUPERHEATER TUBE (IN)
C       NTUBDS   NUMBER OF DESUPERHEATER TUBES PER PASS
C       NPASSC   NUMBER OF DESUPERHEATER TUBE PASSES
C       LTUBDS   LENGTH OF DESUPERHEATER TUBE (FT)
C       AREACS   TOTAL HEAT TRANSFER AREA OF DESUPERHEATER (SQ FT)
C       MASSDS   TOTAL WEIGHT OF DESUPERHEATER ASSEMBLY (LB)
C
C
C    $DRMDCR
C
C       DTUBDD   AVERAGE DIAMETER OF DRUM DOWNCOMER TUBES (IN)
C       LAVDD    AVERAGE LENGTH OF DRUM DOWNCOMER TUBE (FT)
C       NTUBDD   NUMBER OF DRUM DOWNCOMER TUBES
C
C
C    $HDRDCR
C
C       DTUBHD   AVERAGE INSIDE DIAMETER OF HEADER DOWNCOMER (IN)
C       LAVHD    AVERAGE LENGTH OF HEADER DOWNCOMER (FT)
C       NTUBHD   NUMBER OF HEADER DOWNCOMERS
C
C
C    $BOILER
C
C       DSTMDM   DIAMETER OF STEAM DRUM (IN)
C       LSTMDM   LENGTH OF STEAM DRUM (FT)
C       DWTRDM   DIAMETER OF WATER DRUM (IN)
C       LWTRDM   LENGTH OF WATER DRUM (FT)
C       HNORM    HEIGHT OF NORMAL WATER LEVEL ABOVE BENCH MARK (FT)
C       HHDR     HEIGHT OF HEADER (SCREEN) ABOVE BENCH MARK (FT)
C       HWTRDM   HEIGHT OF WATER DRUM ABOVE BENCH MARK (FT)
C       FURVOL   FURNACE VOLUME (CU FT)
C
C       NOTE:   CHOICE OF BENCH MARK IS ARBITRARY
C
C    $THERMO
C
C       HSHOUT   ECONOMIZER OUTLET ENTHALPY (BTU/LBM)
C       HDSOUT   DESUPERHEATER OUTLET ENTHALPY (BTU/LBM)
C       HECIN    ENTHALPY OF ECONOMIZER FEED INLET (BTU/LBM)
C       HECOUT   ENTHALPY OF ECONOMIZER FEED OUTLET (BTU/LBM)
C    (1)KH2O     THERMAL CONDUCTIVITY OF WATER  (BTU/HR.FT.DEG-F)
C    (1)PRH2O    PRANDTL NUMBER FOR WATER
C    (1)VSCH2O   KINEMATIC VISCOSITY FOR WATER (LBM/FT-SEC)
C    (2)KSTM     THERMAL CONDUCTIVITY FOR STEAM (BTU/HR.FT.DEG-F)
C    (2)PRSTM    PRANDTL NUMBER FOR STEAM
C    (2)VSCSTM   KINEMATIC VISCOSITY FOR STEAM (LBM/FT-SEC)
C       RSHOUT   SUPERHEATER OUTLET DENSITY (LBM/CU FT)
C       RDSOUT   DESUPERHEATER OUTLET DENSITY (LBM/CU FT)
C       RFLUE    DENSITY OF FLUE GAS AT TGASSC (LBM/CU FT)
C
C       NOTES:   (1) EVALUATED AT AVERAGE ECONOMIZER WATER TEMPERATURE
C                (2) EVALUATED AT AVERAGE DESUPERHEATER STEAM TEMPERATURE
C
C    $LOSSES
C       KSCSC    ROUGHNESS RATION (SAND EQUIVALENT) FOR SCREEN TUBES
C       KSCMB    ROUGHNESS RATIO (SAND EQUIVALENT) OF MAIN BANK TUBE
C       KSCDD    ROUGHNESS RATIO (SAND EQUIVALENT) FOR DRUM DOWNCOMER
C       KSCHD    ROUGHNESS RATIO (SAND EQUIVALENT) FOR HEADER DOWNCOMER
C       ENTSC    SCREEN TUBE ENTRANCE LOSS
C       BENDSC    SCREEN TUBE BEND LOSS
C       ENTMB    MAIN BANK ENTRANCE LOSS
C       BENDMB   MAIN BANK BEND LOSS FACTOR
C       ENTDD    DRUM DOWNCOMER ENTRANCE LOSS FACTOR
C       BENDDD   DRUM DOWNCOMER BEND LOSS FACTOR
C       ENTHD    HEADER DOWNCOMER ENTRANCE LOSS FACTOR
C       BENDHD   HEADER DOWNCOMER BEND LOSS FACTOR
C
      IMPLICIT REAL(A-Z)
      INTEGER I
      INTEGER J,K,M,N
      INTEGER NPASSE
```

```
      DIMENSION TH2O(20),QPASS(20)
C
C     DEFINE NAMELISTS
C
      NAMELIST/INCOND/CPPNT,TOTSTM,SPHSTM,DSHSTM,PDPUM,SHOT,SHOP,DSHOT,
     1DSHOP,ECONIT,ECONOT,AIRTMP,OILFLO,AIRFLO,XCSAIR,DRAFT,TGASSC,
     2TGASSH,TGASMB,TGASEC,TSCRN,TSPHTR,HRFVCL,PHAS,OILTMP
      NAMELIST/SCREEN/DTUBSC,LAVSC,NTUBSC,PHASSC,MASSSC
      NAMELIST/SPHTR/AREASH,MASSSH
      NAMELIST/MNBANK/DTUBMB,LAVMB,NTUBMB,MASSMB,AREAMB
      NAMELIST/ECON/DTUBEC,NPASSE,NTUBEC,LTUBEC,MASSEC
      NAMELIST/DESPH/DTUBDS,NTUBDS,NPASSD,LTUBDS,AREADS,MASSDS
      NAMELIST/DRMDCR/DTUBDD,LAVDD,NTUBDD
      NAMELIST/HDRDCR/DTUBHD,LAVHD,NTUBHD
      NAMELIST/BOILER/DSTMDM,LSTMDM,DWTRDM,LWTRDM,HNORM,HHOR,HWTRDM,
     $FLRVCL
      NAMELIST/THERMO/HSHOUT,HDSOUT,HECIN,HECOUT,
     1KH2O,PRH2O,VSCH2O,KSTM,PRSTM,VSCSTM,RSHOUT,RDSOUT,RFLUE
      NAMELIST/LOSSES/KSDSC,KSDMB,KSDDD,KSDHD,ENTSC,BENDSC,ENTMB,
     $BENDMB,ENTDD,BENDDD,ENTHD,BENDHD
      NAMELIST/INCON1/TR10,TM10,TM20,TM30,TM40,TM50,GCRC,GSRC,QXCC,QXSC
      NAMELIST/INCON2/HM10,MW10,VRD0,HW60,GW2,TW3,GL,GB,GD2,GD10,VENT
      NAMELIST/INCON3/DRA10,DRA20,GD15,RA1X0,RA2X0,GWFC,GWSC
      NAMELIST/CONST1/KR,KS,KDR,KDS,AR,LR,DR,LR1,AS,LS,DS,LS1,LDR,ADR
      NAMELIST/CONST2/DDR,HNBR,DDS,LDS,HNBS,ADS,MM1,MM2,MM3,MM4,MM5,HXR
      NAMELIST/CONST3/HXS,MR1,VR,VS,VNDP,VDR,LD1R,LD1S
      NAMELIST/CONST4/CR1,CR1A,CR2,CR3,CD1,CD2,CW,CM,KD1,KD2,KR1,KR2,KR3
      NAMELIST/CONST5/KR4,Z1,Z2,Z3,Z4,Z5,Z6,Z7,Z8,HW3,GD10,CZ2,C8,C9,C10
      NAMELIST/CONST6/C11,C7,CSL,KW1,KW2,KW3,KW4,HC
      NAMELIST/OUTPUT/ER1,ER2,ER3,ER4,ED2,G0,GS,X0,XS,RA1,RA2,R0,RS,
     $RW,HW1,HW2,HW3,HW4,HW6,HFG
C
      READ(5,INCOND)
      WRITE(6,INCOND)
      READ(5,SCREEN)
      WRITE(6,601)
      WRITE(6,SCREEN)
      READ(5,SPHTR)
      WRITE(6,601)
      WRITE(6,SPHTR)
      READ(5,MNBANK)
      WRITE(6,601)
      WRITE(6,MNBANK)
      READ(5,ECON)
      WRITE(6,601)
      WRITE(6,ECON)
      READ(5,DESPH)
      WRITE(6,601)
      WRITE(6,DESPH)
      READ(5,DRMDCR)
      WRITE(6,601)
      WRITE(6,DRMDCR)
      READ(5,HDRDCR)
      WRITE(6,601)
      WRITE(6,HDRDCR)
      READ(5,BOILER)
      WRITE(6,601)
      WRITE(6,BOILER)
      READ(5,THERMO)
      WRITE(6,601)
      WRITE(6,THERMO)
      READ(5,LOSSES)
      WRITE(6,601)
      WRITE(6,LOSSES)
C    CALCULATION OF PRELIMINARY CONSTANTS
C
      PI=3.1415927
      G=32.2
      CM=.11
      DRA10=0.0
      DRA20=0.0
      ZERO=0.0
      VENT=CPPNT
```

```
KR=KSCMB
KS=KSCSC
KCR=KSCDD
KCS=KSDHD
Z1=ENTCC
Z2=BENCCD
Z3=ENTMB
Z4=BENCMB
Z5=ENTSC
Z6=BENCSC
Z7=ENTHC
Z8=BENDHD
PC1=PCRUM+14.7
HW1=EXP(0.26452*ALOG(PC1)+4.46708)
HFG=922.15-0.40516*PD1+1.717E-04*PC1**2-4.219E-08*PD1**3
HD1=HW1+HFG
TC1=EXP(.22151*ALOG(PC1)+4.77123)
GB=OILFLO/3600.0
GL=AIRFLO/3600.0
TR10=TGASSC
TM10=TSCRN
TM20=TSPHTR
TR2=TR10
TR3=TGASSH
TR4=TGASMB
TR5=TGASEC
GC1=TCTSTM/3600.0
GC1E=GC1*.0001
GD4=SFHSTM/3600.0
TC2=SHCT
PC2=SHCP+14.7
TC3=DSHCT
PC3=DSHCP+14.7
GC2=DSHSTM/3600.0
TW3=ECONIT
TW4=ECCNCT
EB=HRFVOL*FURVOL*1000.0/3600.0
ER1=FHAS*RHASSC*1000.0/3600.0
LS1=LAVSC
LS=NTUBSC*LAVSC
CS=DTUBSC*NTUBSC/12.0
AS=PI*CTUBSC**2*NTUBSC/(4.0*144.0)
VS=AS*LAVSC
MM1=MASSSC
MM2=MASSSH
LR1=LAVMB
LR=NTUBMB*LAVMB
DR=DTUBMB*NTUBMB/12.0
AR=PI*DTUBMB**2*NTUBMB/(4.0*144.0)
VR=AR*LAVMB
MM3=MASSMB
MM4=MASSEC
MM5=MASSDS
LCR=LAVDD*NTUBDC
LDS=LAVHD*NTUBHC
CCR=CTUBDD*NTUBCD/12.0
DCS=CTUBHD*NTUBHD/12.0
ACR=NTUBDD*(PI*(CTUBDC/24.0)**2)
ACS=NTUBHC*(PI*(CTUBHC/24.0)**2)
VCR=(PI*DSTMDM**2/(4.0*144))*LSTMDM
VNCR=(PI*CWTRDM**2/(4.0*144))*LWTRDM
HW3=HECIN
HW4=HECOUT
GR=GB+GL
RW=63.8-0.01781*TD1+1.132E-05*TC1**2-6.786E-08*TC1**3
VF=1/RW
VFG=524.0/PC1-.1
RD1=1.0/(VF+VFG)
RC2=RSHOUT
RC3=RDSOUT
TW1=TC1
GW2=GC1
MR1=RFLUE*FURVOL
```

```
      CZ2=(DSTMDM/12.0)*LSTMDM*(1.0/12.0)
C
C     CALCULATE LOWER HEATING VALUE OF FUEL OIL
C
      HO=EB/GB
C
C     COMPUTE STOICHIOMETRIC AIR/FUEL RATIO
C
      CSL=(1.0-XCSAIR)*GL/GB
C
C     RADIATION HEAT TRANSFER COEFFICIENT
      KR1=ER1/(((TR10+460.0)/100.0)**4-((TM10+460.0)/100.0)**4)
C
C     COMPUTE HEAT TRANSFER TO THE MAIN TUBE BANK
      ER3=GD1*(HD1-HW4)-GD2*(HSHOUT-HDSOUT)-ER1
C
C     COMPUTE MAIN BANK AVERAGE METAL TEMPERATURE
C
      KW4=(1.0/1.782E06)*AREAME
      TM30=(ER3/(KW4*PD1**(4.0/3.0)))**(1.0/3.0)+TD1
C
C     COMPUTE MAIN BANK GAS SIDE HEAT TRANSFER  COEFFICIENT
      KR3=ER3/(((TR3+TR4)/2.0-TM30)*GR**.6)
C     COMPUTE SCREEN BANK WATER SIDE HEAT TRANSFER COEFFICIENT
      KW3=ER1/((PD1**(4.0/3.0))*(TM10-TD1)**3)
C     HEAT TRANSFER TO THE SUPERHEATER
      ER2=GD1*(HSHOUT-HD1)
C
C     SUPERHEATER GAS SIDE HEAT TRANSFER COEFFICIENT
      KR2=ER2/(((TR2+TR3)/2.0-TM20)*GR**.6)
C     HEAT TRANSFER TO THE ECONOMIZER
      ER4=GD1*(HW4-HW3)
C     COMPUTE SPECIFIC HEATS OF FLUE GAS
C        FURNACE
      CR1=(EE-ER1)/((TR10-80.0)*GR)
C        SUPERHEATER
      CR1A=ER2/(GR*(TR2-TR3))
      CD1=ER2/(GD1*(TD2-TD1))
C        MAIN BANK
      CR2=ER3/(GR*(TR3-TR4))
C        ECONOMIZER
      CR3=ER4/(GR*(TR4-TR5))
C        SPECIFIC HEAT FOR WATER
      CW=ER4/(GD1*(TW4-TW3))
C     COMPUTE AVERAGE HEAT TRANSFER COEFFICIENT
      DEC1=DTUBEC/12.0
      AREAEC=NTUBEC*LTUBEC*PI*DEC1*NPASSE
      KW1=AREAEC*(KH2O/DEC1**1.8)*.023*(4.0/(PI*VSCH2O*NTUBEC))**.8*
     $PRH2O**.4
      LMTDEC=ER4/(KW1*GD1**.8)
      XXXX11=EXP((TW4-TW3)/LMTDEC)
      TM40=(TW3-TW4*XXXX11)/(1.0-XXXX11)
      KR4=ER4/(GR**.6*((TR4+TR5)/2.0-TM40))
C     SPECIFIC HEAT OF STEAM AT AVERAGE DESUPERHEATER TEMPERATURE
      ED2=(GD2*(HSHOUT-HDSOUT))
      CD2=ED2/(GD2*(SHOT-DSHOT))
C     DESUPERHEATER STEAM SIDE HEAT TRANSFER COEFFICIENT
      DDSH1=DTUBDS/12.0
      HXFRDS=(KSTM/DDSH1**1.8)*.023*(4.0*GD2/(PI*VSCSTM*NTUBDS))**.8*
     $PRSTM**.3
C     COMPUTE THE LOG MEAN TEMPERATURE DIFFERENCE FOR THE DESUPERHEATER
      LMTDDS=ED2/(HXFRDS*AREADS)
C     DETERMINE THE DESUPERHEATER METAL TEMPERATURE
      XXXX02=EXP((SHOT-DSHOT)/LMTDDS)
      TM50=(SHOT-XXXX02*DSHOT)/(1.0-XXXX02)
C     DESUPERHEATER WATER SIDE HEAT TRANSFER COEFFICIENT
      KW2=ED2/(TM50-TW1)
C     DESUPERHEATER STEAM SIDE HEAT TRANSFER COEFFICIENT
      KD2=ED2/(GD2**.8*LMTDDS)
C     SUPERHEATER STEAM SIDE HEAT TRANSFER COEFFICIENT
      LMTDSH=(TD2-TD1)/ALOG((TM20-TD1)/(TM20-TD2))
      KD1=ER2/(GD1**.8*LMTDSH)
C     CALCULATE THE THROTTLE VALVE FLOW CONSTANT
```

```
      C11=GC4/(PD2*VENT)
C     SUPERHEATER OUTLET DENSITY
      C8=(PC1+PD2)/(RC1+RD2)
      C10=(PC2+PD3)/(RD2+RD3)
      RAVSH=(RC1+RD2)/2.0
      RAVCS=(RC2+RD3)/2.0
      C7=(PC1-PD2)*RAVSH/GC1**2
      C9=(PC2-PD3)*RAVDS/GD2**2
C
C
C     CIRCULATION SYSTEM CALCULATIONS
C
C
C     COMPUTE LOSS COEFFICIENTS FOR DOWNCOMERS
C
      FCR=(1.C/(1.74-2.0*ALOG10(KSDDD)))**2
      C100=(FCR*LCR/DCR+Z1+Z2+1.0)/(2.0*ACR**2*RW)
      FCS=(1.0/(1.74-2.0*ALOG10(KSDHD)))**2
      C1C1=(FCS*LDS/DDS+Z7+Z8+1.C)/(2.0*ACS**2*RW)
C
C     ITERATIVE PROCEDURE FCP BALANCING CIRCULATICN LOOPS
C
C     SET INITIAL TRIAL VALUES
C
      GC=2CC.0
      GS=200.0
      HW2=HW1-ED2/GO
C
C     START FIRST ITERATICN LOOP
C
 1    HW6=HW2+ED2/GO
      XC=(ER3-GO*(HW1-HW6))/(GO*HFG)
      HXR=HNCRM-HWTRCM
      HNBR=HXR*AMAX1((HW1-HW6),0.0)/((HW1+XC*HFG)-HW6)
      LXR=HXR-HNBR
      RA1=((LXR/(XO*VFG))*ALCG((XO*VFG)/VF+1.0)+RW*HNBR)/HXR
      RC=1.C/(VF+XO*VFG)
      FR=(1.0/(1.74-2.0*ALOG10(KSDMB)))**2*(1.0+16078.58*(XO/PC1)**.96)
      PSIMB=(FR*LR/DR+1.0)*RA1/(2.0*AR**2*RC**2)+Z3/(2.0*AR**2*RW)+
     $Z4/(2.C*AR**2*RC)
      GOX=SCRT((RW-RA1)*HXR*G/(C100+PSIMB))
 400  FORMAT(1H0,G15.5)
C     IF CHECK VALUE EQUALS INITIAL GUESS, CONTINUE; ELSE REITERATE
      IF(ABS(GO-GOX).LT..01)GO TO 2
      GC=(GCX-GC)/2.C+GO
      GC TO 1
C
C     START SECONC ITERATICN LOCP
C
 2    CONTINUE
      XS=(GC1-GO*XC)/GS
      HXS=HNORM-HFCR
      HNBS=HXS*AMAX1((HW1-HW2),0.0)/((HW1+XS*HFG)-HW2)
      LXS=HXS-HNBS
      RA2=((LXS/(XS*VFG))*ALCG((XS*VFG)/VF+1.0)+RW*HNBS)/(HXS)
      RS=1.C/(VF+XS*VFG)
      FS=(1.0/(1.74-2.0*ALOG10(KSDSC)))**2*(1.0+16078.58*(XS/PC1)**.96)
      PSISC=(FS*LS/DS+1.0)*RA2/(2.0*AS**2*RS**2)+Z5/(2.C*AS**2*RW)+
     $Z6/(2.C*AS**2*RS)
      GSX=SCRT((RW-RA2)*HXS*G/(C101+PSISC))
C     IF CHECK VALUE EQUALS INITIAL GUESS, CONTINUE; ELSE REITERATE.
      IF(ABS(GS-GSX).LT..01)GO TO 3
      GS=(GSX-GS)/2.0+GS
      GC TC 2
C
C     START THIRD ITERATICN LOOP
C
 3    HW2X=(GW2/(GS+GC))*(HW4-HW1)+HW1
C     IF CHECK VALUE EQUALS INITIAL GUESS, CONTINUE; ELSE REITERATE.
      IF(ABS(HW2-HW2X).LT..1)GO TO 4
      HW2=(HW2X-HW2)/2.0+HW2
      GC TC 1
 4    CONTINUE
```

```
C
C     CALCULATE INITIAL CONDITIONS
C
      GORO=GC/RC
      GSRO=GS/RS
      MWIC=VCR*RW/2.0
      HMIO=HW1*MWIO
      QXCO=HW1+XO*HFG/2.0
      QXSO=HW1+XS*HFG/2.0
      VFCO=(VDR/2.0)*RC1
      HW6O=HW6
      GCIO=GC1
      GWRO=GO
      GWSO=GS
      RA1XC=(RA1*HXR-RW*HNBR)/LXR
      RA2XO=(RA2*HXS-RW*HNBS)/LXS
      LC1R=LAVDC
      LD1S=LAVHD
      WRITE(6,600)
600   FORMAT(1H1)
      WRITE(6,INCON1)
      WRITE(6,601)
601   FORMAT(1H0)
      WRITE(6,INCON2)
      WRITE(6,601)
      WRITE(6,INCON3)
      WRITE(6,601)
      WRITE(6,CONST1)
      WRITE(6,601)
      WRITE(6,CONST2)
      WRITE(6,601)
      WRITE(6,CONST3)
      WRITE(6,601)
      WRITE(6,CONST4)
      WRITE(6,601)
      WRITE(6,CONST5)
      WRITE(6,601)
      WRITE(6,CONST6)
      WRITE(6,600)
      WRITE(6,OUTPUT)
      WRITE(7,INCON1)
      WRITE(7,INCON2)
      WRITE(7,INCON3)
      WRITE(7,CONST1)
      WRITE(7,CONST2)
      WRITE(7,CONST3)
      WRITE(7,CONST4)
      WRITE(7,CONST5)
      WRITE(7,CONST6)
      STOP
      END
```

```
&INCON1
TR10=  2563.0000    ,TM10=  600.00000   ,TM20=  1033.0000    ,TM30=  515.42749    ,TM40=  360.36450    ,TM50=  600.99976    ,GORO=
  33.578735    ,GSRO=  31.459641    ,QXOO=  505.81152    ,CXSO=  502.34399
&END

&INCON2
HM10=  3562124.0    ,MW10=  8002.9414    ,VRCC=  249.59842    ,HW60=  492.62842    ,GW2=  45.000000    ,TW3=  254.00000    ,GL=
  55.858880    ,GB=  3.3074999    ,GC2=  7.7500000    ,GD10=  45.000000    ,VENT= 0.50999999
&END

&INCON3
CRA1C=  0.0            ,CRA2C=  0.0            ,GC1E= 0.44999979E-02,RA1X0=  34.425598    ,RA2X0=  37.804260    ,GWRO=  844.25098    ,
GWSO=  938.31958
&END

&CONST1
KR= 0.59999991E-04,KS= 0.29999996E-04,KDR= 0.49999999E-05,KCS= 0.49999999E-05,AR=  10.678426    ,LR=  28420.000    ,DR=
  196.57166    ,LR1=  10.000000    ,AS=  4.0646057    ,LS=  3162.2998    ,OS=  35.897476    ,LS1=  12.700000    ,LDR=
  25.000000    ,ACR=  1.4451323
&END

&CONST2
CCR=  1.9185321    ,HABR=  1.2741976    ,DCS=  4.6699991    ,LDS=  94.500000    ,HABS=  3.4920301    ,ADS=  2.8547764    ,MM1=
  7951.3984    ,MM2=  10752.000    ,MM3=  28192.000    ,MM4=  24443.000    ,MM5=  1617.0000    ,HXR=  12.410001
&END

&CONST3
HXS=  15.750000    ,MR1=  71.394867    ,VR=  106.78426    ,VS=  51.620483    ,VNDR=  98.174744    ,VOR=  327.31445    ,LD1R=
  12.500000    ,LD1S=  15.750000
&END

&CONST4
CR1=  0.31999826    ,CR1A= 0.30453670    ,CR2= 0.29042792    ,CR3= 0.26026064    ,CD1= 0.65523028    ,CD2= 0.58347189    ,CW=
  1.0761900    ,CM= 0.10999995    ,KC1=  2.0997734    ,KC2=  18.508804    ,KR1= 0.21132741E-01,KR2= 0.87189436    ,KR3=
  2.2037544
&END

&CONST5
KR4=  2.2576056    ,Z1= 0.99999964E-01,Z2= 0.99999964E-01,Z3= 0.99999964E-01,Z4= 0.14999998    ,Z5= 0.99999964E-01,Z6=
 0.99999964E-01,Z7= 0.99999964E-01,Z8= 0.99999964E-01,HW3=  221.00000    ,GC1C=  45.000000    ,CZ2=  6.9458303    ,C8=
  654.63574    ,C9= 0.23659343    ,C10=  754.03931
&END

&CONST6
C11= 0.10777515    ,C7= 0.18354926E-01,CSL=  14.365544    ,KW1=  10.037349    ,KW2=  14.930669    ,KW3= 0.32769658E-05,KW4=
 0.36683499E-02,HC=  19330.504
&END
```

```
&INCCNC
CPFNT= 0.59999999    ,TOTSTM=  162000.00    ,SPHSTM=  134100.00    ,CSHSTM=  27900.000    ,PDRUM=  698.00000    ,SHOT=
  915.00000    ,SHCP=  663.00000    ,CSHOT=  601.00000    ,CSHOP=  647.00000    ,ECCNIT=  254.00000    ,ECCNCT=  359.00000    ,
AIRTMP=  130.00000    ,OILFLO=  11907.000    ,AIRFLO=  201236.00    ,XCSAIR= 0.14999998    ,DRAFT=  11.629999    ,TGASSC=
  2563.0000    ,TGASSH=  1854.0000    ,TGASMB=  720.00000    ,TGASEC=  390.00000    ,TSCRN=  600.00000    ,TSPHTR=  1033.0000    ,
HRFVCL=  152.79999    ,FHAS=  106.59999    ,OILTMP=  80.000000
&END

&SCREEN
OTUBSC=  1.7299995    ,LAVSC=  12.700000    ,NTUBSC=  249.00000    ,FHASSC=  587.00000    ,MASSSC=  7951.3984
&END

&SPHTR
AREASH=  1964.0000    ,MASSSH=  10752.000
&END

&MNBANK
CTUBMB= 0.62999998    ,LAVMB=  10.000000    ,NTUBMB=  2842.0000    ,MASSMB=  28192.000    ,AREAMB=  6537.0000
&END

&ECCN
CTUBEC=  1.6399994    ,NPASSE=         12,NTUBEC=  14.000000    ,LTUBEC=  15.500000    ,MASSEC=  24443.000
&END

&DESPH
CTUBDS=  1.5999995    ,NTUBDS=  6.0000000    ,NPASSD=  4.0000000    ,LTUBDS=  9.3299995    ,AREAOS=  116.00000    ,MASSOS=
  1917.0000
&END

&CFMCCR
CTUBDC=  11.509999    ,LAVCO=  12.500000    ,NTUBOO=  2.0000000
&END

&HCRCCR
CTUBHC=  9.3399992    ,LAVHO=  15.750000    ,NTUBHO=  6.0000000
&END

&BCILER
CSTMDM=  60.000000    ,LSTMDM=  16.669998    ,CWTRDM=  30.000000    ,LWTRDM=  20.000000    ,HNCRM=  16.750000    ,HHOR=
  1.0000000    ,HWTRDM=  4.3399992    ,FURVCL=  1504.0000
&END

&THERMC
HSHOUT=  1468.4700    ,HDSCLT=  1285.2598    ,HECIN=  221.00000    ,HECCUT=  334.00000    ,KH2O= 0.98869990E-04,PRH2C=
  1.1699991    ,VSCH2O= 0.27679978E-03,KSTM= 0.16050000E-03,PRSTM= 0.99100000    ,VSCSTM= 0.33439996E-04,RSHOUT= 0.99879994    ,
RDSCLT=  1.1774996    ,FFLUE= 0.47470000E-01
&END

&LCSSES
KSCSC= 0.29999996E-04,KSDMB= 0.59999991E-04,KSCDD= 0.49999999E-05,KSCHC= 0.49999999E-05,ENTSC= 0.99999964E-01,BENDSC=
  0.99999964E-01,ENTMB= 0.99999964E-01,BENDMB= 0.14999998    ,ENTOD= 0.99999964E-01,BENDCD= 0.99999964E-01,ENTHC= 0.99999964E-01,
BENDHC= 0.99999964E-01
&END
```

```
&OUTPUT
ER1=  17381.715   ,ER2=  12062.414   ,ER3=  20187.137   ,ER4=  5085.0000   ,EC2=  1419.8789   ,GC=  844.25098   ,GS=
  938.31958   ,X0= 0.30419994E-01,XS= 0.20587761E-01,RA1=  35.911835   ,RA2=  40.264526   ,RC=  25.142426   ,RS=  29.826126   ,
RW=  48.900635   ,HW1=  495.08350   ,HW2=  490.94678   ,HW3=  221.00000   ,HW4=  334.00000   ,HW6=  452.62842   ,HFG=
  705.33276
&END
```

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