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Data Logs and Parameter Estimation for a 160 MW Unit

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Title and subtitle

Dynamic models for boiler-turbine-alternator units: Data logs and parameter estimation for a 160 MW unit.

Abstract

This report outlines a number of non-linear models that have been developed for simulation of fossil-fueled boiler-turbine-alternator units. The development, physical basis and parameter estimates of these models are given. The emphasis in this work has been to capture the essential dynamic features of the boiler-turbine-alternator unit within the smallest possible number of equations.

An extensive set of data collected from a 160 MW oil fired unit is included, and a comparison of the responses of some of the models to this plant data is made.

An IBM formatted floppy disk is available to more easily gain access to the models and data in this report.

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DYNAMIC MODELS FOR BOILER-TURBINE-ALTERNATOR UNITS: DATA LOGS AND PARAMETER ESTIMATION FOR A 160 MW UNIT.

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Introduction

The models developed in this report are for overall response evaluation of large scale fossil fueled boiler-turbine-alternator power generation units. As such the models can be used for control studies as well as macro design simulations. All the models considered use the three inputs of fuel, feedwater and steam flow to predict the three major outputs of drum steam pressure, electrical output and drum water level. Earlier work by Åström and Eklund [1972, 1975] had produced simple non-linear models to predict drum steam pressure and electrical output. This was extended by Bell and Åström [1979] to improve electrical output prediction and to include drum water level. It was felt that the complexity of the models in this last work should be able to be reduced, and the work of Morton and Price [1977] allowed this to occur.

They had proposed very simple models for drum pressure and drum water level. This work was extended and has led to models which have very good prediction of drum water level. This extended work has been combined with the Åström, Eklund, Bell work to form what is considered the least complex models that can be obtained to adequately capture the major dynamic characteristics of these plants.

The methods used to estimate parameters in these models for a 160 Mw unit are given, and then a detailed comparison to data collected from this plant is presented.

The models and data, as well as support documentation for this work have been made available on an IBM formatted floppy disk.

Section A - General model development

1. Basis of models

All the models presented in this report have been developed from the basic conservation laws of mass, energy and momentum; and hence have a firm physical basis related to physical characteristics of the plant. There have been two major sources for these models. They are:-

(i) The work done by Åström and Eklund [1972, 1975] and extended by Bell and Åström [1979].

(ii) The developments of Morton and Price [1977].

In both these studies the emphasis was on developing non-linear models with as simple a structure as possible. However this structure had to be complex enough to capture the major characteristics of the dynamic properties of the plant.

In (i) Åström and Eklund [1972, 1975] produced non-linear models of first and second order, and showed for a 160 Mw oil fired drum boiler that very good predictions could be obtained for drum pressure and electrical output. This work was then extended by Bell and Åström [1979] to include drum water level, but the order of the non-linear model increased to 7.

In (ii) Morton and Price [1977] developed linear models for drum pressure and drum water level. If the parameters in their equations are expressed as functions of operating conditions, then their models become non-linear. The two models developed by Morton and Price are 2nd order, and only predict drum steam pressure and drum water level. Although parameters are estimated for a particular drum boiler no detailed comparison to plant data is made. However, in their results, the drum water level prediction seems particularly good considering the low order of their models.

It is therefore clear that a combination of these two paths of work, could be used to produce a very good model of approximately 3rd order. The final result is a model composed of the drum steam pressure and electrical output from the Åström, Eklund, Bell work, and the drum water level with enhancements from the Morton and Price work. This has resulted in a 3rd order model which captures most of plant's dynamic performance (as can be seen in Section B), a result which was only available with the 7th order model in previous studies.

There are other factors which may influence the selection of a model for a particular application. Two such factors are the form of the inputs to the model, and the data needed to estimate any unknown parameters.

In this report a variety of models are given and these models can be classified according to these factors. The inputs to the models will consist of either the measured mass flow rates (i.e. fuel, feedwater and steam) or the position of actuators that drive the valves that control the mass flow rates. Although there is in general a simple mathematical relationship between these forms of inputs, the historical development has either been in one group or the other, and this has been maintained in this report. The models based on the Åström et al work tend to use actuator position, whereas the Morton and Price models use flows.

Similarly the parameter estimates for most of the models considered were made from dynamic data measured from the plant. This required a plant to be in existence and operational before reasonable models could be evaluated. Both sources of models used this form of parameter estimation, however the work presented in Section B of this report relates the parameters in the Morton and Price models back to physical characteristics of the plant (e.g. volume of drum). Hence plant drawings or design specifications can be used to develop models suitable for simulation of the dynamic performance of such plant.

2. Derivation of models

The details of the derivation of the base models will not be given in this report. Those details are available in the publications by Åström and Eklund [1972, 1975], Bell and Åström [1979], Morton and Price [1977], and Bell and Åström [1987]. In this report the equations from those publications that form the basis of the models will be repeated, and details of extensions given. Finally in Section B the parameter estimation details for a 160 Mw plant are given.

The models used in this investigation have been restricted to relating the three inputs of fuel, feedwater and steam flow to the three outputs drum pressure, electrical output and drum water level.

2.1 Aström, Eklund and Bell group

The basic equations used from the Aström and Eklund work are

$$\frac{dP}{dt} = -\ 0.0018\ u_2\ P^{9/8} + 0.02\ u_1 - 4.4 \times 10^{-4}\ u_3 \qquad \ldots(1)$$

$$Po = 0.6\ u_2\ P^{9/8} \qquad \ldots(2)$$

where u_1 and u_3 are the fuel and feedwater flows in T/hr respectively
u_2 is the control valve position
P and Po are the output variables of drum pressure and electrical output.

This work was extended by Bell and Aström [1979] and resulted in the following model

$$\frac{dP}{dt} = -\ 0.0018\ u_2\ P^{9/8} + 0.9\ u_1 - 0.15\ u_3 \qquad \ldots(3)$$

$$\frac{dPo}{dt} = \{(0.73\ u_2 - 0.16)P^{9/8} - Po\}/10 \qquad \ldots(4)$$

where u_1 and u_3 are the fuel and feedwater actuator positions.
u_2 is the control valve position
P and Po are the drum pressure and electrical output.

Note that the differences between the model in eqns.(3) and (4), and that in (1) and (2) are:-

a) The fuel and feedwater flows have been changed to actuator positions, so that all controls are of the same type.

b) A differential equation has been used instead of the algebraic equation for the electrical output. This is to include the time lag associated with the steam capacity and inertia of the turbine and alternator.

c) An extra constant (0.16) has been included in eqn. (4) to allow for the heat energy passing to the condensers and feedheaters.

d) A small change in the parameters to give an average fit to the 160 Mw plant data rather than a specific curve as used in Aström and Eklund [1972].

Equations (3) and (4) form the model called Bt1

A further extension by Bell and Aström [1979] included equations for predicting drum water level. This model had two forms, the simplest being

$$\frac{dP}{dt} = - 0.0018\ u_2\ P^{9/8} + 0.9\ u_1 - 0.15\ u_3 \qquad \ldots(5)$$

$$\frac{dPo}{dt} = \{(0.73\ u_2 - 0.16)P^{9/8} - Po\}/10 \qquad \ldots(6)$$

$$w_s = (1.1\ u_2 - 0.19)P \qquad \ldots(7)$$

$$\frac{d\rho_f}{dt} = (141\ u_3 - w_s)/V_t \qquad \ldots(8)$$

$$\rho_s = C_{s1}\ P + C_{s2} \qquad \ldots(9)$$

$$\alpha_{cs} = (1/\rho_f - v_w)/(1/\rho_s - v_w) \qquad \ldots(10)$$

$$x_w = 50\ (v_w\ V_t\ \rho + 60\ \alpha_{cs} + 0.05\ w_s - 65.5) \qquad \ldots(11)$$

Where u_1, u_2 and u_3 are the inputs namely fuel, control and feedwater actuator positions respectively.

P, Po and x_w are the outputs, namely drum pressure, electrical output and drum water level respectively.

w_s, ρ_f, ρ_s, and α_{cs} are the intermediate variables steam flow, density of fluid in system, density of steam, and quality of steam respectively.

V_t, C_{s1}, C_{s2} and v_w are constants representing total volume of the drum and risers, C_{s1} and C_{s2} are from least squares fitting of steam tables, v_w is the specific volume of water.

Equations (5) to (11) form the model called Bt2.

Model Bt2 is of 3rd order and does not predict good drum water level shrink/swell for changes in fuel flow. To include this phenomenon it is necessary to include both circulation flow rate changes and a water displacement mechanism proportional to the second derivative of α_{cs}. This is outlined in Bell and Åström [1979]. The following equations

$$\frac{dP}{dt} = -\,0.0018\ u_2\ P^{9/8} + 0.9\ u_1 - 0.15\ u_3 + 0.4\ \frac{dx_3}{dt} \qquad \ldots(12)$$

$$\frac{dPo}{dt} = \{(0.73\ u_2 - 0.16)P^{9/8} - Po\}/10 \qquad \ldots(13)$$

$$w_s = (1.1\ u_2 - 0.19)P \qquad \ldots(14)$$

$$\frac{d\rho_f}{dt} = (141\ u_3 - w_s)/V_t \qquad \ldots(15)$$

$$\rho_s = C_{s1}\ P + C_{s2} \qquad \ldots(16)$$

$$\alpha_{cs} = (1/\rho_f - v_w)/(1/\rho_s - v_w) \qquad \ldots(17)$$

$$\frac{dx_1}{dt} = (\alpha_{cs} - x_1)/T_{c1} \qquad \ldots(18)$$

$$\frac{dx_2}{dt} = \{1000\ (\alpha_{cs} - x_1) - x_2\}/T_{c2} \qquad \ldots(19)$$

$$\frac{dx_3}{dt} = (u_3 - x_3)/20 \qquad \ldots(20)$$

$$\frac{dx_4}{dt} = (3.55\ w_s - x_4)/20 \qquad \ldots(21)$$

$$V_w = v_w\ V_t\ \rho + 20\ \frac{dx_2}{dt} + 60\ \alpha_{cs} + 208\ \frac{dx_3}{dt} + 0.5\ x_3 + 0.03\ x_4 \qquad \ldots(22)$$

$$x_w = 50(V_w - 65.5) \qquad \ldots(23)$$

Where inputs, outputs, intermediate variables and constants are as defined in model Bt2. The extra state variables x_1, x_2, x_3 and x_4 are needed to include the changes in circulation rate and the displacement mechanism - see Bell and Åström [1979]. Constants T_{c1} and T_{c2} are to limit high frequencies in the second derivative term.

Equations (12) to (23) form the model called Bt3.

2.2 Morton and Price group

The key concept that Morton and Price [1977] introduce is an equation for evaporation rate. If this quantity can be predicted accurately then a measure of the steam being produced in the risers is available, and this is the major cause of drum water level variations. Morton and Price's work does not model the electrical output, and their other equations are based on mass flow rates for the input variables. Eqn.(4) from the Bell and Aström work uses control valve position for its input, and hence is not readily applicable. A simpler model based on the difference between the energy content of the steam entering the turbine and that leaving it is used to predict electrical output. The first model for this series becomes:-

$$\frac{dP}{dt} = \frac{k_c}{1+K} \{k_b\ e_f - r\ q_{fw} - q_s\} \qquad \ldots(24)$$

$$\frac{dM_w}{dt} = q_{fw} - q_e + T_s \frac{dq_e}{dt} \qquad \ldots(25)$$

$$\frac{dPo}{dt} = (k_{t1}\ q_s\ (P + k_{t2}) - Po)/t_{c1} \qquad \ldots(26)$$

$$e_f = k_{f1}\ q_f + k_{f2} \qquad \ldots(27)$$

$$q_e = q_s \qquad \ldots(28)$$

$$x_w = (M_w - M_{hf})V_f/a \qquad \ldots(29)$$

Where q_f, q_s and q_{fw} are the inputs of fuel flow rate, steam flow rate and feedwater flow rate respectively.

P, Po and x_w are the outputs of drum steam pressure, electrical output and drum water level respectively.

e_f is the heat energy flow rate of the fuel.

q_e is the evaporation rate

M_w is the mass of water in the system.

k_c, K, k_b, r, T_s, k_{t1}, k_{t2}, t_{c1}, k_{f1}, k_{f2}, M_{hf}, V_f, and a are constants. (See section B for details of estimated values and notation for summary.)

Note eqn.(26) is the simplified electrical output equation mentioned in the text, and eqn.(28) equates the evaporation flow rate as being equal to the steam mass flow rate out of the system. This is the simplest way of expressing evaporation flow rate, but as will be seen in the comparison to plant data in section B gives poor results for drum water response when the fuel input is changed.

Equations (24) to (29) form the model called Bt4.

A more realistic expression for evaporation flow rate is derived by Morton and Price [1977] and is given by

$$q_e = \frac{1}{(1+K)} (k_b \; e_f - r \; q_{fw}) + \frac{K}{(1+K)} q_s \qquad \text{...(30)}$$

Note this expression approaches eqn.(28) as K>>1.

2.3 Combinations and Extensions of the Basic Models

One factor which is not captured by the Morton and Price models is the drum water level variation due to a steady build-up of steam in the system. This can occur when an inbalance between q_e (evaporation rate) and q_s (steam flow leaving the system), while both are under steady state conditions. Such a characterisitic is observed in the 160 Mw plant data in section B under fuel changes. It can be included in the model by modifying eqn.(25) to

$$\frac{dM_w}{dt} = q_{fw} - q_e + T_s \frac{de}{dt} + K_2 \; (q_e - q_s) \qquad \text{...(31)}$$

where K_2 is a constant dependent on the distribution of steam between risers and drum under normal operating conditions.

Equations (24), (31), (26), (27), (30) and (29) form the model called Bt5.

The model assumed by Morton and Price is based on a linear relationship with distance for the mass of steam built up in the risers. Under steady state conditions this is valid, and the mass of water displaced during the transition from one steady state condition to the next will also be proportional to the rate of change of evaporation rate. However during this transient period the distribution of steam in the risers will not be linear. In fact a bulging of steam mass will occur in the region where evaporation is first occurring. This will cause an initial displacement of mass of water which is not accounted for in the Morton and Price equations. This characteristic can be seen very clearly in the drum water level responses for fuel changes in the 160 Mw unit in section B. The model Bt3 does account for this although that model required seven differential equations. Some initial studies have been undertaken to model this phenomena. The first of these uses a term proportional to

$\frac{d^2 q_e}{dt^2}$ in eqn.(25). To limit the high frequency response of such a term it is necessary to include an extra differential equation bringing the total to four. This addition forms the basis of model Bt6.

Two other paths are also being investigated.

They are:-

(i) Mass and energy balance equations for the system treating the steam and water as one fluid. Evaporation rate equation, water mass balance equation for drum, and a separate steam mass balance equation for risers. This leads to 6 differential equations and is called model Bt7.

(ii) Full mass, energy and momentum balance equations for drum and risers. Separate mass and energy balance equations for the steam and water, and an algebraic equation for the momentum balance equation. The energy balance equations to include a term to capture the change in energy content of the water and steam during pressure transients, and thus predict more accurately the evaporation rate.

A preliminary model for (i) is included in the appendix with the program listings, but a lot of work is still needed before these models are producing meaningful results.

Two other models are also included. The first is a combination of the best features of the main sources of models in this work. They are the drum pressure, electrical output, and quality of steam calculations from the Aström, Eklund, Bell work, coupled with the evaporation rate equation of the Morton and Price work. The equations for this model are eqns.(5) to (10), coupled with eqn.(30) and eqn.(11) changed to

$$x_w = 50\,(v_w\, V_t\, \rho + 60\, \alpha_{cs} + T_s\, q_e - 65.5) \qquad \ldots(32)$$

This model has been called Bta.

The second model in this group replaces the evaporation rate equation with one dependent on the physical characteristics of the riser loop. The derivation follows.

Mass balance equation for system

$$\frac{d\,(\rho_w\;V_w)}{dt} = q_{fw} - q_s$$

Drum level

$$A\;x_w = V_w + \bar{a}\;V_r \qquad \text{...(33)}$$

where A = wet surface area of water in drum

$\bar{a}$ = quality of steam in risers

V_r = volume of risers

Momentum balance equation for downcomer/riser loop gives

$$(\rho_w - \rho_s)\;\bar{a}\;V_r = \tfrac{1}{2}\,K_f\;q_c^{\,2} \qquad \text{...(34)}$$

and, $\quad q_c\;x_r = q_s$

where x_r is the mass quality of steam.

$$\bar{a} = \bar{a}\,(x_r) \approx \frac{x_r}{2}\,\frac{\rho_w}{\rho_s}$$

after substituting into momentum balance eqn.(34) and some algebraic manipulation

$$\bar{a}^3 = \frac{K_f\;\kappa_w^{\,2}}{8\;\rho_s^{\,2}\;(\rho_w - \rho_s)}\;q_s^{\,2} \qquad \text{...(35)}$$

Eqn.(35) gives the quality of steam (volume ratio) for the steam in the risers, and this can be combined with the basic Åström, Eklund, Bell model (eqns. (5) to (9)) noting that $q_s = w_s$, to form a particularly simple model for the system.

<u>This model has been called Bt8</u>.

3. Linear Models

Two approaches have been used to produce linear models from the general non-linear ones presented in section 2. They are

(i) By doing a Taylor's series approximation to the non-linear equations. i.e. the general form of all the models in section 2 is

$$\begin{array}{lcl} \dot{x} = f(x,z,u) & \overset{\text{Truncated Taylor's series}}{\Longrightarrow} & \dot{x} = A_1 x + B_1 u + C_1 z + e_1 \\ z = h(x,u) & & z = A_2 x + B_2 u + e_2 \\ y = g(x,z,u) & & y = A_3 x + B_3 z + C_3 u + e_3 \end{array}$$

On substituting for z in both the state and output equations the standard form of

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

$$y = Cx + Du + f$$

is obtained.

Note matricies A, B, C, and D as well as the vectors e and f will be functions of the operating conditions that have been used in the linearisation.

$$\text{e.g.} \quad A = A_1 + C_1 A_2 = \left.\frac{\partial f}{\partial x}\right|_{\substack{x_0\\z_0\\u_0\\y_0}} + \left.\frac{\partial f}{\partial z}\right|_{\substack{x_0\\z_0\\u_0\\y_0}} \left.\frac{\partial h}{\partial x}\right|_{\substack{x_0\\z_0\\u_0\\y_0}}$$

(ii) By using the symbolic manipulation program MACSYMA and special macro routines outlined in Holmberg [1986].

The advantage of (i) is that the elements in the A, B, C and D matricies are analytic functions of operating conditions and hence some insight into their behaviour can be gained as these conditions are changed. The method in (ii) on the other hand is particularly easy for the user. It is relatively expensive as far as computer time is concerned (approximately 1 hr for the Morton simple model on a VAX 11/780) but can save days of work for the analyser. At the time of writing this report, only the Morton simple model had been linearised by method (ii), however the method does look very promising.

The only models available in linearised form are the 3rd and 7th order ones (models Bt2 and Bt3) from the Bell and Aström [1979] work. These are called LBt2 and LBt3 respectively.

Section B - Modelling a 160 Mw Unit.

The boiler-turbine-alternator unit used to evaluate the models in this report is a 160 Mw oil fired natural circulation drum unit operated by Sydkraft AB in Malmo, Sweden. Full details of the unit are available in Eklund [1968] and Eklund [1971]. The main specifications of this plant are:-

Rated power 160 Mw -	oil fired
Steam flow at rated load	140 Kg/sec
Drum steam pressure	140 Kg/cm²
Superheated steam temperature	535°C
Volume of drum	40 m³
Volume of downcomers	11 m³
Volume of risers	38 m³
Mass of water in system at normal operating conditions	40,000 Kg
Mass of steam in system at normal operating conditions	2,000 Kg
Feedwater temperature	300°C.

The plant is currently only used for peak load operation. It has been selected for evaluation of the models in this report because of the extensive dynamic data that was collected from it in 1969. This data is described in this section under plant response comparison (section B3).

The language used to obtain all the responses in this report was the simulation language SIMNON, see Elmquist, Aström and Schönthal [1986]. Appendix B contains the SIMNON program listings for all models, connect systems and figure macros that have been used to generate the responses in this report. These listings are documented with information about their function and allocation of variable names.

1. Parameter Estimation.

Three methods have been used to evaluate parameters in the models in this study. They are:-

(i) Using the test data recorded from the plant, and then select a particular feature of that data to evaluate a parameter. Åström and Eklund [1972, 1975], and Morton and Price [1977] have in general used this approach to estimate the parameters in the basic models.

(ii) Use the plant physical characteristics e.g. volume of drum (etc). If an analysis is made of most of the parameters in the models in this work, then it is possible to relate them back to static physical characteristics of this form.

(iii) Use the plant dynamic data to automatically do parameter estimation. i.e. fit the model's responses to the plant's responses for all or a subset of the parameters in the model.

There are advantages and disadvantages of all the above methods. Method (ii) is particularly valuable if models are to be developed for plants at the pre-design or design stage. Method (iii) is only just starting to appear in simulation languages such as SIMNON. It has been available in specialised form or for linear models for many years, however availability of an automated algorithm within a non-linear simulation language would be an asset for the model builder.

In this work the approach has been to use either (i) or (ii) to evaluate reasonable parameter estimates. Method (iii) has only just started to be evaluated with the recent inclusion of automated parameter estimation algorithms in SIMNON.

Parameter estimates and the methods used to calculate them for basic models from the Åström, Eklund [1972, 1975] and the Bell, Åström [1979] are available in those publications. Those steps will not be repeated here, but the models in section A have the estimated values in them, and the notation section at the end of this report summarises the values with the symbolic name used in the programs.

The parameter estimates for the Morton and Price [1977] work have been calculated below for the 160 Mw unit, since the parameters given in their paper were for a smaller unit. Also the parameters used in these models have been derived in terms of physical characteristics of the plant, and operating conditions, so that more realistic models can be obtained.

The parameters to be estimated for the Morton and Price models as well as extensions are (see eqn.(24) to (31))

k_c, K, k_b, r, T_s, k_{t1}, k_{t2}, t_{c1}, k_{f1}, k_{f2}, M_{bf}, V_f, a, and K_2

Note $K = k_a\ k_b\ k_c$ (see Morton and Price [1977]).

Parameter k_a.

$$k_a = \frac{\Delta \text{ energy stored}}{\Delta \text{ pressure}} \qquad \text{(see Morton and Price [1977])}$$

$$= \frac{m_f\ \Delta h_f}{\Delta P}$$

$$= \frac{m_w\ \Delta h_w}{\Delta P} + \frac{m_s\ \Delta h_s}{\Delta P} \qquad \text{...(36)}$$

Equation (36) could be used as a more realistic expression for k_a in the model. $\frac{\Delta h_w}{\Delta P}$ and $\frac{\Delta h_s}{\Delta P}$ will be function of drum pressure P and can be evaluated from steam tables. m_w and m_s will come from the mass balance equations in the model.

For the models considered in this report and the 160 Mw plant

$$k_a \approx m_w \frac{\Delta h}{\Delta P} = 4.15\ m_w \qquad \text{(average value of } \frac{\Delta h}{\Delta P} \text{ at normal operating conditions)}$$

and m_w = 40,000 Kg at normal operating conditions

So k_a = 166,000 KJ/Kg/cm^2.

Parameter k_b

$$k_b = \frac{1}{h_{fg}} \qquad \text{(see Morton and Price [1977])} \qquad \text{...(37)}$$

where h_{fg} is the latent heat of vaporisation.

For the 160 Mw plant h_{fg} varies from 1319.4 KJ/Kg to 1066.6 KJ/Kg over the normal operating conditions. Equation (36) could be used with a steam table look-up procedure to give good estimates for k_b. However for the initial studies k_b has been assumed constant at 0.0008.

So, k_b = 0.0008 Kg/KJ.

Parameter k_c

$$k_c = \frac{\Delta P}{\Delta m_s} \qquad \text{(see Morton and Price [1977])}$$

Assuming that the volume occupied by the steam at normal operating constant is approximately constant, then

$$\Delta m_s = V_{ss} \ \Delta \rho_s$$

$$\text{and} \quad k_c = \frac{\Delta P}{V_{ss} \ \Delta \rho_s} \qquad \ldots(38)$$

The quantity $\frac{\Delta P}{\Delta \rho_s}$ can be evaluated from steam tables, and V_{ss} would be available from the mass balance equation for steam in the system. However for initial studies it has been assumed that V_{ss} is half the total volume of the drum, downcomers and risers, and $\frac{\Delta P}{\Delta \rho_s}$ is evaluated from the steam tables at 140 Kg/cm^2.

Then $k_c = 0.0261 \quad Kg/cm^2/Kg$.

Parameter K

$$K = k_a \ k_b \ k_c \qquad \text{(see Morton and Price [1977])}$$

Using the constant values for k_a, k_b and k_c above, gives

$$K = 166{,}000 \times 0.0008 \times 0.0261$$

$$= 3.466$$

Parameter r

$$r = \frac{h_f - h_w}{h_{fg}} \qquad \text{(see Morton and Price [1977])} \qquad \ldots(39)$$

The enthalpy of the feedwater h_w depends on its temperature, and the enthalpy of saturated water h_f depends on the drum steam pressure. The latent heat of vaporisation also depends on the drum steam pressure. Again the initial studies in this work have assumed these are constant and have been evaluated at a feedwater temperature of 300°C and a drum pressure of 140 Kg/cm^2.

$r = 0.08912$.

Parameter T_s

Water displaced from risers $= (m_{sr2} - m_{sr1})\,\dfrac{v_s}{v_w}$

where m_{sr2} = mass of steam in risers for evaporation rate q_{e2}

m_{sr1} = " " " " " " " " q_{e1}

v_s = specific volume of steam

v_w = specific volume of water

Now $m_{sr} = V_{sr}\,\rho_s$, V_{sr} = volume occupied by steam

ρ_s = density of steam

Assuming a linear relationship for steam volume along the risers, gives after some algebraic manipulation

$$m_{sr} = \frac{A_t\;l\;\rho_w\;q_e}{q_c}$$

where A_t is total area at the outlet of riser - assumed constant for length of riser.

l is the length of the risers.

ρ_w is the density of water.

q_e is the evaporation rate, and

q_c is the circulation flow rate.

$$\therefore\ \text{Water displaced from risers} = \frac{A_t\;l\;\rho_w}{q_c}\,(q_{e2} - q_{e1})\,\frac{v_s}{v_w}$$

But water displaced $= T_s\,\Delta q_e$

$$\therefore\ T_s = \frac{A_t\;l\;\rho_w}{q_c}\,\frac{v_s}{v_w} = \frac{V_r\;\rho_w^2\;v_s}{q_c} \qquad \ldots(40)$$

At normal operating conditions $q_c = 2000$, $v_s = 0.015$

$\therefore\ T_s = 126.$

Again for a more accurate model eqn.(40) should be used to calculate T_s with ρ_w, v_s and q_c being functions of plant operating conditions.

General note about parameters k_a, k_b, k_c, r and T_s. If eqns.(35) to (40) are used to calculate these parameters then only plant physical characteristics e.g. volume of risers (etc) are used, the other variables in these expression are calculated from the other model equations. This allows such a model to be used for simulating the dynamic response of a plant at the pre-design or design stage.

Parameters k_{t1}, k_{t2}, t_{c1}

These have been estimated from steam tables and the response time of the turbine alternator. No data was readily available for the weight and physical size of the turbine alternator section so dynamic responses were used.

k_{t1} = 0.0063

k_{t2} = 0.5

t_{c1} = 10.0 seconds.

Parameters k_{f1} and k_{f2}

These relate the fuel mass flow rate to heat energy released to the risers. This relationship depends on furnace heat distribution and characteristics of the burning process. No data was available for these so a linear relationship was assumed and the plant data fitted for both high and low load.

k_{f1} = 20200

k_{f2} = -11700

Parameter M_{hf}

This parameter gives the mass of water in the system when the drum is half full. The normal zero point for drum water level is the centre of the drum.

$\therefore$ M_{hf} = 40,000 Kg.

Parameters V_f and a

V_f = 0.0015 This is the specific volume of saturated water - assumed constant and obtained from steam tables at 322°C.

a = 27 m^2 The free surface area of water in drum (Eklund [1978]).

Parameter K_2

This parameter gives a measure of the amount of water displaced from the risers as a steady build-up of steam occurs in the system. It is proportional to the ratio of the steam in the risers to the steam in the drum, and also the difference in specific volume of the water and the steam. At normal operating conditions if it is assumed approximately one third of the steam exists in the risers and the specific volume ratio is 10, then

$$K_2 = \frac{1}{3} \times 10 = 3.3$$

See the notation section for a complete summary of all the parameters and their values. Included in this summary are the parameters used in the Bell Aström models against the symbolic representation used in the program.

2. Step response Analysis

Appendix A contains a summary of all the models under investigation in this work. Appendix C figures 1 to 9 show the step responses at low load for each of the models listed in Appendix A.

These step responses give a good initial indication of a model's potential. Figure 3 for the 7th order Bell Aström model is representative of what should be obtained. When comparing these step responses take into account that there are two groups of models. Models Bt1, Bt2, Bt3, Bt8 and Bt9 all use control valve position as inputs, whereas Bt4, Bt5, Bt6 and Bt7 use steam flow rate as an input.

A set of step responses at high load would also be useful especially to gain a measure of the degree of non-linearity in the plant. This work is one of the items listed under future directions.

3. Plant response comparison

Brief details of the plant were given at the start of this section. A very extensive data log was carried out on the plant in 1969. Basically the aim was to gain as much information about the plant dynamics, over as wide an operating range as possible. Part of the data from that data log are included in this report. Table 1 gives details of this data.

Data run	Data log name		Control varied		Operating conditions	
	ASCII	binary	Name	Range (Kg/sec)	Pressure (Kg/cm^2)	Load (Mws)
1	D107A.T	BD107A.DAT	Fuel	± 0.56	110	68 low
2	D108A.T	BD108A.DAT	Feedwater	± 5.56	110	68 low
3	D111A.T	BD111A.DAT	Control valve	± 3%	110	70 low
4	D201A.T	BD201A.DAT	Fuel	± 0.56	125	140 high
5	D102A.T	BD102A.DAT	Feedwater	± 5.56	125	140 high
6	D105A.T	BD105A.DAT	Control valve	± 3%	135	135 high

Table 1 - Summary of data logs from 160 Mw unit

The variations in controls were in the form of pseudo-random noise, and during each run only the control indicated was varied. The controls and their variations with time for each run are shown in Appendix D figs.7 to 12. The plant was operated under open loop conditions when the data was collected. More details of the variables logged from the plant, sampling times, and units for the variables are given in Appendix D figs.1 to 6 where the header page of each of the data logs is given.

This data can be used to find linear models about a certain load operating condition, since the input or control variations are small. It can also be used to verify non-linear models since there are two groups of data and these are at the limits of the normal load operating conditions of the plant.

Not all the model responses are included in this report. Some of the models are still in their development phase and hence including responses at this stage would be meaningless.

The approaches used to estimate parameters in the models has been:

(i) use either plant specifications or analysis of dynamic data to obtain initial estimates. The Morton and Price [1977] based models use plant specifications, whereas the Åström and Eklund [1972, 1975] based models use dynamic data.

(ii) improve parameter estimates by fitting model responses to plant data. This was initially done by changing individual parameters to see the effect on model response, and in the latest version of the simulation language being used an automatic non-linear parameter estimation procedure has been used.

Five of the developed models are compared to plant data and to each other. At the stage of writing this report, these were the models that had shown most promise. All of them have deficiencies and they all have their individual strengths. In selecting a model for a particular application a compromise is normally made between complexity and accuracy of response - in general the more complex the better the model performance.

Model name	Basis	No. of d.e's.	Form of inputs	Parameter estimates	General comments
Bt2	Bell and Aström[1979]	3	Actuator position	Dynamic data	Slightly more complex than Bt4. No fast drum water level response for fuel changes, but better response than Bt4.
Bt3	Bell and Aström[1979]	7	Actuator position	Dynamic data	The best overall response, but also the most complex. Some problems with drum pressure and electrical output at high load for control valve changes. A small spike in drum water level for feedwater change may cause some problems.
Bt4	Morton and Price[1977]	3	Mass flow rates	Plant specifications	The simplest model. Assumes evaporation rate equals steam flow. Poor drum water response for fuel changes.
Bt5	Morton and Price[1977]	3	Mass flow rates	Plant specifications	Separate evaporation rate equation. Extra term to enhance drum water level response. No fast drum water level response for fuel changes.
Bta	Bell and Aström[1979] Morton and Price[1977]	3	Actuator position	Dynamic data and Plant specifications	Combines best features of both sources of model. No fast drum water level response for fuel change.

Table 2 - Summary of models in comparison

A comparison of responses of the models in table 2 to those recorded from the plant are given in Appendix D, figures 13 to 43. These figures are in groups of six, representing the data for the six data logs given in table 1. Each of these figures contains the three outputs drum pressure, electrical output, and drum water level. In each case the curve marked 1 is the model, and 2 is the plant. Each group of six figures for the models in table 2 contain responses for the data in the order given in table 1 i.e. low load fuel, feedwater and the control changes followed by the high load data with same input sequence.

From these figures it can be seen that model Bt3 gives the best drum water level responses - see figures 19 to 24. Note the fast drum water level swell shrink with fuel changes in figures 19 (low load) and 22 (high load). As mentioned in table 2 in the general comments there are some problems in predicting drum pressure and electrical output for high load conditions and control valve changes (figure 24). One deficiency of the data logged from the plant was the lack of information about control valve position, this data was only recorded by hand. It is thought that this could be the major problem with this result.

A comparison of the drum water level response for the two Morton and Price based models Bt4 and Bt5 (figs.25 to 36) shows the effect of assuming evaporation rate is just equal to the steam mass flow rate. The major difference is in the drum water level response for fuel changes (compare fig.25 to fig.31) where it is seen that the initial swell/shrink due to change in steam in the risers when the fuel is stopped is not predicted with simple approximation. Drum water level shrink/swell is predicted well for steam mass flow rate changes (figs.27 and 36) in both models.

4. Actuator dynamics and co-ordinated control

If control studies are to be undertaken with the models presented in this report, then actuator dynamics will be needed. Figure 1 gives a block diagram for the realisation of such dynamics. The constants for these dynamics are,

i) Fuel flow

$$\left| \frac{du_1}{dt} \right| \leq 0.007 \text{ / second} \qquad 0 < u_1 < 1$$

(ii) Feedwater flow

$$\left| \frac{du_3}{dt} \right| \leq 0.05 \text{ / second} \qquad 0 < u_3 < 1$$

(iii) Control valve

$$\left| \frac{du_2}{dt} \right| \leq 0.2 \text{ / second} \qquad \text{(opening or upper rate)}$$

$$\left| \frac{du_2}{dt} \right| \leq 2 \text{ / second} \qquad \text{(closing or lower rate limit)}$$

$$0 < u_2 < 1$$

A basic co-ordinated controller has also been implemented. Its structure is shown in figure 2, only PI controllers have been used, and reset wind-up in the integration terms are removed by limiting as outlined in Bell [1970].

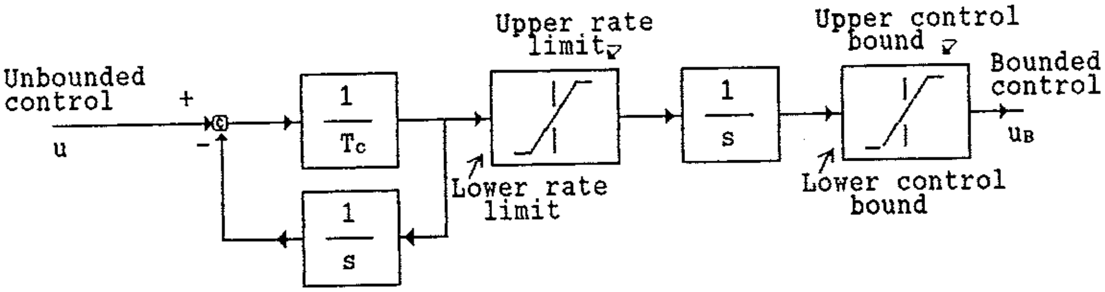

Fig. 1 - Representation of actuator dynamics.

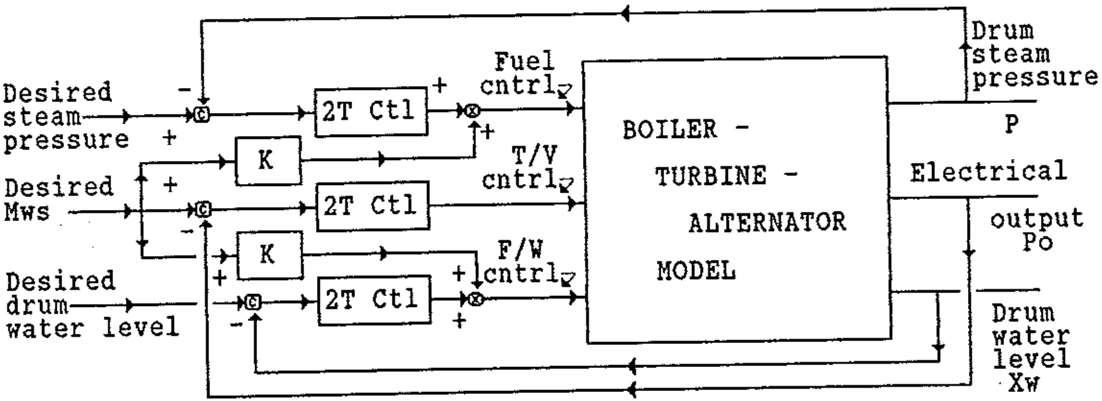

Fig. 2 - Co-ordinated controller structure.

In appendix E figures 1 to 5 show step responses of model Bt2 for set point change in electrical output, drum steam pressure, and drum water level.

Actuator limiting and dynamics for this simulation have been included in the controllers rather than developing separate modules. This structure has been used to reduce the number of program modules in the simulation. See program listings in Appendix E.

Section C. - Model and data availability

To gain easy access to the simulation programs and plant data used in this report, an IBM formatted floppy disk containing this information has been produced. A directory listing of the contents of this disk is given in Appendix F. To minimise the amount of cross referencing required to gain access to the information on this disk, file names have been made the same as model names. e.g. file Bt2.t contains the SIMNON program listing for model Bt2. Similarly any connect systems or figure macros will have a file name and actual name that contains a reference to the model that is used. e.g. f1bd1Bt3.t contains SIMNON code for a macro to produce a figure (f1) from boiler data 1 (bd1) for model Bt3. The name of this figure macro is f1bd1Bt3 to agree with the file name.

Because the PC version of SIMNON uses a different procedure to interface plant data to a model, it is necessary to modify the figure macros. A listing of one of these modified programs is included in Appendix F so that a comparison to the VAX simnon macro given in Appendix B can be made. It is also necessary to include a discrete system, in this case called ifile. A listing of this system is given in Appendix F. Refer to the latest PC SIMNON users manual for details of these procedures.

The plant data logs are given as both ASCII files and binary files on the floppy disk. Table 1 in section B3 gives the file names used to identify the different data logs.

A demonstration macro, called demo, has been included on the floppy disk. This macro allows a user to select, via menus, a model, type of response, and plant data so that a quick appreciation of the different models capabilities can be obtained. Note that some of the models have not been fully developed and as such will give meaningless results for some plant data.

Conclusions.

This report summarises the results of developing a range of non linear models suitable for predicting the major dynamic behaviour of large fossil fueled drum-turbine-alternator power generation units. The models realised range in complexity from three to seven differential equations. Even with this low order it has been shown by comparison to plant data that good prediction is obtained for drum pressure, electrical output and drum water level. In particular the phenomenon of drum water level swell shrink has been well modelled.

One of the aims of this work was to produce models which could be used by other researchers as easily as possible. To satisfy this need we have produced an IBM formatted floppy disk containing the models as well as the data logged from a 160 Mw oil fired power station. It is hoped this information can be used as a starting point for more ambitious model development or as a start to the accumulation of a number of data sets from different size power stations. The development of practical realisable controllers depends greatly on realistic models and it is hoped that this work will aid that process.

Acknowledgements.

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References.

Eklund, K. (1968): "Linear Mathematical Models of the Drum-Downcomer-Riser Loop of a Drum Boiler", Report TFRT-3005, Dept. of Automatic Control, Lund Institute of Technology, Sweden.

Eklund, K. (1971): "Linear Drum Boiler-Turbine Models", Report TFRT-1001, Dept. of Automatic Control, Lund Institute of Technology, Sweden.

Åström, K. J. and Eklund, K. (1972): "A simplified Non linear Model of a Drum Boiler-Turbine Unit", Int. J. Control, vol.16, No.1, 145-169.

Bell, R.D. (1973): "The on-line optimal control of constrained non-linear processes and its application to steam generators", PhD Thesis, University of N.S.W., Australia, March 1973.

Åström, K. J. and Eklund, K. (1975): "A Simple Non-linear Drum Boiler Model", Int. J. Control, vol.22, No.5, 739-740.

Lindahl, S. (1976): "Design and Simulation of a Coordinated Drum Boiler-Turbine Controller". Report TFRT3143, Dept. of Automatic Control, Lund Institute of Technology, Sweden.

Morton, A. J. and Price, P. H. (1977): "The Controllability of Steam Output, Pressure and Water Level in Drum Boilers", Proc. I. Mech. Eng. 1977, p75-84.

Bell, R. D. and Åström, K. J. (1979): "A Low Order Nonlinear Dynamic Model for Drum Boiler-Turbine-Alternator Units", Report TFRT-7162, Dept. of Automatic Control, Lund Institute of Technology, Sweden.

Elmqvist, H. Åström, K. J., and Schönthal, T. (1986): "SIMNON, User's Guide for MS-DOS Computers", Dept. of Automatic Control, Lund Institute of Technology, Sweden, August 1986.

Holmberg, V. (1986): "Some MACSYMA Functions for Analysis of Multivariable Linear Systems", Report TFRT-7333, Dept. of Automatic Control, Lund Institute of Technology, Sweden.

Bell, R. D. and Aström, K. J. (1987): "Simplified Models of Boiler-Turbine Units", Report TFRT 3191, Dept. of Automatic Control, Lund Institute of Technology, Sweden.

Notation.

p	Drum steam pressure	Kg/cm^2
P_o	Electrical output	Mw's
x_w	Drum water level	mm
q_f	Fuel mass flow rate	Kg/s or T/hr
q_{fw}	Feedwater mass flow rate	Kg/s or T/hr
w_s or q_s	Steam mass flow rate	Kg/s
e_f	Rate of heat supplied from fuel	kw
u_1	Fuel actuator position (0-1)	
u_2	Control valve position (0-1)	
u_3	Feedwater actuator position (0-1)	
V_t	Total volume of drum, downcomer and risers	m^3
v_w	Specific volume of water	m^3/Kg
ρ_f	Density of fluid (mixture of steam and water) in the system	Kg/m^3
ρ_s	Density of steam in the system	Kg/m^3
α_{cs}	Quality of steam in the system	-
$x_1, x_2, x_3,$ and x_4	Intermediate state variables in Bell/Aström model	-
V_w	Volume of water in system	m^3
k_a	Increase in boiler energy storage per unit rise in pressure	$KJ/Kg/cm^2$
k_b	The reciprocal of latent heat ($1/h_{fg}$)	Kg/KJ
k_c	The increase in pressure per unit mass of steam accumulated in the drum and associated parts	$Kg/cm^2/Kg$
$K = k_a k_b k_c$	Additional mass of steam evaporated per unit mass lost from the system	-
r	The loss of fuel energy that would be used for evaporation per unit mass of feedwater entering ($(h_f - h_w)/h_{fg}$)	-

h_{fg}	Latent heat of evaporisation	KJ/Kg
h_f	Enthalphy of saturated water	KJ/Kg
h_w	Enthalphy of feedwater	KJ/Kg
k_{t1}, k_{t2}	Constants for electrical output eqn.	
t_{c1}	Time constant of turbine alternator	s
k_{f1}, k_{f2}	Constants to convert fuel flow rate to heat content	
M_w	Mass of water in the system	Kg
M_{hf}	Mass of water in the system when the drum is half full and under rated operating conditions	Kg
a	Surface are of water in the drum at normal operating level	m^2
q_e	Evaporation mass flow rate	Kg/s
T_s	The fall of mass of water in boiler per unit increase in evaporation rate at normal operating point	s
ρ_w	Specific density of water	Kg/m^3
$\bar{a}$	Quality of steam in risers (volume ratio)	-
V_r	Volume of risers	m^3
x_r	Quality of steam in risers (mass ratio)	-
m_{sr}	Mass of steam in risers	Kg
A_t	Total internal area of risers	m^2
l	length of risers	m

Appendix A. - Summary of all models.

Name	No. of differential eqns	General comments
Bt1	2	Bell/Aström model, no drum water level, based on the original Aströom/Eklund model.
Bt2	3	Bell/Aström simple model with drum water level.
Bt3	7	Bell/Aström model with full drum water level equations.
Bt4	3	Morton/Price simple model, with simple electrical output equation.
Bt5	3	Morton/Price advanced model with extensions and electrical output equation.
Bt6	4	Expanded version of Bt5 with fast drum water level shrink/swell.
Bt7	6	Mass and energy balance equations for complete system + evaporation rate eqn and steam mass balance.
Bt8	3	Model Bt2 with quality of steam derived from evaporation rate.
Bta	3	Model Bt2 + drum water level equations from Bt5.

Appendix B. - SIMNON programs for all models, connect systems, and figure macros.

Appendix C. - Step responses of all models.

```
CONTINUOUS SYSTEM bt1
"2 nd order boiler-turbine model from Bell Astrom TFRT7162.
"This model does not give drum water level.

"Author Bell 29/5/87

INPUT u1 u2 u3 PDP POP
OUTPUT P PO qs
STATE x1 x2
DER d1 d2

"States and outputs are:-
"P,x1 - Drum steam pressure (Kg/cm2)
"PO,x2 - Electrical output (MW)

"Controls are:-
"u1 - normalised fuel flow (0-1 corresponds to 0-14 Kg/s)
"u2 - normalised control valve position (0-1)
"u3 - normalised feedwater flow rate (0-1 corresponds to 0-140 Kg/s)

"Constants
cp1:0.0018          "]
cp2:0.9             "]Pressure eqn constants.
cp3:0.15            "]
ce1:0.73            ")Electrical output eqn constants.
ce2:0.16            ")
tce:10.0            " Time constant of turbine/alternator

"Initial conditions
x1:108
x2:67

"Auxiliary equations
qs=(1.1*u2-0.19)*x1    "Steam flow eqn. not needed in main eqns.

"Dynamics
d1=-cp1*u2*P^(9/8)+cp2*u1-cp3*u3
d2=((ce1*u2-ce2)*P^(9/8)-x2)/tce

"Outputs
P=x1
PO=x2

END

----------------------------------------------------------------
```

```
CONTINUOUS SYSTEM bt2
"3 rd order boiler-turbine model from Bell Astrom TFRT7162

"Author Bell 10/5/87 updated 29/5/87

INPUT u1 u2 u3 PDP POP xwP
OUTPUT P PO xw rhf qs
STATE x1 x2 x3
DER d1 d2 d3

"States , outputs and other variables are:-
"P,x1 - Drum steam pressure (Kg/cm2)
"PO,x2 - Electrical output (MW)
"xw - Drum water level deviation about mean (mm)
"rhf,x3 - Drum/riser fluid density (Kg/m3)
"qs - Steam mass flow rate (kg/s)
"al - Steam quality (vol. ratio)
"vwd - Volume of water in drum (m3)

"Controls are:-
"u1 - normalised fuel flow (0-1 corresponds to 0-14 Kg/s)
"u2 - normalised control valve position (0-1)
"u3 - normalised feedwater flow rate (0-1 corresponds to 0-140 Kg/s)

"Constants
vt:85.0          "Total volume of drum, downcomers and risers
vw:0.001538      "Specific volume of water at 320 C
cqs1:1.1
cqs2:0.19
cs1:0.8          "Constant from fitting data to steam tables
cs2:-25.6        "    "       "      "     "   "    "    "
cvwd1:100.0
cvwd2:0.05
cp1:0.0018
cp2:0.9
cp3:0.15
ce1:0.73
ce2:0.16
tc1:10.0
cu3:141
c9d8:1.125     "Constant 9/8 for dp/dt and dpo/dt eqns
cxw1:50.0
cxw2:65.6

"Initial conditions
x1:108
x2:67
x3:440.66

"Auxiliary equations
qs=(cqs1*u2-cqs2)*P
rhs=cs1*P+cs2
al=((1/rhf)-vw)/((1/rhs)-vw)
vwd=vw*vt*rhf+cvwd1*al+cvwd2*qs

"Dynamics
d1=-cp1*u2*P^(c9d8)+cp2*u1-cp3*u3
d2=((ce1*u2-ce2)*P^(c9d8)-PO)/tc1
d3=(cu3*u3-qs)/vt
```

```
"Outputs
P=x1
PO=x2
rhf=x3
xw=cxw1*(vwd-cxw2)

END

----------------------------------------------------------------

CONTINUOUS SYSTEM bt3
"7 th order boiler-turbine model from Bell Astrom TFRT7162
"Data from 160 MW oil fired natural circulation unit

"Author Bell 10/5/87 updated 29/5/87

INPUT u1 u2 u3 PDP xwP POP
OUTPUT P PO xw rhf
STATE x1 x2 x3 x4 x5 x6 x7
DER d1 d2 d3 d4 d5 d6 d7

"States, outputs and other variables are:-
"P,x1 - Drum steam pressure (Kg/cm2)
"PO,x2 - Electrical output (MW)
"xw - Drum water level deviation about mean (mm)
"rhf,x3 - Drum/riser fluid density (Kg/m3)
"x4 - state x1 in report
"x5 - state x2 in report
"x6 -   "   x3  "   "
"x7 -   "   x4  "   "
"qs - Steam mass flow rate (kg/s)
"rhs - Specific density of steam (kg/m3)
"al - Steam quality (vol. ratio)
"vwd - Volume of water in drum (m3)

"Controls are:-
"u1 - normalised fuel flow (0-1 corresponds to 0-14 Kg/s)
"u2 - normalised control valve position (0-1)
"u3 - normalised feedwater flow rate (0-1 corresponds to 0-140 Kg/s)

"Constants
vt:85.0
vw:0.001538
cs1:0.8
cs2:-25.6
tc1:10.0 "Turbine/alternator time constant
tc2:10.0 "Time constant to limit high frequency
tc3:10.0
tc4:20.0
c9d8:1.125  "Constant 9/8 for P and PO eqns.
cqs1:1.1
cqs2:0.19
cvwd1:60.0
cvwd2:20.0
cvwd3:208.0
cvwd4:0.5
cvwd5:0.03
cf51:1000.0
cp1:0.0018
cp2:0.9
cp3:0.15
ce1:0.73
ce2:0.16
cu3:141.0
```

```
cqs:3.55
cxw1:50.0
cxw2:66.0

"Initial conditions
x1:108
x2:67
x3:428
x4:0.054
x5:-0.385
x6:0.44
x7:220

"Auxiliary equations
qs=(cqs1*u2-cqs2)*P
rhs=cs1*P+cs2
al=((1/rhf)-vw)/((1/rhs)-vw)
vwd=vw*vt*rhf+cvwd1*al+cvwd2*f5+cvwd3*f6+cvwd4*x6+cvwd5*x7
f5=(cf51*(al-x4)-x5)/tc3        "Eqn to allow derivative in o/p
f6=(u3-x6)/tc4                  " "   "   "       "        "  "

"Dynamics
d1=-cp1*u2*P^(c9d8)+cp2*u1-cp3*u3
d2=((ce1*u2-ce2)*P^(c9d8)-PO)/tc1
d3=(cu3*u3-qs)/vt
d4=(al-x4)/tc2
d5=f5
d6=f6
d7=(cqs*qs-x7)/tc4

"Outputs
P=x1
PO=x2
rhf=x3
xw=cxw1*(vwd-cxw2)

END

------------------------------------------------------------------
```

```
CONTINUOUS SYSTEM bt4

" 3rd order model based on the paper:-
" "The Controllability of Steam Output, Pressure and
"       Water Level in Drum Boilers",
"     Morton and Price, I.Mech.E, 1977

"Author : R.D.Bell 17/5/87

INPUT qf qs qfw pdp pop xwp
OUTPUT p po xw
STATE x1 x2 x3
DER d1 d2 d3

"Inputs
" qf - Fuel flow (0-10 kg/s)
" qs - Steam flow (0-140 kg/s)
" qfw - Feedwater mass flow rate (0-140 kg/s)
" ef - energy flow rate of fuel (kws)

"States and outputs
"p,x1 - Drum steam pressure (bar)
"xw,x2 - Drum water level (mm)
"po,x3 - Electrical power o/p (MWs)

"Constants
  dhdp:4.15 "Change in enthalpy of water per unit
            "pressure change. Calculated from steam
            "tables at p=120 bar.
  dpdvs:1.2 "Change in pressure per unit change in
            "specific volume. Calculated from steam
            "tables at p=120 bar.
  vss:40.0  "Volume in system occupied by steam at
            "normal operating conditions.
  r:0.08912 "(hf-hw)/hfg loss of evaporation per
            "unit mass of feed entering boiler.
  vf:0.0015 "Specific vol. of saturated water at
            "normal operating conditions (m3/kg).
  vs:0.015  "Specific vol. of saturated steam at
            "normal operating conditions (m3/kg).
  vr:38     "Volume of risers (m3).
  qc:2000   "Circulation flow rate (kg/s).
  a:27      "Free surface area of water in drum (m2)
  tc2:10.0  "Time constant for dynamics of turbines
            "and alternator.
  ce1:0.0063 "Constant for electrical o/p eqn.
  ce2:0.5    "    "     "       "      "   "   .
  cu11:20200.0 "Constant for converting fuel flow
               "to energy.
  cu12:-11700.0 "Constant for converting fuel flow
                "to energy.
  dwl0:2900    "Zero reference for drum water level.
  kb:0.0008    "1/hfg reciprocal of latent heat at
               "normal operating conditions (kg/kj).

 "Initial conditions
  x1:108
  x2:2.5
  x3:67.0
```

```
"Auxiliary equations
  mfd=a*x2/vf  "Mass of fluid in drum.
  ka=mfd*dhdp  "Increase in boiler energy storage
               "per unit rise in pressure (kj/bar).
  kc=dpdvs/vss "Increase in pressure per unit mass
               "of steam accumulated in drum and
               "associated parts (bar/kg).
  vstvf=vs/vf  "Ratio of specific volume of steam
               "to water at normal operating
               "conditions.
  ts=vstvf*vr/(qc*vf) "Increase in mass of water in
                      "drum per unit increase in
                      "evaporation rate at normal
                      "working level (s).
  ef=cu11*qf+cu12
  K=ka*kb*kc    "Additional mass of steam evaporated
                "per unit mass lost from system
                "(=ka*kb*kc).
  msd = qs "Rate of evaporation is equal to steam
           "flow (kg/s).

"Dynamics
  d1 = (kb*ef-r*qfw - qs)*kc/(1+K)
  d2 = (qfw - msd)*vf/a
  d3 = (qs*(ce1*p+ce2) - po)/tc2

"Outputs
  p = x1
  po= x3
  xw = (x2 + ts*msd*vf/a)*1e3-dwl0

END

-----------------------------------------------------------------


CONTINUOUS SYSTEM bt5

" 3rd order model based on paper by
" Morton and Price 1977

"Author : R.D.Bell 15/5/87 updated 4/6/87

INPUT qf qfw qs PDP POP xwP
OUTPUT P PO xw
STATE x1 x2 x3
DER d1 d2 d3

"Inputs
" qf - Fuel flow (0-10 kg/s)
" qfw - Feedwater mass flow rate (0-140 kg/s)
" qs - Steam mass flow rate (0-140 kg/s)
" ef - Energy flow rate of fuel (kws)

"States and outputs
"P,x1 - Drum steam pressure (bar)
"xw,x2 - Drum water level (mm)
"PO,x3 - Electrical o/p (MWs)
```

```
"Constants
  ka:166000  "Increase in boiler energy storage per
             "unit rise in pressure (kj/bar)
  kb:0.0008 "1/hfg reciprocal of latent heat (kg/kj)
  kc:0.0261 "Increase in pressure per unit mass of
            "steam accumulated in drum and
            "associated parts (bar/kg).
  r:0.08912 "(hf-hw)/hfg loss of evaporation
            "per unit mass of feed entering boiler.
  vf:0.0015 "Specific vol. of saturated water (m3/kg)
  a:27      "Free surface area of water in drum (m2)
  ts:126    "Fall in mass of water in boiler
            "per unit increase in evaporation rate
            "at normal working level (s).
  ce1:0.0063 "Constant for electrical o/p eqn
  ce2:0.5    "    "     "      "      "   "
  tc2:10.0   "Time constant for dynamics of turbines
             "and alternator.
  cu11:20200.0  "Constant for converting fuel flow
                "to energy.
  cu12:-11700.0 "Constant for converting fuel flow
                "to energy.
  sf1:1e3      "Scale factor for state eqn.
  mhf:40000    "Mass of water in system at normal
               "working level.
  dw10:310     "Drum water level correction for
               "water displaced from risers.
  k1:2.0

"Initial conditions
  x1:110
  x2:40.0       "40.0e3/sf1
  x3:67

"Auxiliary equations
  ef=cu11*qf+cu12
  K=ka*kb*kc    "Additional mass of steam evaporated
                "per unit mass lost from system
                "(=ka*kb*kc).
  msd=(kb*ef-r*qfw)/(1+K) + qs*K/(1+K) "Rate of
                                       "evaporation
                                       "(kg/s).
  disp=k1*(msd-qs)

"Dynamics
  d1 = (kb*ef - r*qfw - qs)*kc/(1+K)
  d2 = (qfw - msd + disp)/sf1
  d3 = (qs*(ce1*P + ce2) - PO)/tc2

"Outputs
  P = x1
  xw = ((x2*sf1-mhf + ts*msd)*vf/a)*1e3-dw10
  PO = x3

END
------------------------------------------------------------
```

```
CONTINUOUS SYSTEM bt6

" 4th order model based on paper by Morton and Price 1977

"Author : R.D.Bell 15/5/87 updated 5/6/87

INPUT qf qfw u2 PDP POP xwP
OUTPUT P PO xw qs
STATE x1 x2 x3 x4
DER d1 d2 d3 d4

"Inputs
" qf - Fuel flow (0-10 kg/s)
" qfw - Feedwater mass flow rate (0-140 kg/s)
" qs - Steam mass flow rate (0-140 kg/s)
" ef - Energy flow rate of fuel (kws)

"States and outputs
"P,x1 - Drum steam pressure (bar)
"xw,x2 - Drum water level (mm)
"
"PO,x4 - Electrical o/p (MWs)

"Constants
  ka:166000  "Increase in boiler energy storage per
             "unit rise in pressure (kj/bar)
  kb:0.0008 "1/hfg reciprocal of latent heat (kg/kj)
  kc:0.0261"Increase in pressure per unit mass of steam
             "accumulated in drum and associated parts (bar/kg)
  r:0.08912 "(hf-hw)/hfg loss of evaporation per unit mass
             "of feed entering boiler
  vf:0.0015 "Specific vol. of saturated water (m3/kg)
  a1:27      "Free surface area of water in drum (m2)
  a2:27      "Free surface area of water in drum and risers (m2)
  ts:126     "Fall in mass of water in boiler per unit increase
             "in evaporation rate at normal working level (s)
  ce1:0.0063 "Constant for electrical o/p eqn
  ce2:0.5    "    "     "       "       "   "
  tc2:10.0   "Time constant for dynamics of turbines and alternator
  cu11:20200.0  "Constant for converting fuel flow to energy
  cu12:-11700.0 "    "     "       "      "     "   "    "
  sf1:1e3       "Scale factor for state eqn
  mhf:40000     "Mass of water in system at normal working level
  dwl0:310      "Drum water level correction for water displaced from risers
  k1:3.0
  tc1:5.0
  k2:0.0
  cqs1:1.1
  cqs2:0.19

 "Initial conditions
  x1:110
  x2:40.0       "40.0e3/sf1
  x3:60.0
  x4:67

 "Auxiliary equations
  ef=cu11*qf+cu12
  qs=(cqs1*u2-cqs2)*P
  K=ka*kb*kc     "Additional mass of steam evaporated per unit
                 "mass lost from system (=ka*kb*kc)
  msd=(kb*ef-r*qfw)/(1+K) + qs*K/(1+K) "Rate of evaporation (kg/s)
  disp=k1*(msd-qs)
```

```
"Dynamics
  d1 = (kb*ef - r*qfw - qs)*kc/(1+K)
  d2 = (qfw - qs + disp)/sf1
  d3 = (msd - x3)/tc1
  d4 = (qs*(ce1*P + ce2) - PO)/tc2

"Outputs
  P = x1
  xw = ((x2*sf1 - mhf)*vf/a2 + (ts*msd + k2*d3)*vf/a1)*1e3-dwl0
  PO = x4

END

------------------------------------------------------------------


CONTINUOUS SYSTEM bt7
"
" 6th order model based on separate energy and mass balance
" equations for the drum . Energy and mass
" balance eqns are written for the total fluid.
" The physical characteristics (e.g. pressure, density) of the
" steam is found from assuming a saturated state for the fluid.
" Separate mass balance eqns for the steam in the drum and risers.
" The energy absorbed or released from the stored energy during
" transients is assumed to all occur in the risers steam mass
" balance equation.

" Author R.D.Bell 23/5/87

INPUT u1 u2 u3 pdp pop xwp
OUTPUT xw P PO               "mfs msd msr mwd mwdc vss
STATE x1 x2 x3 x4 x5 x6
DER d1 d2  d3 d4 d5 d6

"Outputs
"P - Drum steam pressure (kg/cm2)
"PO - Electrical output (MWs)
"xw - Drum water level (m)

"Inputs
"u1 - Fuel control (0-1 corresponds to 0-10 kg/s)
"u2 - Control valve position (0-1 corresponds to 0-160 MWs)
"u3 - Feedwater control (0-1 corresponds to 0-140 kg/s)
"ef - Energy flow rate for fuel (KWs)
"qfw - Feedwater mass flow rate (kg/sec)
"qs - Steam mass flow rate (kg/sec)

"States
"x1 - Energy of fluid in system (kj*sf1)
"x2 - Mass of fluid in system (kgs*sf2)
"x3 - Mass of water in drum (kgs*sf2)
"x4 - Mass of steam in risers (kgs*sf2)
"x5 - Output electrical energy flow rate (MWs)

"Constants
   vd:29 "Volume of drum (m3)
   vdd:11 "Volume of downcomers (m3)
   vr:37 "Volume of risers (m3)
   adc:27 "Area of drum at centre (m2)
   hfw:1200 "Enthalpy of feedwater (kj/kg)
   mhf:12000.0 "Mass of water in half full drum (kg)
"  z:29     "Height of downcomers or risers (m)
"  g:9.81   "Gravitation constant (m/s2)
```

```
"  kf1:0.4  "
   kf2:150     " ka*kb in Mortons paper
   r:0.202     " loss of evaporation per unit mass of
               " feed entering boiler. Should be a function
               " of feedwater temp and hl.
   tc2:1.0     "Time constant to limit dpdt factor
   qir:2800   "Circulation flow rate (kg/sec). Constant for
              "initial test. Guess assuming 20x steam flow
   c1e:0.664     "Constant in electrical output state
   c2e:0.034   "   "      "     "       "     "
   tc1:10 "Time constant for turbine/alternator section
   vw:0.0015 "Specific volume of water at 320 C (m3/kg)
   c1:-0.00016     "Coefficients from fitting data from steam tables
   c2:0.0357       "      "        "      "      "     "     "     "
   c3:0.000004118  "      "        "      "      "     "     "     "
   c4:0.001043207  "      "        "      "      "     "     "     "
   c5:-2.24        "      "        "      "      "     "     "     "
   c6:2947.265     "      "        "      "      "     "     "     "
   c7:4.039        "      "        "      "      "     "     "     "
   c8:991.1        "      "        "      "      "     "     "     "
   c21:1.125  "Constant 9/8 for electrical o/p state eqn
   sf1:1e6    "Scale factor for energy d.e.s
   sf2:1e3    "Scale factor for mass d.e.s
   hl:1250    "Specific heat of evaporation-constant for this test (kj/kg)
   cu11:1.6e5      "Conversion constant for fuel control
   cu12:38000      "     "         "      "   "     "
   cu3:143         "Conversion constant for feedwater control
   cu21:1.1        "Conversion constant for control valve
   cu22:0.19       "     "         "      "     "      "

"Initial conditions
   x1:60.0               "=60.0e6/sf1
   x2:40.0               "=40.0e3/sf2
   x3:11.838            "=14.e3/sf2 mass of steam in drum
   x4:0.4275            "=0.614e3/sf2 mass of steam in risers
   x5:67
   x6:108.0

"Auxiliary equations

" Conversion eqns for controls
   ef=cu11*u1+cu12
   qfw=cu3*u3
   qs=(cu21*u2-cu22)*P

" Complete system
   mfs=x2*sf2           "mfs=total mass of fluid in system
   ufs=x1*sf1/mfs       "ufs=internal energy of fluid in system
   vt=vd+vdd+vr         "vt=total volume of system
   rfs=mfs/vt           "rfs=specific density of fluid in system
   vfs=1/rfs            "vfs=specific volume of fluid in system
" Calculate system steam pressure
   as=mfs*c1*c7
   bs=0.5*vt*(c5-c7)-mfs*(c1*ufs-c1*c8-c2*c7)
   cs=0.5*vt*(c6-c8)-mfs*(c2*ufs-c2*c8)
   bss=bs*bs
   facs=4*as*cs
   srfs=if bss<facs then 0.0 else sqrt(bss-facs)
   P1s=(-bs+srfs)/(2*as)
   P2s=(-bs-srfs)/(2*as)
   Pts=if P1s<0.0 then (if P2s<0.0 then 0.0001 else P2s) else P1s
   P=if Pts>222.0 then 222.0 else Pts
```

```
" Calculate other properties from linearised steam tables
   vss=c1*P+c2          "vss=specific volume of steam in system
   vws=c3*P+c4          "vws=specific volume of water in system
   hss=(c5*P+c6)        "hss=specific enthalpy of steam in system
   hws=(c7*P+c8)        "hws=specific enthalpy of water in system
" Mass of water in drum
   mwd=x3*sf2           "mwd=mass of water in drum

" Riser Section (steam mass only calculated)
   msr=x4*sf2           "msr=mass of steam in risers
   Vsr=vss*msr          "Vsr=volume occupied by steam in risers
   Vwr=vr-Vsr           "Vwr=volume occupied by water in risers
   mwr=Vwr/vw           "mwr=mass of water in risers
   amr=msr/mwr          "amr=quality of steam in risers (mass ratio)
"  did=(z*g*(1/vw-rfr)-(Pr-P))/(vw*2)
"  srfdc=if did>0.0 then did else 0.001
"  qir=kf1*sqrt(srfdc)
   qor=qir           "qor=mass flow rate out of risers
   dpdt=(P-x6)/tc2   "dpdt=rate of change of steam pressure

"Output equations
   PO=x5
   xw=vw*(mwd-mhf)/adc*1e3

"Dynamics
   d1=(ef+qfw*hfw-qs*hss)/sf1
   d2=(qfw-qs)/sf2
   d3=(qfw-qir+(1-amr)*qor+(vss/vws)*d4*sf2)/sf2
   d4=(ef/hl-amr*qor-r*qfw-kf2*dpdt)/sf2
   d5=((c1e*qs/P-c2e)*P^c21-x5)/tc1
   d6=dpdt                              "dpdt=(P-x6)/tc2

END
```

```
CONTINUOUS SYSTEM bt8
"3 rd order boiler-turbine model from Karl Astrom
"Data from 160 MW oil fired natural circulation unit

"Author Bell 30/5/87

INPUT u1 u2 u3  PDP POP xwP
OUTPUT P PO xw
STATE x1 x2 x3
DER d1 d2 d3

"States, outputs and other variables are:-
"P,x1 - Drum steam pressure (Kg/cm2)
"PO,x2 - Electrical output (MW)
"xw - Drum water level deviation about mean (mm)
"rhf,x3 - Drum/riser fluid density (Kg/m3)
"qs - Steam mass flow rate (kg/s)
"a - Quality of steam in risers (vol ratio)
"vwd - volume of water in drum (m3)

"Controls are:-
"u1 - normalised fuel flow (0-1 corresponds to 0-14 Kg/s)
"u2 - normalised control valve position (0-1)
"u3 - normalised feedwater flow rate (0-1 corresponds to 0-140 Kg/s)
```

```
"Constants
vt:85.0
vw:0.001538
cs1:0.8
cs2:-25.6
vr:37
cqs1:1.1
cqs2:0.19
c9d8:1.125
cp1:0.0018
cp2:0.9
cp3:0.15
kf:0.02
kdr:300
kp:1.0
ce1:0.73
ce2:0.16
tc1:10
cu3:141.0
cxw1:50.0
cxw2:59.1
dwl0:120

"Initial conditions
x1:108
x2:67
x3:428

"Auxiliary equations
qs=(cqs1*u2-cqs2)*P
rhs=cs1*P+cs2
vwd=vw*vt*rhf        "This assumes mass of water in drum>>mass of steam
a3=(0.5*kf*qs^2)/(kdr*vr)
a=kp*a3^(1/3)

"Dynamics
d1=-cp1*u2*P^(c9d8)+cp2*u1-cp3*u3
d2=((ce1*u2-ce2)*P^(c9d8)-PO)/tc1
d3=(cu3*u3-qs)/vt

"Outputs
P=x1
PO=x2
rhf=x3
xw=cxw1*(vwd+a*vr-cxw2)-dwl0

END

---------------------------------------------------------------
```

```
CONTINUOUS SYSTEM bta
"3 rd order boiler-turbine model from Bell Astrom TFRT7162
"with Morton's evaporation rate eqn.

"Author Bell 10/5/87 updated 19/6/87

INPUT u1 u2 u3 PDP POP xwP
OUTPUT P PO xw rhf qs
STATE x1 x2 x3
DER d1 d2 d3

"States , outputs and other variables are:-
"P,x1 - Drum steam pressure (Kg/cm2)
"PO,x2 - Electrical output (MW)
"xw - Drum water level deviation about mean (mm)
"rhf,x3 - Drum/riser fluid density (Kg/m3)
"qs - Steam mass flow rate (kg/s)
"al - Steam quality (vol. ratio)
"vwd - Volume of water in drum (m3)

"Controls are:-
"u1 - normalised fuel flow (0-1 corresponds to 0-14 Kg/s)
"u2 - normalised control valve position (0-1)
"u3 - normalised feedwater flow rate (0-1 corresponds to 0-140 Kg/s)

"Constants
vt:85.0        "Total volume of drum, downcomers and risers
vw:0.001538    "Specific volume of water at 320 C
cqs1:1.1
cqs2:0.19
cs1:0.8        "Constant from fitting data to steam tables
cs2:-25.6      "    "      "      "    "  "   "    "
cvwd1:100.0
cvwd2:0.05
cp1:0.0018
cp2:0.9
cp3:0.15
ce1:0.73
ce2:0.16
tc1:10.0
cu3:141
c9d8:1.125   "Constant 9/8 for dp/dt and dpo/dt eqns
cxw1:50.0
cxw2:68.3
ka:166000
kb:0.0008
kc:0.0261
r:0.08912
ts:2000
vf:0.0015
a:27
qfcf:12.6  "50*0.252
qfwcf:126    "500*0.252
cu11:20200.0
cu12:-11700.0

"Initial conditions
x1:108
x2:66
x3:431
```

```
"Auxiliary equations
qs=(cqs1*u2-cqs2)*P
rhs=cs1*P+cs2
al=((1/rhf)-vw)/((1/rhs)-vw)
qf=qfcf*u1
ef=cu11*qf+cu12
K=ka*kb*kc
qfw=qfwcf*u3
msd=(kb*ef-r*qfw)/(1+K) + qs*K/(1+K)
vwd=vw*vt*rhf+cvwd1*al+ts*msd*vf/a

"Dynamics
d1=-cp1*u2*P^(c9d8)+cp2*u1-cp3*u3
d2=((ce1*u2-ce2)*P^(c9d8)-PO)/tc1
d3=(cu3*u3-qs)/vt

"Outputs
P=x1
PO=x2
rhf=x3
xw=cxw1*(vwd-cxw2)

END

----------------------------------------------------------------

CONTINUOUS SYSTEM lbt2

"          A linear version of the Bell/Astrom boiler model

" Author R.D.Bell 11/5/87

" Form of model:-
"   xdot=Ax+Bu+e x(0)=x0
"   y=Cx+Du+f
"
" state x=[x1,x2,x3]'
"       where x1=p=drum pressure
"             x2=po=electrical output
"             x3=rho=density of fluid in complete system
"
" controls u=[u1,u2,u3]'
"        where u1=normalised fuel flow (0-1)
"              u2=    "      control valve position (0-1)
"              u3=    "      feedwater flow (0-1)
"
" outputs y=[p,po,xw]'
"        where xw=drum water level
"
" vectors e and f are vectors from linearisation
INPUT u1 u2 u3 pdp pop xwp
OUTPUT p po xw
STATE x1 x2 x3
DER d1 d2 d3

"
"  Constants
"
    vt:85          " Total volume
    vw:0.001538    " Specific volume of water
    cs1:0.8        " Constant from L.S. fitting of steam tables
    cs2:-25.6      "     "      "  "      "     "   "      "
```

```
"
"  Linearisation point
"
    u20:0.69  " half load point
    p0:108    " half load point
    rho0:428  " "   "     "
"
" Initial calculations
"
    ws0=(1.1*u20-0.19)*p0
    alp0=(rho0^(-1)-vw)/((cs1*p0+cs2)^(-1)-vw)
    dwsdp=1.1*u20-0.19
    dwsdu2=1.1*p0
    dalpdrho=-((rho0)^(-2))*(((cs1*p0+cs2)^(-1)-vw)^(-1))
    t2=((cs1*p0+cs2)^(-2))
    dalpdp=cs1*(rho0^(-1)-vw)*(((cs1*p0+cs2)^(-1)-vw)^(-2))*t2
"
" e vector
"
    e1=0.002025*u20*p0^(9/8)
    e2=-0.082125*u20*p0^(9/8)+0.002*p0^(9/8)
    e3=(dwsdu2*u20+dwsdp*p0-ws0)/vt
"
" A matrix
"
    a11=-0.002025*u20*p0^(1/8)
    a12:0.0
    a13:0.0
    a21=(9/8)*(0.073*u20-0.016)*p0^(1/8)
    a22:-0.1
    a23:0.0
    a31=-dwsdp/vt
    a32:0.0
    a33:0.0
"
" B matrix
"
    b11:0.9
    b12=-0.0018*p0^(9/8)
    b13:-0.13
    b21:0.0
    b22=0.073*p0^(9/8)
    b23:0.0
    b31:0.0
    b32=-dwsdu2/vt
    b33=141/vt
"
" C matrix
"
    c11:1.0
    c12:0.0
    c13:0.0
    c21:0.0
    c22:1.0
    c23:0.0
    c31=0.05*(60)*dalpdp
    c32:0.0
    c33=0.05*(vw*vt+(60)*dalpdrho)
```

```
" D matrix
"
    d11:0.0
    d12:0.0
    d13:0.0
    d21:0.0
    d22:0.0
    d23:0.0
    d31:0.0
    d32:0.0
    d33:0.52
"
" f vector
"
    f1:0.0
    f2:0.0
    t3=3*(alp0-dalpdrho*rho0-dalpdp*p0)-3.175
    f3=t3
"
" Initial conditions
"
    x1:108
    x2:67
    x3:428
"
" step state equations
" dynamic section
"
  d1=a11*x1+a12*x2+a13*x3+b11*u1+b12*u2+b13*u3+e1
  d2=a21*x1+a22*x2+a23*x3+b21*u1+b22*u2+b23*u3+e2
  d3=a31*x1+a32*x2+a33*x3+b31*u1+b32*u2+b33*u3+e3
"
" Output section
"
  p=c11*x1+c12*x2+c13*x3+d11*u1+d12*u2+d13*u3+f1
 po=c21*x1+c22*x2+c23*x3+d21*u1+d22*u2+d23*u3+f2
 xw=(c31*x1+c32*x2+c33*x3+d31*u1+d32*u2+d33*u3+f3)*1e3
END
```

```
CONTINUOUS SYSTEM lbt3
"      A linear version of the Bell/Astrom boiler model

"  Author R.D.Bell 11/5/87

" Form of model:-
"   xdot=Ax+Bu+e, x(0)=x0
"   y=Cx+Du+f
"
" state x=[p,po,rho,x1,x2,x3,x4]'
"       where p=drum pressure
"             po=electrical output
"             rho=density of fluid in complete system
"
" controls u=[u1,u2,u3]'
"        where u1=normalised fuel flow (0-1)
"              u2=    "      control valve position (0-1)
"              u3=    "      feedwater flow (0-1)
"
" outputs y=[p,po,xw]'
"        where xw=drum water level
"
" vectors e and f are vectors from linearisation
```

```
INPUT u1 u2 u3 pdp pop xwp
OUTPUT p po xw
STATE x1 x2 x3 x4 x5 x6 x7
DER d1 d2 d3 d4 d5 d6 d7

"
"  Constants
"
    dt:1.0          " Step size (secs)
    vt:85           " Total volume
    vw:0.001538     " Specific volume of water
    tc1:10          " Time constant to remove high frequency
    tc2:10         "  "      "     "    "     "      "
    cs1:0.8         " Constant from L.S. fitting of steam tables
    cs2:-25.6       "     "      "   "      "     "   "      "
"
"  Linearisation point
"
    u20:0.69  " half load point
    p0:108    " half load point
    rho0:428  " "   "     "
"
" Initial calculations
"
    ws0=(1.1*u20-0.19)*p0
    alp0=(rho0^(-1)-vw)/((cs1*p0+cs2)^(-1)-vw)
    dwsdp=1.1*u20-0.19
    dwsdu2=1.1*p0
    dalpdrho=-((rho0)^(-2))*(((cs1*p0+cs2)^(-1)-vw)^(-1))
    t2=((cs1*p0+cs2)^(-2))
    dalpdp=cs1*(rho0^(-1)-vw)*(((cs1*p0+cs2)^(-1)-vw)^(-2))*t2
"
" e vector
"
    e1=0.002025*u20*p0^(9/8)
    e2=-0.082125*u20*p0^(9/8)+0.002*p0^(9/8)
    e3=(dwsdu2*u20+dwsdp*p0-ws0)/vt
    e4=(alp0-dalpdrho*rho0-dalpdp*p0)/tc1
    e5=1000*(alp0-dalpdrho*rho0-dalpdp*p0)/tc2
    e7=3.55*(ws0-dwsdu2*u20-dwsdp*p0)/20
"
" A matrix
"
    a11=-0.002025*u20*p0^(1/8)
    a16:-0.02
    a21=(9/8)*(0.073*u20-0.016)*p0^(1/8)
    a22:-0.1
    a31=-dwsdp/vt
    a41=dalpdp/tc1
    a43=dalpdrho/tc1
    a44=-1/tc1
    a51=1000*dalpdp/tc2
    a53=1000*dalpdrho/tc2
    a54=-1000/tc2
    a55=-1/tc2
    a66=-1/20
    a71=3.55*dwsdp/20
    a77=-1/20
```

```
"
" B matrix
"
    b11:0.9
    b12=-0.0018*p0^(9/8)
    b13:-0.13
    b22=0.073*p0^(9/8)
    b32=-dwsdu2/vt
    b33=141/vt
    b63=1/20
    b72=3.55*dwsdu2/20
"
" C matrix
"
    c11:1.0
    c22:1.0
    c31=0.05*(20000/tc2+60)*dalpdp
    c33=0.05*(vw*vt+(20000/tc2+60)*dalpdrho)
    c34=-20000*0.05/tc2
    c35=-20*0.05/tc2
    c36=-198*0.05/20
    c37=0.03*0.05
"
" D matrix
"
    d33:0.52
"
" f vector
"
    t3=3*(alp0-dalpdrho*rho0-dalpdp*p0)-3.275
    f3=1000*(alp0-dalpdrho*rho0-dalpdp*p0)/tc2+t3
"
" Initial conditions
"
    x1: 108
    x2: 67
    x3: 428
    x4: 0.054
    x5: -0.385
    x6: 0.44
    x7: 220
"
" step state equations
" dynamic section
"
    d1=a11*x1+a16*x6+b11*u1+b12*u2+b13*u3+e1
    d2=a21*x1+a22*x2+b22*u2+e2
    d3=a31*x1+b32*u2+b33*u3+e3
    d4=a41*x1+a43*x3+a44*x4+e4
    d5=a51*x1+a53*x3+a54*x4+a55*x5+e5
    d6=a66*x6+b63*u3
    d7=a71*x1+a77*x7+b72*u2+e7
"
" Output section
"
    p=c11*x1
    po=c22*x2
    xw=(c31*x1+c33*x3+c34*x4+c35*x5+c36*x6+c37*x7+d33*u3+f3)*1e3

   END
```

```
----------------------------------------------------------------
               Connect systems for step responses
----------------------------------------------------------------


connecting system c1bt1
time t
u1[bt1]=if t<ts then u1ll else u1lu
u2[bt1]=if t<ts then u2ll else u2lu
u3[bt1]=if t<ts then u3ll else u3lu
pdp[bt1]=120
pop[bt1]=80

ts:100
u1ll:0.34
u1lu:0.34
u2ll:0.69
u2lu:0.69
u3ll:0.44
u3lu:0.44

end
---------------------------------------------------------------

connecting system c1bt2
time t
u1[bt2]=if t<ts then u1ll else u1lu
u2[bt2]=if t<ts then u2ll else u2lu
u3[bt2]=if t<ts then u3ll else u3lu
pdp[bt2]=120
pop[bt2]=80
xwp[bt2]=0.0

ts:100
u1ll:0.34
u1lu:0.34
u2ll:0.69
u2lu:0.69
u3ll:0.44
u3lu:0.44

end
---------------------------------------------------------------

connecting system c1bt3
time t
u1[bt3]=if t<ts then u1ll else u1lu
u2[bt3]=if t<ts then u2ll else u2lu
u3[bt3]=if t<ts then u3ll else u3lu
pdp[bt3]=120
pop[bt3]=80
xwp[bt3]=0.0

ts:100
u1ll:0.34
u1lu:0.34
u2ll:0.69
u2lu:0.69
u3ll:0.44
u3lu:0.44

end
----------------------------------------------------------------
```

```
connecting system c1bt4
time t
qf[bt4]=if t<ts then qfll else qflu
qs[bt4]=if t<ts then qsll else qslu
qfw[bt4]=if t<ts then qfwll else qfwlu
pdp[bt4]=120
pop[bt4]=80
xwp[bt4]=0.0

ts:100
qfll:4.36
qflu:4.36
qsll:56.5
qslu:56.5
qfwll:56.5
qfwlu:56.5

end
```

```
connecting system c1bt5
time t
qf[bt5]=if t<ts then qfll else qflu
qs[bt5]=if t<ts then qsll else qslu
qfw[bt5]=if t<ts then qfwll else qfwlu
pdp[bt5]=120
pop[bt5]=80
xwp[bt5]=0.0

ts:100
qfll:4.36
qflu:4.36
qsll:56.5
qslu:56.5
qfwll:56.5
qfwlu:56.5

end
```

```
connecting system c1bt6
time t
qf[bt6]=if t<ts then qfll else qflu
u2[bt6]=if t<ts then u2ll else u2lu
qfw[bt6]=if t<ts then qfwll else qfwlu
pdp[bt6]=120
pop[bt6]=80
xwp[bt6]=0.0

ts:100
qfll:4.36
qflu:4.36
u2ll:0.69
u2lu:0.69
qfwll:56.5
qfwlu:56.5

end
```

```
connecting system c1bt7
time t
u1[bt7]=if t<ts then u1l1 else u1lu
u2[bt7]=if t<ts then u2l1 else u2lu
u3[bt7]=if t<ts then u3l1 else u3lu
pdp[bt7]=120
pop[bt7]=80
xwp[bt7]=0.0

ts:100
u1l1:0.34
u1lu:0.34
u2l1:0.69
u2lu:0.69
u3l1:0.44
u3lu:0.44

end
```

```
connecting system c1bt8
time t
u1[bt8]=if t<ts then u1l1 else u1lu
u2[bt8]=if t<ts then u2l1 else u2lu
u3[bt8]=if t<ts then u3l1 else u3lu
pdp[bt8]=120
pop[bt8]=80
xwp[bt8]=0.0

ts:100
u1l1:0.34
u1lu:0.34
u2l1:0.69
u2lu:0.69
u3l1:0.44
u3lu:0.44

end
```

```
connecting system c1bta
time t
u1[bta]=if t<ts then u1l1 else u1lu
u2[bta]=if t<ts then u2l1 else u2lu
u3[bta]=if t<ts then u3l1 else u3lu
pdp[bta]=120
pop[bta]=80
xwp[bta]=0.0

ts:100
u1l1:0.34
u1lu:0.34
u2l1:0.69
u2lu:0.69
u3l1:0.44
u3lu:0.44

end
```

```
CONNECTING SYSTEM c1lbt2
"Connecting system for open loop simulation of B-T models
TIME t
u1[lbt2]=if t<t1 then u1ll else u1lu
u2[lbt2]=if t<t1 then u2ll else u2lu
u3[lbt2]=if t<t1 then u3ll else u3lu
pdp[lbt2]=120
pop[lbt2]=80
xwp[lbt2]=0.0

t1:100.0
u1ll:0.33
u1lu:0.33
u2ll:0.69
u2lu:0.69
u3ll:0.4
u3lu:0.5

END
---------------------------------------------------------------

CONNECTING SYSTEM c1lbt3
"Connecting system for open loop simulation of B-T models
TIME t
u1[lbt3]=if t<t1 then u1ll else u1lu
u2[lbt3]=if t<t1 then u2ll else u2lu
u3[lbt3]=if t<t1 then u3ll else u3lu
pdp[lbt3]=120
pop[lbt3]=80
xwp[lbt3]=0.0

t1:100.0
u1ll:0.33
u1lu:0.33
u2ll:0.69
u2lu:0.69
u3ll:0.4
u3lu:0.5

END
```

```
----------------------------------------------------------------
                 Connect systems for plant data.
----------------------------------------------------------------

CONNECTING SYSTEM c2bt1

TIME T

u1[bt1]=C9[IFILE]/U1SC
u2[bt1]=if C10[IFILE]>wssw then u2m+u2r else u2m-u2r
u3[bt1]=C2[IFILE]/U3SC
PDP[bt1]=if C13[IFILE]<50.0 then c4[ifile] else c13[ifile]
POP[bt1]=C8[IFILE]

U1SC:50.0
u2m:0.693
u2r:0
wssw:220
U3SC:500.0

END

--------------------------------------------------------------

CONNECTING SYSTEM c2bt2

TIME T

u1[bt2]=C9[IFILE]/U1SC
u2[bt2]=if C10[IFILE]>wssw then u2m+u2r else u2m-u2r
u3[bt2]=C2[IFILE]/U3SC
PDP[bt2]=if C13[IFILE]<50.0 then c4[ifile] else c13[ifile]
POP[bt2]=C8[IFILE]
xwP[bt2]=c3[ifile]

U1SC:50.0
u2m:0.693
u2r:0
wssw:220
U3SC:500.0

END

-------------------------------------------------------------

CONNECTING SYSTEM c2bt3

TIME T

u1[bt3]=C9[IFILE]/U1SC
u2[bt3]=if C10[IFILE]>wssw then u2m+u2r else u2m-u2r
u3[bt3]=C2[IFILE]/U3SC
PDP[bt3]=if C13[IFILE]<50.0 then c4[ifile] else c13[ifile]
POP[bt3]=C8[IFILE]
xwP[bt3]=c3[ifile]

U1SC:50.0
u2m:0.693
u2r:0
wssw:220
U3SC:500.0

END
```

```
CONNECTING SYSTEM c2bt4

TIME T

qf[bt4]=C9[IFILE]*qfcf
qs[bt4]=(c10[ifile]+c11[ifile])*qscf
qfw[bt4]=C2[IFILE]*qfwcf
PDP[bt4]=if C13[IFILE]<50.0 then c4[ifile] else c13[ifile]
POP[bt4]=C8[IFILE]
xwP[bt4]=c3[ifile]

qfcf:0.252
qscf:0.231
qfwcf:0.252

END
------------------------------------------------------------------

CONNECTING SYSTEM c2bt5

TIME T

qf[bt5]=C9[IFILE]*qfcf
qs[bt5]=(c10[ifile]+c11[ifile])*qscf
qfw[bt5]=C2[IFILE]*qfwcf
PDP[bt5]=if C13[IFILE]<50.0 then c4[ifile] else c13[ifile]
POP[bt5]=C8[IFILE]
xwP[bt5]=c3[ifile]

qfcf:0.252
qscf:0.231
qfwcf:0.252

END
------------------------------------------------------------------

CONNECTING SYSTEM c2bt6

TIME T

qf[bt6]=C9[IFILE]*qfcf
u2[bt6]=if c10[ifile]>wssw then u2m+u2r else u2m-u2r
qfw[bt6]=C2[IFILE]*qfwcf
PDP[bt6]=if C13[IFILE]<50.0 then c4[ifile] else c13[ifile]
POP[bt6]=C8[IFILE]
xwP[bt6]=c3[ifile]

qfcf:0.252
wssw:220
u2m:0.693
u2r:0.0
qfwcf:0.252

END
------------------------------------------------------------------
```

```
CONNECTING SYSTEM c2bt7

TIME T

u1[bt7]=C9[IFILE]/U1SC
u2[bt7]=if C10[IFILE]>wssw then u2m+u2r else u2m-u2r
u3[bt7]=C2[IFILE]/U3SC
PDP[bt7]=if C13[IFILE]<50.0 then c4[ifile] else c13[ifile]
POP[bt7]=C8[IFILE]
xwP[bt7]=c3[ifile]

U1SC:50.0
u2m:0.693
u2r:0
wssw:220
U3SC:500.0

END
-----------------------------------------------------------------

CONNECTING SYSTEM c2bt8

TIME T

u1[bt8]=C9[IFILE]/U1SC
u2[bt8]=if C10[IFILE]>wssw then u2m+u2r else u2m-u2r
u3[bt8]=C2[IFILE]/U3SC
PDP[bt8]=if C13[IFILE]<50.0 then c4[ifile] else c13[ifile]
POP[bt8]=C8[IFILE]
xwP[bt8]=c3[ifile]

U1SC:50.0
u2m:0.693
u2r:0
wssw:220
U3SC:500.0

END
-----------------------------------------------------------------

CONNECTING SYSTEM c2bta

TIME T

u1[bta]=C9[IFILE]/U1SC
u2[bta]=if C10[IFILE]>wssw then u2m+u2r else u2m-u2r
u3[bta]=C2[IFILE]/U3SC
PDP[bta]=if C13[IFILE]<50.0 then c4[ifile] else c13[ifile]
POP[bta]=C8[IFILE]
xwP[bta]=c3[ifile]

U1SC:50.0
u2m:0.693
u2r:0
wssw:220
U3SC:500.0

END
```

```
------------------------------------------------------------------
                  Step response figure macros.
------------------------------------------------------------------

MACRO f2sllbt1
"Generates fig comparing step responses for fuel,control valve and feedwater
"at low load for bt1 model i.e. 2nd order Bell/Astrom model (no dwl eqn)
write 'Has data been generated for this fig? (yes or no)'
read ans YESNO
if ans EQ  YES  goto start
f2fslbt1
f2cslbt1
f2wslbt1
label start
split 2 2
axes h 0 400 v 90 120
show p -mark/b1
show p -mark/b2
show p -mark/b3
text 'Drum pressure (kg/cm2)'
axes h 0 400 v 55 80
show po -mark/b1
show po -mark/b2
show po -mark/b3
text 'Electrical output (MWs)'
axes h 0 400 v 50 100
show qs -mark/b1
show qs -mark/b2
show qs -mark/b3
text 'Steam flow (kg/s)'

END

-----------------------------------------------------------------

macro f2fslbt1
" Macro to obtain fuel step response for bt1 model
syst bt1 clbt1
store p po qs
par u1lu:0.44
par u2lu:0.69
par u3lu:0.44
axes h 0 400 v 100 130
plot p
simu 0 400/b1

end

-----------------------------------------------------------------

macro f2wslbt1
" Macro to obtain feedwater step response for bt1 model
syst bt1 clbt1
store p po qs
par u1lu:0.29
par u2lu:0.69
par u3lu:0.54
axes h 0 400 v 100 130
plot p
simu 0 400/b3

end

---------------------------------------- --------------------------
```

```
macro f2cslbt1
" Macro to obtain control valve step response for bt1 model
syst bt1 c1bt1
store p po qs
par u1lu:0.29
par u2lu:0.79
par u3lu:0.44
axes h 0 400 v 100 130
plot p
simu 0 400/b2

end
```

Figure macros for models bt2, bt3, bt7, bt8, and bta are the same as f2sllbt1, f2fslbt1, f2wslbt1, and f2cslbt1 except that all references to bt1 are replaced by bt2, bt3, bt7, bt8, or bta for the respective model.

```
MACRO f2sllbt4
"Generates fig comparing step responses for fuel,control valve
"and feedwater at low load for bt4 model i.e. 3rd order Morton
"simple model.
write 'Has data been generated for this fig? (yes or no)'
read ans YESNO
if ans EQ  YES  goto start
f2fslbt4
f2cslbt4
f2wslbt4
label start
split 2 2
axes h 0 400 v 90 120
show p -mark/b1
show p -mark/b2
show p -mark/b3
text 'Drum pressure (kg/cm2)'
axes h 0 400 v 55 80
show po -mark/b1
show po -mark/b2
show po -mark/b3
text 'Electrical output (MWs)'
axes h 0 400 v -80 200
show xw -mark/b1
show xw -mark/b2
show xw -mark/b3
text 'Drum water level (m)'
axes h 0 400 v 55 80
show qs -mark/b1
show qs -mark/b2
show qs -mark/b3
text 'Steam flow (kg/s)'

END
```

```
macro f2fslbt4
" Macro to obtain fuel step response for bt4 model
syst bt4 clbt4
store p po xw qs
par qflu:5.36
par qslu:56.5
par qfwlu:56.5
axes h 0 400 v -200 200
plot xw
simu 0 400/b1

end
-----------------------------------------------------------------

macro f2wslbt4
" Macro to obtain feedwater step response for bt4 model
syst bt4 clbt4
store p po xw qs
par qflu:4.36
par qslu:56.5
par qfwlu:66.5
axes h 0 400 v -200 200
plot xw
simu 0 400/b3

end

-----------------------------------------------------------------

macro f2cslbt4
" Macro to obtain control valve step response for bt4 model
syst bt4 clbt4
store p po xw qs
par qflu:4.36
par qslu:66.5
par qfwlu:56.5
axes h 0 400 v -200 200
plot xw
simu 0 400/b2

end

-----------------------------------------------------------------

MACRO f2sllbt6
"Generates fig comparing step responses for fuel,control valve and feedwater
"at low load for bt6 model i.e. 4th order extension of Morton's model.
write 'Has data been generated for this fig? (yes or no)'
read ans YESNO
if ans EQ  YES  goto start
f2fslbt6
f2cslbt6
f2wslbt6
label start
split 2 2
axes h 0 400 v 90 120
show p -mark/b1
show p -mark/b2
show p -mark/b3
text 'Drum pressure (kg/cm2)'
axes h 0 400 v 55 80
show po -mark/b1
show po -mark/b2
show po -mark/b3
```

```
text 'Electrical output (MWs)'
axes h 0 400 v -80 200
show xw -mark/b1
show xw -mark/b2
show xw -mark/b3
text 'Drum water level (m)'
axes h 0 400 v 55 80
show qs -mark/b1
show qs -mark/b2
show qs -mark/b3
text 'Steam flow (kg/s)'

END
--------------------------------------------------------------

macro f2fslbt6
" Macro to obtain fuel step response for bt6 model
syst bt6 c1bt6
store p po xw qs
par qflu:5.36
par u2lu:0.69
par qfwlu:56.5
axes h 0 400 v -200 200
plot xw
simu 0 400/b1

end
--------------------------------------------------------------

macro f2wslbt6
" Macro to obtain feedwater step response for bt6 model
syst bt6 c1bt6
store p po xw qs
par qflu:4.36
par u2lu:0.69
par qfwlu:66.5
axes h 0 400 v -200 200
plot xw
simu 0 400/b3

end
--------------------------------------------------------------

macro f2cslbt6
" Macro to obtain control valve step response for bt6 model
syst bt6 c1bt6
store p po xw qs
par qflu:4.36
par u2lu:0.79
par qfwlu:56.5
axes h 0 400 v -200 200
plot xw
simu 0 400/b2

end
--------------------------------------------------------------
```

```
MACRO f2s11lb2
"Generates fig comparing step responses for fuel,control valve
"and feedwater at low load for lbt2 model i.e. 3rd order
"Bell/Astrom linear model.
write 'Has data been generated for this fig? (yes or no)'
read ans YESNO
if ans EQ  YES  goto start
f2fs1lb2
f2cs1lb2
f2ws1lb2
label start
split 2 2
axes h 0 400 v 90 120
show p -mark/b1
show p -mark/b2
show p -mark/b3
text 'Drum pressure (kg/cm2)'
axes h 0 400 v 55 75
show po -mark/b1
show po -mark/b2
show po -mark/b3
text 'Electrical output (MWs)'
axes h 0 400 v -80 200
show xw -mark/b1
show xw -mark/b2
show xw -mark/b3
text 'Drum water level (m)'
END
------------------------------------------------------------------
macro f2fs1lb2
" Macro to obtain fuel step response for lbt2 model
syst lbt2 c1lbt2
store p po xw
par u1lu:0.44
par u2lu:0.69
par u3lu:0.44
axes h 0 400 v -200 200
plot xw
simu 0 400/b1
end
------------------------------------------------------------------
macro f2ws1lb2
" Macro to obtain feedwater step response for lbt2 model
syst lbt2 c1lbt2
store p po xw
par u1lu:0.29
par u2lu:0.69
par u3lu:0.54
axes h 0 400 v -200 200
plot xw
simu 0 400/b3
end
------------------------------------------------------------------
macro f2cs1lb2
" Macro to obtain control valve step response for lbt2 model
syst lbt2 c1lbt2
store p po xw
par u1lu:0.29
par u2lu:0.79
par u3lu:0.44
axes h 0 400 v -200 200
plot xw
simu 0 400/b2
end
------------------------------------------------------------------
```

```
MACRO f2sl1lb3
"Generates fig comparing step responses for fuel,control valve
"and feedwater at low load for lbt3 model i.e. 7th order
"Bell/Astrom linear model.
write 'Has data been generated for this fig? (yes or no)'
read ans YESNO
if ans EQ  YES  goto start
f2fs1lb3
f2cs1lb3
f2ws1lb3
label start
split 2 2
axes h 0 400 v 90 120
show p -mark/b1
show p -mark/b2
show p -mark/b3
text 'Drum pressure (kg/cm2)'
axes h 0 400 v 55 75
show po -mark/b1
show po -mark/b2
show po -mark/b3
text 'Electrical output (MWs)'
axes h 0 400 v -80 200
show xw -mark/b1
show xw -mark/b2
show xw -mark/b3
text 'Drum water level (m)'
END
-------------------------------------------------------------
macro f2fs1lb3
" Macro to obtain fuel step response for lbt3 model
syst lbt3 c1lbt3
store p po xw
par u1lu:0.44
par u2lu:0.69
par u3lu:0.44
axes h 0 400 v -200 200
plot xw
simu 0 400/b1
end
-------------------------------------------------------------
macro f2ws1lb3
" Macro to obtain feedwater step response for lbt3 model
syst lbt3 c1lbt3
store p po xw
par u1lu:0.29
par u2lu:0.69
par u3lu:0.54
axes h 0 400 v -200 200
plot xw
simu 0 400/b3
end
-------------------------------------------------------------
macro f2cs1lb3
" Macro to obtain control valve step response for lbt3 model
syst lbt3 c1lbt3
store p po xw
par u1lu:0.29
par u2lu:0.79
par u3lu:0.44
axes h 0 400 v -200 200
plot xw
simu 0 400/b2
end
```

Figure macros for plant data.

```
macro f1bd1bt1
"Generates fig comparing model and plant data.
" Uses plant data d107a low load fuel change.
" Uses bt1 model i.e. 2nd order Astrom/Bell model without dwl.

let n.ifile=13
,fname.ifile=bd107a
syst bt1 ifile c2bt1
par dt[ifile]:10.0
store p pdp po pop
split 1 1
axes h 0 3000 v 90 120
plot p pdp
simu 0 3000 /b1
split 2 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'

end
```

Figure macros for models bt2, bt3, bt4, bt5, bt6, bt8, and bta are the same as f1bd1bt1 except that all references to bt1 are replaced by bt2, bt3, bt4, bt5, bt6, bt7, bt8, or bta for the respective model.

```
macro f1bd2bt1
"Generates fig comparing model and plant data.
" Uses plant data d108a low load feedwater change.
" Uses bt1 model i.e. 2nd order Astrom/Bell model without dwl.

let n.ifile=13
,fname.ifile=bd108a
syst bt1 ifile c2bt1
par dt[ifile]:10.0
init x1:110             "Steam pressure initial condition
store p pdp po pop
split 1 1
axes h 0 3000 v 107 112
plot p pdp
simu 0 3000 /b1
split 2 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'

end
```

Figure macros for models bt2, bt3, bt4, bt5, bt6, bt8, and bta are the same as f1bd2bt1 except that all references to bt1 are replaced by bt2, bt3, bt4, bt5, bt6, bt7, bt8, or bta for the respective model.

```
macro f1bd3bt1
"Generates fig comparing model and plant data.
" Uses plant data d111a low load control valve change.
" Uses bt1 model i.e. 2nd order Astrom/Bell model without dwl.
let n.ifile=13
,fname.ifile=bd111a
syst bt1 ifile c2bt1
par dt[ifile]:10.0
init x1:110                 "Steam pressure initial condition
init x2:69                  "Electrical o/p    "         "
par wssw:125                "Mean value of steam flow for low load
par u2m:0.71                "Mean position of control valve
par u2r:0.07                "Step on each side of mean. Step size=2*u2r
store p pdp po pop
split 1 1
axes h 0 3000 v 100 115
plot p pdp
simu 0 3000 /b1
split 2 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'
end
-----------------------------------------------------------------
```

Figure macros for models bt2, bt3, bt4, bt5, bt6, bt8, and bta are the same as f1bd2bt1 except that all references to bt1 are replaced by bt2, bt3, bt4, bt5, bt6, bt7, bt8, or bta for the respective model.

```
-----------------------------------------------------------------
macro f1bd4bt1
"Generates fig comparing model and plant data.
" Uses plant data d201a high load fuel valve change.
" Uses bt1 model i.e. 2nd order Astrom/Bell model without dwl.
let n.ifile=13
,fname.ifile=bd201a
syst bt1 ifile c2bt1
par dt[ifile]:10.0
init x1:127                 "Steam pressure initial condition
init x2:140                 "Electrical o/p    "         "
par wssw:220                "Mean value of steam flow for high load
par u2m:1.06                "Mean position of control valve
par u2r:0.0                 "Step on each side of mean. Step size=2*u2r
store p pdp po pop
split 1 1
axes h 0 3000 v 115 140
plot p pdp
simu 0 3000 /b1
split 2 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'
end
-----------------------------------------------------------------
```

Figure macros for models bt2, bt3, bt4, bt5, bt6, bt8, and bta are the same as f1bd2bt1 except that all references to bt1 are replaced by bt2, bt3, bt4, bt5, bt6, bt7, bt8, or bta for the respective model.

```
macro f1bd5bt1
"Generates fig comparing model and plant data.
" Uses plant data d102a high load feedwater valve change.
" Uses bt1 model i.e. 2nd order Astrom/Bell model without dwl.
let n.ifile=13
,fname.ifile=bd102a
syst bt1 ifile c2bt1
par dt[ifile]:10.0
init x1:126             "Steam pressure initial condition
init x2:140             "Electrical o/p    "        "
par wssw:220            "Mean value of steam flow for high load
par u2m:1.06            "Mean position of control valve
par u2r:0.0             "Step on each side of mean. Step size=2*u2r
store p pdp po pop
split 1 1
axes h 0 3000 v 123 128
plot p pdp
simu 0 3000 /b1
split 2 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'
end
```

Figure macros for models bt2, bt3, bt4, bt5, bt6, bt8, and bta are the same as f1bd2bt1 except that all references to bt1 are replaced by bt2, bt3, bt4, bt5, bt6, bt7, bt8, or bta for the respective model.

```
macro f1bd6bt1
"Generates fig comparing model and plant data.
" Uses plant data d105a high load control valve change.
" Uses bt1 model i.e. 2nd order Astrom/Bell model without dwl.
let n.ifile=13
,fname.ifile=bd105a
syst bt1 ifile c2bt1
par dt[ifile]:10.0
init x1:134             "Steam pressure initial condition
init x2:138             "Electrical o/p    "        "
par wssw:220            "Mean value of steam flow for high load
par u2m:0.99            "Mean position of control valve
par u2r:0.03            "Step on each side of mean. Step size=2*u2r
store p pdp po pop
split 1 1
axes h 0 3000 v 125 140
plot p pdp
simu 0 3000 /b1
split 2 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'
end
```

Figure macros for models bt2, bt3, bt4, bt5, bt6, bt8, and bta are the same as f1bd2bt1 except that all references to bt1 are replaced by bt2, bt3, bt4, bt5, bt6, bt7, bt8, or bta for the respective model.

Figure 1. - Step response of model Bt1.
1=fuel flow step (increase), 2=control valve step (increase),
3=feedwater flow step (increase).

87.06.26 - 08:11:27 nr: 1
hcopy

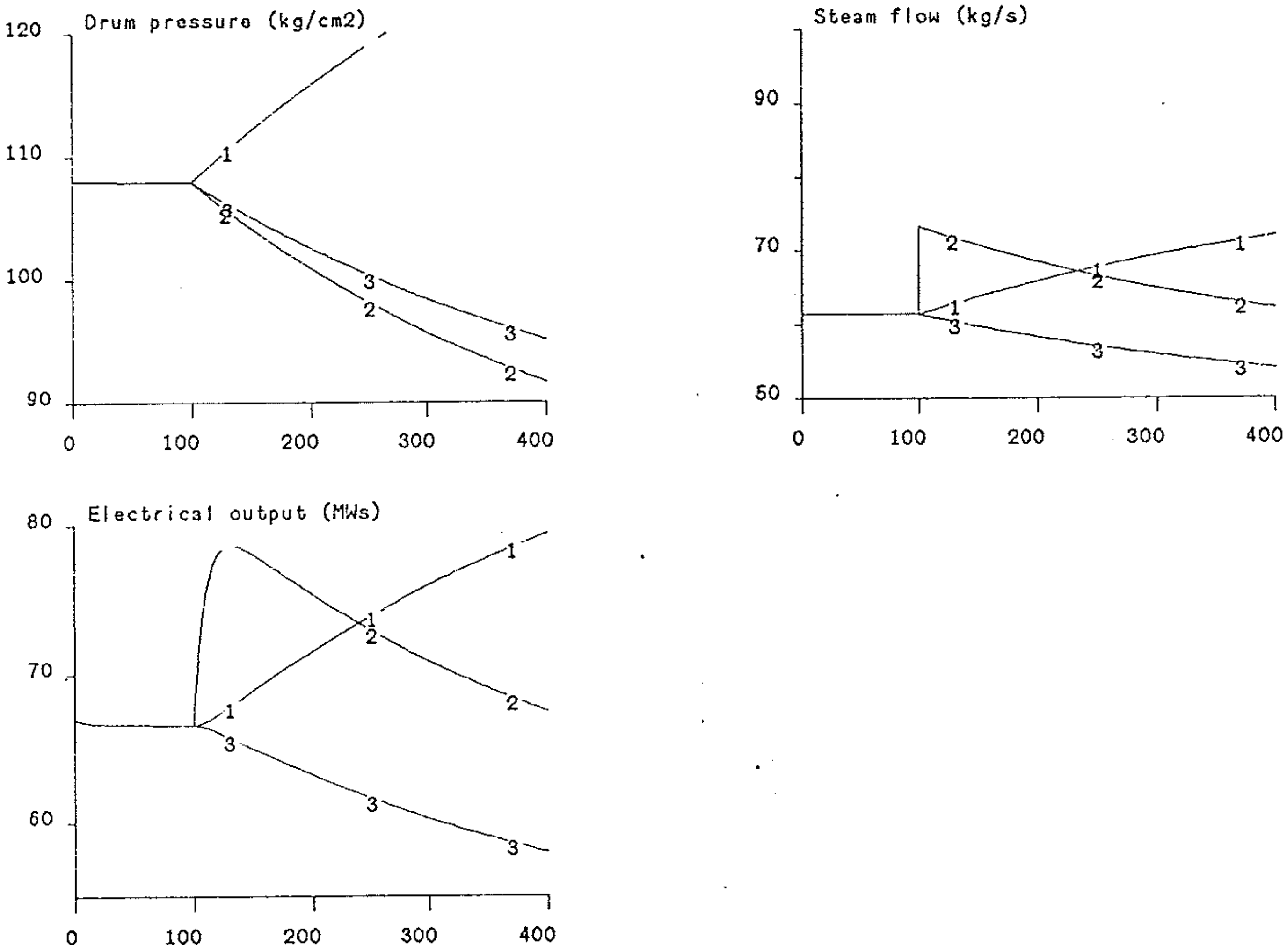


Figure 2. - Step response of model Bt2.
1=fuel flow step (increase), 2=control valve step (increase),
3=feedwater flow step (increase).

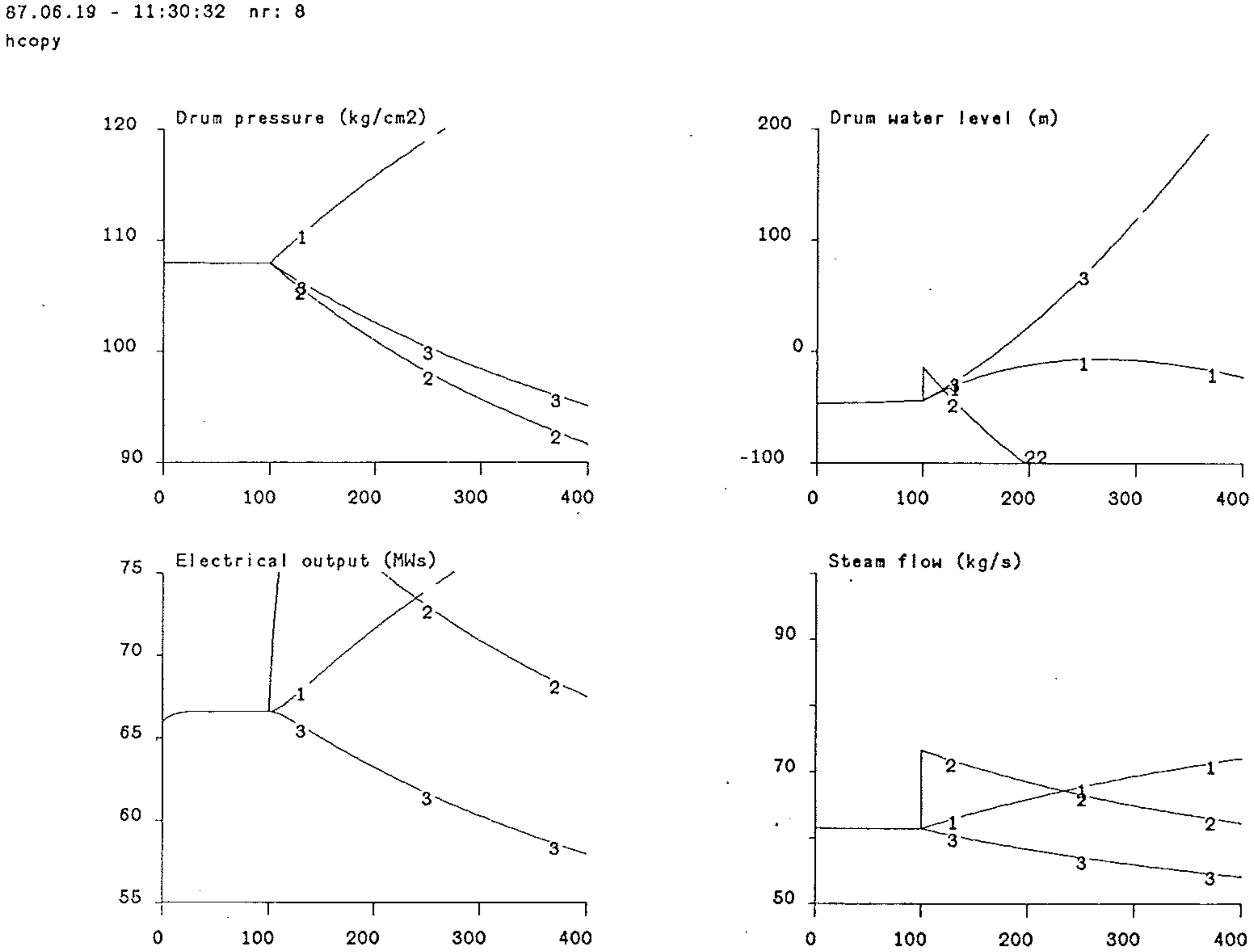


Figure 3. - Step response of model Bt3.
1=fuel flow step (increase), 2=control valve step (increase),
3=feedwater flow step (increase).

87.05.31 - 10:31:11 nr: 2
hcopy

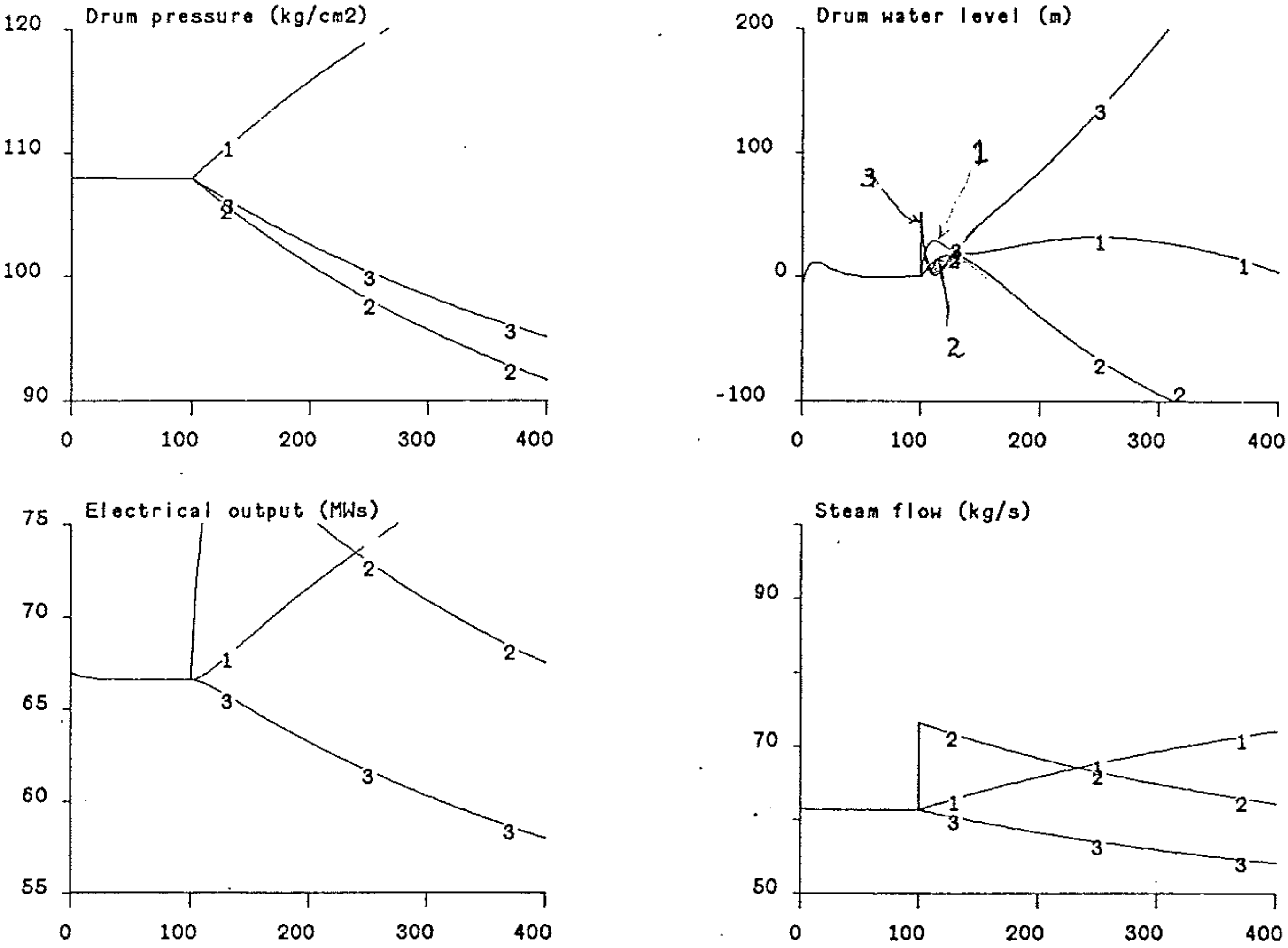


Figure 4. - Step response of model Bt4.
1=fuel flow step (increase), 2=steam flow step (increase),
3=feedwater flow step (increase).

87.06.02 - 17:24:44 nr: 8
hcopy

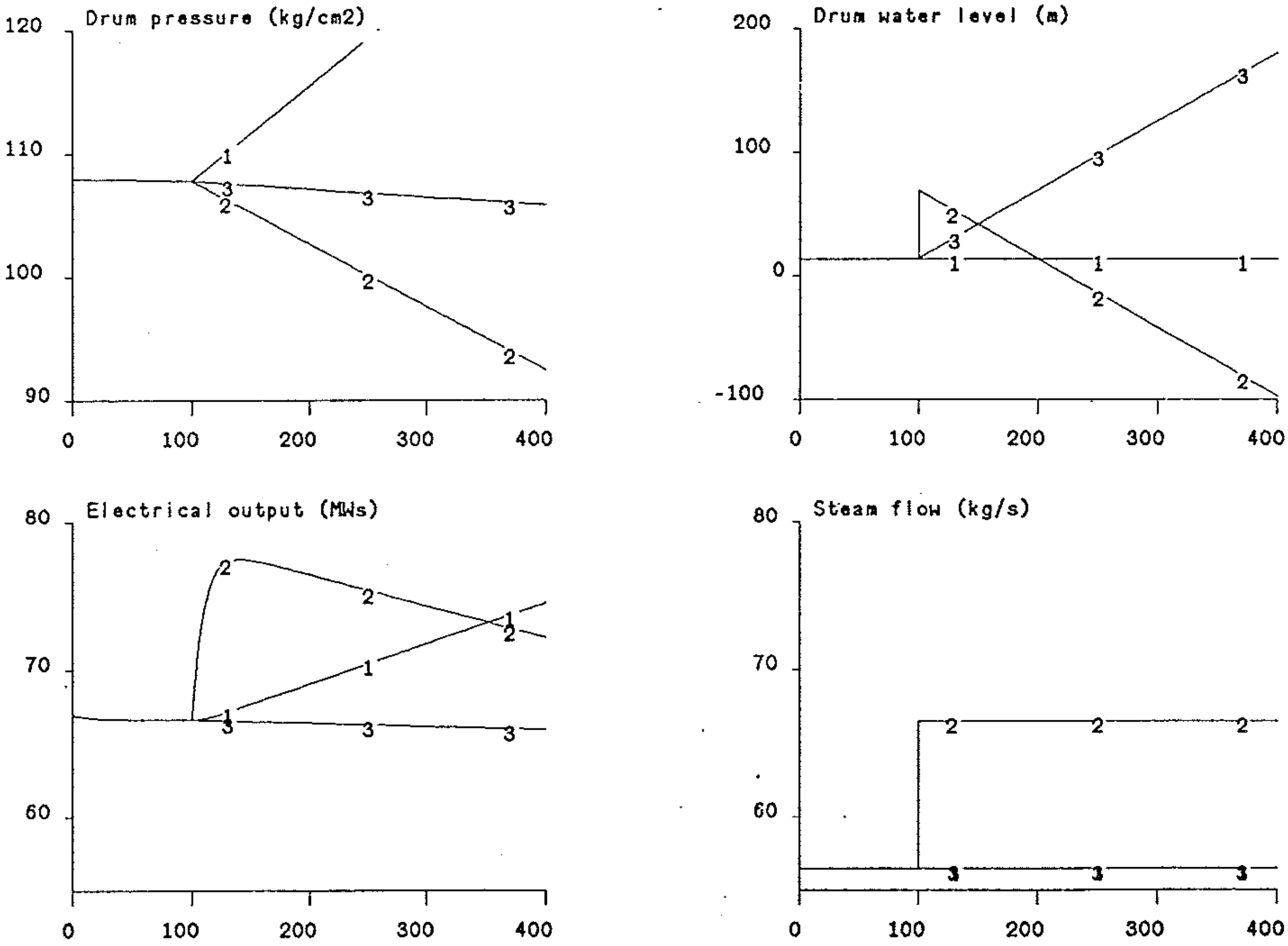


Figure 5. - Step response of model Bt5.
1=fuel flow step (increase), 2=steam flow step (increase),
3=feedwater flow step (increase).

87.06.05 - 09:07:10 nr: 1
hcopy

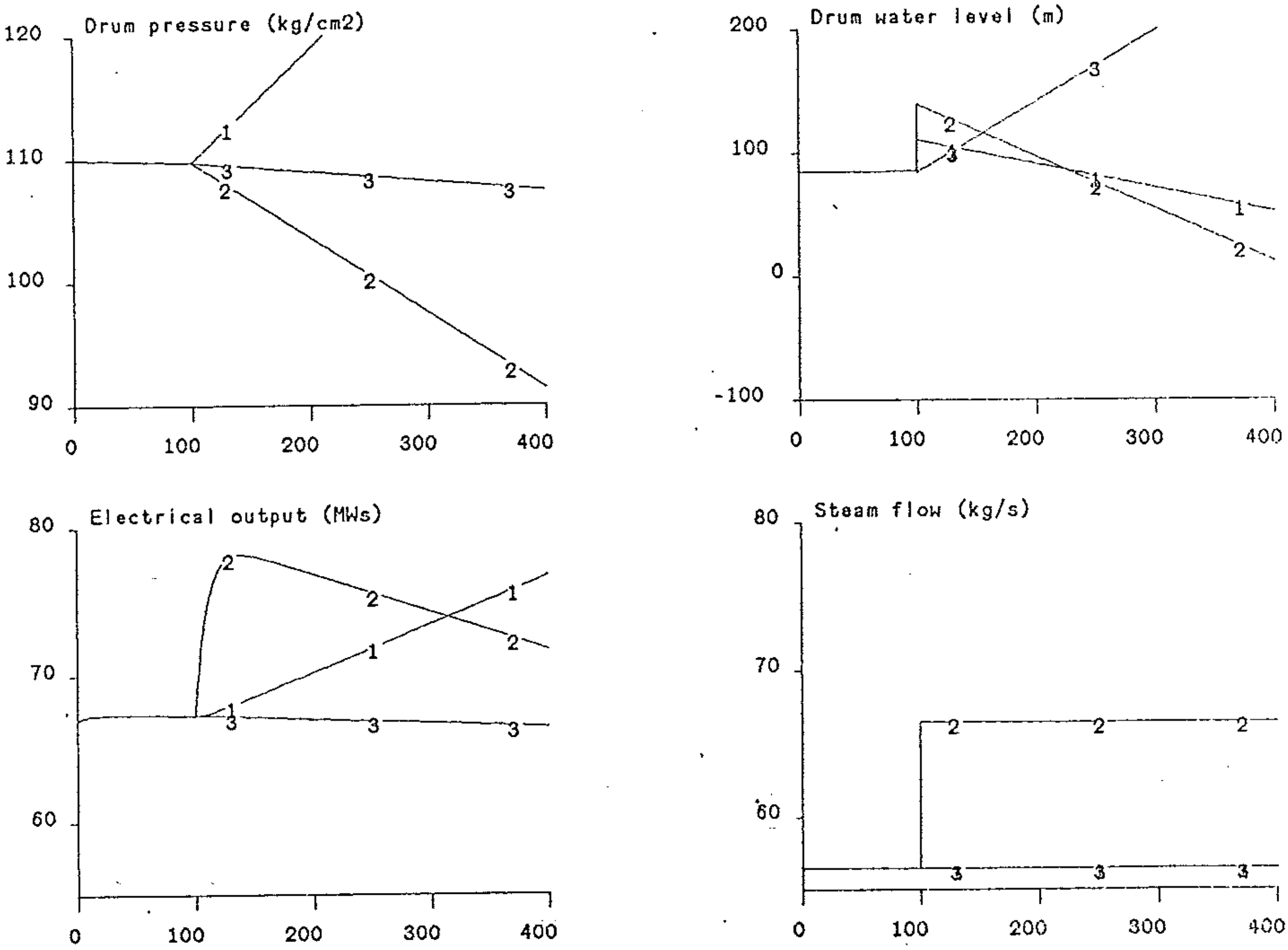


Figure 6. - Step response of model Bt6.
1=fuel flow step (increase), 2=steam flow step (increase),
3=feedwater flow step (increase).

87.06.04 - 11:03:07 nr: 6
hcopy

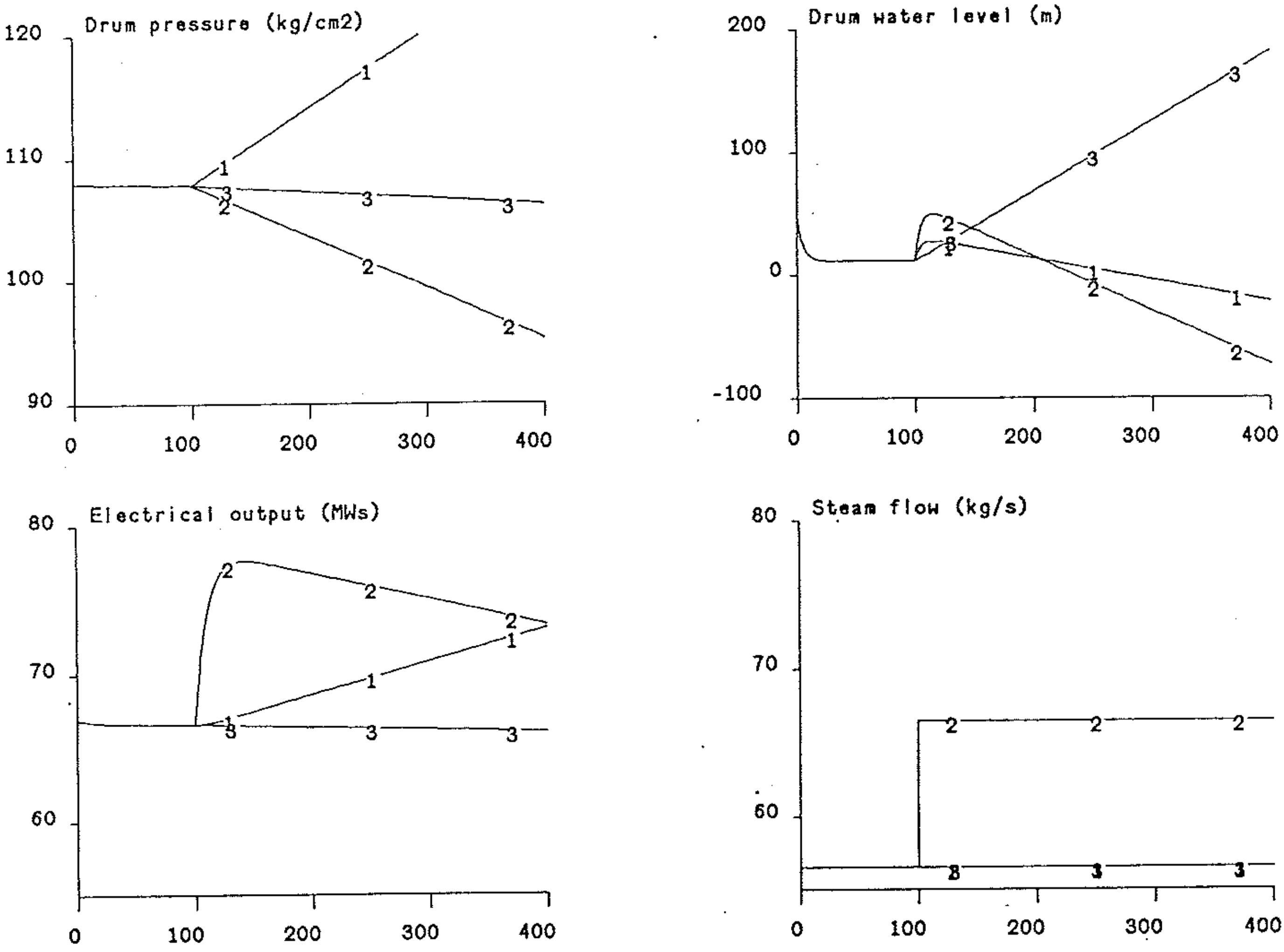
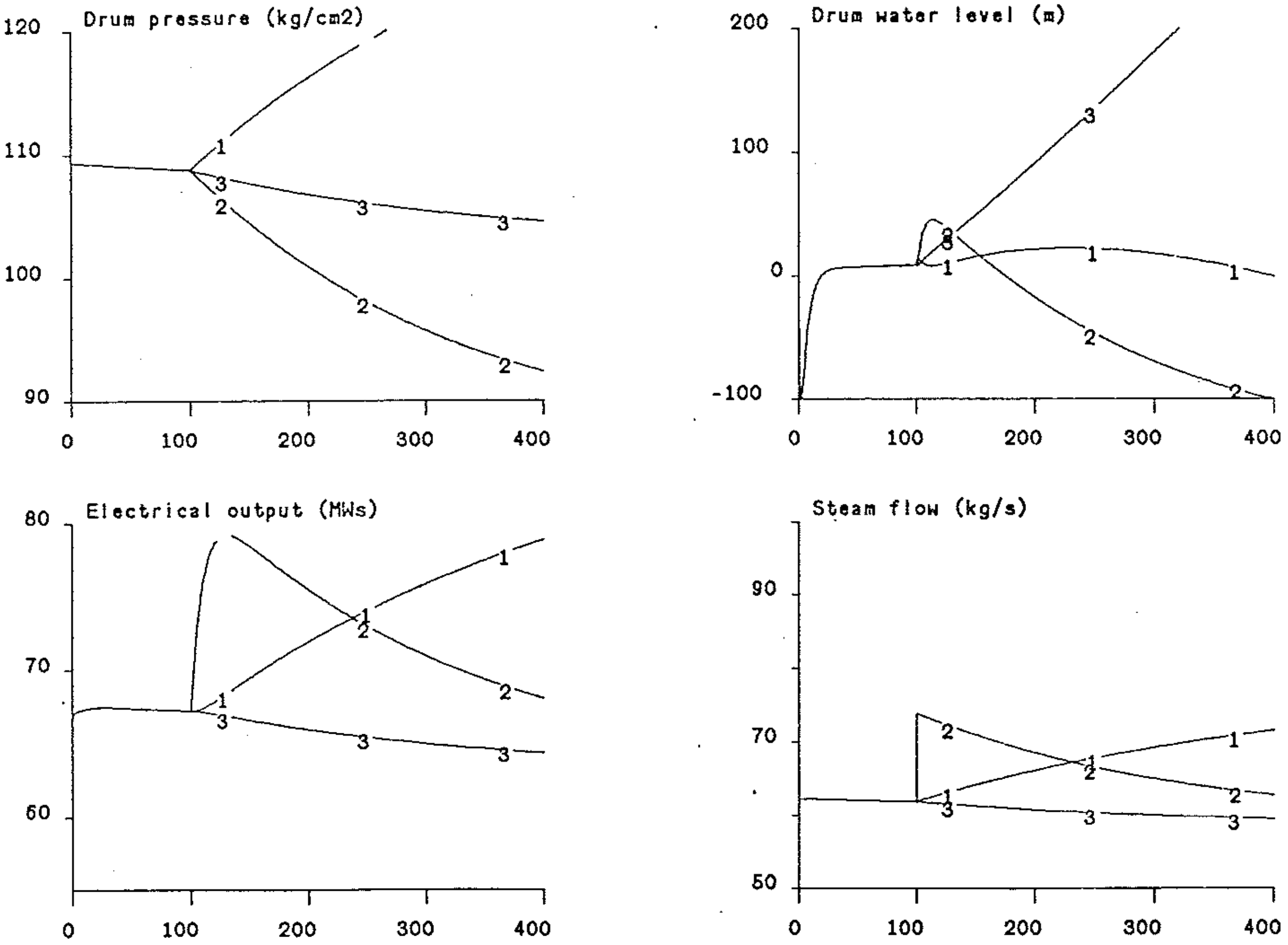


Figure 7. - Step response of model Bt7.
1=fuel flow step (increase), 2=control valve step (increase),
3=feedwater flow step (increase).

87.05.31 - 14:49:59 nr: 1
hcopy



<u>Figure 8.</u> - Step response of model Bt8.
1=fuel flow step (increase), 2=control valve step (increase),
3=feedwater flow step (increase).

87.05.30 - 17:36:47 nr: 5
hcopy

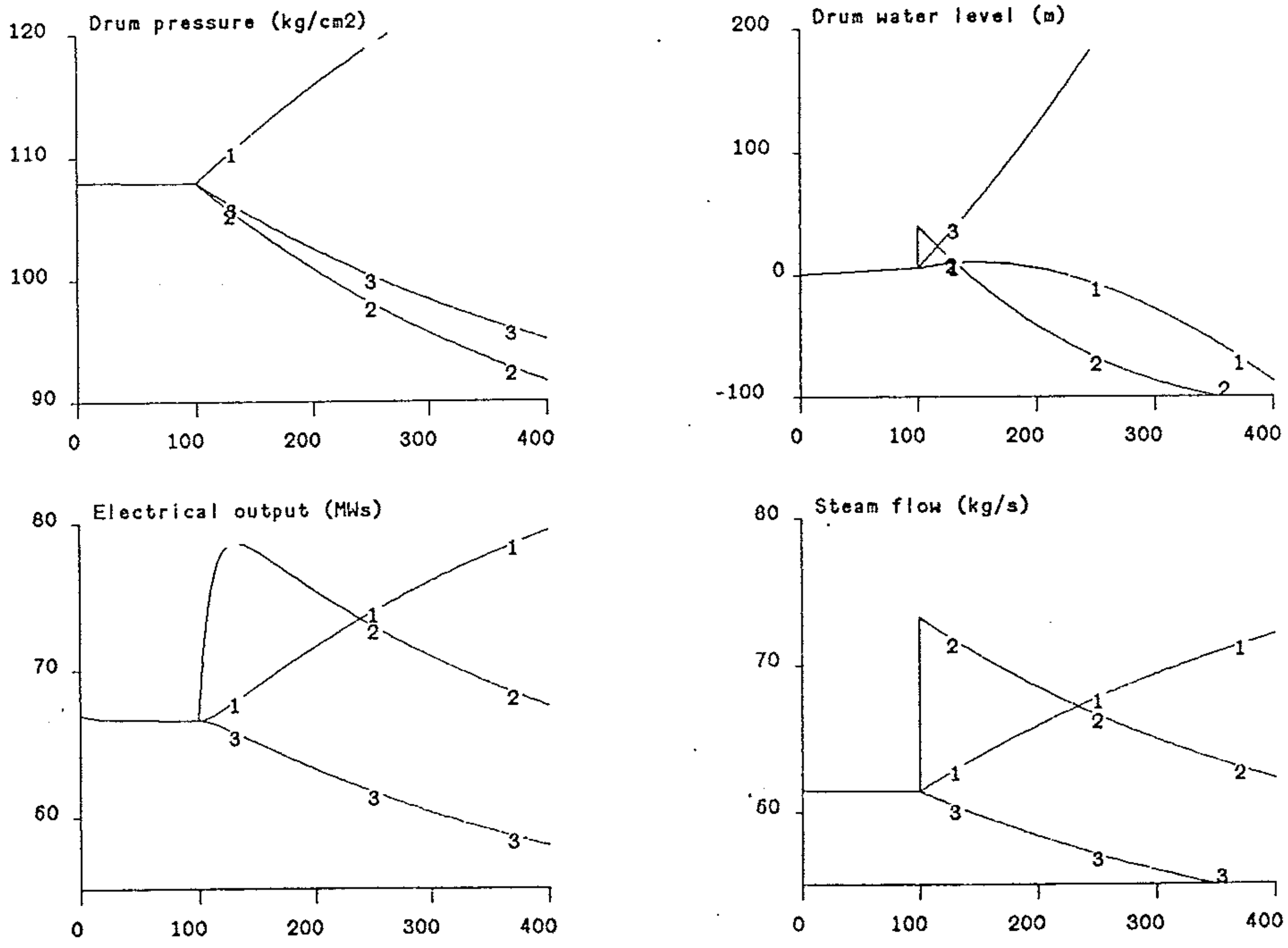
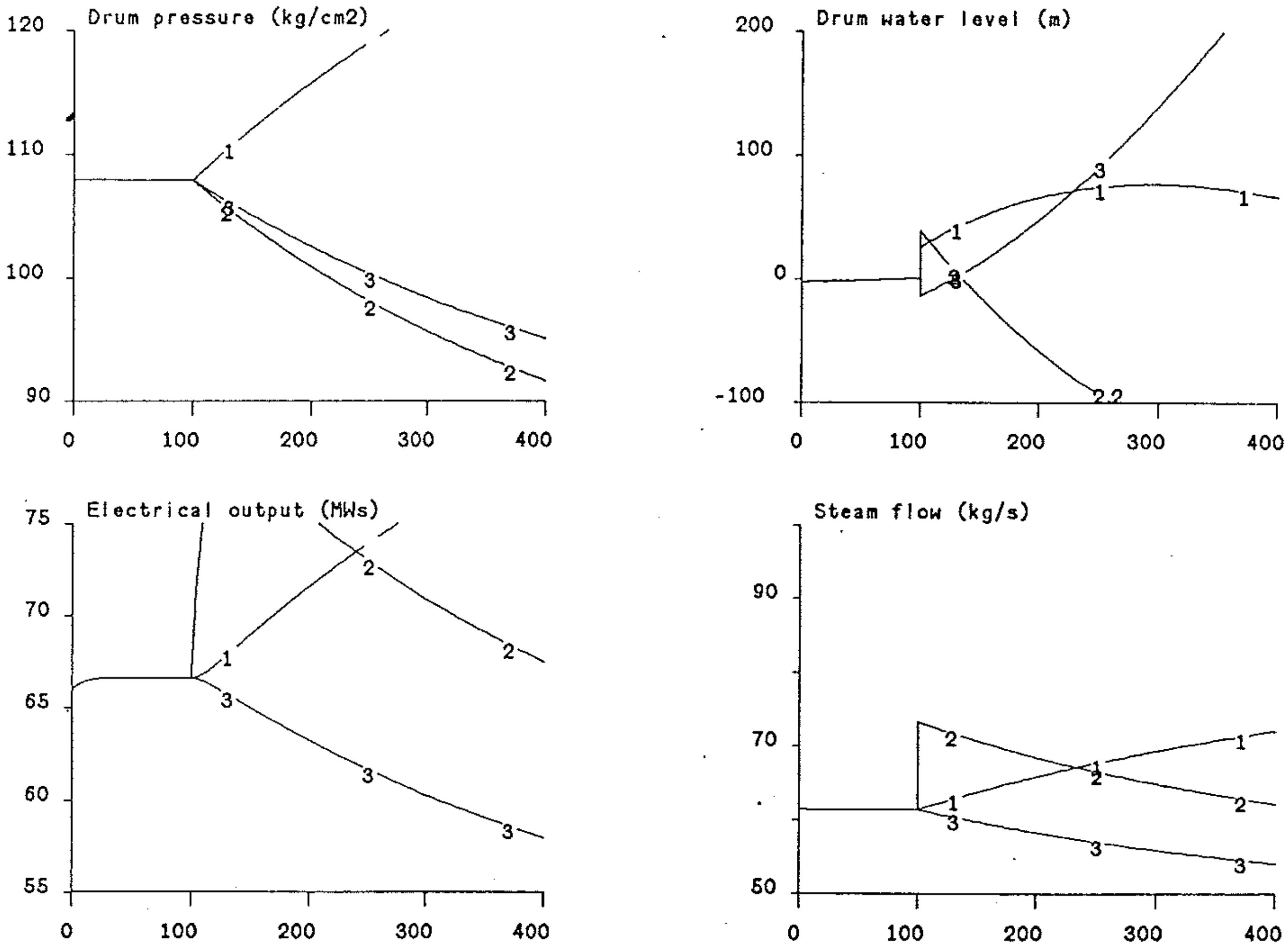


Figure 9. - Step response of model Bta.
1=fuel flow step (increase), 2=control valve step (increase),
3=feedwater flow step (increase).


87.06.19 - 10:53:55 nr: 2
hcopy

Appendix D. - Comparison of plant and model responses.

Conversion factors used for all the following input figures i.e. fig. 7 to 12.

$q_f = 0.252\, q_{f\ \mathrm{measured}}$ ($q_{f\ \mathrm{measured}}$ in T/hr).

$q_s = 0.231\, q_{s\ \mathrm{measured}}$ ($q_{s\ \mathrm{measured}}$ in T/hr).

$q_{fw} = 0.252\, q_{fw\ \mathrm{measured}}$ ($q_{fw\ \mathrm{measured}}$ in T/hr).

giving units of Kg/sec for fuel flow (q_f), steam flow (q_s), and feedwater flow (q_{fw}).

Figure 1. - Data D107A.DAT header page. Low load fuel variations.

```
THE STANDARD DOCUMENTATION FILE.

PARAMETERS DEFINING THE EXPERIMENT.
N     =  359
NVAR =    25
TSAMP= 10.0000

NBUFF1=    45
NBUFF2=     2

IDEXPERIMENT    1 07 16 1500    DATE JUNE 1969
REFERENCE, KARL EKLUND
DESCRIPTION OF THE EXPERIMENT (SEE MEDDELANDE FRÅN
PROGRAMBIBLIOTEKET NR 3 OM DOKUMENTATION AV DATA).
 1) IDEXPERIMENT     1 07 16 1500    DATE JUNE 1969
    MADE ON THE BOILER P16 AND THE TURBINE G16 AT
    ÖRESUNDSVERKET OF SYDSVENSKA KRAFT AB.
 2) NUMBER OF SAMPLING EVENTS:  359
 3) NUMBER OF MEASUREMENT VARIABLES NVAR=25.
    SAMPLING PERIOD TSAMP 10.0
    NOTATIONS. (FOR DETAILS SEE PROCESSDESCRIPTION)
    VAR 1= TIME                                              SEK
    VAR 2= FLOW OF FEEDWATER                                 T/H
    VAR 3= DRUM LEVEL                                        MM
    VAR 4= PRESSURE IN DRUM 600MM                            KG/CM2
    VAR 5= PRESSURE BEFORE VALVE HT                          KG/CM2
    VAR 6= PRESSURE AFTER CONTROL VALVE                      KG/CM2
    VAR 7= PRESSURE BEFORE VALVE VT                          KG/CM2
    VAR 8= ACTIVE POWER
    VAR 9= FUEL FLOW                                         T/H
    VAR10= STEAM FLOW L                                      T/H
    VAR11= STEAM FLOW R                                      T/H
    VAR12= TEMP. AFTER ATTEMPERATOR 1                        GRAD C
    VAR13= DRUM PRESSURE                                     KG/CM2
    VAR14= TEMP. AFTER ATTEMPERATOR 2                        GRAD C
    VAR15= TEMP. AFTER HIGH PRESSURE REHEATER R              GRAD C
    VAR16= TEMP. AFTER REHEATER R                            GRAD C
    VAR17= FLOW OF ATTEMPERATOR 1 L                          T/H
    VAR18= FLOW OF ATTEMPERATOR 2 L                          T/H
    VAR19= FLOW OF ATTEMPERATOR 1 R                          T/H
    VAR20= FLOW OF ATTEMPERATOR 2 R                          T/H
    VAR21= STEAMTEMP. BEFORE ATTEMPERATOR 1 R                FE-KONST
    VAR22= STEAMTEMP. BEFORE REHEATER R                      FE-KONST
    VAR23= FEEDWATERTEMP. AFTER ECO L                        FE-KONST
    VAR24= FEEDWATERTEMP. AFTER ECO R                        FE-KONST
    VAR25= STEAMTEMP. BEFORE ATTEMPERATOR 2 R                FE-KONST
 4) DATA ARE PUCHED (SEE KARL EKLUND REPORT 7117)
 5) STATIONARY CONDITIONS ARE ACHIVED WHEN THE INPUT
    SIGNAL IS APPLIED (SEE REPORT 7117)
 6) DATA ARE AVAILABLE ON UNIVAC 1108 TAPE 19,FILE   12
    TO READ THE INFORMATION USE THE SUBROUTINE
    INDATA(DAT,IA,IB,N,NVAR,IH,IW,KA) IH=1, IW=10.
 7) SEE NOTICES                            10     8
 8) DATA ARE PLOTTED.
 9) DATA ARE LISTED IN THIS PROGRAM OUTPUT.

USE AS DRUM PRESSURE= VAR 13
```

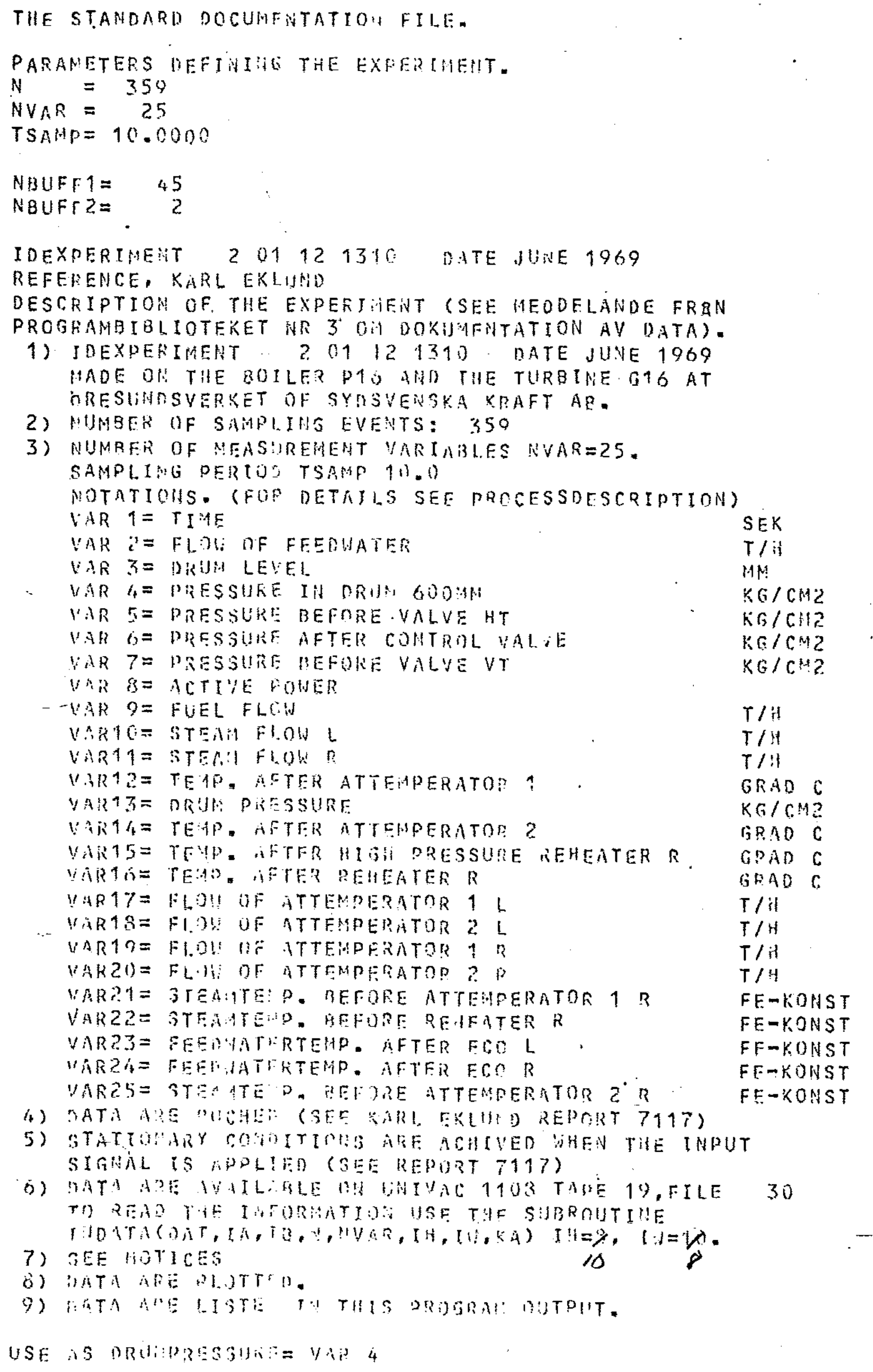
Figure 2. - Data D108A.DAT header page. Low load feedwater variations.

```
THE STANDARD DOCUMENTATION FILE.

PARAMETERS DEFINING THE EXPERIMENT.
N     =  359
NVAR =    25
TSAMP= 10.0000

NBUFF1=    45
NBUFF2=     2

IDEXPERIMENT    1 08 16 1640    DATE JUNE 1969
REFERENCE, KARL EKLUND
DESCRIPTION OF THE EXPERIMENT (SEE MEDDELANDE FRAN
PROGRAMBIBLIOTEKET NR 3 OM DOKUMENTATION AV DATA).
 1) IDEXPERIMENT    1 08 16 1640    DATE JUNE 1969
    MADE ON THE BOILER P16 AND THE TURBINE G16 AT
    ÖRESUNDSVERKET OF SYDSVENSKA KRAFT AB.
 2) NUMBER OF SAMPLING EVENTS:  359
 3) NUMBER OF MEASUREMENT VARIABLES NVAR=25.
    SAMPLING PERIOD TSAMP 10.0
    NOTATIONS. (FOR DETAILS SEE PROCESSDESCRIPTION)
    VAR 1= TIME                                             SEK
    VAR 2= FLOW OF FEEDWATER                                T/H
    VAR 3= DRUM LEVEL                                       MM
    VAR 4= PRESSURE IN DRUM 600MM                           KG/CM2
    VAR 5= PRESSURE BEFORE VALVE HT                         KG/CM2
    VAR 6= PRESSURE AFTER CONTROL VALVE                     KG/CM2
    VAR 7= PRESSURE BEFORE VALVE VT                         KG/CM2
    VAR 8= ACTIVE POWER
    VAR 9= FUEL FLOW                                        T/H
    VAR10= STEAM FLOW L                                     T/H
    VAR11= STEAM FLOW R                                     T/H
    VAR12= TEMP. AFTER ATTEMPERATOP 1                       GRAD C
    VAR13= DRUM PRESSURE                                    KG/CM2
    VAR14= TEMP. AFTER ATTEMPERATOP 2                       GRAD C
    VAR15= TEMP. AFTER HIGH PRESSURE REHEATER R             GRAD C
    VAR16= TEMP. AFTER REHEATER R                           GRAD C
    VAR17= FLOW OF ATTEMPERATOR 1 L                         T/H
    VAR18= FLOW OF ATTEMPERATOR 2 L                         T/H
    VAR19= FLOW OF ATTEMPERATOR 1 R                         T/H
    VAR20= FLOW OF ATTEMPERATOR 2 R                         T/H
    VAR21= STEAMTEMP. BEFORE ATTEMPERATOP 1 R               FE-KONST
    VAR22= STEAMTEMP. BEFORE REHEATER R                     FE-KONST
    VAR23= FEEDWATERTEMP. AFTER ECO L                       FE-KONST
    VAR24= FEEDWATERTEMP. AFTER ECO R                       FE-KONST
    VAR25= STEAMTEMP. BEFORE ATTEMPERATOP 2 R               FE-KONST
 4) DATA ARE PUCHED (SEE KARL EKLUND REPORT 7117)
 5) STATIONARY CONDITIONS ARE ACHIVED WHEN THE INPUT
    SIGNAL IS APPLIED (SEE REPORT 7117)
 6) DATA ARE AVAILABLE ON UNIVAC 1108 TAPE 19,FILE   14
    TO READ THE INFORMATION USE THE SUBROUTINE
    INDATA(DAT,IA,IB,N,NVAR,IH,IW,KA) IH=1, IW=19.
                                         10      8
 7) SEE NOTICES
 8) DATA ARE PLOTTED.
 9) DATA ARE LISTED IN THIS PROGRAM OUTPUT.

USE AS DRUMPRESSURE= VAR 13
```

Figure 3. - Data D111A.DAT header page. Low load control valve variations.

```
THE STANDARD DOCUMENTATION FILE.

PARAMETERS DEFINING THE EXPERIMENT.
N     =  359
NVAR =    25
TSAMP= 10.0000

NBUFF1=    45
NBUFF2=     2

IDEXPERIMENT    1 11 17 0800   DATE JUNE 1969
REFERENCE, KARL EKLUND
DESCRIPTION OF THE EXPERIMENT (SEE MEDDELANDE FRAN
PROGRAMBIBLIOTEKET NR 3 OM DOKUMENTATION AV DATA).
 1) IDEXPERIMENT     1 11 17 0800    DATE JUNE 1969
    MADE ON THE BOILER P16 AND THE TURBINE G16 AT
    ORESUNDSVERKET OF SYDSVENSKA KRAFT AB.
 2) NUMBER OF SAMPLING EVENTS:  359
 3) NUMBER OF MEASUREMENT VARIABLES NVAR=25.
    SAMPLING PERIOD TSAMP 10.0
    NOTATIONS. (FOR DETAILS SEE PROCESSDESCRIPTION)
    VAR 1= TIME                                             SEK
    VAR 2= FLOW OF FEEDWATER                                T/H
    VAR 3= DRUM LEVEL                                       MM
    VAR 4= PRESSURE IN DRUM 600MM                           KG/CM2
    VAR 5= PRESSURE BEFORE VALVE HT                         KG/CM2
    VAR 6= PRESSURE AFTER CONTROL VALVE                     KG/CM2
    VAR 7= PRESSURE BEFORE VALVE VT                         KG/CM2
    ~~VAR 8= ACTIVE POWER~~
    VAR 9= FUEL FLOW                                        T/H
    VAR10= STEAM FLOW L                                     T/H
    VAR11= STEAM FLOW R                                     T/H
    VAR12= TEMP. AFTER ATTEMPERATOR 1                       GRAD C
    VAR13= DRUM PRESSURE                                    KG/CM2
    VAR14= TEMP. AFTER ATTEMPERATOR 2                       GRAD C
    VAR15= TEMP. AFTER HIGH PRESSURE REHEATER R             GRAD C
    VAR16= TEMP. AFTER REHEATER R                           GRAD C
    VAR17= FLOW OF ATTEMPERATOR 1 L                         T/H
    VAR18= FLOW OF ATTEMPERATOR 2 L                         T/H
    VAR19= FLOW OF ATTEMPERATOR 1 R                         T/H
    VAR20= FLOW OF ATTEMPERATOR 2 R                         T/H
    VAR21= STEAMTEMP. BEFORE ATTEMPERATOR 1 R               FE-KONST
    VAR22= STEAMTEMP. BEFORE REHEATER R                     FE-KONST
    VAR23= FEEDWATERTEMP. AFTER ECO L                       FE-KONST
    VAR24= FEEDWATERTEMP. AFTER ECO R                       FE-KONST
    VAR25= STEAMTEMP. BEFORE ATTEMPERATOR 2 R               FE-KONST
 4) DATA ARE PUCHED (SEE KARL EKLUND REPORT 7117)
 5) STATIONARY CONDITIONS ARE ACHIVED WHEN THE INPUT
    SIGNAL IS APPLIED (SEE REPORT 7117)
 6) DATA ARE AVAILABLE ON UNIVAC 1108 TAPE 19,FILE   20
    TO READ THE INFORMATION USE THE SUBROUTINE
    INDATA(DAT,IA,IB,N,NVAR,IH,IW,KA) IH=~~1~~, IW=~~10~~.
                                         10      8
 7) SEE NOTICES
 8) DATA ARE PLOTTED.
 9) DATA ARE LISTED IN THIS PROGRAM OUTPUT.

USE AS DRUMPRESSURE= VAR 13
```

Figure 4. - Data D201A.DAT header page. High load fuel variations.



```
THE STANDARD DOCUMENTATION FILE.

PARAMETERS DEFINING THE EXPERIMENT.
N    =  359
NVAR =   25
TSAMP= 10.0000

NBUFF1=   45
NBUFF2=    2

IDEXPERIMENT   2 01 12 1310   DATE JUNE 1969
REFERENCE, KARL EKLUND
DESCRIPTION OF THE EXPERIMENT (SEE MEDDELANDE FRÅN
PROGRAMBIBLIOTEKET NR 3 OM DOKUMENTATION AV DATA).
 1) IDEXPERIMENT   2 01 12 1310   DATE JUNE 1969
    MADE ON THE BOILER P16 AND THE TURBINE G16 AT
    ÖRESUNDSVERKET OF SYDSVENSKA KRAFT AB.
 2) NUMBER OF SAMPLING EVENTS:  359
 3) NUMBER OF MEASUREMENT VARIABLES NVAR=25.
    SAMPLING PERIOD TSAMP 10.0
    NOTATIONS. (FOR DETAILS SEE PROCESSDESCRIPTION)
    VAR 1= TIME                                   SEK
    VAR 2= FLOW OF FEEDWATER                      T/H
    VAR 3= DRUM LEVEL                             MM
    VAR 4= PRESSURE IN DRUM 600MM                 KG/CM2
    VAR 5= PRESSURE BEFORE VALVE HT               KG/CM2
    VAR 6= PRESSURE AFTER CONTROL VALVE           KG/CM2
    VAR 7= PRESSURE BEFORE VALVE VT               KG/CM2
    VAR 8= ACTIVE POWER
    VAR 9= FUEL FLOW                              T/H
    VAR10= STEAM FLOW L                           T/H
    VAR11= STEAM FLOW R                           T/H
    VAR12= TEMP. AFTER ATTEMPERATOR 1             GRAD C
    VAR13= DRUM PRESSURE                          KG/CM2
    VAR14= TEMP. AFTER ATTEMPERATOR 2             GRAD C
    VAR15= TEMP. AFTER HIGH PRESSURE REHEATER R   GRAD C
    VAR16= TEMP. AFTER REHEATER R                 GRAD C
    VAR17= FLOW OF ATTEMPERATOR 1 L               T/H
    VAR18= FLOW OF ATTEMPERATOR 2 L               T/H
    VAR19= FLOW OF ATTEMPERATOR 1 R               T/H
    VAR20= FLOW OF ATTEMPERATOR 2 R               T/H
    VAR21= STEAMTEMP. BEFORE ATTEMPERATOR 1 R     FE-KONST
    VAR22= STEAMTEMP. BEFORE REHEATER R           FE-KONST
    VAR23= FEEDWATERTEMP. AFTER ECO L             FE-KONST
    VAR24= FEEDWATERTEMP. AFTER ECO R             FE-KONST
    VAR25= STEAMTEMP. BEFORE ATTEMPERATOR 2 R     FE-KONST
 4) DATA ARE PUCHED (SEE KARL EKLUND REPORT 7117)
 5) STATIONARY CONDITIONS ARE ACHIVED WHEN THE INPUT
    SIGNAL IS APPLIED (SEE REPORT 7117)
 6) DATA ARE AVAILABLE ON UNIVAC 1108 TAPE 19,FILE   30
    TO READ THE INFORMATION USE THE SUBROUTINE
    IUDATA(DAT,IA,IB,N,NVAR,IH,IU,KA) IH=~~2~~, IU=~~10~~.
                                         10       8
 7) SEE NOTICES
 8) DATA ARE PLOTTED.
 9) DATA ARE LISTED IN THIS PROGRAM OUTPUT.

USE AS DRUMPRESSURE= VAR 4
```

Figure 5.- Data D102A.DAT header page. High load feedwater variations.

```
THE STANDARD DOCUMENTATION FILE.

PARAMETERS DEFINING THE EXPERIMENT.
N     =  359
NVAR =    25
TSAMP= 10.0000

NBUFF1=    45
NBUFF2=     2

IDEXPERIMENT   102 12 1510    DATE JUNE 1969
REFERENCE, KARL EKLUND
DESCRIPTION OF THE EXPERIMENT (SEE MEDDELANDE FRAN
PROGRAMBIBLIOTEKET NR 3 OM DOKUMENTATION AV DATA).
 1) IDEXPERIMENT    102 12 1510    DATE JUNE 1969
    MADE ON THE BOILER P16 AND THE TURBINE G16 AT
    ÖRESUNDSVERKET OF SYDSVENSKA KRAFT AB.
 2) NUMBER OF SAMPLING EVENTS:  359
 3) NUMBER OF MEASUREMENT VARIABLES NVAR=25.
    SAMPLING PERIOD TSAMP 10.0
    NOTATIONS. (FOR DETAILS SEE PROCESSDESCRIPTION)
    VAR 1= TIME                                          SEK
    VAR 2= FLOW OF FEEDWATER                             T/H
    VAR 3= DRUM LEVEL                                    MM
    VAR 4= PRESSURE IN DRUM 600MM                        KG/CM2
    VAR 5= PRESSURE BEFORE VALVE HT                      KG/CM2
    VAR 6= PRESSURE AFTER CONTROL VALVE                  KG/CM2
    VAR 7= PRESSURE BEFORE VALVE LT                      KG/CM2
    VAR 8= ACTIVE POWER
    VAR 9= FUEL FLOW                                     T/H
    VAR10= STEAM FLOW L                                  T/H
    VAR11= STEAM FLOW R                                  T/H
    VAR12= TEMP. AFTER ATTEMPERATOR 1                    GRAD C
    VAR13= DRUM PRESSURE                                 KG/CM2
    VAR14= TEMP. AFTER ATTEMPERATOR 2                    GRAD C
    VAR15= TEMP. AFTER HIGH PRESSURE REHEATER R          GRAD C
    VAR16= TEMP. AFTER REHEATER R                        GRAD C
    VAR17= FLOW OF ATTEMPERATOR 1 L                      T/H
    VAR18= FLOW OF ATTEMPERATOR 2 L                      T/H
    VAR19= FLOW OF ATTEMPERATOR 1 R                      T/H
    VAR20= FLOW OF ATTEMPERATOR 2 R                      T/H
    VAR21= STEAMTEMP. BEFORE ATTEMPERATOR 1 R            FE-KONST
    VAR22= STEAMTEMP. BEFORE REHEATER R                  FE-KONST
    VAR23= FEEDWATERTEMP. AFTER ECO L                    FE-KONST
    VAR24= FEEDWATERTEMP. AFTER ECO R                    FE-KONST
    VAR25= STEAMTEMP. BEFORE ATTEMPERATOR 2 R            FE-KONST
 4) DATA ARE PUCHED (SEE KARL EKLUND REPORT 7117)
 5) STATIONARY CONDITIONS ARE ACHIVED WHEN THE INPUT
    SIGNAL IS APPLIED (SEE REPORT 7117)
 6) DATA ARE AVAILABLE ON UNIVAC 1108 TAPE 19,FILE     2
    TO READ THE INFORMATION USE THE SUBROUTINE
    IDDATA(DAT,IA,IB,N,NVAR,IH,IJ,KA) IH=~~X~~. IJ=~~N~~.
                                          10      8
 7) SEE NOTICES
 8) DATA ARE PLOTTED.
 9) DATA ARE LISTED IN THIS PROGRAM OUTPUT.

USE AS DRUMPRESSURE= VAR 4
```

Figure 6.- Data D105A.DAT header page. High load control valve variations.

```
THE STANDARD DOCUMENTATION FILE.

PARAMETERS DEFINING THE EXPERIMENT.
N     =  358
NVAR =    25
TSAMP= 10.0000

NBUFF1=   45
NBUFF2=    2

IDEXPERIMENT   1 05 12 1815   DATE JUNE 1969
REFERENCE, KARL EKLUND
DESCRIPTION OF THE EXPERIMENT (SEE MEDDELANDE FRÅN
PROGRAMBIBLIOTEKET NR 3 OM DOKUMENTATION AV DATA).
 1) IDEXPERIMENT    1 05 12 1815   DATE JUNE 1969
    MADE ON THE BOILER P16 AND THE TURBINE G16 AT
    ÖRESUNDSVERKET OF SYDSVENSKA KRAFT AB.
 2) NUMBER OF SAMPLING EVENTS:  358
 3) NUMBER OF MEASUREMENT VARIABLES NVAR=25.
    SAMPLING PERIOD TSAMP 10.0
    NOTATIONS. (FOR DETAILS SEE PROCESSDESCRIPTION)
    VAR 1= TIME                                        SEK
    VAR 2= FLOW OF FEEDWATER                           T/H
    VAR 3= DRUM LEVEL                                  MM
    VAR 4= PRESSURE IN DRUM 600MM                      KG/CM2
    VAR 5= PRESSURE BEFORE VALVE HT                    KG/CM2
    VAR 6= PRESSURE AFTER CONTROL VALVE                KG/CM2
    VAR 7= PRESSURE BEFORE VALVE VT                    KG/CM2
    VAR 8= ACTIVE POWER
    VAR 9= FUEL FLOW                                   T/H
    VAR10= STEAM FLOW L                                T/H
    VAR11= STEAM FLOW R                                T/H
    VAR12= TEMP. AFTER ATTEMPERATOR 1                  GRAD C
    VAR13= DRUM PRESSURE                               KG/CM2
    VAR14= TEMP. AFTER ATTEMPERATOR 2                  GRAD C
    VAR15= TEMP. AFTER HIGH PRESSURE REHEATER R        GRAD C
    VAR16= TEMP. AFTER REHEATER R                      GRAD C
    VAR17= FLOW OF ATTEMPERATOR 1 L                    T/H
    VAR18= FLOW OF ATTEMPERATOR 2 L                    T/H
    VAR19= FLOW OF ATTEMPERATOR 1 R                    T/H
    VAR20= FLOW OF ATTEMPERATOR 2 R                    T/H
    VAR21= STEAMTEMP. BEFORE ATTEMPERATOR 1 R          FE-KONST
    VAR22= STEAMTEMP. BEFORE REHEATER R                FE-KONST
    VAR23= FEEDWATERTEMP. AFTER ECO L                  FE-KONST
    VAR24= FEEDWATERTEMP. AFTER ECO R                  FE-KONST
    VAR25= STEAMTEMP. BEFORE ATTEMPERATOR 2 R          FE-KONST
 4) DATA ARE PUCHED (SEE KARL EKLUND REPORT 7117)
 5) STATIONARY CONDITIONS ARE ACHIVED WHEN THE INPUT
    SIGNAL IS APPLIED (SEE REPORT 7117)
 6) DATA ARE AVAILABLE ON UNIVAC 1108 TAPE 19,FILE     8
    TO READ THE INFORMATION USE THE SUBROUTINE
    INDATA(DAT,IA,IB,N,NVAR,IH,IW,KA) IH=1, IW=10.
 7) SEE NOTICES                          10      8
 8) DATA ARE PLOTTED.
 9) DATA ARE LISTED IN THIS PROGRAM OUTPUT.

USE AS DRUMPRESSURE= VAR 4
```

Figure 7. - Input data. Low load fuel variations (D107A.DAT)
(all flows in Kg/sec, time axis in seconds).

87.06.02 - 16:42:09 nr: 6
hcopy

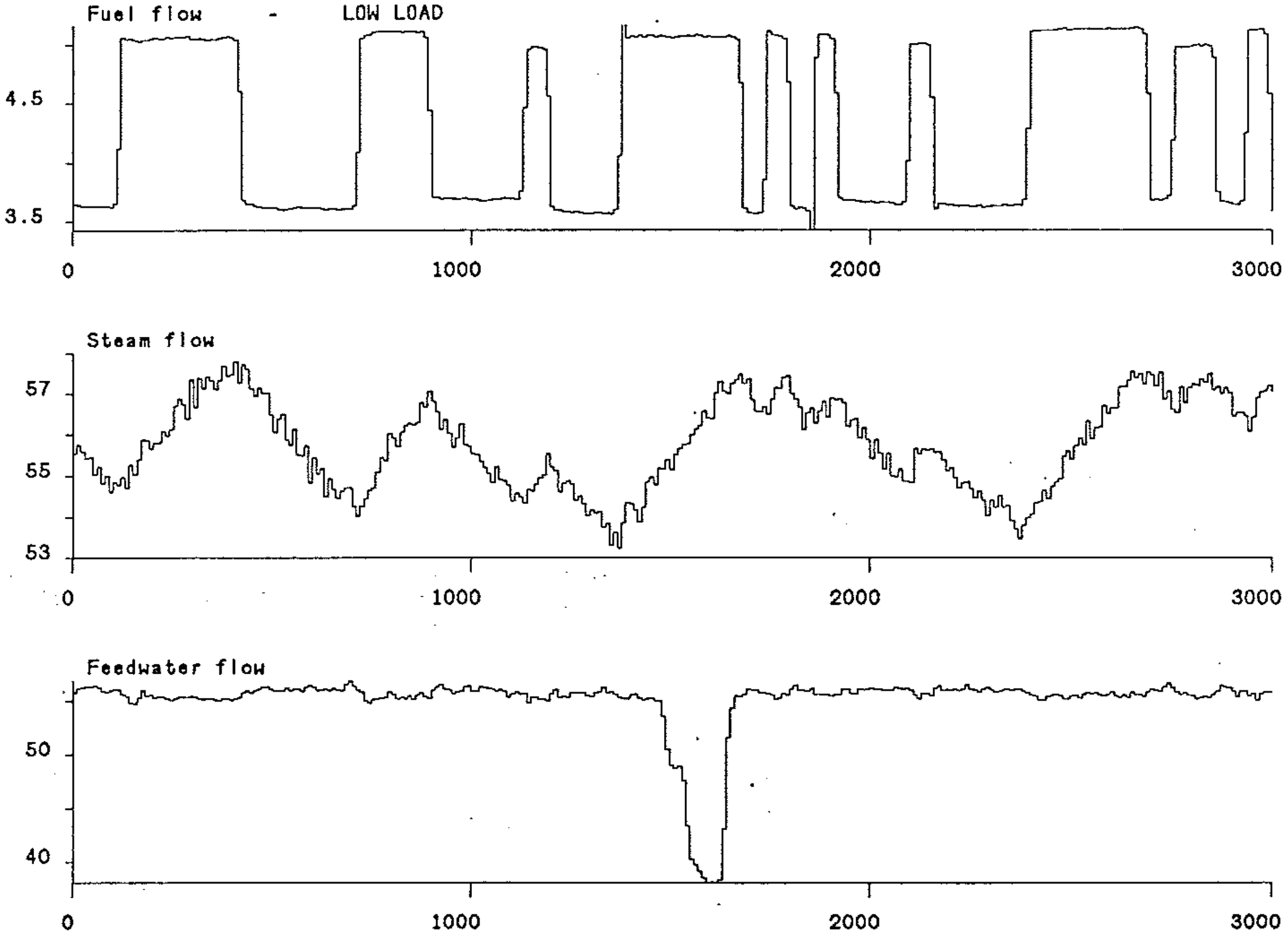


Figure 8. - Input data. Low load feedwater variations (D108A.DAT)
(all flows in Kg/sec, time axis in seconds).

87.06.02 - 11:33:34 nr: 8
hcopy

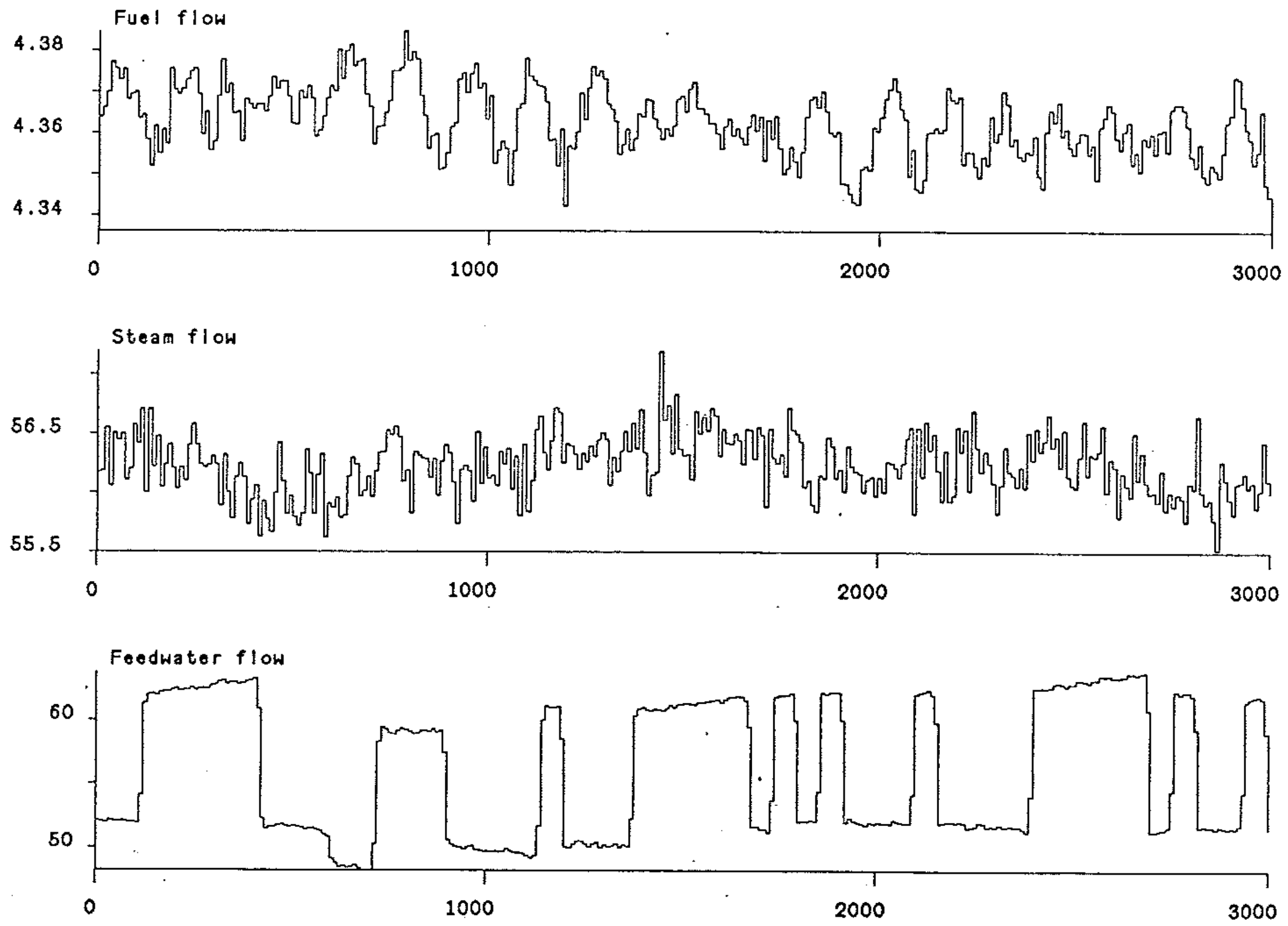


Figure 9. - Input data. Low load control valve variations (D111A.DAT) (all flows in Kg/sec, time axis in seconds).

87.06.02 - 11:12:18 nr: 6
hcopy

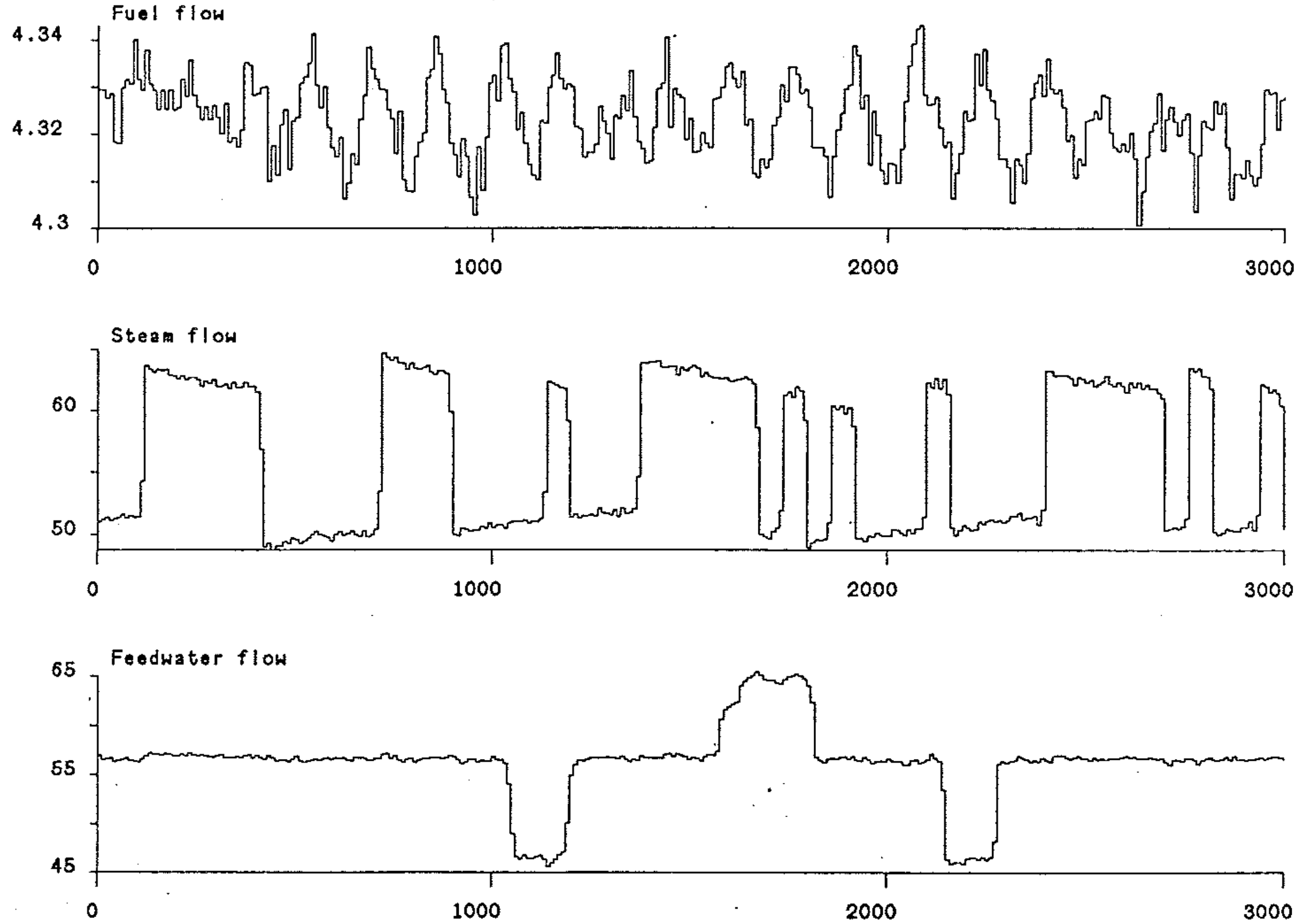


Figure 10. - Input data. High load fuel variations (D201A.DAT)
(all flows in Kg/sec, time axis in seconds).

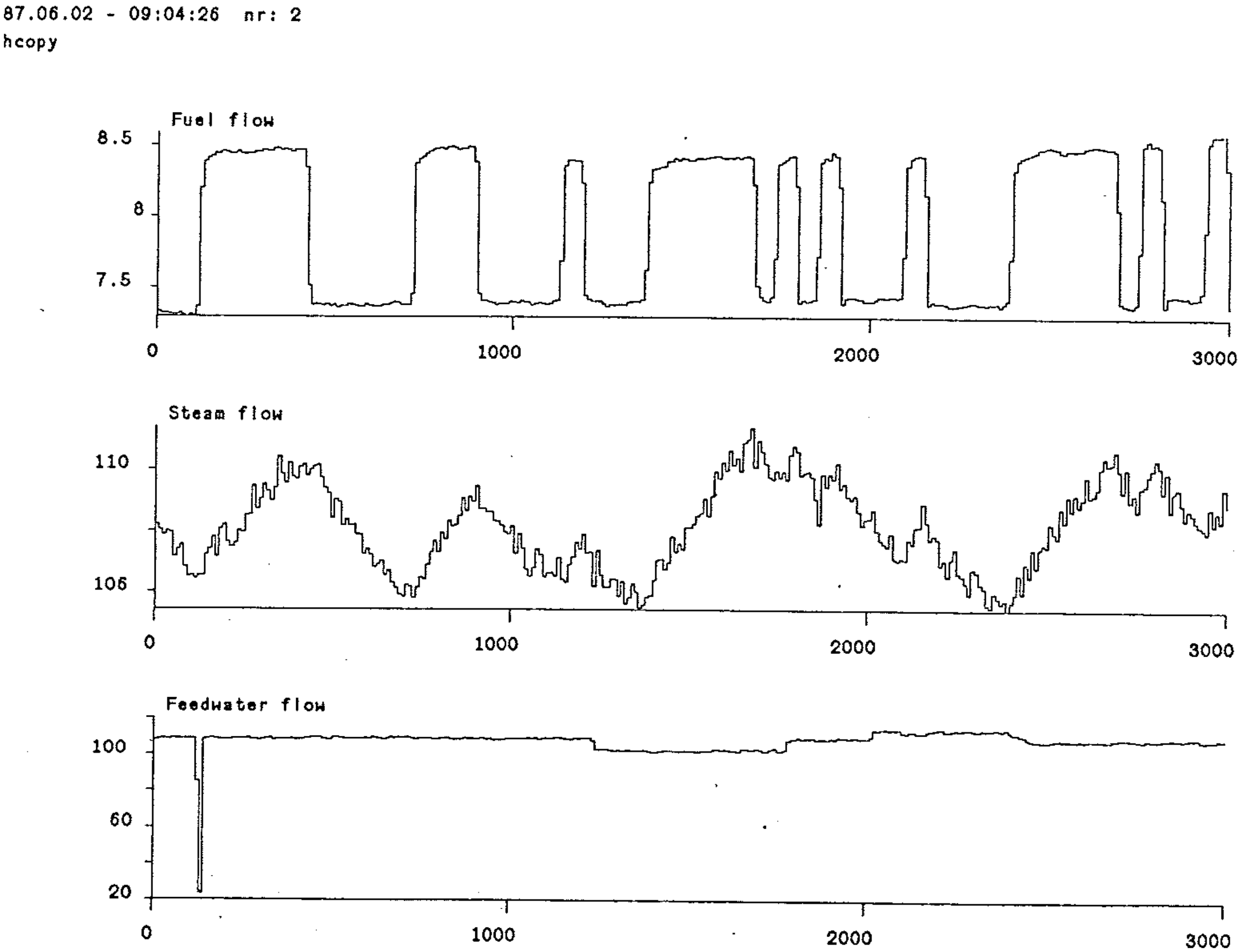


Figure 11. - Input data. High load feedwater variations (D102A.DAT) (all flows in Kg/sec, time axis in seconds).

87.06.02 - 12:16:56 nr: 10
hcopy

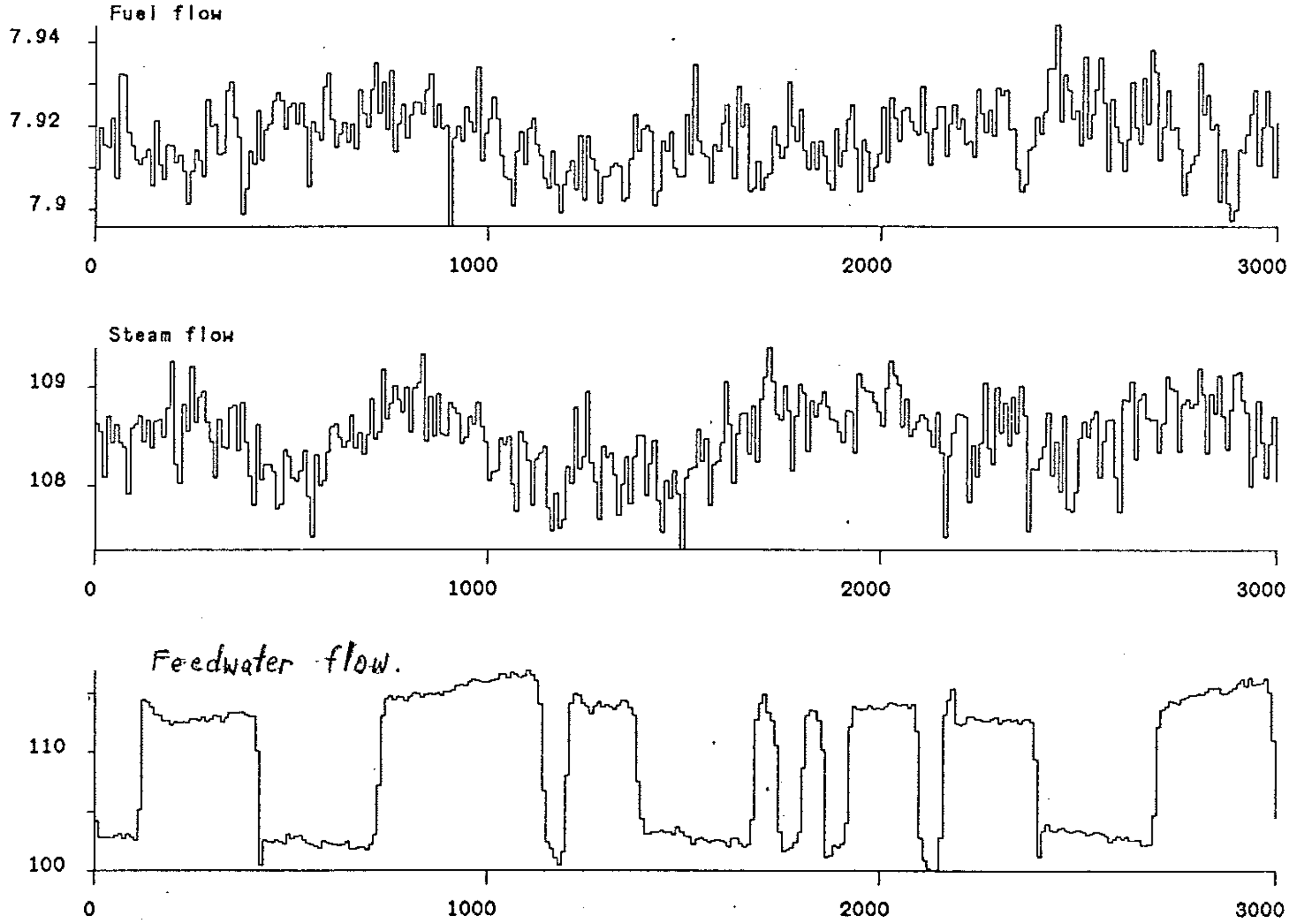


Figure 12. - Input data. High load control valve variations (D105A.DAT) (all flows in Kg/sec, time axis in seconds).

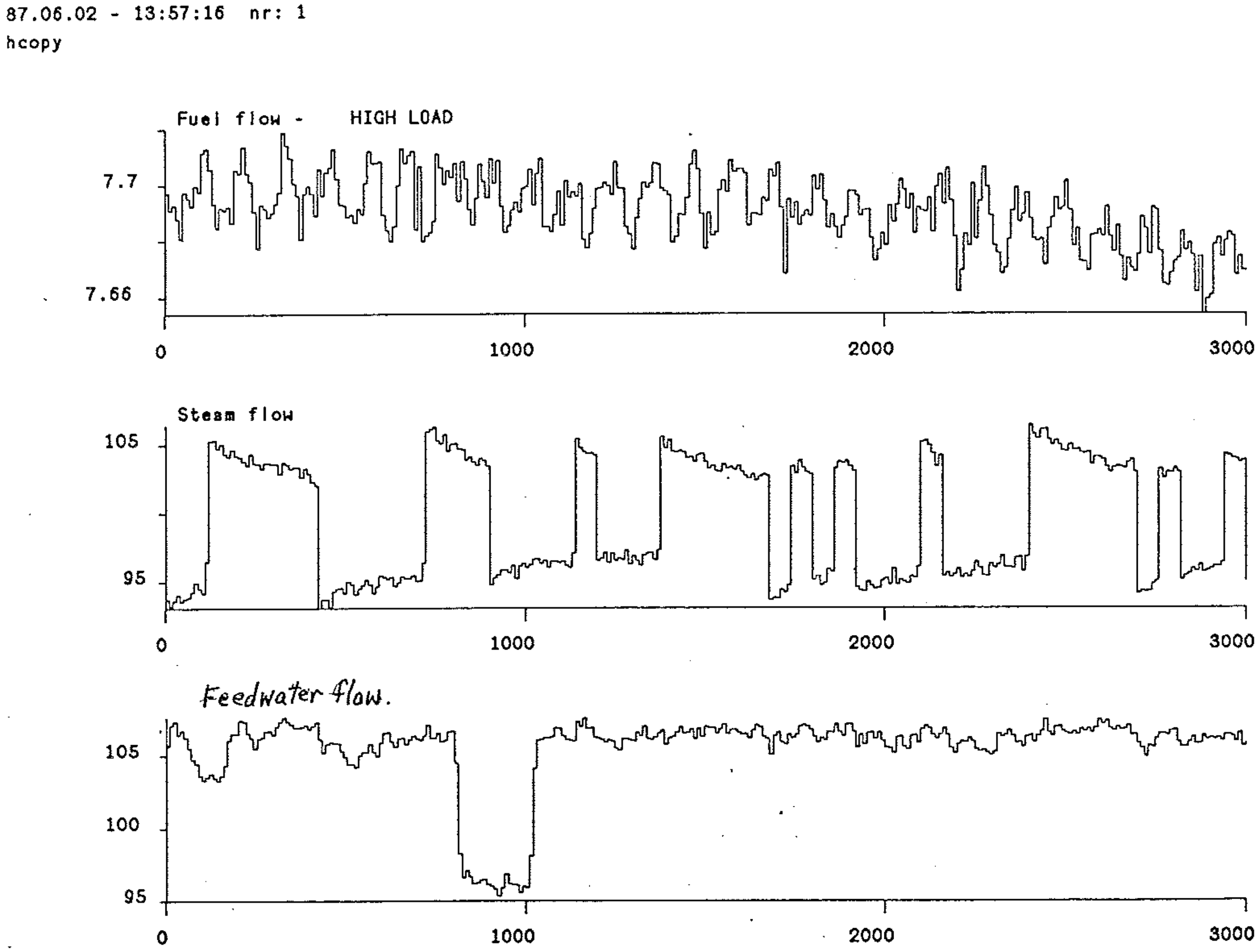


Figure 13. - Comparison of model Bt2 and plant outputs.
Low load fuel variations (D107A.DAT).

87.06.19 - 11:34:01 nr: 9
hcopy

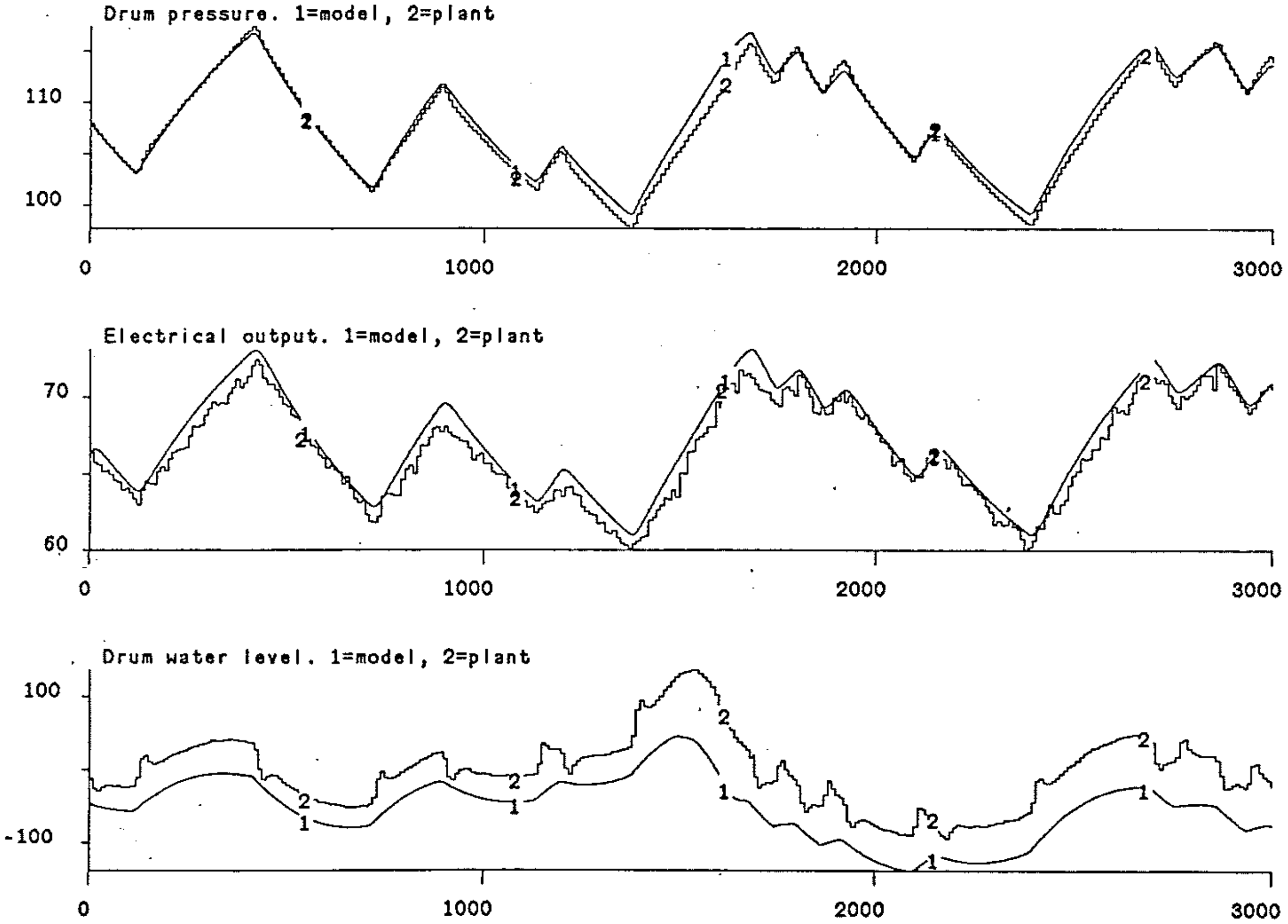


Figure 14. - Comparison of model Bt2 and plant outputs.
Low load feedwater variations (D108A.DAT).

87.06.19 - 11:37:40 nr: 10
hcopy

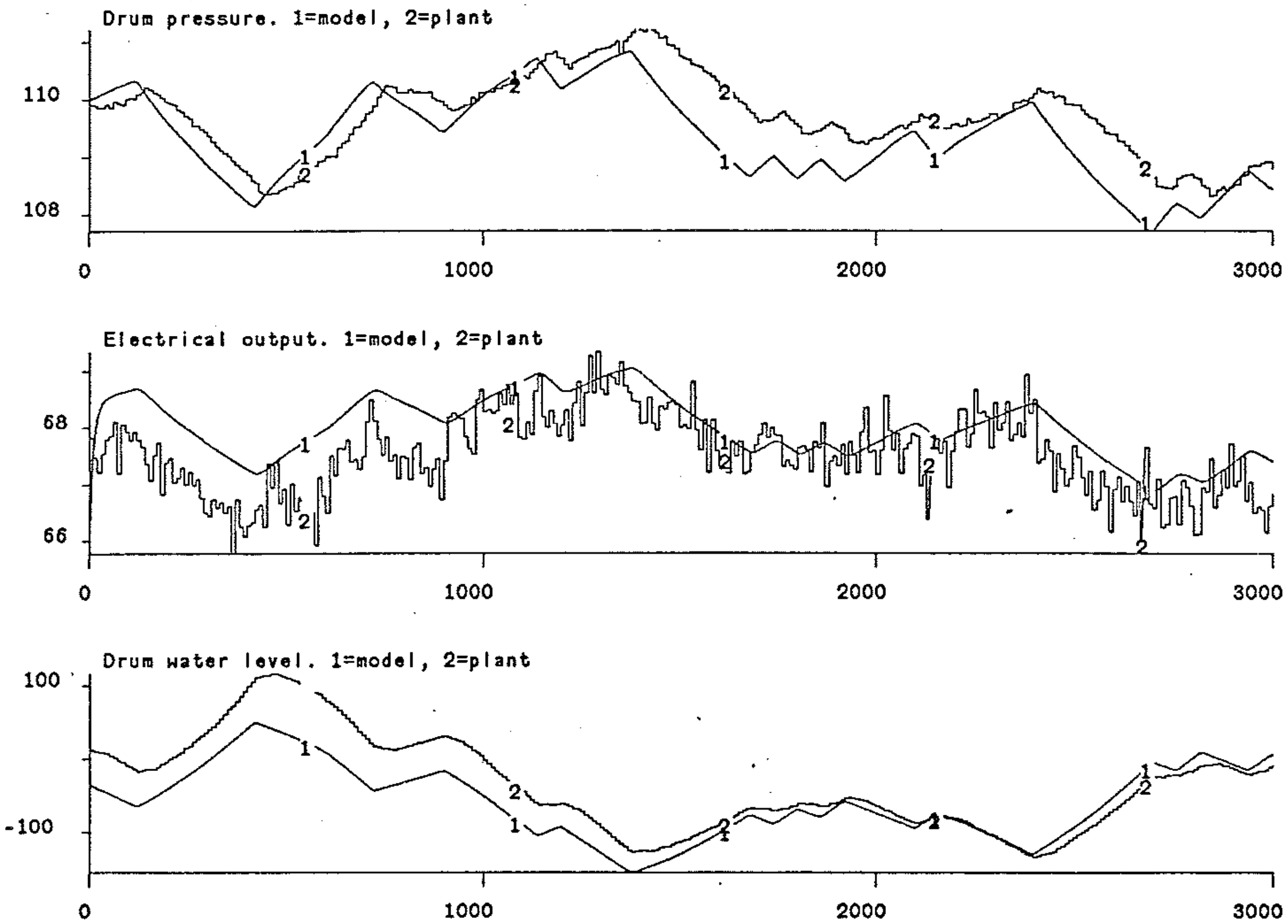


Figure 15. - Comparison of model Bt2 and plant outputs.
Low load control valve variations (D111A.DAT).

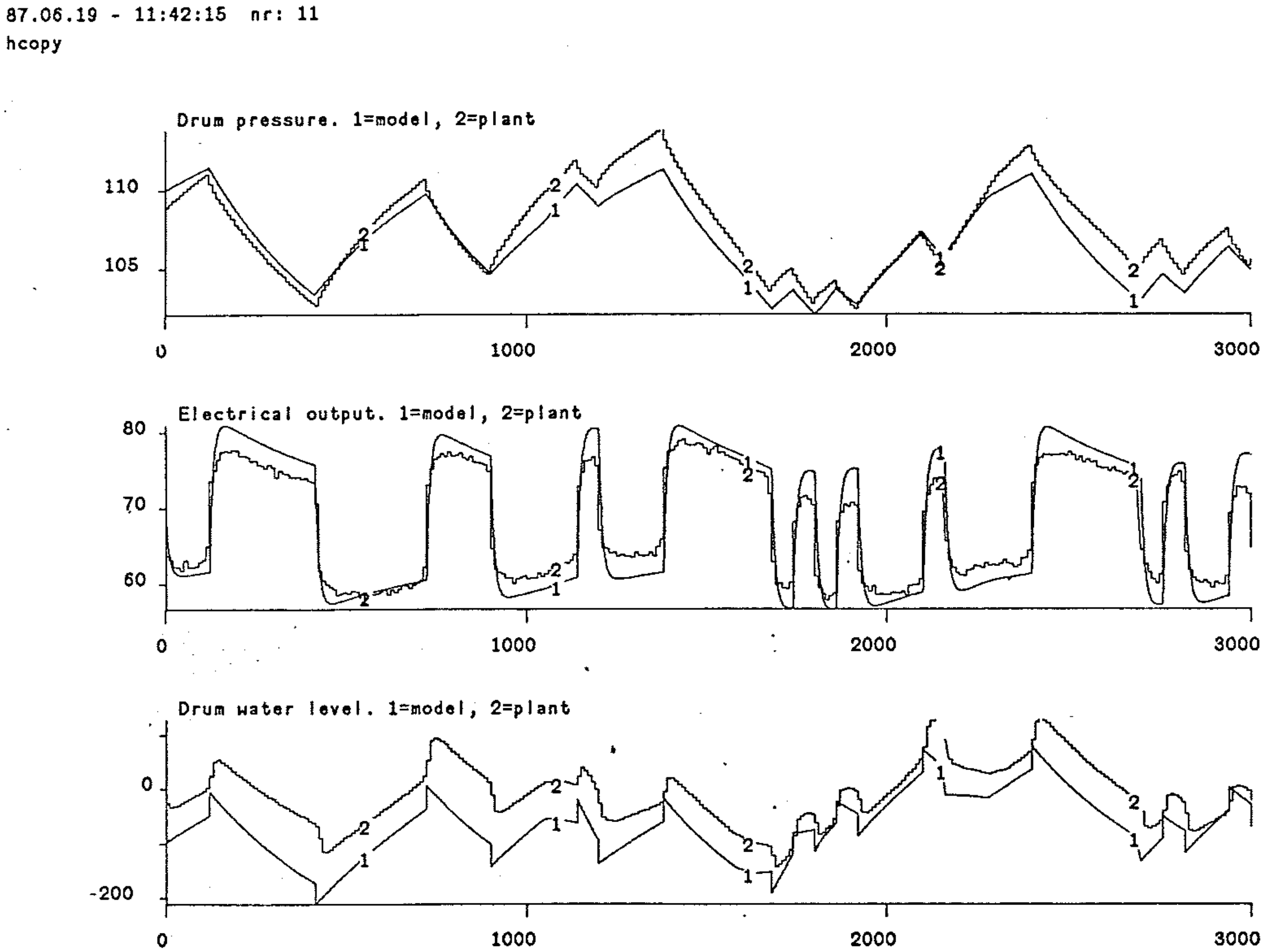


Figure 16. - Comparison of model Bt2 and plant outputs.
High load fuel variations (D201A.DAT).

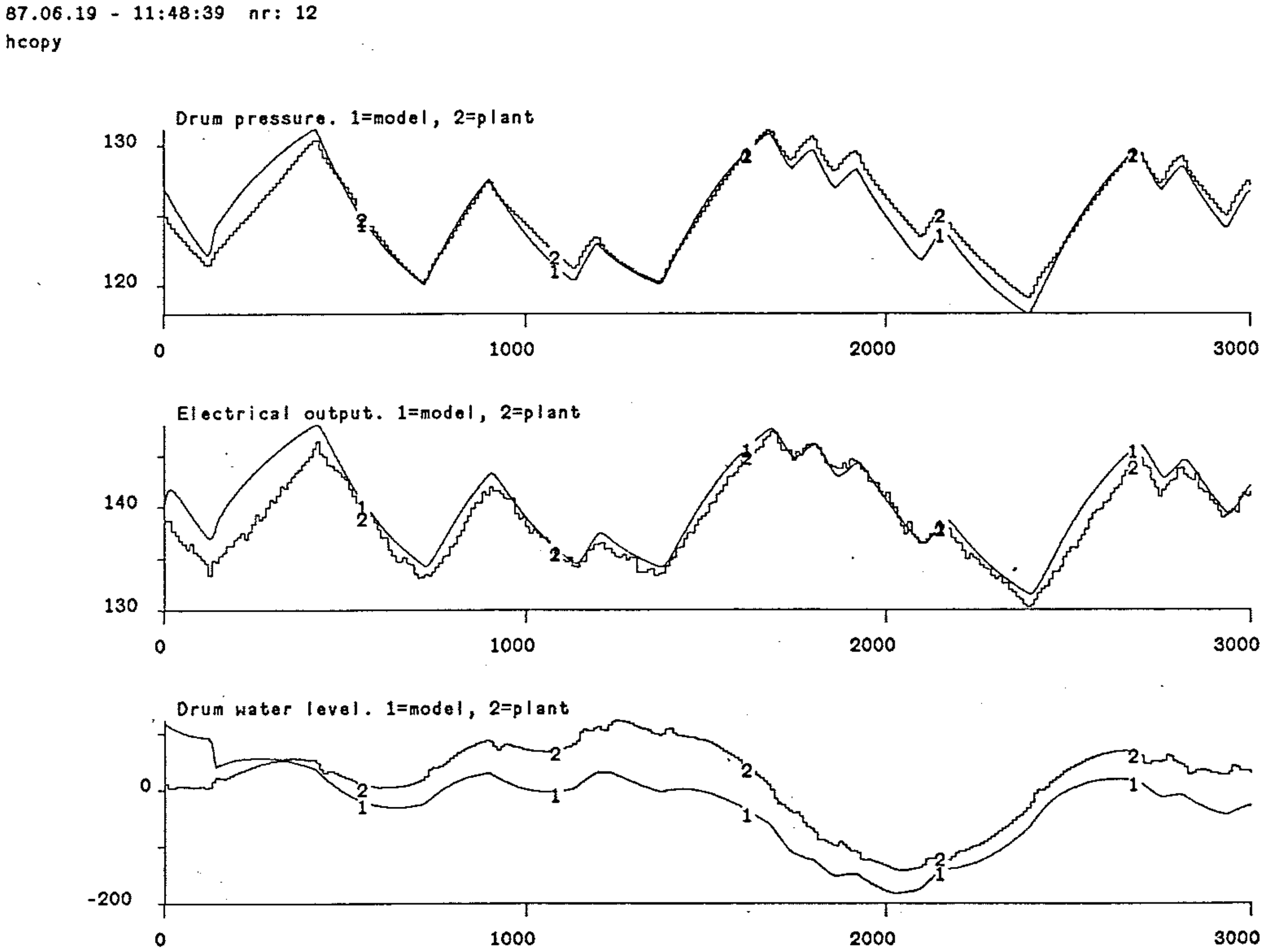


Figure 17. - Comparison of model Bt2 and plant outputs.
High load feedwater variations (D102A.DAT).

87.06.19 - 11:55:33 nr: 13
hcopy

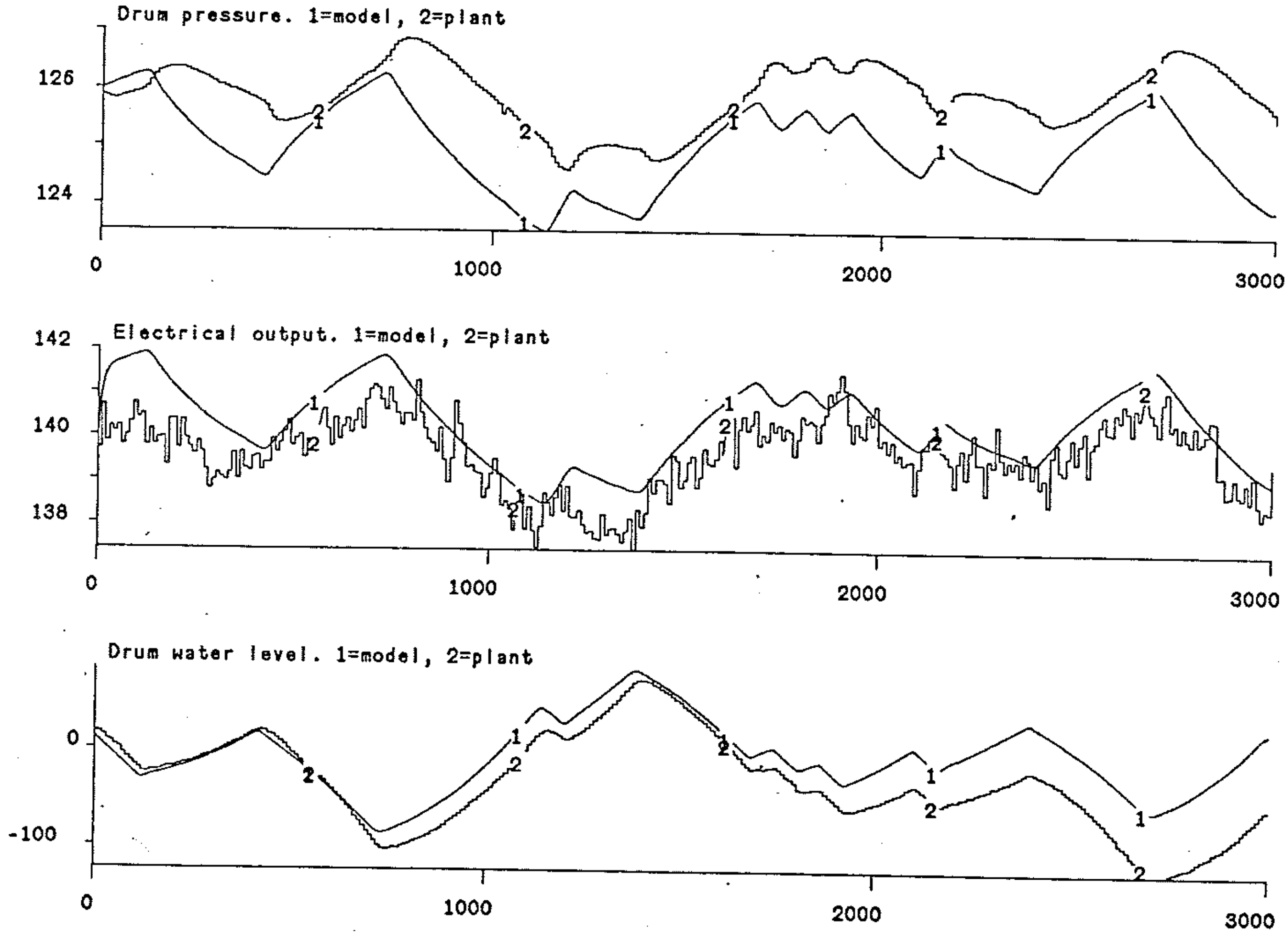


Figure 18. - Comparison of model Bt2 and plant outputs.
High load control valve variations (D105A.DAT).

87.06.19 - 12:00:31 nr: 14
hcopy

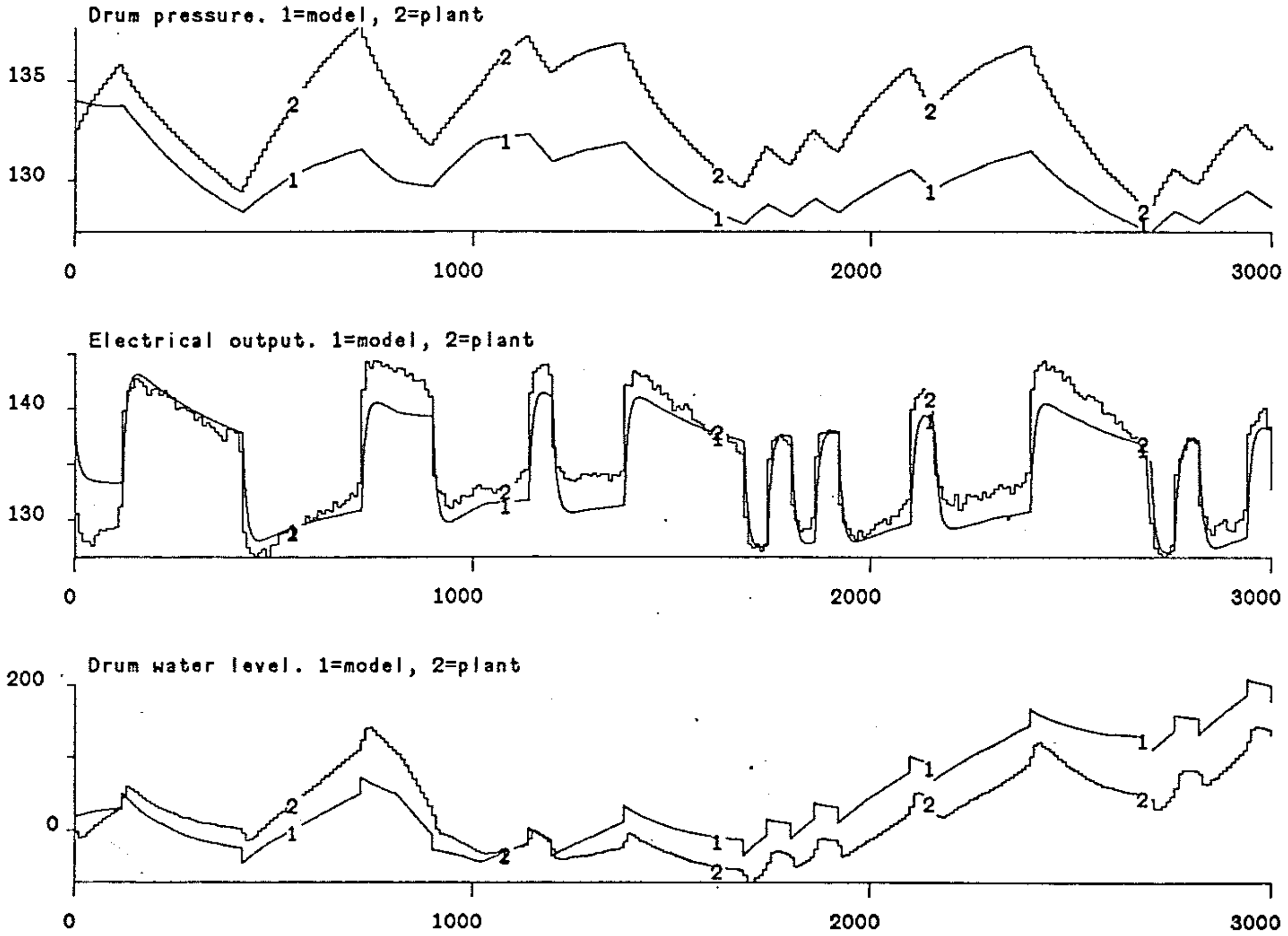


Figure 19. - Comparison of model Bt3 and plant outputs.
Low load fuel variations (D107A.DAT).

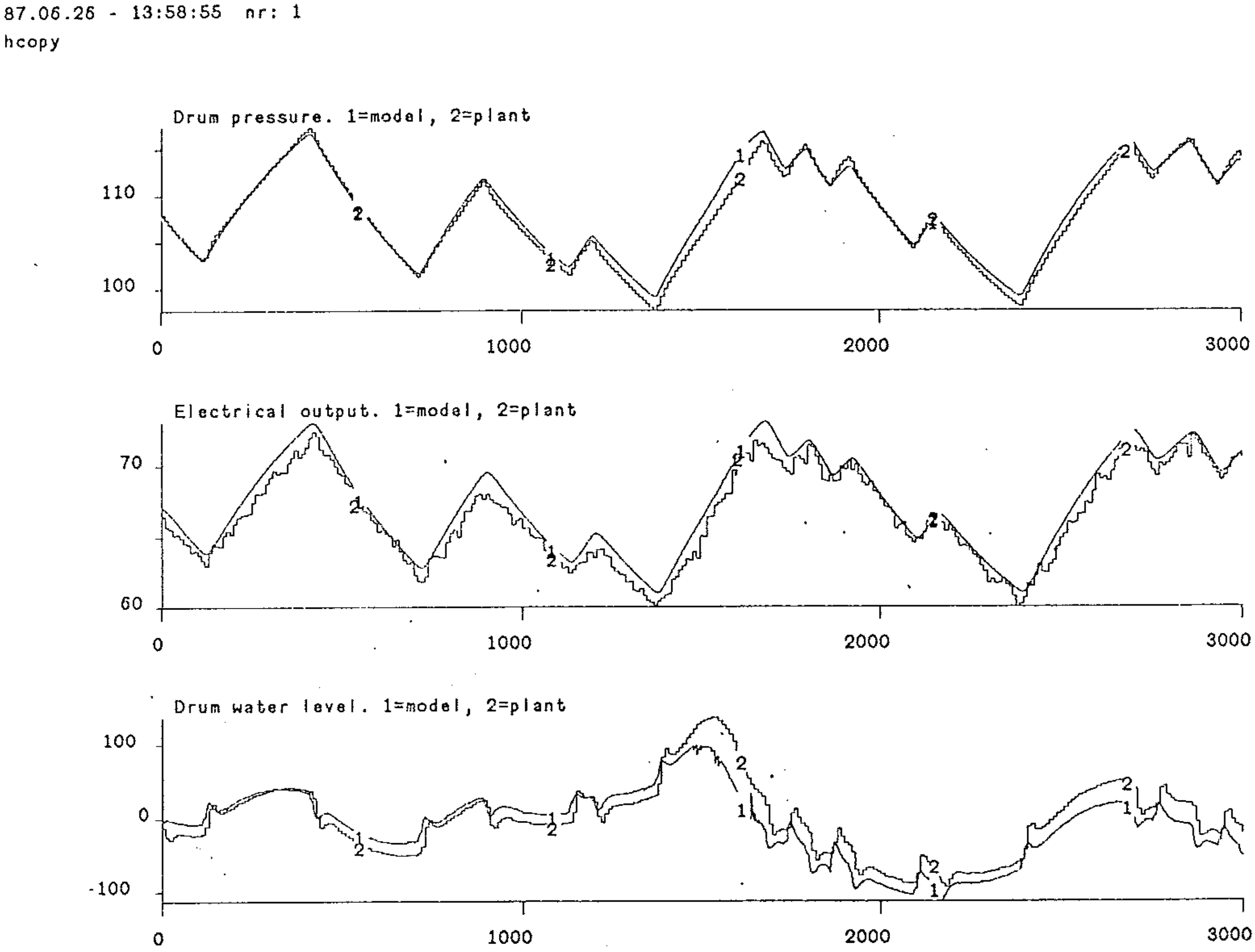


Figure 20. - Comparison of model Bt3 and plant outputs.
Low load feedwater variations (D108A.DAT).

87.06.26 - 14:02:49 nr: 2
hcopy

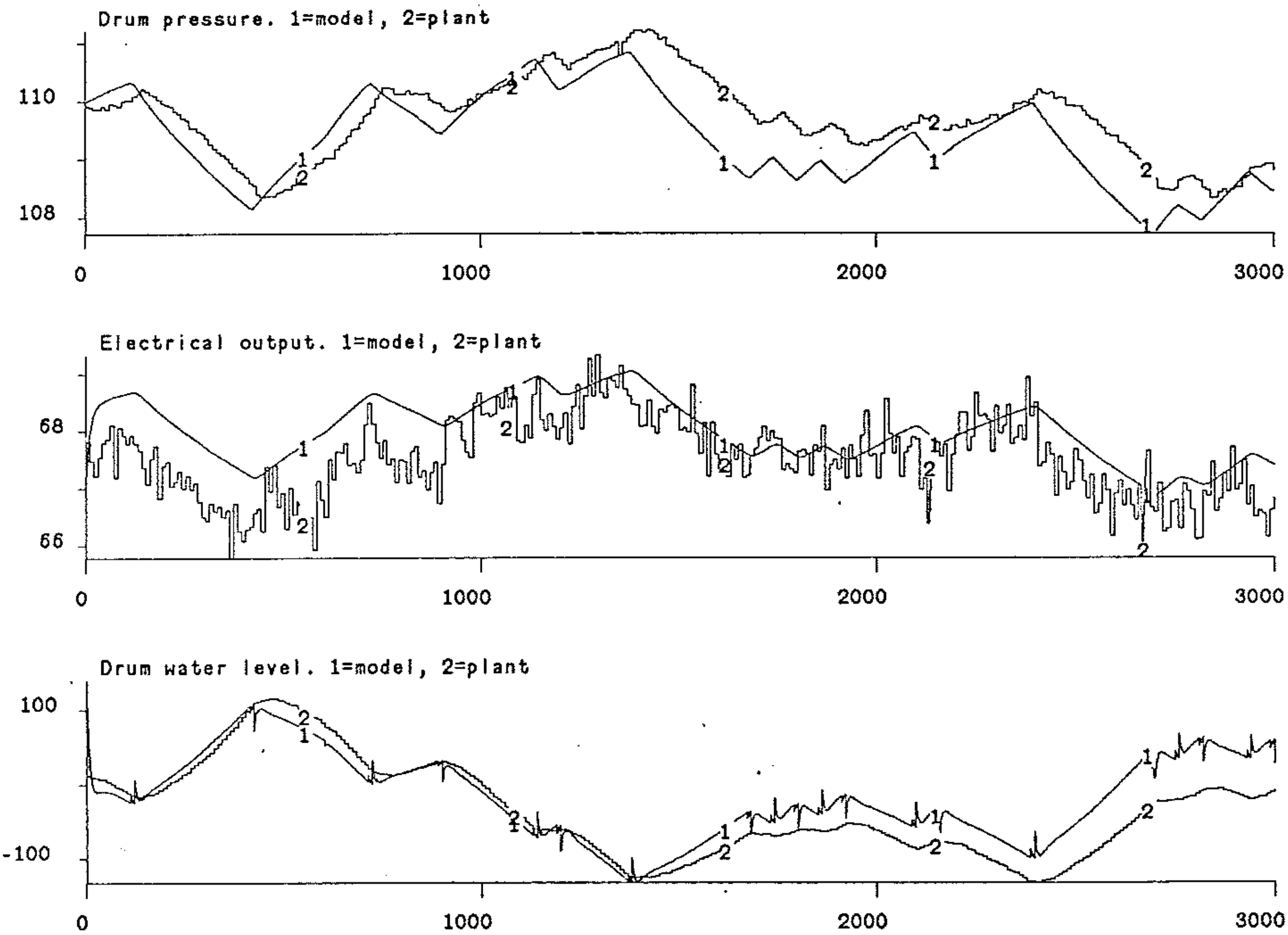


Figure 21. - Comparison of model Bt3 and plant outputs.
Low load control valve variations (D111A.DAT).

87.06.26 - 14:06:27 nr: 3
hcopy

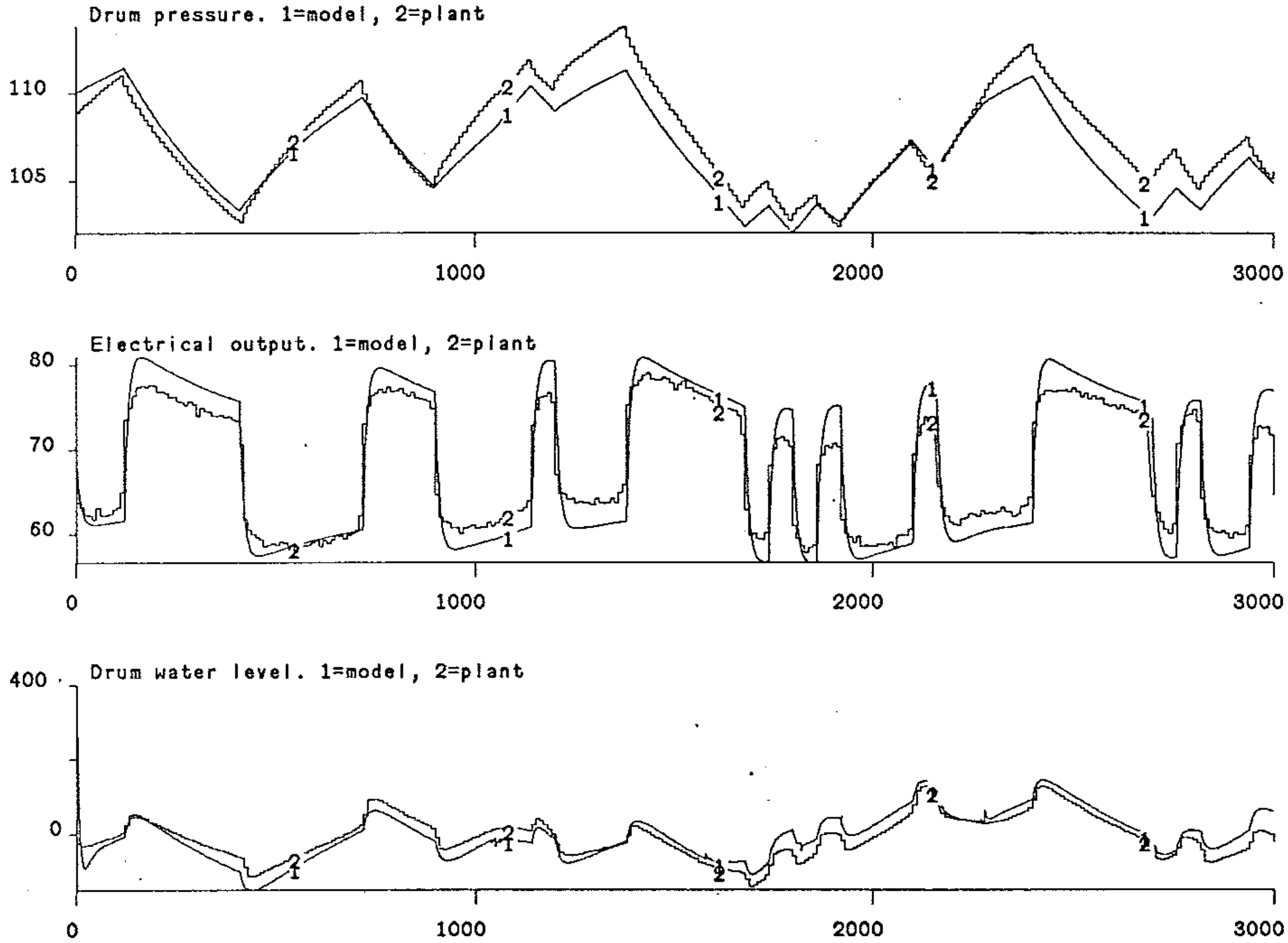


Figure 22. - Comparison of model Bt3 and plant outputs.
High load fuel variations (D201A.DAT).

87.06.26 - 14:32:11 nr: 4
hcopy

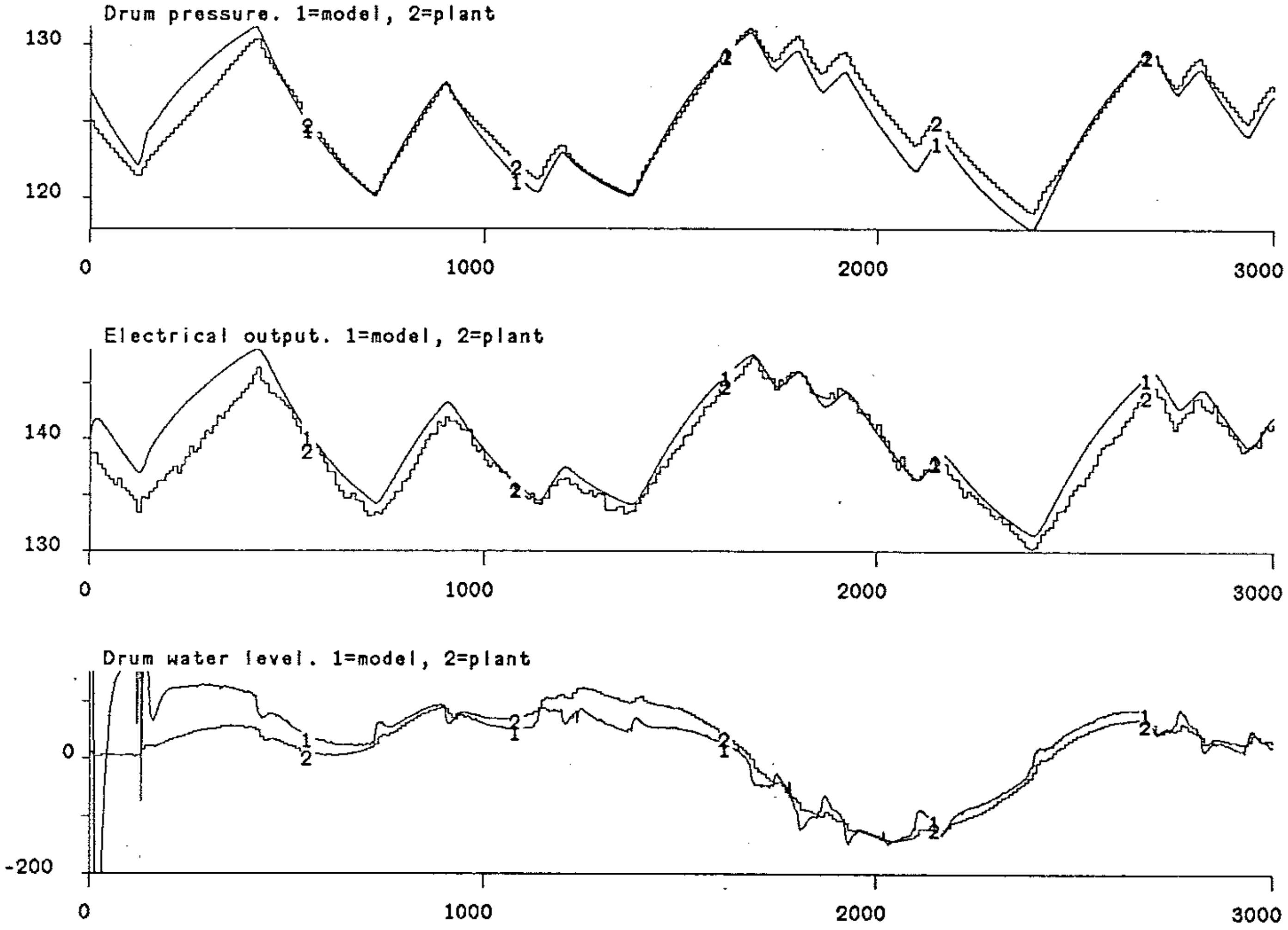


Figure 23. - Comparison of model Bt3 and plant outputs.
High load feedwater variations (D102A.DAT).

87.06.26 - 14:36:23 nr: 5
hcopy

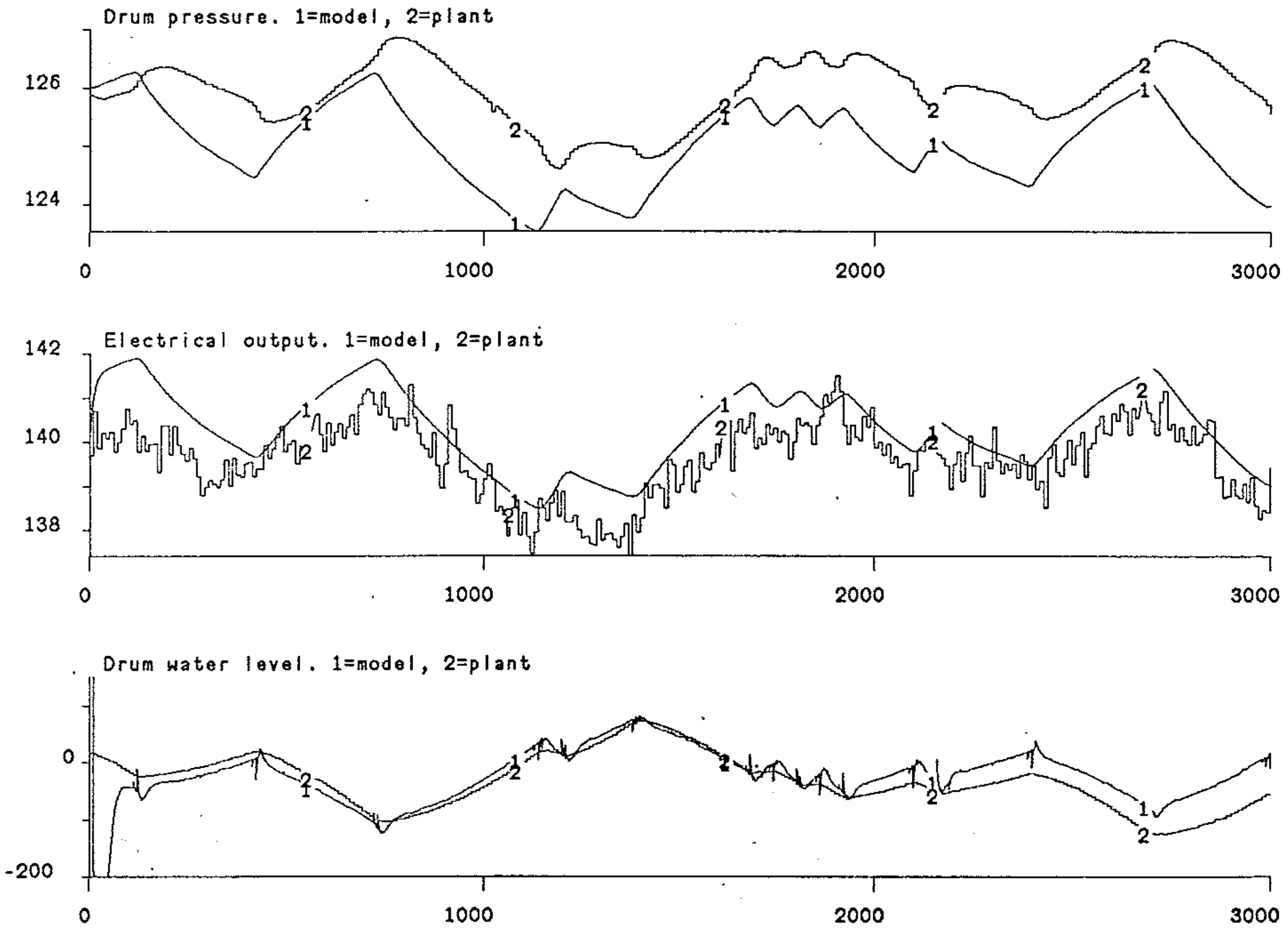
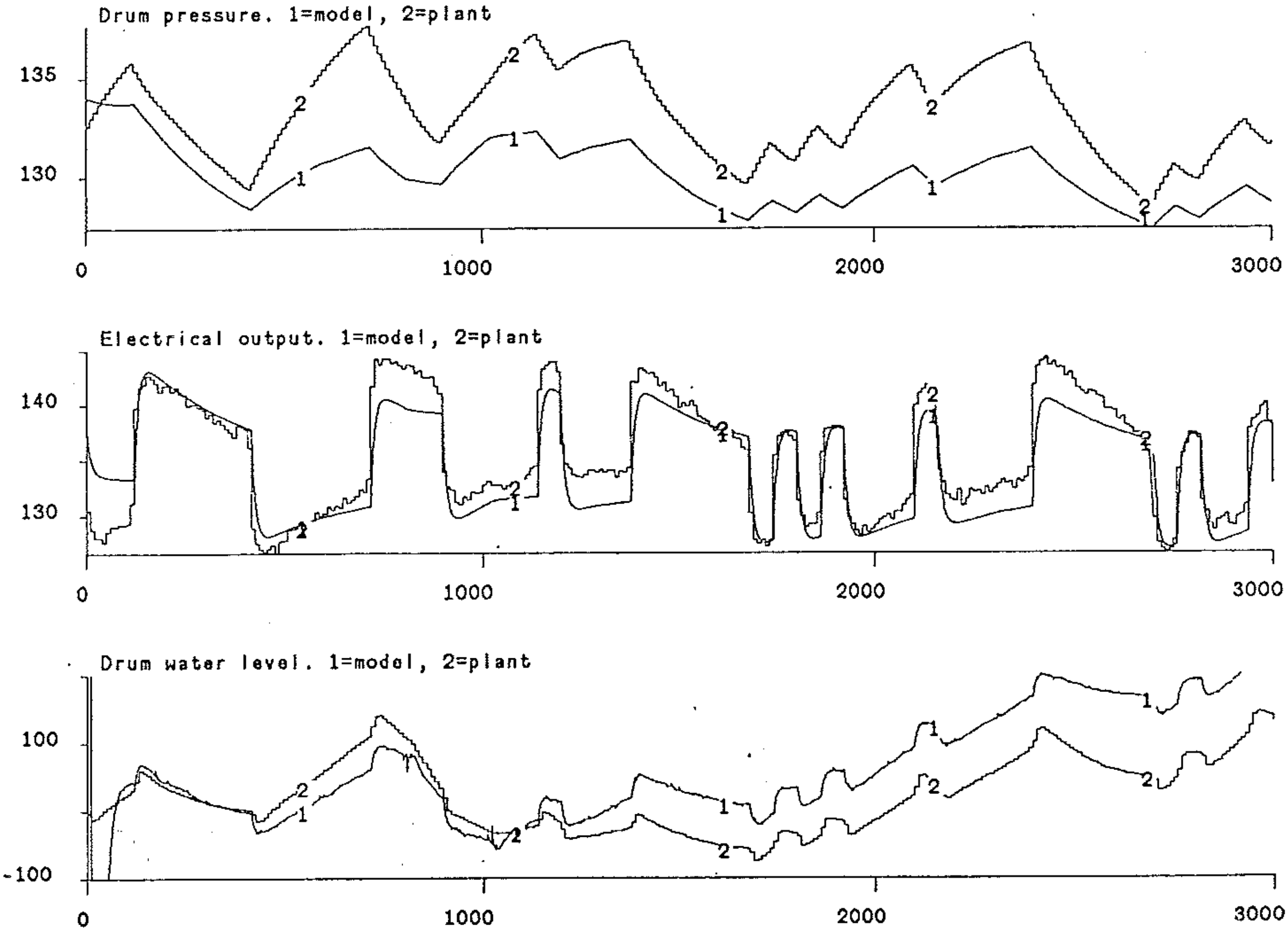


Figure 24. - Comparison of model Bt3 and plant outputs.
High load control valve variations (D105A.DAT).

87.06.26 - 14:48:12 nr: 6
hcopy


Drum pressure. 1=model, 2=plant

Electrical output. 1=model, 2=plant

Drum water level. 1=model, 2=plant

Figure 25. - Comparison of model Bt4 and plant outputs.
Low load fuel variations (D107A.DAT).

87.06.02 - 10:45:24 nr: 4
hcopy

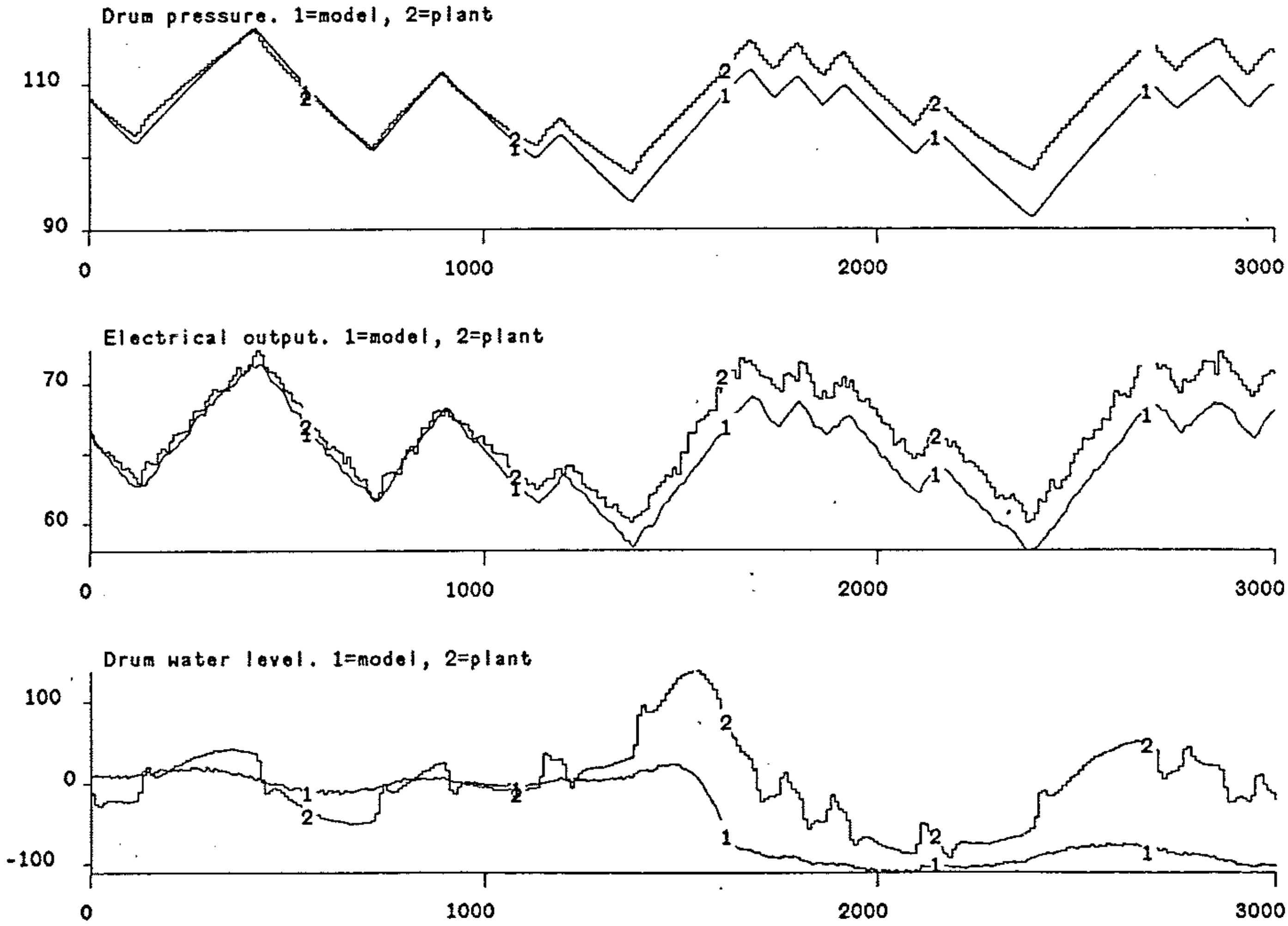


Figure 26. - Comparison of model Bt4 and plant outputs.
Low load feedwater variations (D108A.DAT).

87.06.02 - 11:30:35 nr: 7
hcopy

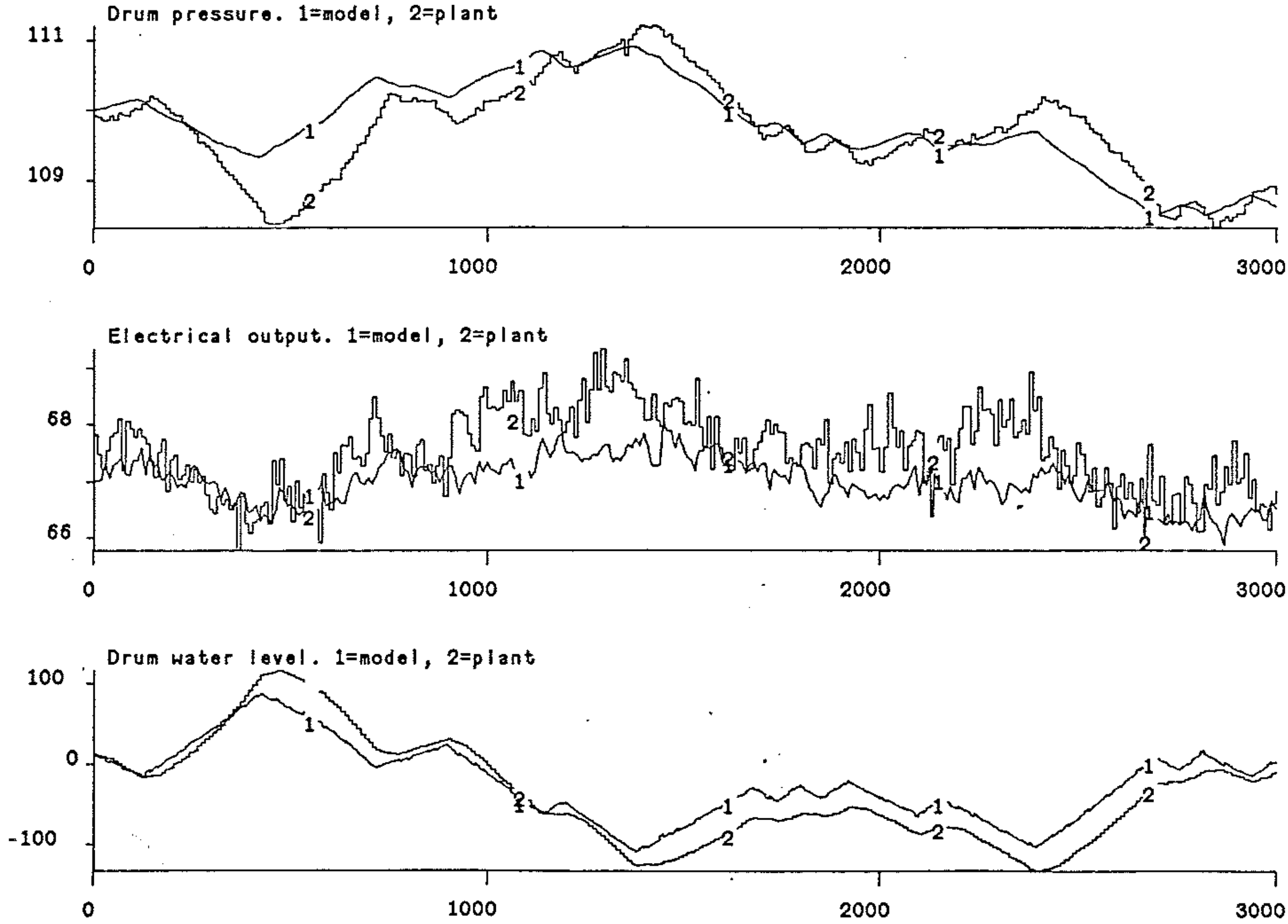


Figure 27. - Comparison of model Bt4 and plant outputs.
Low load control valve variations (D111A.DAT).

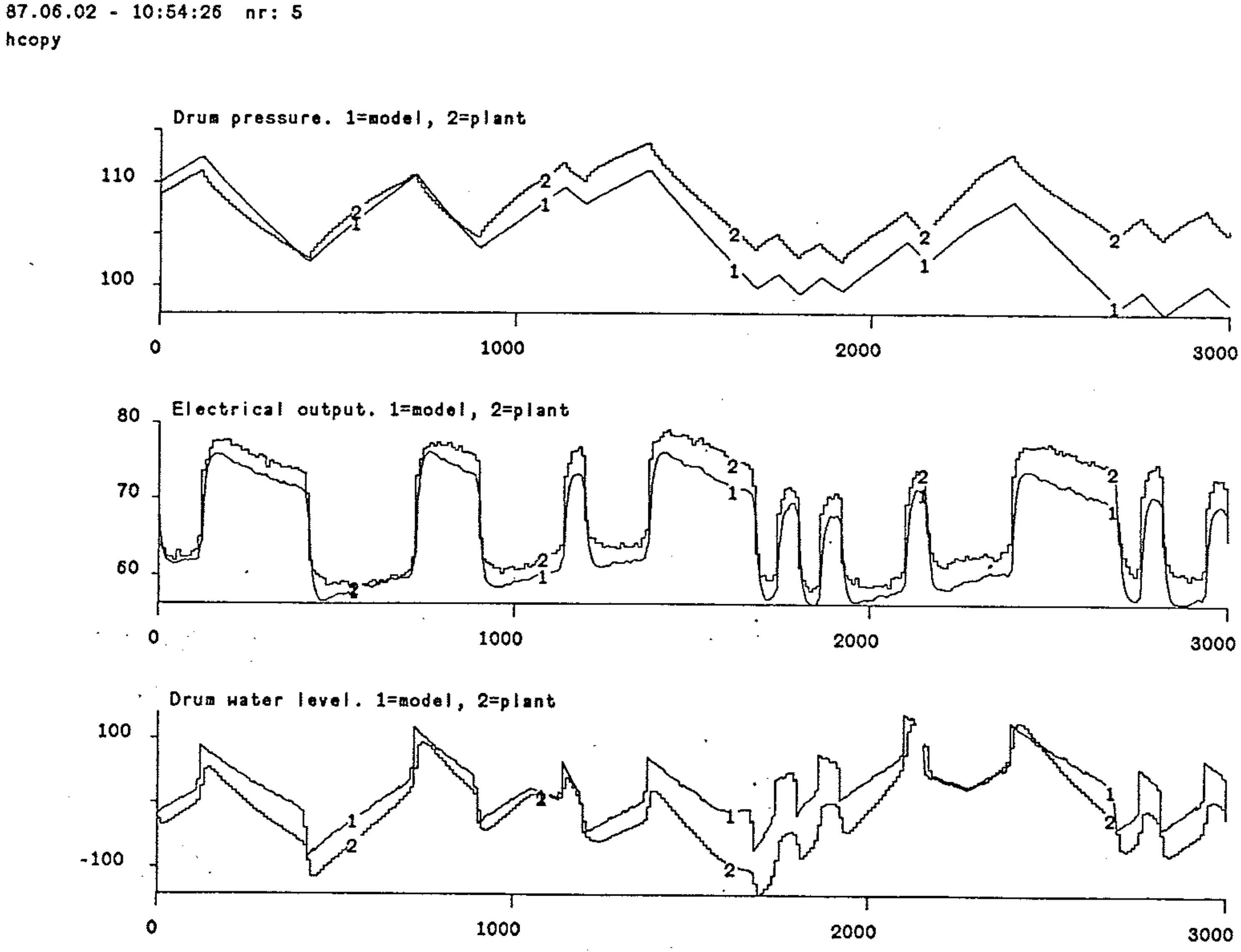


Figure 28. - Comparison of model Bt4 and plant outputs.
High load fuel variations (D201A.DAT).

87.06.02 - 16:49:16 nr: 7
hcopy

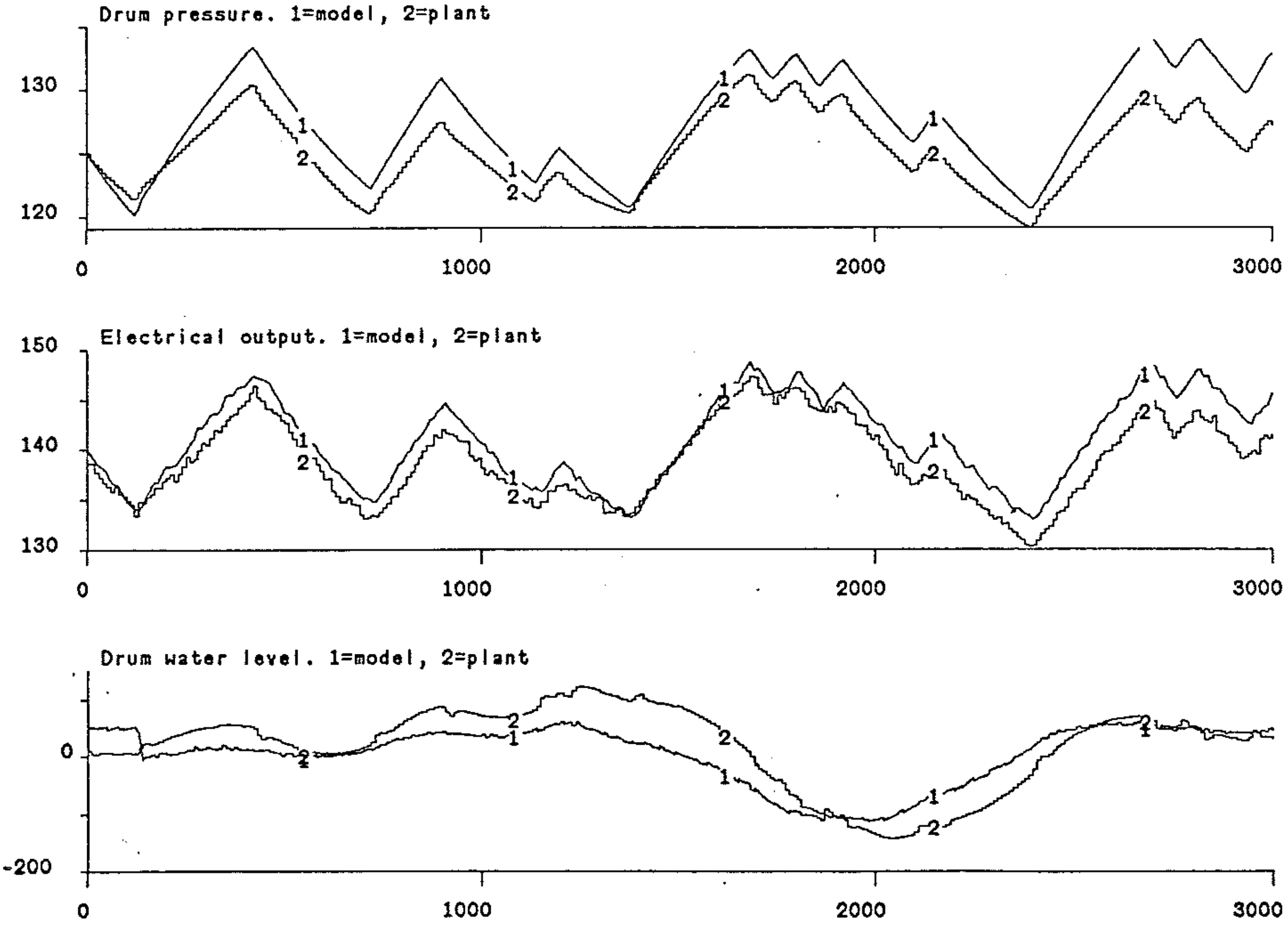
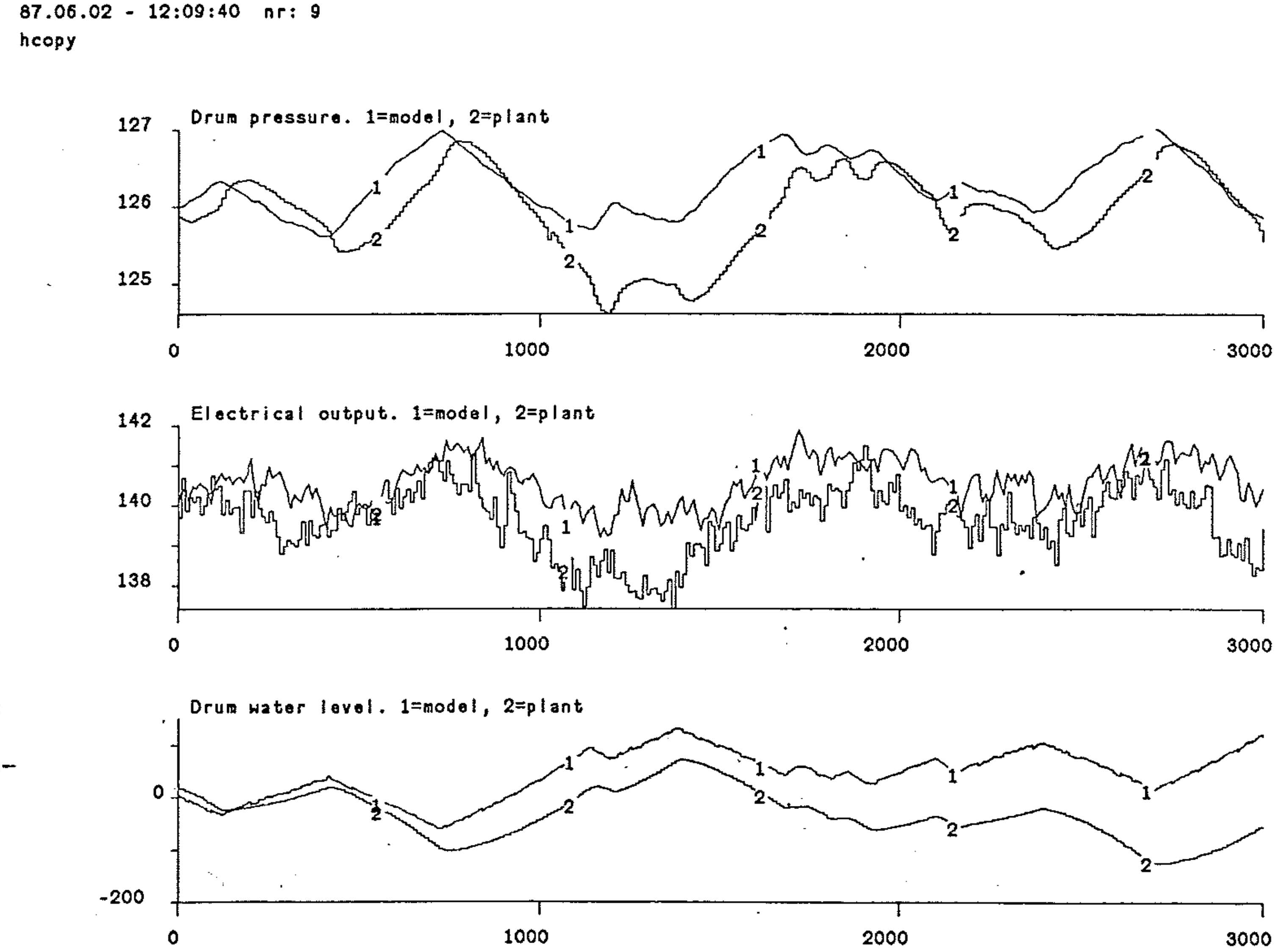


Figure 29. - Comparison of model Bt4 and plant outputs.
High load feedwater variations (D102A.DAT).



<u>Figure 30.</u> - Comparison of model Bt4 and plant outputs.
High load control valve variations (D105A.DAT).

87.06.02 - 16:29:57 nr: 5
hcopy

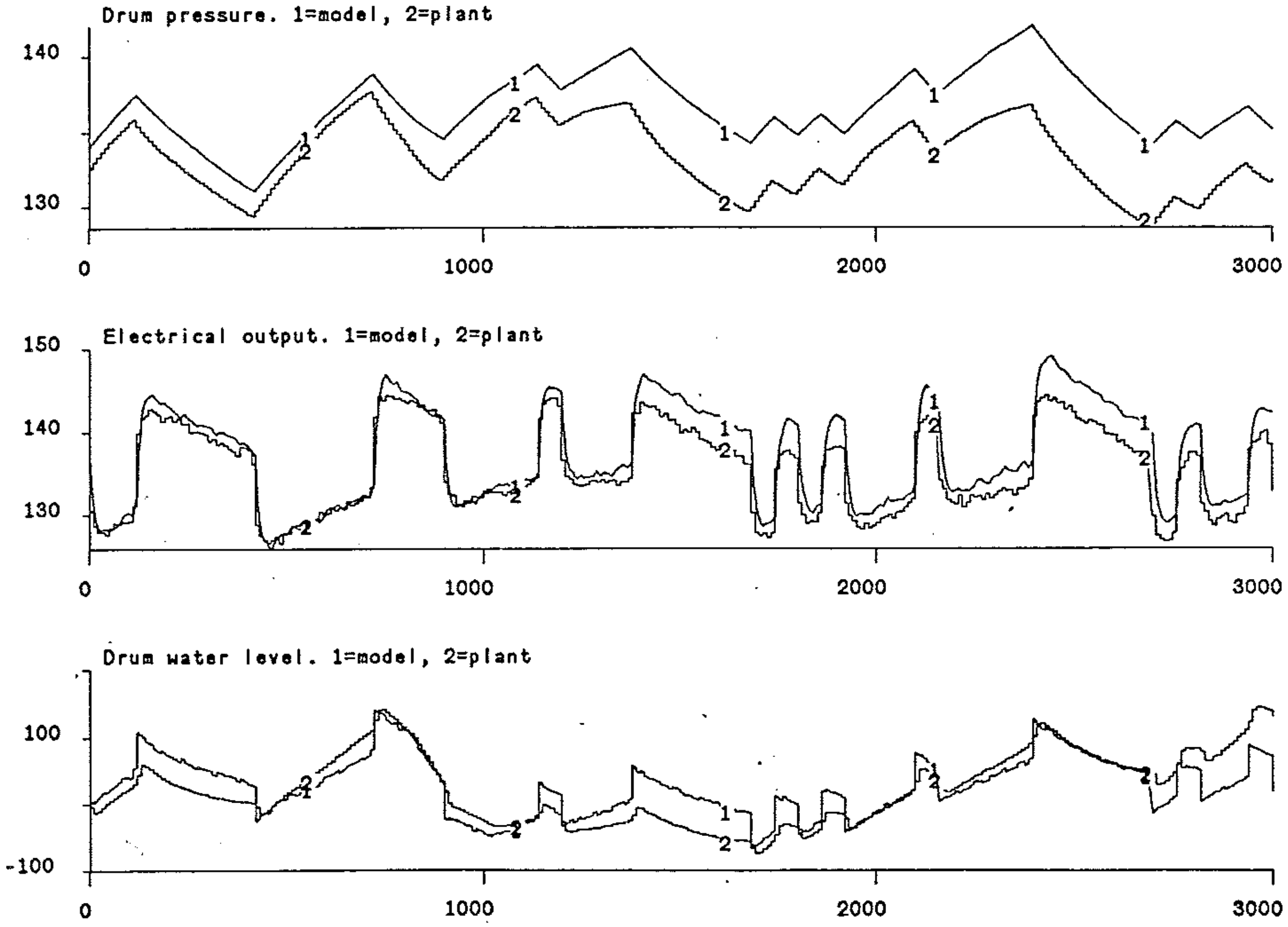


Figure 31. - Comparison of model Bt5 and plant outputs.
Low load fuel variations (D107A.DAT).

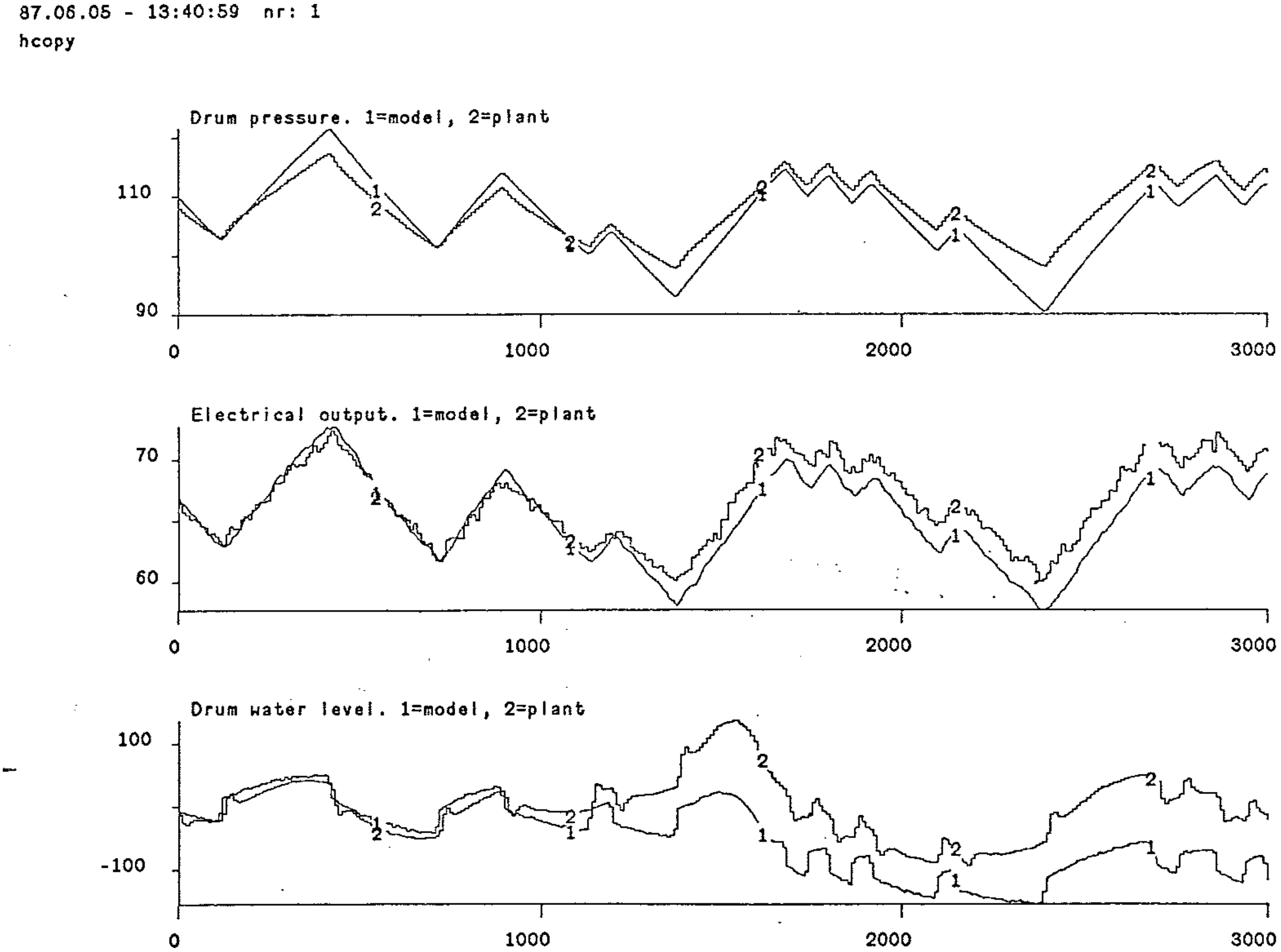


Figure 32. - Comparison of model Bt5 and plant outputs.
Low load feedwater variations (D108A.DAT).

87.06.05 - 09:23:02 nr: 3
hcopy

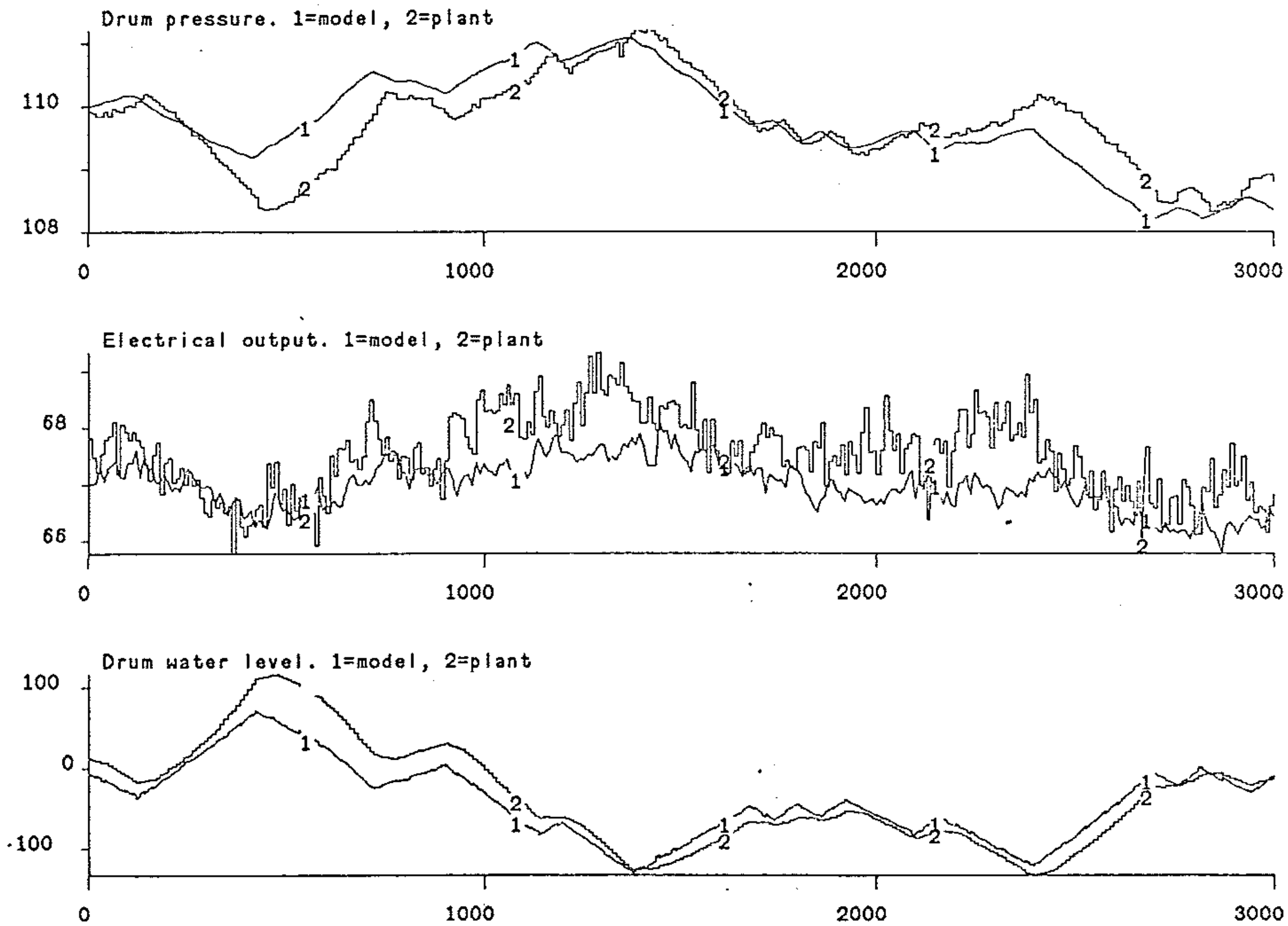


Figure 33. - Comparison of model Bt5 and plant outputs. Low load control valve variations (D111A.DAT).

87.06.05 - 09:29:27 nr: 4
hcopy

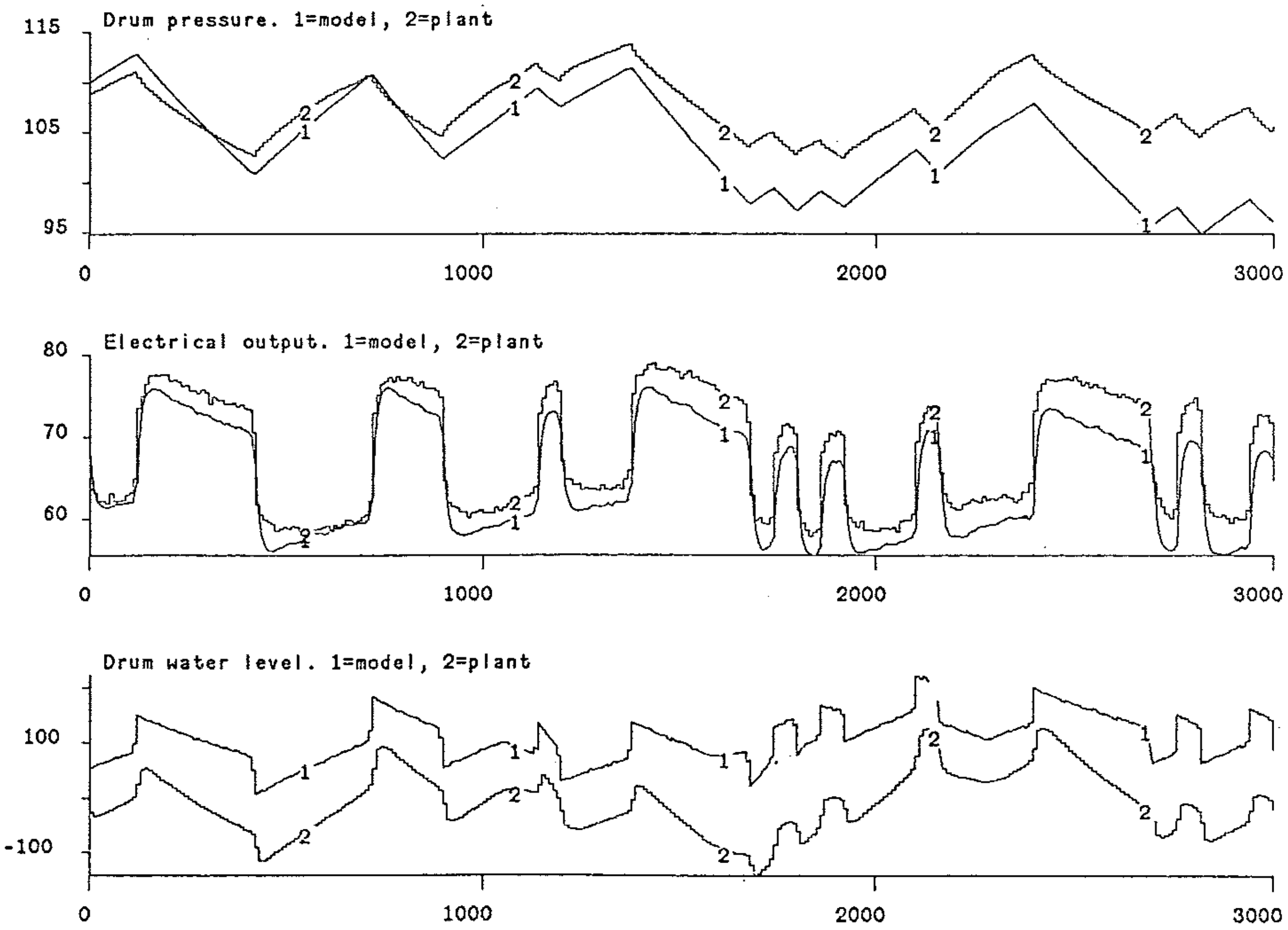


Figure 34. - Comparison of model Bt5 and plant outputs.
High load fuel variations (D201A.DAT).

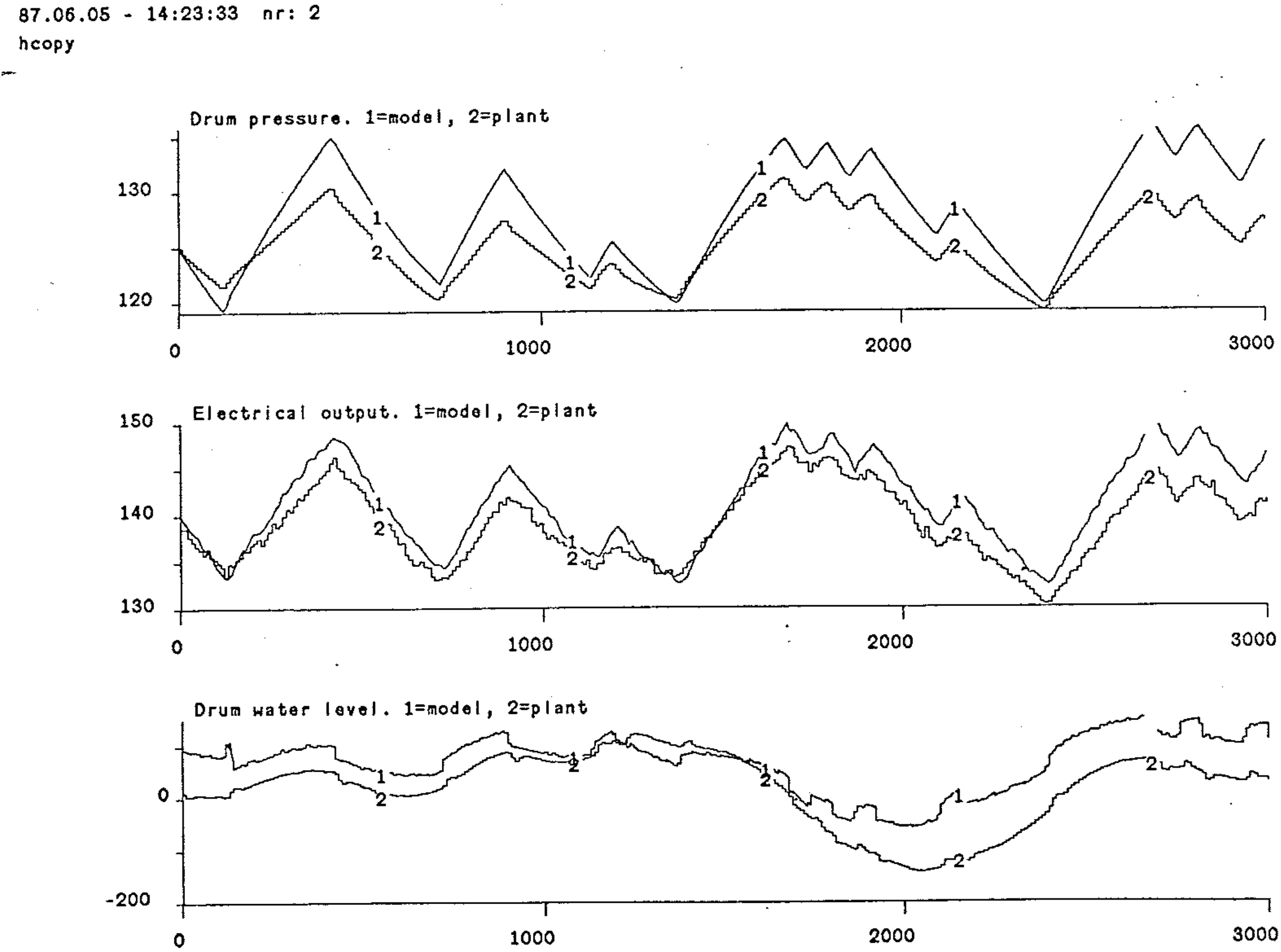


Figure 35. - Comparison of model Bt5 and plant outputs.
High load feedwater variations (D102A.DAT).

87.06.05 - 09:40:51 nr: 6
hcopy

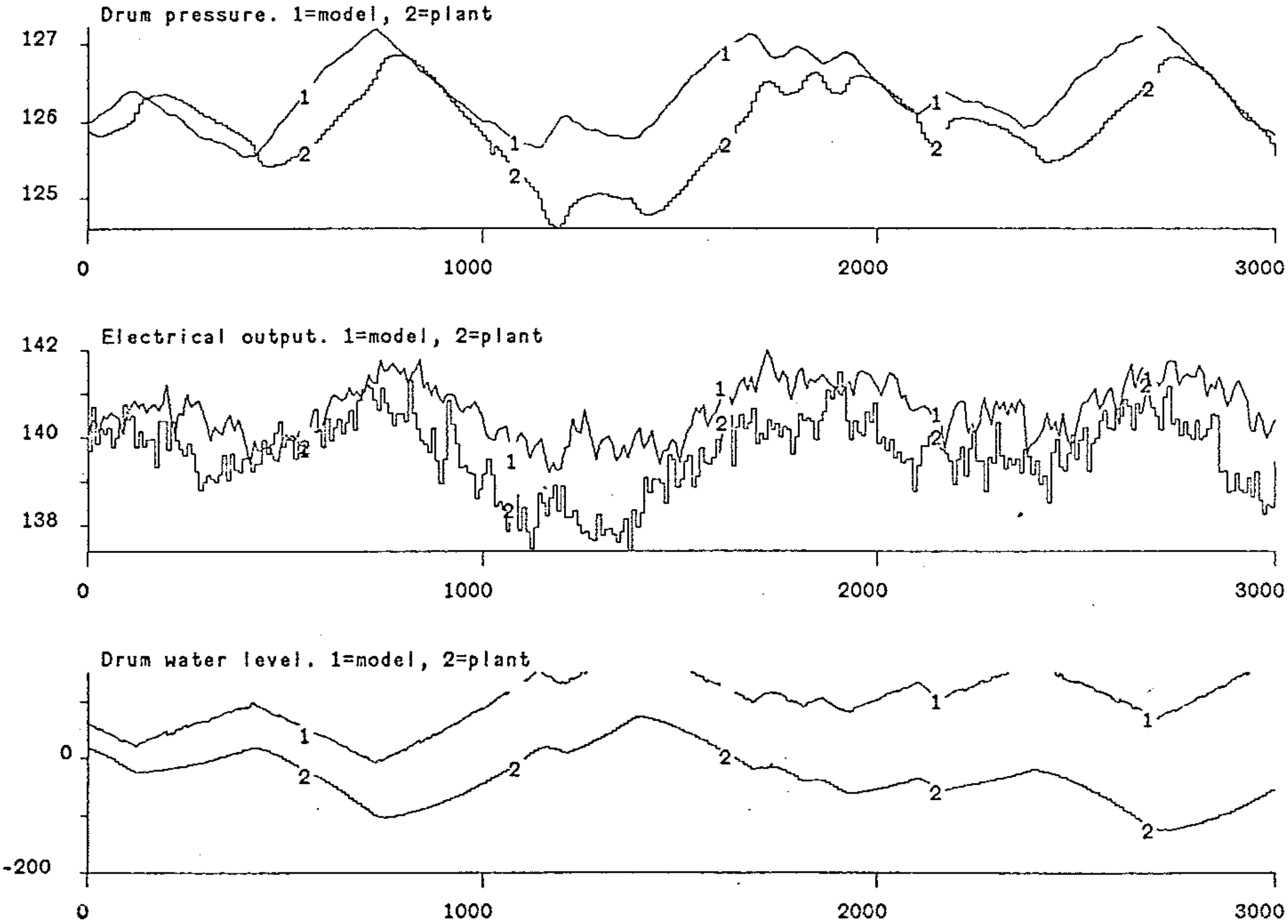


Figure 36. - Comparison of model Bt5 and plant outputs.
High load control valve variations (D105A.DAT).

87.06.05 - 14:50:09 nr: 3
hcopy

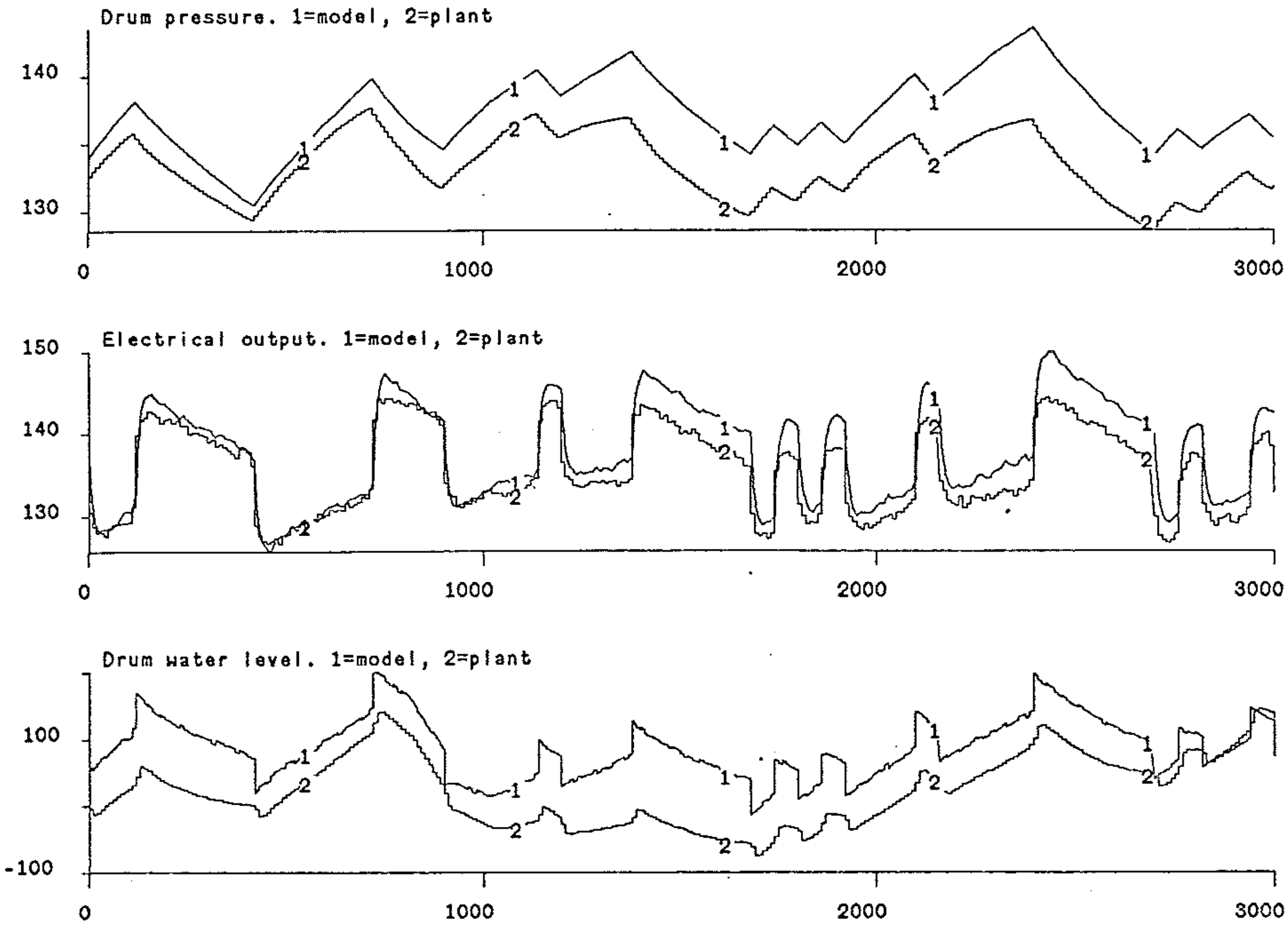


Figure 37. - Comparison of model Bta and plant outputs.
Low load fuel variations (D107A.DAT).

87.06.19 - 10:57:47 nr: 3
hcopy

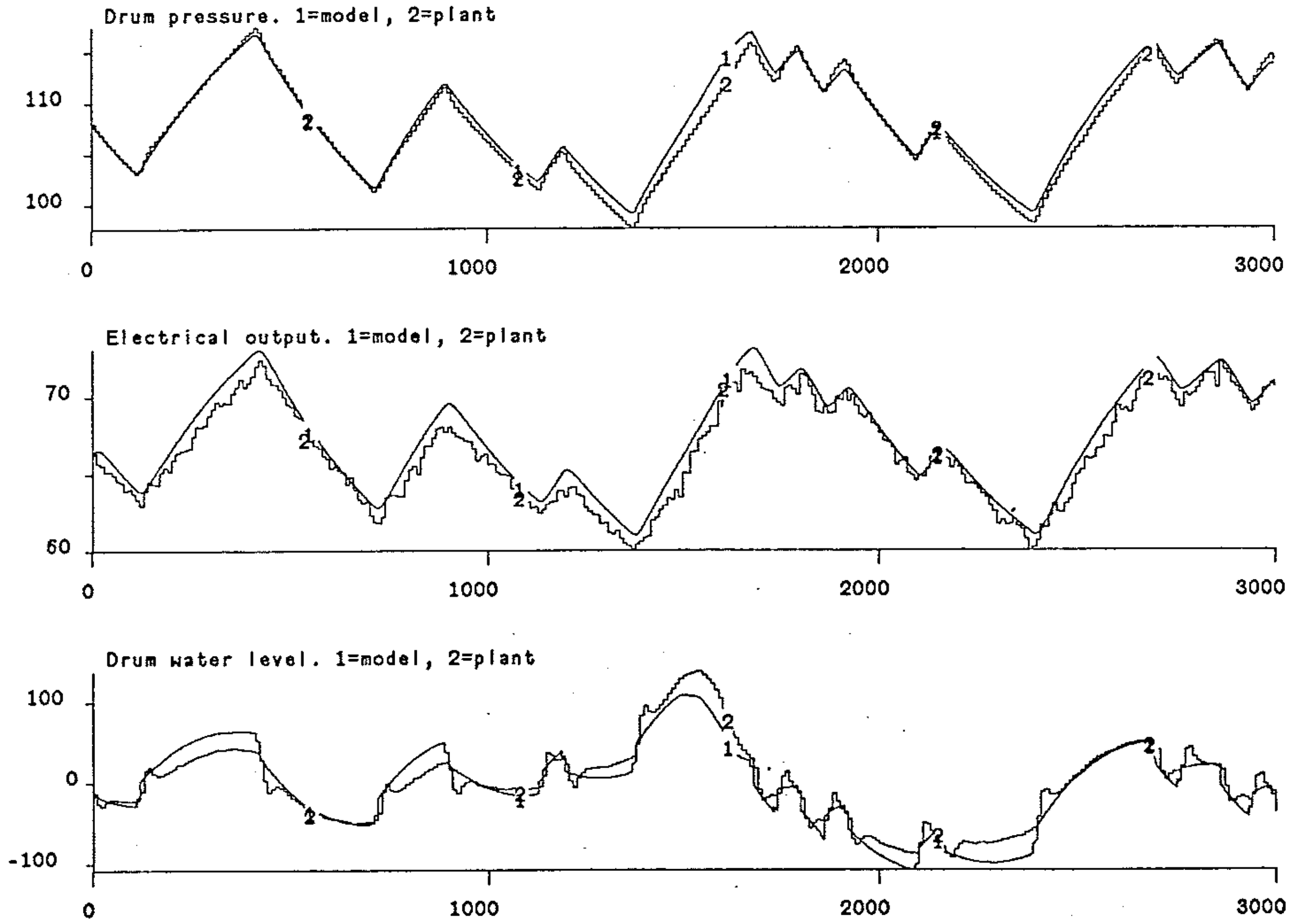


Figure 38. - Comparison of model Bta and plant outputs.
Low load feedwater variations (D108A.DAT).

87.06.19 - 11:02:00 nr: 4
hcopy

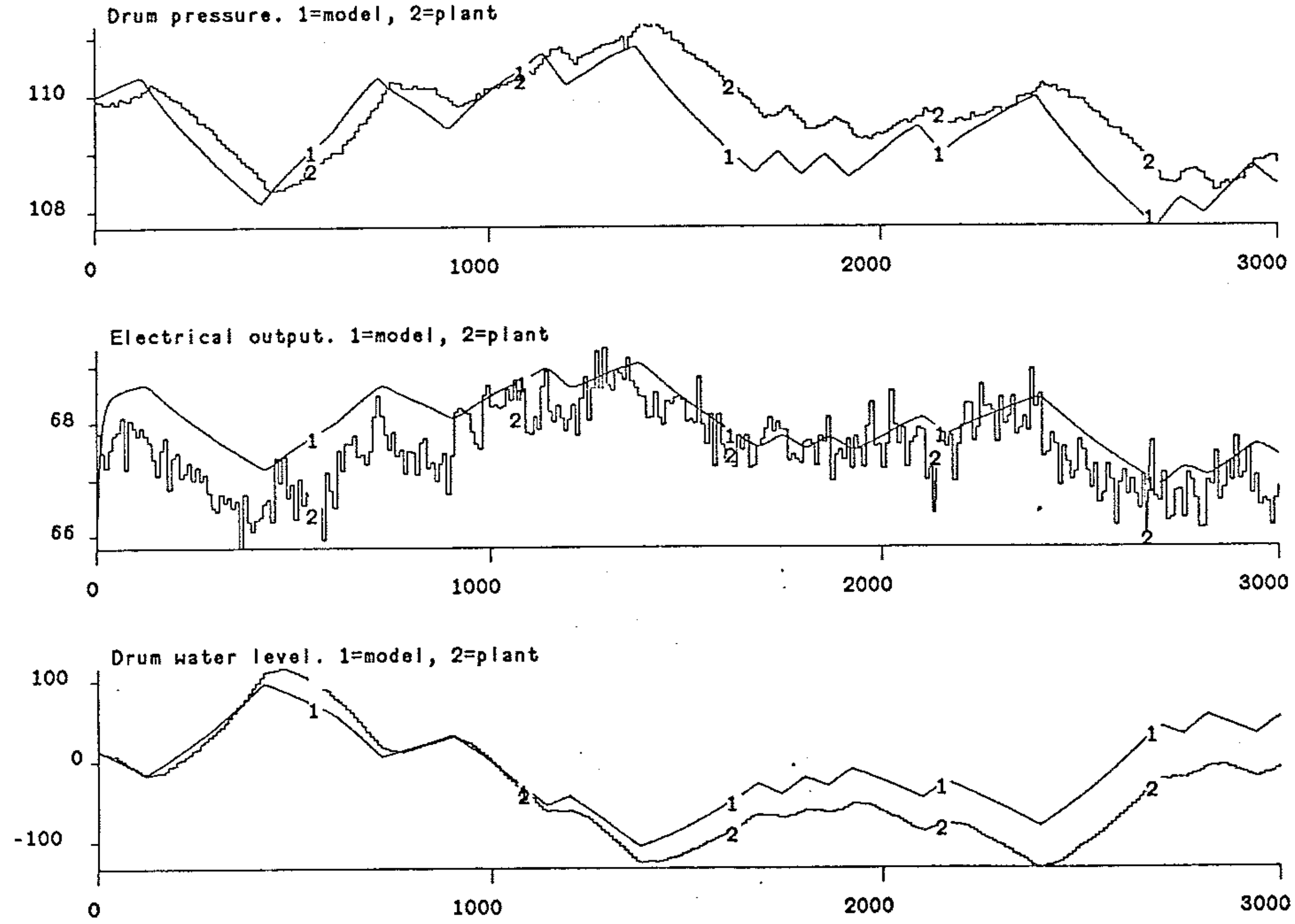


Figure 39. - Comparison of model Bta and plant outputs.
Low load control valve variations (D111A.DAT).

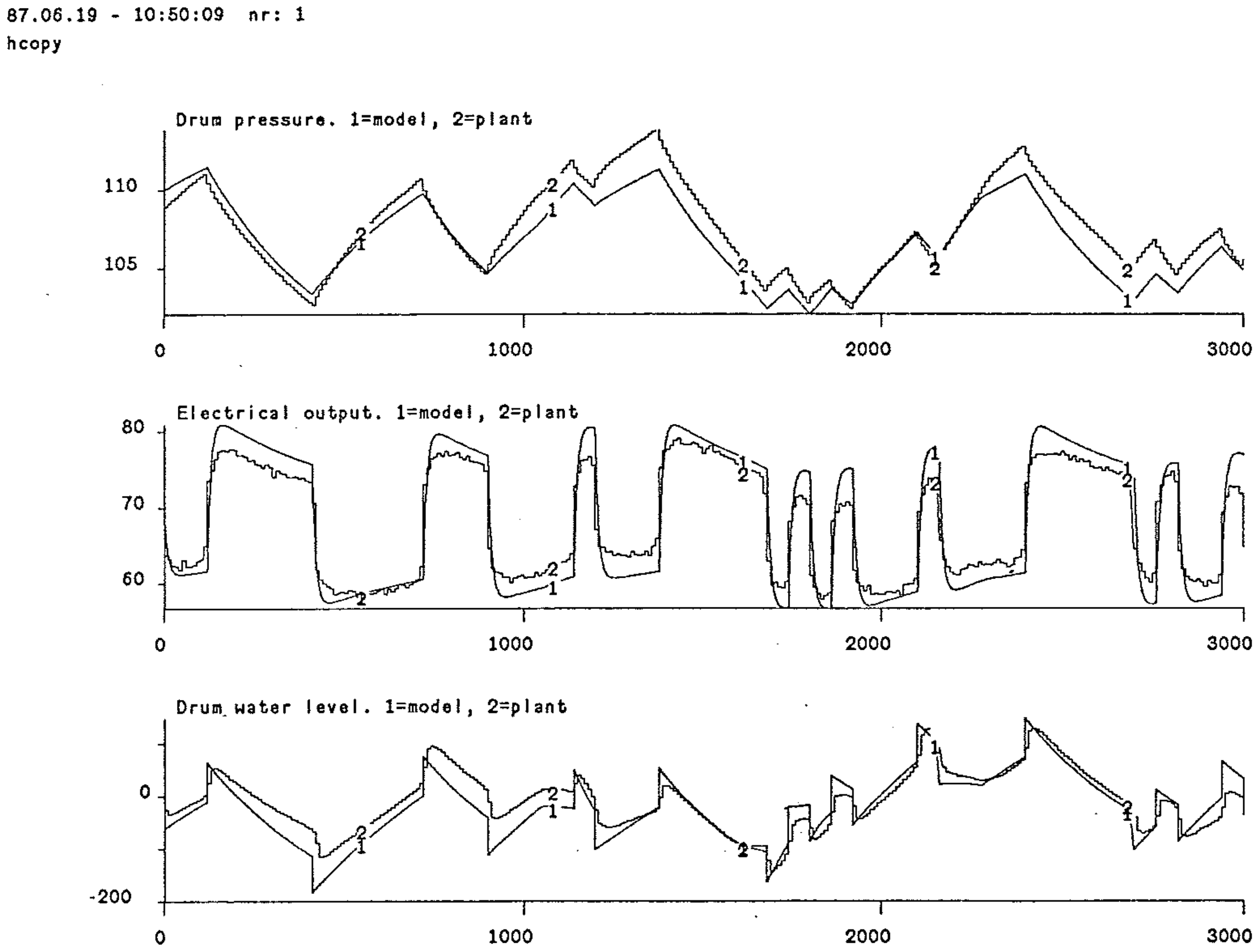


Figure 40. - Comparison of model Bta and plant outputs.
High load fuel variations (D201A.DAT).

87.06.19 - 11:06:05 nr: 5
hcopy

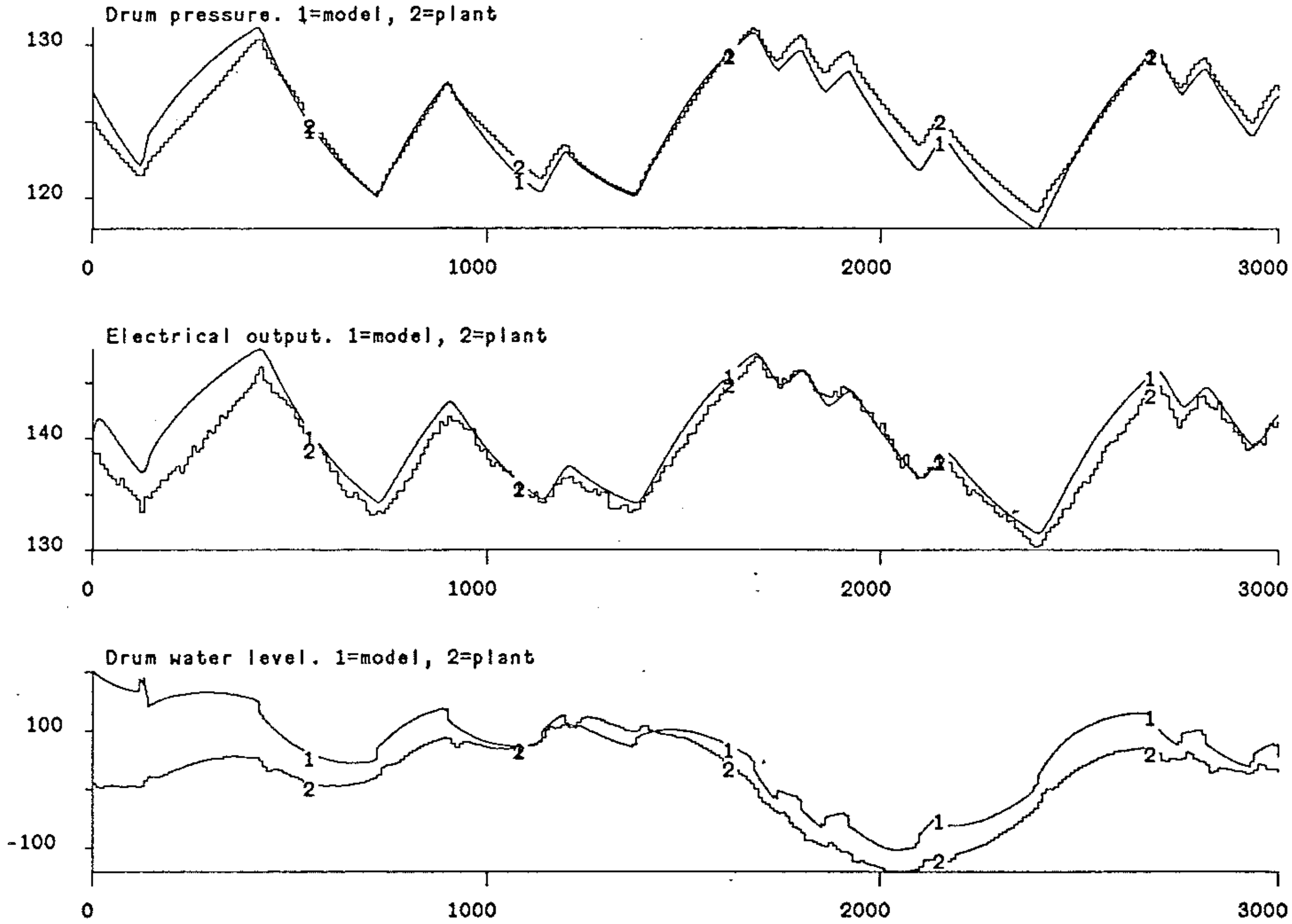


Figure 41. - Comparison of model Bta and plant outputs.
High load feedwater variations (D102A.DAT).

87.06.19 - 11:13:56 nr: 6
hcopy

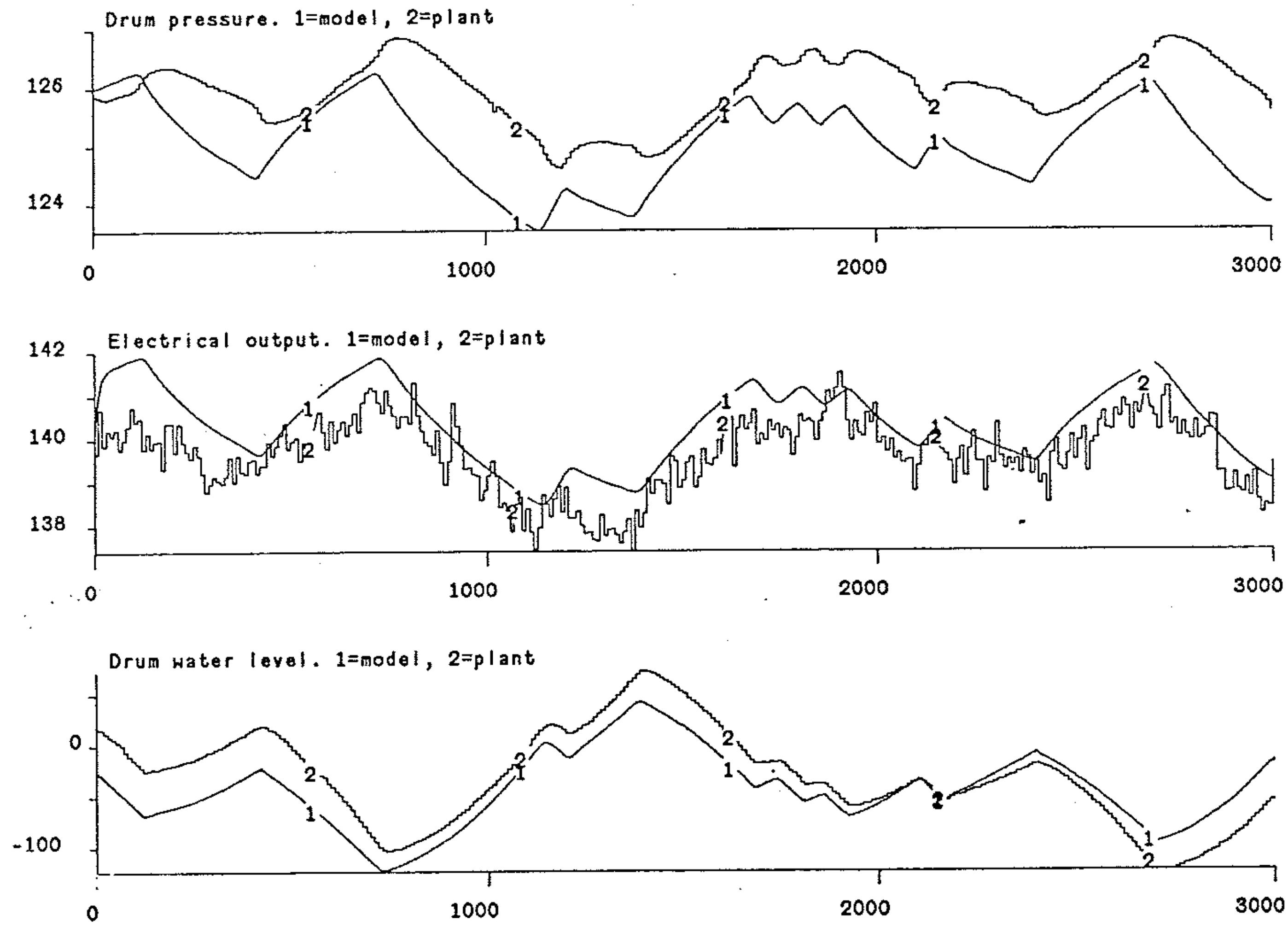
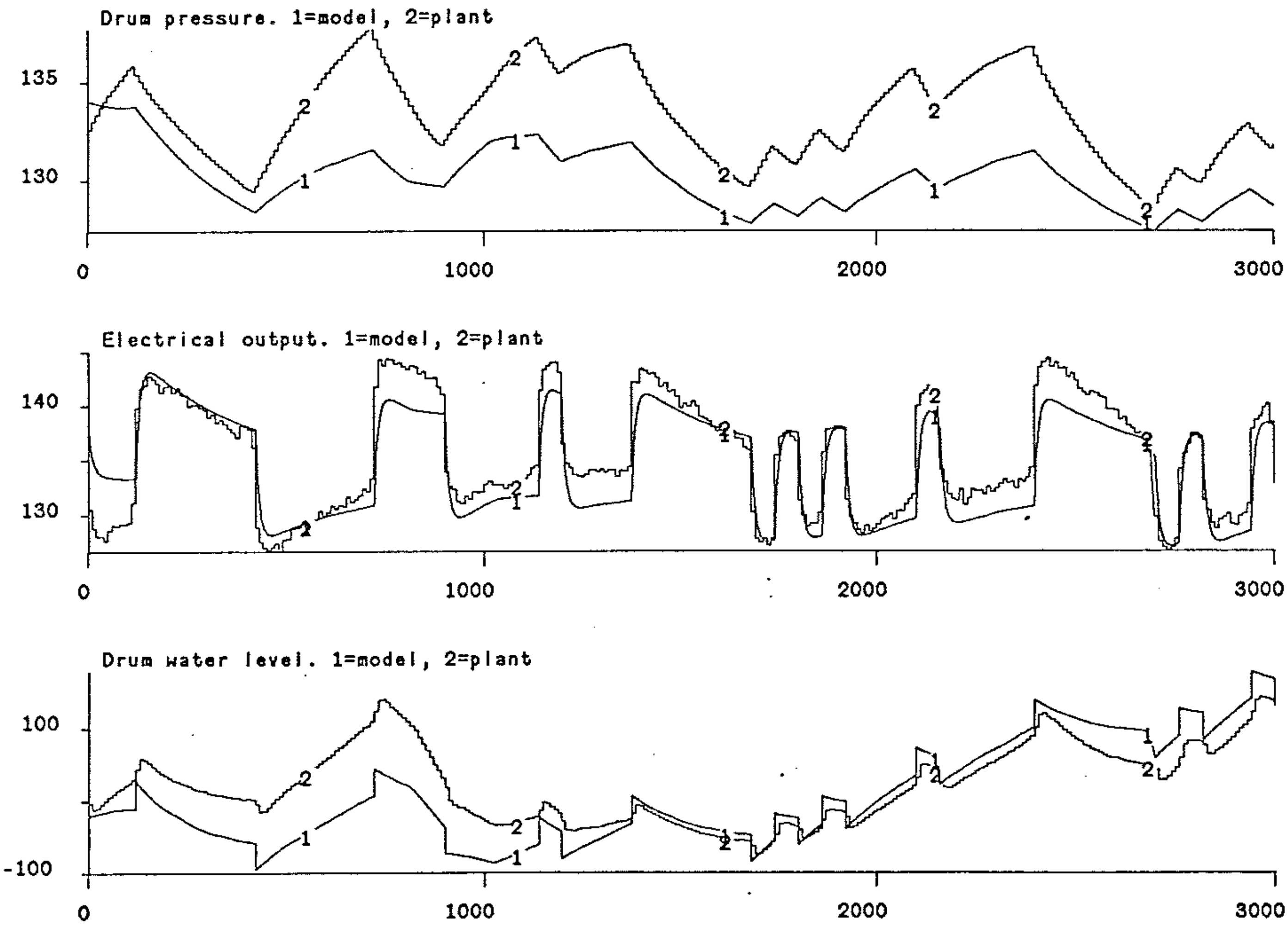


Figure 42. - Comparison of model Bta and plant outputs.
High load control valve variations (D105A.DAT).

87.06.19 - 11:21:56 nr: 7
hcopy



Appendix E. - Co-ordinated controller programs and responses.

```
macro ccm

"Macro to place co-ordinated controller around bt2 model, and
"plot out the results.

syst bt2 ppi wpi mpi nlc3c
store mwref[ppi] po[bt2] pdref[ppi] p[bt2] ldref[wpi] xw[bt2]
axes h 0 100 v 50 100
plot mwref[ppi] po
simu 0 100/b1
split 3 1
ashow mwref po
ashow pdref p
ashow ldref xw
end
```

```
CONTINUOUS SYSTEM PPI


"          MAIN PRESSURE CONTROLLER

"PROP. + INT. CONTROLLER
"WITH:-
"  1. INTEGRAL REMOVAL WHEN CONTROL SATURATES TO STOP
"     RESET WIND-UP (SEE BELL 1970)
"  2. FEEDFORWARD TERM FROM DESIRED MEGAWATTS (CO-ORDINATED)
"  3. Rate limiting on control output

"WRITTEN BY R.D.BELL 8TH DEC.1978 updated 28/6/87

"INPUTS:-
"   PDREF    SET POINT FOR STEAM PRESSURE
"   PD       ACTUAL STEAM PRESSURE
"   MWREF    SET POINT FOR MEGAWATTS

"OUTPUTS:-
"   UF       FUEL CONTROL

INPUT PDREF PD MWREF
OUTPUT UF
STATE I x1 x2
DER DI dx1 dx2

OUTPUT
E=PDREF-PD
P=KP*E
U=P+I+KF*MWREF
UD=(U-x1)/tc1
UDUB=if UD>UDH then UDH else UD
UDB=if UDUB<UDL then UDL else UDUB
UFi=x2

TIB=IF UFi>UFUB OR UFi<UFLB THEN 1E10 ELSE TI
UFi1=if UFi>UFUB then UFUB else UFi
UF=if UFi1<UFLB then UFLB else UFi1

DYNAMICS
DI=E/TIB
DX1=UD
DX2=UDB
```

```
"CONSTANTS
KP:0.5
TI:20
KF:0.003713
tc1:1

"CONTROL BOUNDS
UFUB:1
UFLB:0

"Control rate bounds
UDH:0.007
UDL:-0.007

"INITIAL CONDITIONS
I:0.11229
X1:0.360896
X2:0.360896

END

---------------------------------------------------------------

CONTINUOUS SYSTEM MPI


"             MEGAWATT COTROLLER OR TURBINE GOVERNOR


"PROP.+INT. CONTROLLER
"WITH:-
"   1. INTEGRAL REMOVAL IF CONTROL SATURATES TO STOP
"      RESET WIND-UP
"  2. RATE LIMITING ON CONTROL OUTPUT


"WRITTEN BY R.D.BELL 8TH DEC. 1978


"INPUTS:-
"   MWREF   SET POINT FOR MEGAWATTS
"   MW      ACTUAL MEGAWATTS

"OUTPUTS:-
"   UCV     THROTTLE VALVE CONTROL

INPUT MWREF MW
OUTPUT UCV
STATE I X1 X2
DER DI DX1 DX2

OUTPUT
E=MWREF-MW
P=KP*E
U=P+I
UD=(U-X1)/TC1
UDUB=IF UD>UDH THEN UDH ELSE UD
UDB=IF UDUB<UDL THEN UDL ELSE UDUB
UCVi=X2

TIB=IF UCVi>UCVUB OR UCVi<UCVLB THEN 1E10 ELSE TI
UCVi1=if UCVi>UCVUB then UCVUB else UCVi
UCV=if UCVi1<UCVLB then UCVLB else UCVi1
```

```
DYNAMICS
DI=E/TIB
DX1=UD
DX2=UDB

"CONSTANTS:-
KP:0.05
TI:100
TC1:1

"RATE BOUNDS
UDH:0.2
UDL:-2.0

"INITIAL CONDITIONS
I:0.60338
X1:0.60338
X2:0.60338

"CONTROL BOUNDS
UCVUB:2
UCVLB:0

END
```

```
CONTINUOUS SYSTEM WPI

"          DRUM WATER LEVEL CONTROLLER


"PROP.+INT. CONTROLLER
"WITH:-
" 1.INTEGRAL REMOVAL IF CONTROL SATURATES TO STOP
"   RESET WIND-UP.
" 2.FEEDFORWARD TERM FROM DESIRED MEGAWATTS CO-ORDINATED
" 3.Rate limiting on control output

" WRITTEN BY R.D.BELL 8TH DEC.1978 and updated 28/6/87


"INPUTS:-
"   LDREF    SET POINT FOR DRUM WATER LEVEL
"   LD       ACTUAL DRUM WATER LEVEL
"   MWREF    SET POINT FOR MEGAWATTS

"OUTPUTS:-
"   UFW      FEEDWATER CONTROL


INPUT LDREF LD MWREF
OUTPUT UFW
STATE I x1 x2
DER DI dx1 dx2

OUTPUT
E=LDREF-LD
P=KP*E
U=P+I+KFW*MWREF
UD=(U-X1)/tc1
UDUB=if UD>UDH then UDH else UD
UDB=if UDUB<UDL then UDL else UDUB
UFWi=X2
```

```
TIB=IF UFWi>UFWUB OR UFWi<UFWLB THEN 1E10 ELSE TI
UFWi1=if UFWi>UFWUB then UFWUB else UFWi
UFW=if UFWi1<UFWLB then UFWLB else UFWi1

DYNAMICS
DI=E/TIB
DX1=UD
DX2=UDB

"CONSTANTS
KP:0.1
TI:500
KFW:0.005825
tc1:1

"CONTROL BOUNDS
UFWUB:1
UFWLB:0

"Control rate bounds
UDH:0.05
UDL:-0.05

"INITIAL CONDITIONS
I:0.046359
X1:0.437007
X2:0.437007

END
-----------------------------------------------------------------

CONNECTING SYSTEM NLC3C

TIME T

PDREF[PPI]=IF T<TS THEN PREFI ELSE PREFF
PD[PPI]=P[bt2]
U1[bt2]=UF[PPI]
MWREF[PPI]=IF T<TS THEN MREFI ELSE MREFF
MWREF[WPI]=IF T<TS THEN MREFI ELSE MREFF
LDREF[WPI]=IF T<TS THEN LREFI ELSE LREFF
LD[WPI]=XW[bt2]
U3[bt2]=UFW[WPI]
MWREF[MPI]=IF T<TS THEN MREFI ELSE MREFF
MW[MPI]=PO[bt2]
U2[bt2]=UCV[MPI]

pdp[bt2]=130
xwp[bt2]=0.0
pop[bt2]=67

TS:10.0
PREFI:130
PREFF:130
LREFI:0.0
MREFF:77
MREFI:67
LREFF:0.0
END
```

Figure 1. - Responses from model Bt2 with co-ordinated controller. Large MW step, no rate limiting on actuators.

87.06.28 - 14:31:36 nr: 1
hcopy "83MW step co-ordinated controller no rate limiting on actuators"

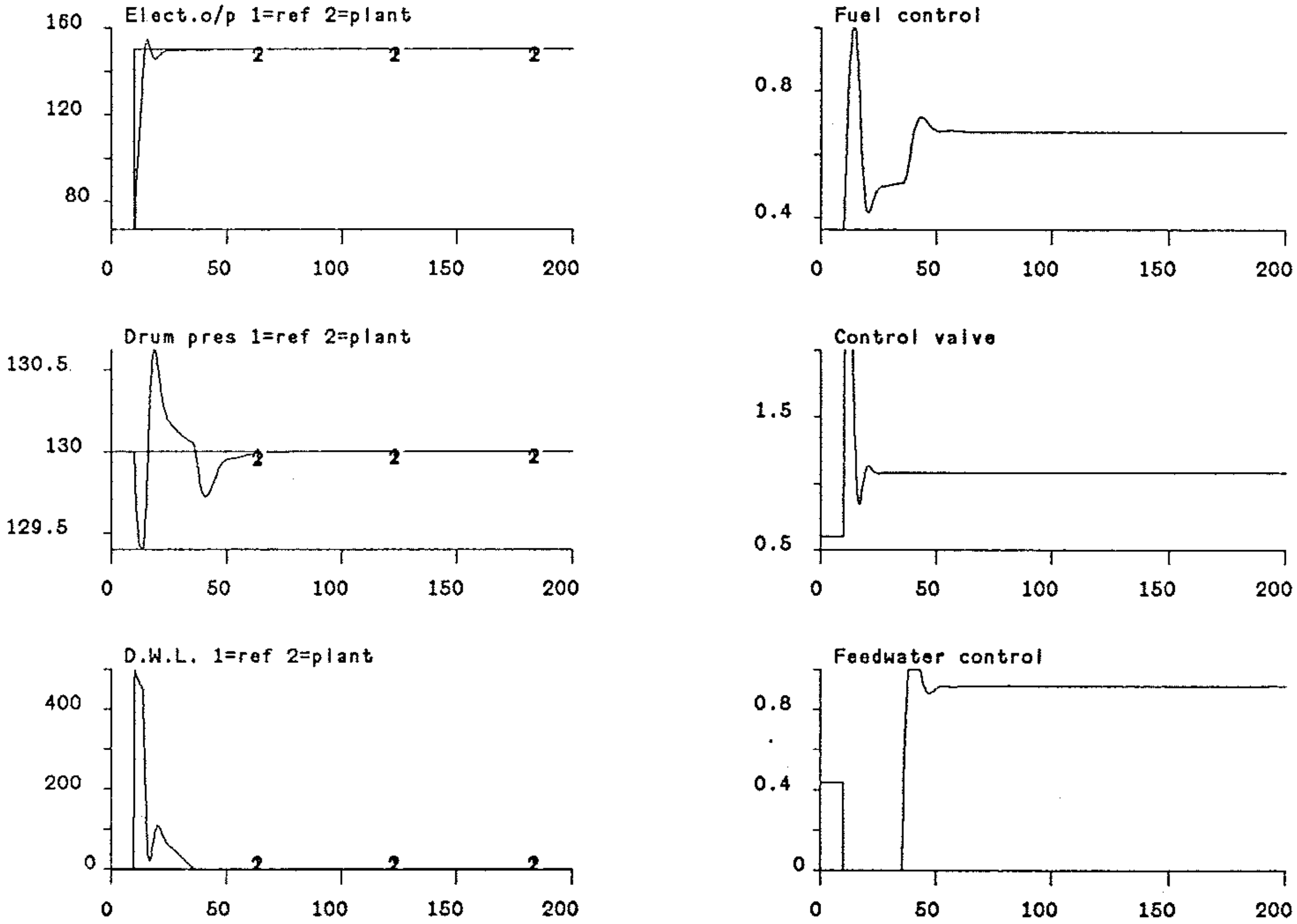


Figure 2. - Responses from model Bt2 with co-ordinated controller.
Large MW step, rate limiting on actuators.

87.06.28 - 12:00:40 nr: 4
hcopy "83 MW step co-ordinated controller"

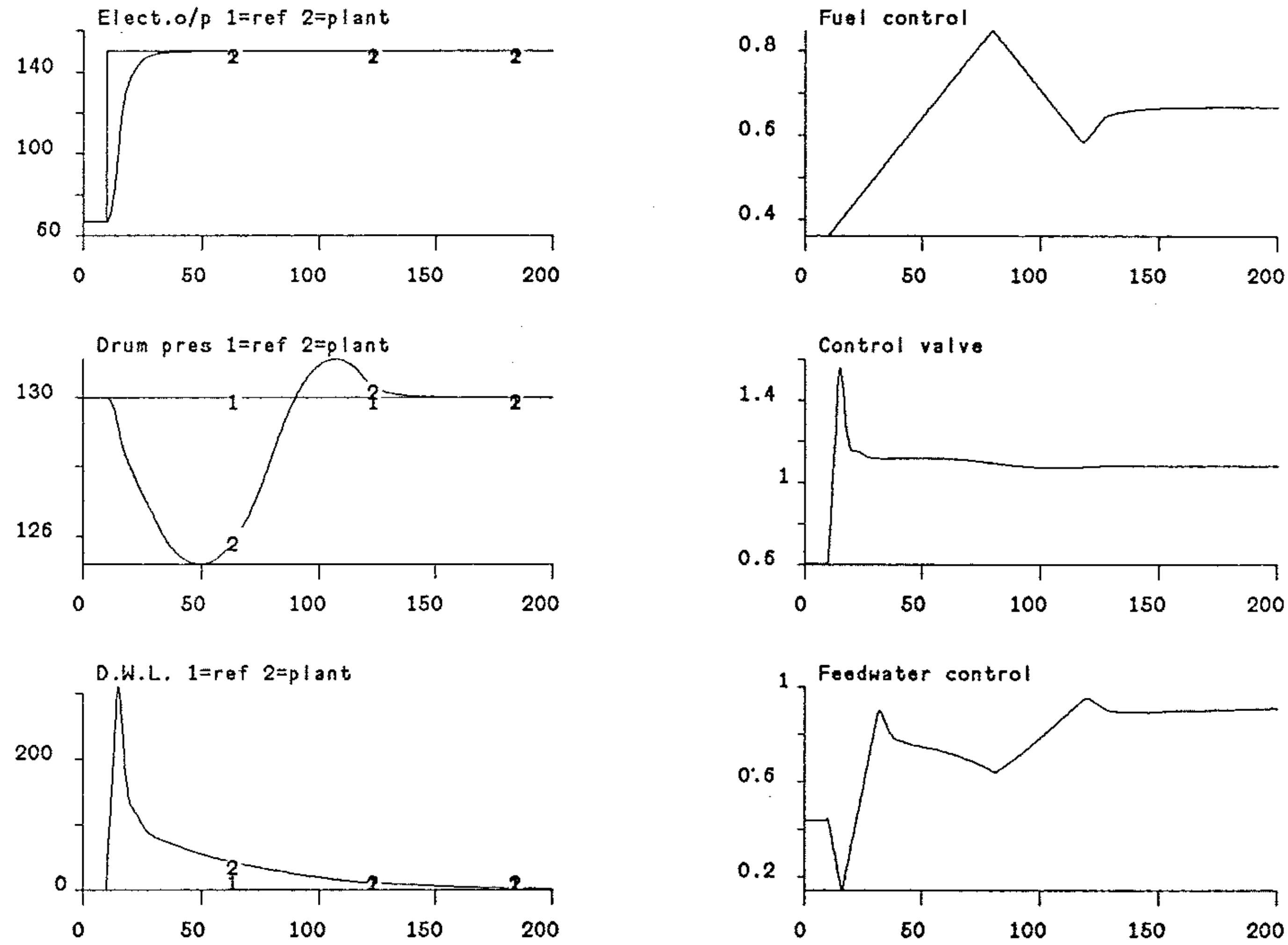
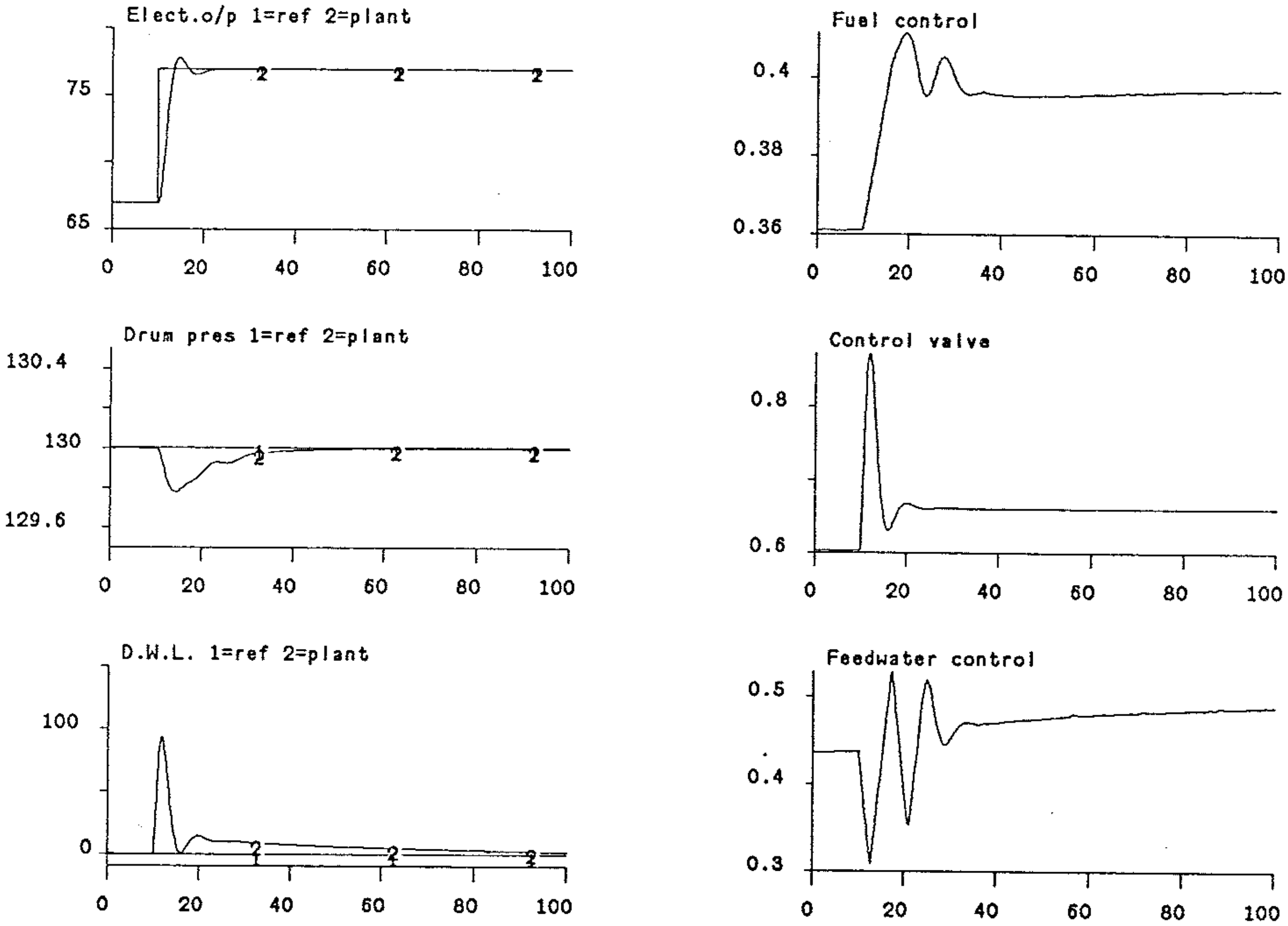


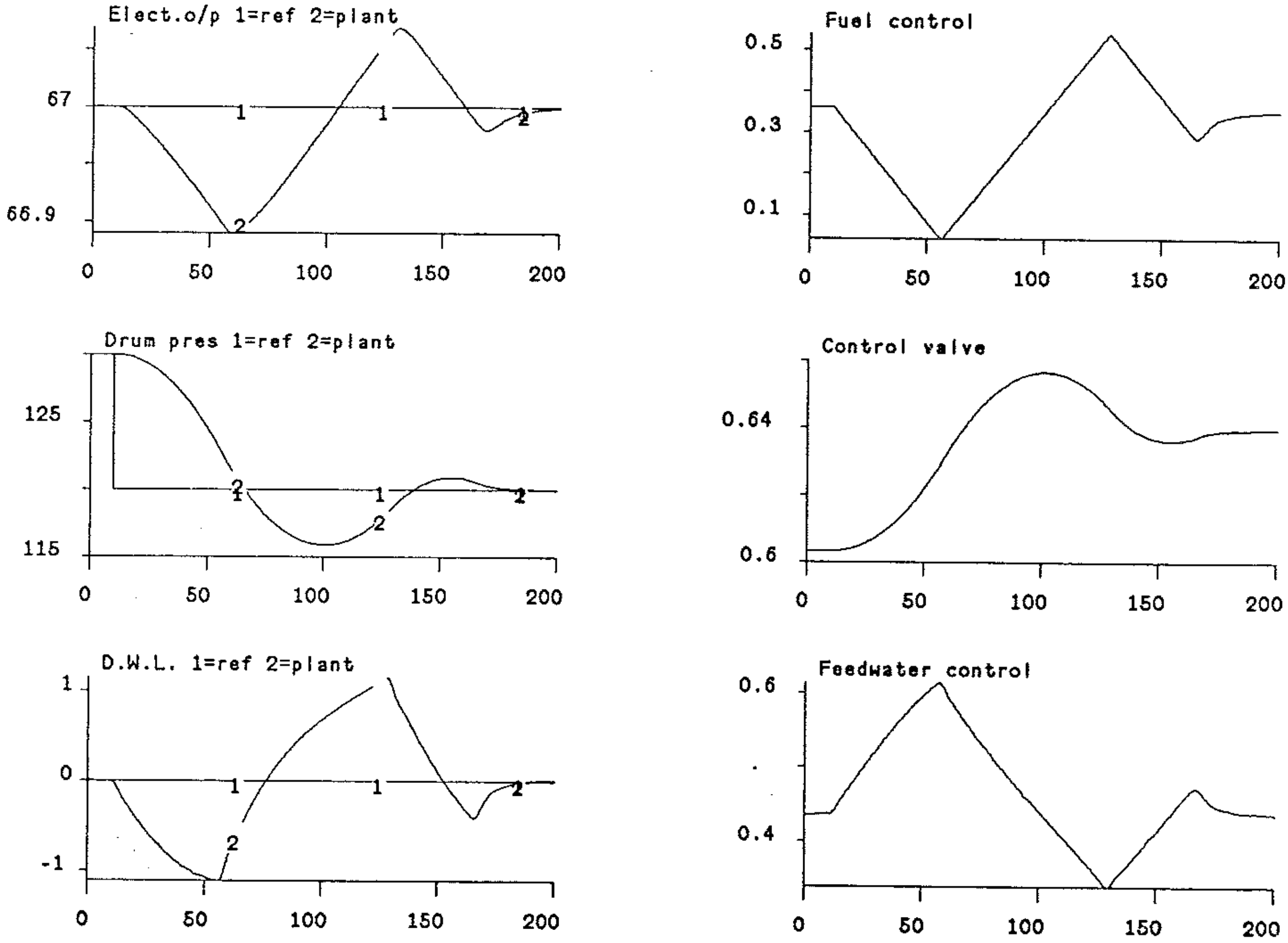
Figure 3. - Responses from model Bt2 with co-ordinated controller.
Small MW step, rate limiting on actuators.



87.06.28 - 11:57:00 nr: 3
hcopy "10 MW step Co-ordinated contoller"

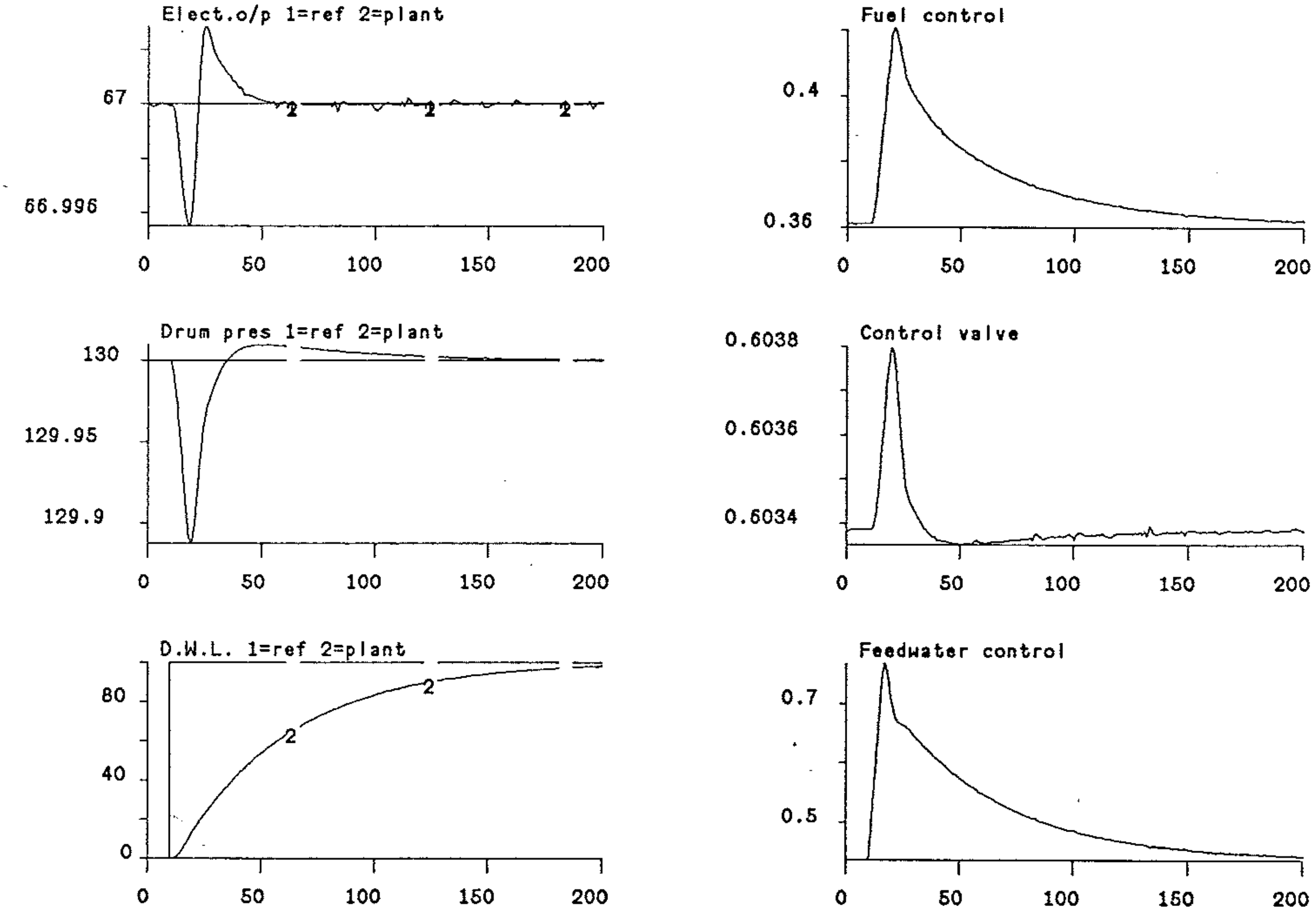
Figure 4. - Responses from model Bt2 with co-ordinated controller.
Drum pressure set-point step, rate limiting on actuators.

87.06.28 - 12:05:42 nr: 5
hcopy "d.p step co-ordinated controller"



<u>Figure 5.</u> - Responses from model Bt2 with co-ordinated controller.
Drum water level set-point step, rate limiting on actuators.

```
87.06.28 - 12:07:58  nr: 6
hcopy "D.W.L. step co-ordinated controller"
```



Appendix F. - IBM floppy disk details.

```
 Volume in drive A has no label
 Directory of  A:\

BTMODELS     <DIR>       6-11-87   8:17
BDATA        <DIR>       6-11-87   8:17
READ-ME.TEX             11-11-87  12:00
        2 File(s)    506368 bytes free

 Volume in drive A has no label
 Directory of  A:\BTMODELS

.                ..               F1BD5BTA T       F1BD6BT4 T       F1BD2BT6 T
F1BD6BT5 T       F1BD1BT1 T       F1BD1BT3 T       F1BD1BT4 T       F1BD1BT5 T
F1BD1BT6 T       F1BD1BT7 T       F1BD1BT8 T       F1BD1BTA T       F1BD2BT1 T
F1BD2BT2 T       F1BD2BT3 T       F1BD2BT4 T       F1BD2BT5 T       F1BD2BT7 T
F1BD2BT8 T       F1BD2BTA T       F1BD3BT1 T       F1BD3BT2 T       F1BD3BT3 T
F1BD3BT4 T       F1BD3BT5 T       F1BD3BT6 T       F1BD3BT7 T       F1BD3BT8 T
F1BD3BTA T       F1BD4BT1 T       F1BD4BT2 T       F1BD4BT3 T       F1BD4BT4 T
F1BD4BT5 T       F1BD4BT6 T       F1BD4BT7 T       F1BD4BT8 T       F1BD4BTA T
F1BD5BT1 T       F1BD5BT2 T       F1BD5BT3 T       F1BD5BT4 T       F1BD5BT5 T
F1BD5BT6 T       F1BD5BT7 T       F1BD5BT8 T       F1BD6BT1 T       F1BD1BT2 T
F1BD6BT2 T       F1BD6BT3 T       F1BD6BT6 T       F1BD6BT7 T       F1BD6BT8 T
F1BD6BTA T       F2CSLBT1 T       F2CSLBT2 T       F2CSLBT3 T       F2CSLBT4 T
F2CSLBT5 T       F2CSLBT6 T       F2CSLBT7 T       F2CSLBT8 T       F2CSLBTA T
F2FSLBT1 T       F2FSLBT2 T       F2FSLBT3 T       F2FSLBT4 T       F2FSLBT5 T
F2FSLBT6 T       F2FSLBT7 T       F2FSLBT8 T       F2FSLBTA T       F2SLLBT1 T
F2SLLBT2 T       F2SLLBT3 T       F2SLLBT4 T       F2SLLBT5 T       F2SLLBT6 T
F2SLLBT7 T       F2SLLBT8 T       F2SLLBTA T       F2WSLBT1 T       F2WSLBT2 T
F2WSLBT3 T       F2WSLBT4 T       F2WSLBT5 T       F2WSLBT6 T       F2WSLBT7 T
F2WSLBT8 T       F2WSLBTA T       C1BT1    T       C1BT2    T       C1BT3    T
C1BT4    T       BT1      T       C1BT5    T       C1BT6    T       C1BT7    T
C1BT8    T       C1BTA    T       C2BT1    T       C2BT2    T       C2BT3    T
C2BT4    T       C2BT5    T       C2BT6    T       C2BT7    T       C2BT8    T
C2BTA    T       C2LBTM1  T       C2LBTM2  T       LBT2     T       BD107A   D
BD108A   D       BD111A   D       BT2      T       BT3      T       BT4      T
LBT3     T       BT5      T       BT6      T       MPI      T       BT7      T
BT8      T       BTA      T       NLC3C    T       BD102A   D       BD105A   D
PPI      T       WPI      T       BD201A   D       IFILE    T       CCM      T
B3       D       B1       D       DEMO     T       B2       D
      139 File(s)    506368 bytes free

 Volume in drive A has no label
 Directory of  A:\BDATA

.                ..               D102A    T       D105A    T       D107A    T
D108A    T       D111A    T       D201A    T
        8 File(s)    506368 bytes free
```

```
MACRO demo
"Generates a selection menu to simulate different boiler-turbine
"models for either step response or using plant data.
label start
write 'Select model (1,or 2,or 3 .....,or 8) or quit (9)'
write '  1 = Bt2 model'
write '  2 = Bt3 model'
write '  3 = Bt4 model'
write '  4 = Bt5 model'
write '  5 = Bt6 model'
write '  6 = Bt7 model'
write '  7 = Bt8 model'
write '  8 = Bta model'
write '  9 = Quit'
write ' '
read ans1 INT
if ans1 EQ 9 goto finish
write ' '
write 'Select response'
write '   1 = Step responses'
write '   2 = Plant data'
write '   3 = Model select'
write ' '
read ans2 INT
if ans2 EQ 1 goto step
if ans2 EQ 2 goto plant
if ans2 EQ 3 goto start
label step
if ans1 EQ 1 goto MBt2
if ans1 EQ 2 goto MBt3
if ans1 EQ 3 goto MBt4
if ans1 EQ 4 goto MBt5
if ans1 EQ 5 goto MBt6
if ans1 EQ 6 goto MBt7
if ans1 EQ 7 goto MBt8
if ans1 EQ 8 goto MBta
goto start
label MBt2
f2sllbt2
goto finish
label MBt3
f2sllbt3
goto finish
label MBt4
f2sllbt4
goto finish
label MBt5
f2sllbt5
goto finish
label MBt6
f2sllbt6
goto finish
label MBt7
f2sllbt7
goto finish
label MBt8
f2sllbt8
goto finish
label MBta
f2sllbta
goto finish
label plant
```

```
write 'Select plant data ( 1 to 6)'
write '   1 = d107a Low load fuel change'
write '   2 = d108a Low load feedwater change'
write '   3 = d111a Low load control valve change'
write '   4 = d201a High load fuel change'
write '   5 = d102a High load feedwater change'
write '   6 = d105a High load control valve change'
write ' '
read ans4 INT
if ans4 EQ 1 goto d1
if ans4 EQ 2 goto d2
if ans4 EQ 3 goto d3
if ans4 EQ 4 goto d4
if ans4 EQ 5 goto d5
if ans4 EQ 6 goto d6
label d1
if ans1 EQ 1 goto d1bt2
if ans1 EQ 2 goto d1bt3
if ans1 EQ 3 goto d1bt4
if ans1 EQ 4 goto d1bt5
if ans1 EQ 5 goto d1bt6
if ans1 EQ 6 goto d1bt7
if ans1 EQ 7 goto d1bt8
if ans1 EQ 8 goto d1bta
label d1bt2
f1bd1bt2
goto finish
label d1bt3
f1bd1bt3
goto finish
label d1bt4
f1bd1bt4
goto finish
label d1bt5
f1bd1bt5
goto finish
label d1bt6
f1bd1bt6
goto finish
label d1bt7
f1bd1bt7
goto finish
label d1bt8
f1bd1bt8
goto finish
label d1bta
f1bd1bta
goto finish
label d2
if ans1 EQ 1 goto d2bt2
if ans1 EQ 2 goto d2bt3
if ans1 EQ 3 goto d2bt4
if ans1 EQ 4 goto d2bt5
if ans1 EQ 5 goto d2bt6
if ans1 EQ 6 goto d2bt7
if ans1 EQ 7 goto d2bt8
if ans1 EQ 8 goto d2bta
label d2bt2
f1bd2bt2
goto finish
label d2bt3
f1bd2bt3
```

```
goto finish
label d2bt4
f1bd2bt4
goto finish
label d2bt5
f1bd2bt5
goto finish
label d2bt6
f1bd2bt6
goto finish
label d2bt7
f1bd2bt7
goto finish
label d2bt8
f1bd2bt8
goto finish
label d2bta
f1bd2bta
goto finish
label d3
if ans1 EQ 1 goto d3bt2
if ans1 EQ 2 goto d3bt3
if ans1 EQ 3 goto d3bt4
if ans1 EQ 4 goto d3bt5
if ans1 EQ 5 goto d3bt6
if ans1 EQ 6 goto d3bt7
if ans1 EQ 7 goto d3bt8
if ans1 EQ 8 goto d3bta
label d3bt2
f1bd3bt2
goto finish
label d3bt3
f1bd3bt3
goto finish
label d3bt4
f1bd3bt4
goto finish
label d3bt5
f1bd3bt5
goto finish
label d3bt6
f1bd3bt6
goto finish
label d3bt7
f1bd3bt7
goto finish
label d3bt8
f1bd3bt8
goto finish
label d3bta
f1bd3bta
goto finish
label d4
if ans1 EQ 1 goto d4bt2
if ans1 EQ 2 goto d4bt3
if ans1 EQ 3 goto d4bt4
if ans1 EQ 4 goto d4bt5
if ans1 EQ 5 goto d4bt6
if ans1 EQ 6 goto d4bt7
if ans1 EQ 7 goto d4bt8
if ans1 EQ 8 goto d4bta
label d4bt2
f1bd4bt2
```

```
goto finish
label d4bt3
f1bd4bt3
goto finish
label d4bt4
f1bd4bt4
goto finish
label d4bt5
f1bd4bt5
goto finish
label d4bt6
f1bd4bt6
goto finish
label d4bt7
f1bd4bt7
goto finish
label d4bt8
f1bd4bt8
goto finish
label d4bta
f1bd4bta
goto finish
label d5
if ans1 EQ 1 goto d5bt2
if ans1 EQ 2 goto d5bt3
if ans1 EQ 3 goto d5bt4
if ans1 EQ 4 goto d5bt5
if ans1 EQ 5 goto d5bt6
if ans1 EQ 6 goto d5bt7
if ans1 EQ 7 goto d5bt8
if ans1 EQ 8 goto d5bta
label d5bt2
f1bd5bt2
goto finish
label d5bt3
f1bd5bt3
goto finish
label d5bt4
f1bd5bt4
goto finish
label d5bt5
f1bd5bt5
goto finish
label d5bt6
f1bd5bt6
goto finish
label d5bt7
f1bd5bt7
goto finish
label d5bt8
f1bd5bt8
goto finish
label d5bta
f1bd5bta
goto finish
label d6
if ans1 EQ 1 goto d6bt2
if ans1 EQ 2 goto d6bt3
if ans1 EQ 3 goto d6bt4
if ans1 EQ 4 goto d6bt5
if ans1 EQ 5 goto d6bt6
if ans1 EQ 6 goto d6bt7
if ans1 EQ 7 goto d6bt8
if ans1 EQ 8 goto d6bta
```

```
label d6bt2
flbd6bt2
goto finish
label d6bt3
flbd6bt3
goto finish
label d6bt4
flbd6bt4
goto finish
label d6bt5
flbd6bt5
goto finish
label d6bt6
flbd6bt6
goto finish
label d6bt7
flbd6bt7
goto finish
label d6bt8
flbd6bt8
goto finish
label d6bta
flbd6bta
goto finish
label finish
write 'Exit demo (yes no)'
read ans3 YESNO
split 1 1
if ans3 EQ no goto start

END
```

The PC version of Simnon uses a different method to play data from a plant to a model. This difference requires a change in the figure macros for plant data (see pages B31 to B33), and the inclusion of a discrete system called ifile. Only figure macro f1bd1bt1 is given below to highlight the changes required.

```
macro f1bd1bt1
"Generates fig comparing model and plant data.
" Uses plant data d107a low load fuel change.
" Uses bt1 model i.e. 2nd order Astrom/Bell model without dwl.

syst bt1 ifile c2bt1
par dt[ifile]:10.0
store p pdp po pop
split 1 1
axes h 0 3000 v 90 120
plot p pdp
simu 0 3000 /b1/bd107a  "File containing data included here.
split 2 1
ashow p pdp -mark/b1
text 'Drum pressure. 1=model, 2=plant'
ashow po pop -mark/b1
text 'Electrical output. 1=model, 2=plant'

end
```

```
discrete system ifile
time t
tsamp ts
output c2 c3 c4 c8 c9 c10 c11 c13

c2=rfile(2,t)
c3=rfile(3,t)
c4=rfile(4,t)
c8=rfile(8,t)
c9=rfile(9,t)
c10=rfile(10,t)
c11=rfile(11,t)
c13=rfile(13,t)
ts=if timecol<0 then rfile(timecol,t) else t+dt

dt:5
timecol:-1 "reads from rfile

end
```