REAL-TIME PROCESS SIMULATION SYSTEM FOR TRAINING PLANT OPERATORS

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Abstract: To improve the safety and productivity of continuous processes, it is becoming increasingly necessary to have simulators to train operators. This paper describes a real-time simulator developed for this purpose by Yokogawa in cooperation with the Tokyo Gas Company. This simulator — based on the YEWCOM computer -- not only trains operators, but also evaluates their proficiency.

1. Introduction

Objectives and Development Plan. The "STUDY" (Simulator for Training and Upgrading Plant Operators, Developed on YEWCOM) real-time process simulator system was developed for training plant operators to manage total control systems used in industries such as petroleum, gas, or electric power.

In recent years, planned training programs — with drills and guidance to improve plant operator skills -- have been advocated as a type of preventive maintenance. Most enterprises provide such courses in the form of lectures. However, training that relies exclusively on lectures is of limited use ; drills that can be repeated under the guidance of an instructor in an environment similar to that of the actual plant are needed.

The objectives in developing the "STUDY" simulator system were to meet these needs as follows:
(1) The system should realistically simulate the real plant control system.
(2) The system should evaluate the trainee operator's proficiency, and provide appropriate and easy-to-comprehend guidance.
(3) The system should be easy to maintain.
(4) The system should provide various training curriculums.

The basic core configuration of a STUDY system consists of Yokogawa's YEWCOM industrial minicomputer with real-time process model and automatic evaluation system, a DDC system (CENTUM or YEWPACK) connected to YEWCOM via a high speed bus, and a field control simulator. Using this system, an operator can control the simulator with a sense of controlling the actual plant. The instructor simply provides overall supervision and guides the direction of the training via a YEWCOM terminal. Figure 1 shows the basic hardware configuration of STUDY.

The following four models have been developed so far : Gas Calorific Value Control Plant, ORV (Open Rack Vaporizer), SMV (Submerged Vaporizer), and LPG vaporizer. The main graphic control panels for the Gas Calorific Value and SMV plants — are shown in Figs. 2 and 3 respectively. Figure 4 shows a trend graph of the ORV startup characteristics.

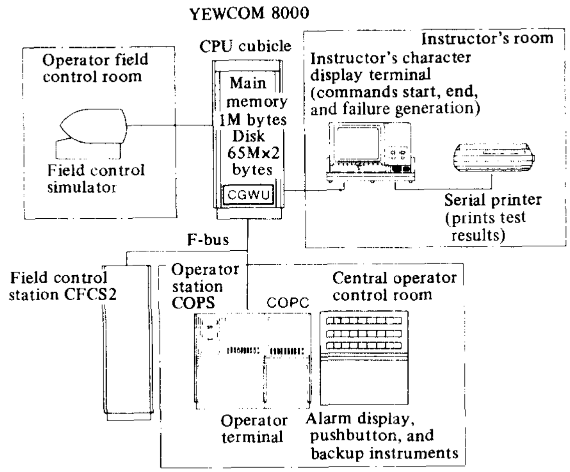


Figure 1 Basic hardware configuration of STUDY

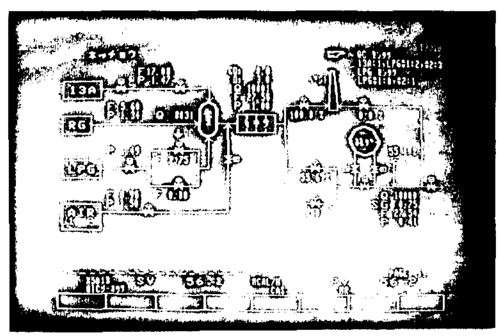


Figure 2 Main control graphic panel for gas calorie control plant

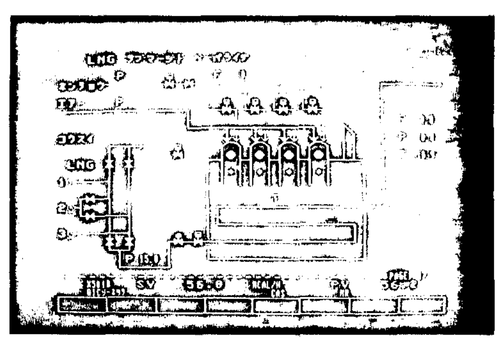


Figure 3 Main control graphic panel for submerged vaporizer (SMV)

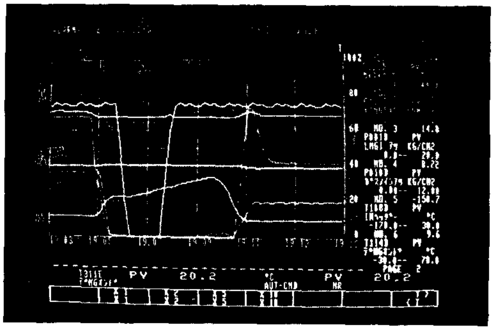


Figure 4 Start-up characteristics of open rack vaporizer (ORV)

Outline of Functions. Training functions of the STUDY system are described below :

(1) **Flexible training course management.**
The STUDY system manages training as courses and subcourses. There's one course for each plant model, and subcourses divide the operation of the plant into stages such as "Start-up", "Normal operation", "Shut down", etc. to make the training practical and easy-to-comprehend (see Fig. 5).

Training course
- 1. Real-time simulation model
- 2. Failure definition
- 3. Subcourse definition
  - Initial status (Status to be automatically determined at the start of training).
  - Evaluation specifications.

The training course is incorporated in the above form into the management data base.

Figure 5 Training course structure

(2) **Free-curriculum training.**
The course or subcourses can be instantaneously selected by simple commands entered from the YEWCOM terminal. Training curriculums to suit various user purposes can be freely developed and easily put into practical use.

(3) **Failure training.**
Twenty failures types can be freely defined. Seven of these -- e.g. instrument, final control element and plant failures -- are predefined. The instructor can generate and clear failure status by simple commands from his terminal.

(4) **Automatic evaluation.**
A consistent and accurate evaluation of any trainee can be obtained by entering an evaluation standard in each subcourse.

Figure 6 shows the functional configuration of YEWCOM. Details of each function will be described in the next section "FUNCTIONS". The software configuration for the simulator section is described below.

The software configuration of the simulator section is organized so that continuous processes (process components) can be emulated faithfully without any need for changes or omissions. Continuous processes are generally constructed in the form shown in Fig. 7, where the plant components include pipes, tanks, instrumentation such as transmitters, and valves; the field terminal board is where signal wires of the instrumentation equipment are terminated, and cables connect the field terminal board to the control system.

These components are classified and represented in software modules in the simulator section of the STUDY system. This makes the system easy to understand and easy to maintain.

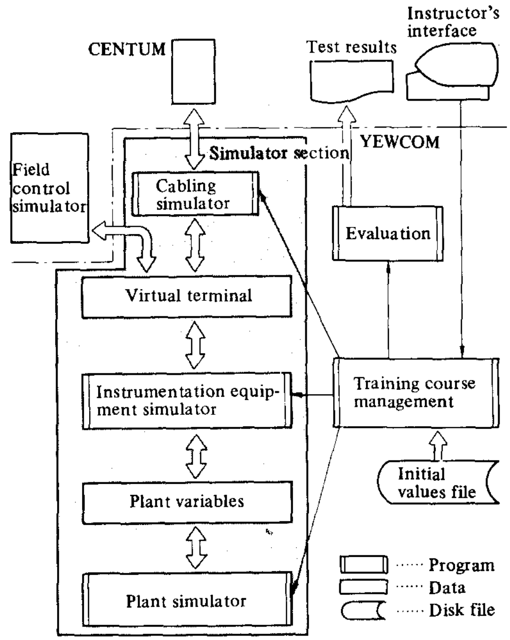


Figure 6 Functional structure within YEWCOM

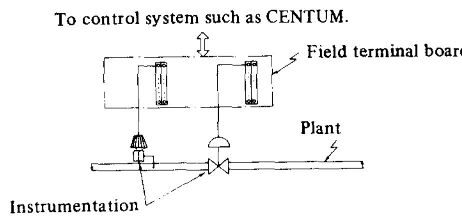


Figure 7 Continuous plant configuration

The training course management program is provided for the purpose of controlling the above simulation, and acts as an interface for the instructor.

Features:

(1) Construction and maintenance costs are low because the plant is emulated in software.
(2) The system can simulate, in real-time, a large-scale continuous plant.
(3) The system can automatically evaluate the operator's "dynamic response" and progress.
(4) The system can be automatically configured to represent various states of the plant and control equipment.
(5) The system can easily implement training for failure conditions that are difficult to temporarily realize in an actual live plant environment.
(6) The system has abundant builder/maintenance functions in a FIB (Fill-in-the-Blanks) format, for preparing and maintaining the specifications for simulation and evaluation.
(7) Since the plant model equations are expressed with physical equations in the MKSA unit system, the significance of each variable is clear.
(8) Field equipment is functionally divided on a unit basis, and has high maintainability.

The solution is determined by successive approximation of the form:

where : The latest value of x
: Values of x and y at the preceding point in time
: Interval between adjacent points in time

Accordingly, the integrated variable ("x" in this case) can be determined from the value at the preceding point of time. On the other hand, variables other than the integrated variables must be determined using variables at the same point of time.

In other words, when the equation is $y = f_2(z)$, y_1 should be determined using $y_1 = f_2(z_1)$. Therefore, z_1 (the value of z at time t_1) must be determined before y_1 can be determined.

Actual Simulation Equations.

Examples of some simulation equations that are actually used in the STUDY system are shown below.

For example, consider the simulation equations for a process where a gas is supplied at a certain received pressure, its temperature is raised in a large capacity bath, and it is sent out at a certain supply pressure. Figure 9 indicates the configuration and plant model.

The variables are classified, and the simulator equations for this model are described below.

(1) Classification of variables

(a) Manipulated variable: K_i (Valve conductance),

(b) Constants: K_o (Pipe conductance), V (Internal volume of tank in the bath), H (Heat transfer coefficient between the bath and tank), A (Heat transfer area), R (Gas constant), M (Gas molecular weight), and C (Specific heat of gas at constant pressure)

(c) External variables: P_i (Received gas pressure), P_o (Supply gas pressure), T_i (Received gas temperature), T_B (Bath temperature -- assumed to be constant, since bath heat capacity is large)

(d) State variables: F_i (Gas inflow rate), F_o (Gas outflow rate), W (Mass of gas within the tank), Q (Heat flow between bath and tank), T_o (Supply gas temperature -- equal to the temperature in the tank), and P (Tank pressure).

(2) Simulation Equations

$$\frac{dW}{dt} = F_i - F_o \quad \cdots\cdots (1)$$

$$\frac{dT_o}{dt} = \frac{1}{C \cdot W} \times \{ C \times F_i \times (T_i - T_o) \} \quad \cdots (2)$$

$$P = \frac{W \times R \times T_o}{M \times V} \quad \cdots\cdots (3)$$

$$Q = H \times A \times (T_B - T_o) \quad \cdots\cdots (4)$$

$$F_i = K_i \times \sqrt{P_i - P} \quad \cdots\cdots (5)$$

$$F_o = K_o \times \sqrt{P - P_o} \quad \cdots\cdots (6)$$

Instrumentation Simulator. The instrumentation for an actual plant is classified by function in Table 1.

Instruments are independent of each other, and have different specifications (such as span, bias, etc. for transmitters, and CV characteristics for valves).

A separate instrumentation module is provided in the STUDY system; the instrumentation is classified as shown in Table 1. A separate program is provided for of the four types of instruments. The user simply enters parameters such as span, bias, etc, into the prototype program for each type (see Fig. 10).

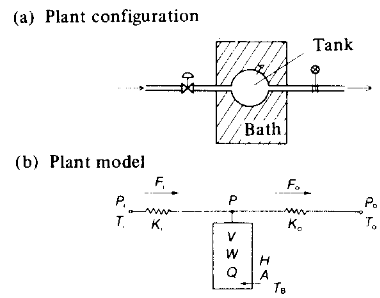


Figure 9 Plant configuration and model

Table 1 Types of instrumentation and their functions

Instrumentation	Functions
Instruments	Converts physical quantities such as flowrate to 4 to 20 mA signals.
Final control elements	Converts 0 to 100% signals into physical quantities such as conductance.
Limit switches	Converts physical quantities such as pressures and valve opening into digital signals.
ON-OFF elements (shut-off valve, pump, etc.)	Converts digital signals into physical quantities as conductance.

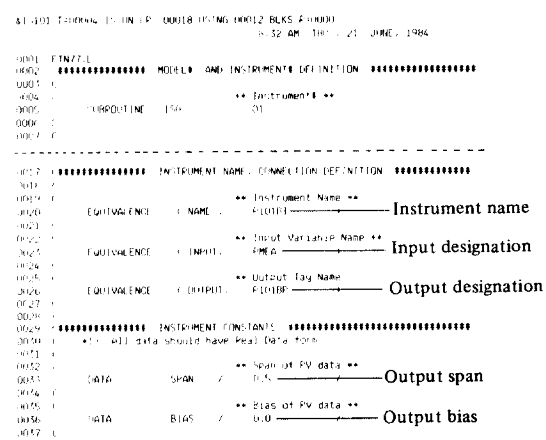


Figure 10 Instrument specification (example)

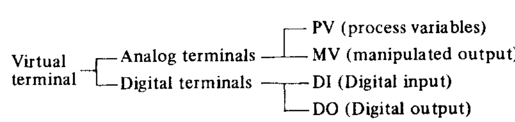


Figure 11 Classification of virtual terminals

Virtual Terminal. The STUDY simulator section accesses an external system such as CENTUM via virtual connections (see Fig. 6). These virtual connections are classified as shown in Fig. 11.

Labels up to eight characters long (in the same format as standard system tag numbers) can be allocated, to access connection terminals via subroutines. This makes for a very flexible system to which external equipment can be easily added.

2. Functions

Plant Simulator. The plant simulator for the STUDY system simulates the plant response, and includes techniques for simulating static and dynamic conditions. Because the STUDY system is an operator-training system, it must also respond to operator actions in real time -- so a real-time (dynamic) simulator is required.

The real-time simulator used in the STUDY system is described in this section.

Computing Method.

The computing functions of the plant simulator must meet the following requirements:

(1) The equations should be physically understandable -- so it's easy to maintain them, and to enter data.
(2) The equations should not take long to compute, or require expensive high-speed computing hardware.

There are two methods for simulating dynamic characteristics. One method is to use block diagrams, with individual blocks representing physical quantities such as first-order lag. The other method is to use equations to calculate each physical quantity. Though both methods have similar computational speed, the block diagram method has drawbacks such as poor physical association. Blocks such as time constant and gain blocks have no direct physical significance, but are simply used as "tuning elements". Also, while at first glance the block diagram method appears simple, if the block interconnections are complex, the diagrams are hard to interpret.

The STUDY system therefore uses physical equations -- a series of simultaneous differential equations -- to represent the dynamic characteristics.

The following rules were drawn up to facilitate the preparation of physical equations for plant simulation:

(1) The differential equations should be solvable using Euler approximation (real-time computation is easily realized, and high accuracy is not required in the training simulator).
(2) Classification of variables should be clear.
(3) The basic form of equations should be fixed.
(4) Variables should be handled in the MKSA unit system.

Basic Form of Equations.

The following five basic forms were fixed:

(1) Equation for material balance.
(2) Equation for gas state.
(3) Flow equation.
(4) Equations for heat conduction.
(5) Equation for heat balance.

For details of each equation, refer to Figure 8.

Classification of Variables.

Many plant variables are encountered in simulation (see plant variables in Fig. 6). The authors decided to classify these variables logically, as shown below:

(a) Manipulated variables : A variable which can be changed under the plant operator's control. Examples : Valve conductance, pump pressure.
(b) Constants : Constants include values intrinsic to the plant, values determined when the plant was constructed, and other physical constants. Examples : Tank volumes, pipe conductances, gas constants and atomic weights.
(c) External variables : Boundary values for a particular plant. Examples : Raw material supply pressure, ambient temperature.

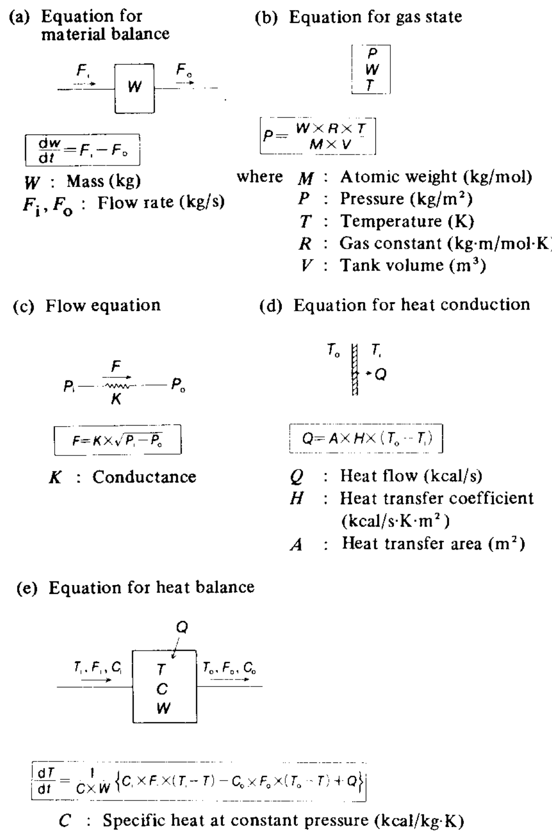


Figure 8 Basic forms of equations

(d) State variables : So-called PV values. These variables represent the plant status. Simulation is used to determine these values. Examples : Flow rate, pressure, etc.

State variables are classified into integral variables and non-integral variables. Integral variables are state variables determined by differential equations. The integral variables used in this simulation are mass and temperature (see Fig. 8).

(e) Intermediate variables : Variables that are produced in the process of setting up equations. Example : Effective conductance.

Euler Method and Time Dependence of Variables.

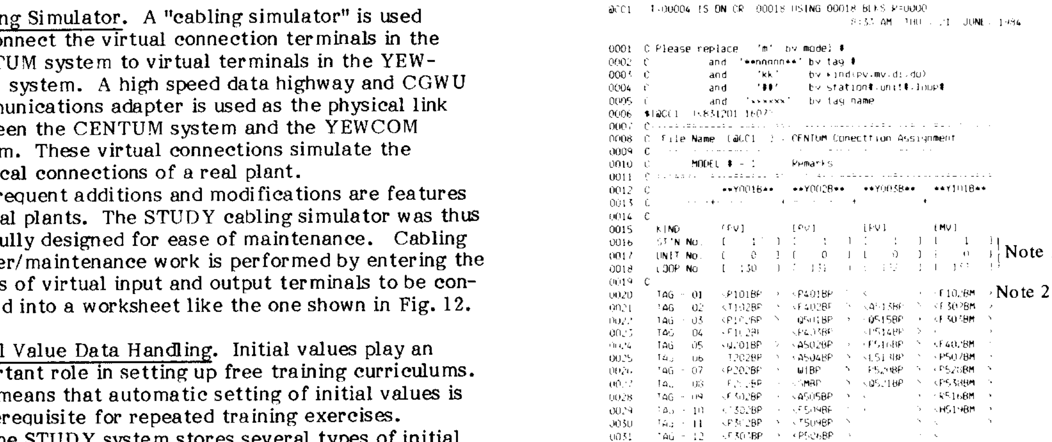
The process model computations use differential equations. Euler method approximation is used to solve the differential equations. (While Runge-Kutta or similar methods must be used where high accuracy is required, the Euler method provides both sufficient accuracy and short computing time -- ideal for the real-time training simulator.)

For the Euler method, variables must be functions of time. Solution by Euler-method approximation is performed as described below:

Assume a differential equation

Cabling Simulator. A "cabling simulator" is used to connect the virtual connection terminals in the CENTUM system to virtual terminals in the YEW-COM system. A high speed data highway and CGWU communications adapter is used as the physical link between the CENTUM system and the YEWCOM system. These virtual connections simulate the physical connections of a real plant.

Frequent additions and modifications are features of real plants. The STUDY cabling simulator was thus carefully designed for ease of maintenance. Cabling builder/maintenance work is performed by entering the names of virtual input and output terminals to be connected into a worksheet like the one shown in Fig. 12.



Note 1: Addresses of CENTUM virtual terminals.
Note 2: Data designations of YEWCOM virtual terminals to be supplied.

Figure 12 Example of cabling specification entry sheet

Initial Value Data Handling. Initial values play an important role in setting up free training curriculums. This means that automatic setting of initial values is a prerequisite for repeated training exercises.

The STUDY system stores several types of initial conditions -- for CENTUM instruments (mode, MV, PH, PL, etc.) and the simulator -- in files, and automatically loads them from the files according to the training course selected by the instructor. The instructor can thus assign any training course to the trainee simply by entering a command from his terminal.

Although initial values must be entered into the initial value file in advance, this is easily done with the utility program provided in the STUDY system. In other words, if a user creates an initial status for performing control with the CENTUM system and activates the STUDY utility program at that time, the status is automatically stored in the initial value file. The user can create the initial value file automatically without being aware of the file structure and without being forced to make any unnecessary settings.

Evaluation Package. This section describes the form of the automatic student evaluation package provided in the STUDY system.

Fundamental Concepts of Automatic Evaluation.

(1) Automatic evaluation requires separate specifications for every subcourse.
(2) Automatic evaluation grades the operational steps taken by an operator (the "operating procedure").
(3) The preferred operating procedure is a function of the plant status. That is, the operating procedure is the series of steps that changes the plant status from one status to another.
(4) The subcourse is ended when the plant proceeds from its initial state via a series of predetermined states (called basic states) to its final state.

Details of Automatic Evaluation.

(1) Subcourse and basic status.

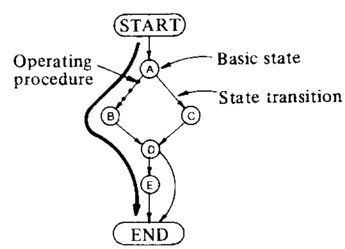
The basic status is defined using the elements shown in Table 2. A subcourse includes START (a start declaration by the instructor) and END (an end declaration by the instructor), with a number of basic states defined between them.

For each basic state, up to ten possible next states can be defined. A typical subcourse state transition diagram is shown in Fig. 13.

The automatic evaluation routine determines the state transitions through which an operator has passed, by the state history in a subcourse (PV or other trend data). (Refer to Fig. 13).

Table 2 Basic state definition element

State No.	State name	Contents
1	Equipment status	ON/OFF for designated equipment
2	PV-H	PV for designated tag exceeds a certain value.
3	PV-L	PV for designated tag falls below a certain value.
4	Alarm	Designated tag is in alarm status.
5	MV-H	MV for designated tag exceeds a certain value.
6	MV-L	MV for designated tag falls below a certain value.
7	Tag mode	Mode of designated tag is changed to designated mode.



If it is assumed that the basic states are detected in the order A → B → D → E, the operator is considered to have finished the training lesson along the route shown by a heavy line.

Figure 13 Training configuration and state transitions for a course

(2) Operating procedure and operating conditions.

The designation of operating procedure will be explained first.

As shown in Figure 13, the operating procedure is performed to move from one basic state to another -- i.e. to designate the path to be followed in the state transition diagram.

Table 3 Types of operating procedure (example)

	Operating procedure	Description
1	Pushbutton operation	Press pushbutton.
2	MV adjustment	Change MV to a certain value.
3	HC control	Control a certain value by adjusting MV.

Table 3 shows the types of operating procedures. The operating procedure is evaluated by determining whether or not the desired operating procedure was followed at every state transition through which the operator passes.

Table 4 Type of operating condition (example)

Operating condition No.	Operating condition name	Contents
1	Equipment status	ON/OFF status of ON/OFF equipment.
2	Tag mode	Designated tag mode
3	PV range	Range in which PV for designated tag is present.
4	SV range	Range in which SV for designated tag is present.

Next, the proficiency of the operator is evaluated and a grade is assigned. This involves a check of the operating conditions. Table 4 shows the types of operating conditions. Basically, the operating conditions represent the process status when the operating procedure was executed, or the conditions for execution and the process status after execution. A grade is assigned by subtracting points for incorrect operating procedures from the basic grades for the correct operating procedures.

Figure 14 shows a flow chart for automatic evaluation. Figure 15 indicates the training results output from the automatic evaluation system.

Failure Generating Function. Training the student how to deal with failures which rarely occur during normal operation, by generating them with the simulator, is an important simulator application.

STUDY can define up to 20 types of failures -- such as those in Table 5 -- for each course, and permits the instructor to generate or clear these failures from the instructor terminal at any time during the training.

3. Conclusions

It is important for both users and manufacturers of systems to find ways to develop operator skills by training on "real" instrumentation systems.

The STUDY system was developed by Yokogawa Electric Corp. in cooperation with Tokyo Gas Co., Ltd. and the expected results were achieved. The authors, however, believe that the system should be further improved and developed into a system that can more fully contribute to the instruction and training of personnel who will be responsible for the operation of future advanced instrumentation systems.

4. Acknowledgements

The authors wish to thank the many individuals whose efforts or assistance brought the STUDY system to fruition.

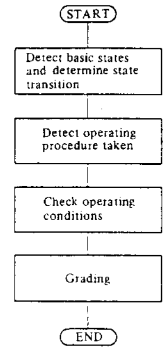


Figure 14 Flow for automatic evaluation

(a) Training results (Subcourse) 1/2, Tokyo Gas Co., Ltd., Training Center

Date	Feb. 1 '84; Wednesday	
Trainee	Location code	802
	Location	Training center
	Personal No.	
	Name	

Training course	Title	ORV simulated normal operation
Sub-course	Title	Individual operation
	Started at	13 : 21
	Ended at	14 : 08
	Starting mode	Initialized

Score	59
Comment	Proficiency slightly insufficient both in understanding training course contents and operating procedure training. Subsequent efforts are needed.

(b) Training course (Subcourse) 2/2, Tokyo Gas Co., Ltd. Training Center
Total demerits for operation groups: 0

Standard operating procedure	Execution	Score	Details for demerit
C-180-1	O	6/6	Reasons for demerits
C-180-2	O	6/6	due to operating conditions
C-180-3	O	6/6	
C-210	O	4/6	(12:C-220)
C-220	X	0/6	
C-240	O	0/6	(11:C-220) (12:C-250)
C-261	X	0/6	
E-350	O	3/6	(11:C-261)
E-360	O	6/6	
E-370	O	6/6	
E-380	O	6/6	
E-390	O	6/6	

Execution: Yes or no for executing operation

Details of the evaluation are printed out. The trainee can see the details of his evaluation by reading the printed output.

Figure 15 Training results

Table 5 Types of failures (example)

	Type	Action	Items to be designated
1	Instrument failure	Designated tag values (PV values at virtual terminal) are substituted for the designated values.	(1) Instrument tag (2) Designated value
2	Controller hunting	The proportional band of the designated tag No. is changed to the designated value. Contents of DDC list in CENTUM can be directly changed.	(1) Tag No. (2) Normal value (3) Failed value