Evaluation of a conventional process-alarm system in a fertilizer plant

Evaluation of a Conventional Process-Alarm System in a Fertilizer Plant

H. KRAGT AND J. BONTEN

Abstract—A study to gain insight into the way "process-alarm systems" are actually used and evaluated in practice, and to know how busy the human operator is in dealing with the system is presented. Observations and interviews were carried out with eight experienced control room operators from a fertilizer plant. For 63 h all the warning signals of the conventional system were recorded and rated by the operators. The method of observation is briefly described. The actual ratings were compared with those assumed in advance. The results indicated that in the fertilizer plant the process-alarm system was mainly used as a monitoring tool and not as an alarm system requiring action. Therefore "annunciator system" would be a better term. The number of warning signals recorded was surprisingly high. Suggestions are given to reduce this number; e.g., annunciator systems can be improved by reducing the number of irrelevant cluster and oscillation signals. In interviews outside the control room favorable and less favorable aspects of the system were discussed with the operators and critical incidents (human errors) were analyzed. Five incidents are briefly described. On the basis of this study, the various functions of the annunciator system are discussed. A plea is made for further research in the laboratory, so as to tackle some of the "interface" problems that were found.

Manuscript received April 4, 1983; revised June 11, 1983. This work was supported by the Commission of the European Communities.

The authors are with the Department of Industrial Engineering, University of Technology, Den Dolech 2, P.O. Box 513, 5600 MB Eindhoven, The Netherlands.

I. Introduction

A "PROCESS-ALARM system" forms part of the instrumentation system that operators in a central control room have at their disposal. One of the functions of the process-alarm system is to alert the operator to changes in the process.

From the related literature (Andow and Lees [1], Edwards and Lees [2], Williams [3], the Purdue Workshop [4], the report on Three Mile Island [5], and Sheridan [6]) and from the previous experience of the first author, we conclude that from an *ergonomic* point of view the design of a process-alarm system should be improved. In many cases "alarm inflation" occurs [7] and the operator seems to lose confidence in the system. Particularly in the more

0018-9472/83/0700-0586$01.00

advanced systems where it is easy to add new alarm points, it is often difficult for the operator to get a good overall view. In order to gain insight into the way process-alarm systems are actually used and evaluated in practice, and to see how busy the operator is in dealing with the system, it was decided that an exploratory study would be conducted. This was carried out in a Dutch chemical industry (DSM) in two control rooms: a polyethylene plant and a fertilizer plant. The study presented in this article took place in the fertilizer plant. The study can be subdivided as follows.

Observations: For 63 h covering the various shifts, all the signals of the process-alarm system were recorded by observers and rated by experienced operators.

Interviews: After the observations had been made, the operators were interviewed individually about critical incidents and the favorable and less favorable aspects of the system.[1]

Up to now the term process-alarm system has been used. In view of the results of the study, however, we would suggest using the term "annunciator system." Before presenting the methods and techniques that were applied, and the results of the study, we shall describe the annunciator system and the operator-process situation in more detail.

II. Annunciator Systems

A. Purpose and Construction

Since a control room operator cannot be alert to everything all the time, his attention must be directed to (important) changes in the process state as soon as they are taking place. His attention is drawn by warning signals (often unjustly called alarms). Such a warning signal consists of an audible and a visual signal, and is generated by the annunciator system.

An annunciator system can be divided into four subsystems: the audible, the visual, the acknowledgment, and the system that coordinates the tasks of those three subsystems and links them with the process.

1) The Audible Subsystem: In general, an audible signal is suitable for making the operator immediately aware of, for instance, an off-normal condition somewhere in the process (attention function). After detecting this signal the operator looks for the related changes in the process variables. In some systems the sound also indicates (e.g., by another pitch) the specific process section which needs his attention. This subsystem may consist of one or more of the following: horns, bells, etc.

2) The Visual Subsystem: Visual signals are suitable for pinpointing the place of the change and the type of change (specification function) in the process. In some systems visual signals are also used to guide the operator in detecting the changes; for instance, he can look at a central fascia to see in which process section the change has taken place. We distinguish among three types of visual systems:

- systems in which the information is presented via lights or switches (conventional systems);
- systems in which the information is presented via computer-connected visual display units (VDU's) and printers (advanced systems);
- combinations of both systems.

Conventional annunciator systems include the so-called "push-button system for fascia lights" (PF system). This PF system was investigated in the fertilizer plant. The visual subsystem of a PF system consists of illuminated fascias that are placed on panels. Hence the warning signals are shown over a whole wall surface and the operator can see at a glance what is happening. He simply recognizes a warning signal by its position. (In annunciator systems with a printer or a VDU, however, the different warning signals are all presented in one and the same place. Therefore the operator has to search for information in those systems.) The lights that are linked with the process contacts are called annunciators; they present the change of state.

When a process variable exceeds the alarm limit and consequently the process contact switches, the associated light flashes rapidly (see Fig. 1). Such a warning signal is called an oncoming warning signal. When the process variable returns to normal, the light flashes slowly. This is called a return-to-normal signal. In both cases the flashing persists until the operator acknowledges the warning signal by pressing the push-button. When no change of state has to be presented, the annunciator presents a continuous signal. This signal corresponds with the state of the associated process contact. Two ways of presenting this state are used, the "light-field system" (normal equals lit; off-normal equals dark) and the "dark-field system" (normal equals dark; off-normal equals lit).

In summary, each annunciator of a PF system has both a specification and a memory function. Thus, at any time, the operator can notice at a glance the state of the process contacts (e.g., which temperatures are too high) and consequently he can get an overall picture of the state of the process.

3) The Acknowledgment Subsystem: The audible and the (flashing) visual signals continue until the operator signifies to the annunciator system (by pressing a push-button) that he has perceived and identified them. For the remainder of this article this reaction is called "acknowledgment." In practice we find that sometimes the operator acknowledges only to get rid of the audible signal.

The acknowledgment subsystem may consist of one or more push-buttons. If, as is sometimes the case in a PF system, each annunciator is provided with such a button, the way of acknowledgment is called "individual." In this case the light is generally placed inside the push-button. If the annunciators are arranged in groups and each group is provided with an acknowledgment button, we have "group acknowledgment." This system has disadvantages as we will show later on.

[1]This yields valuable information for understanding the observations, and about the strong and weak points of the process-alarm system.

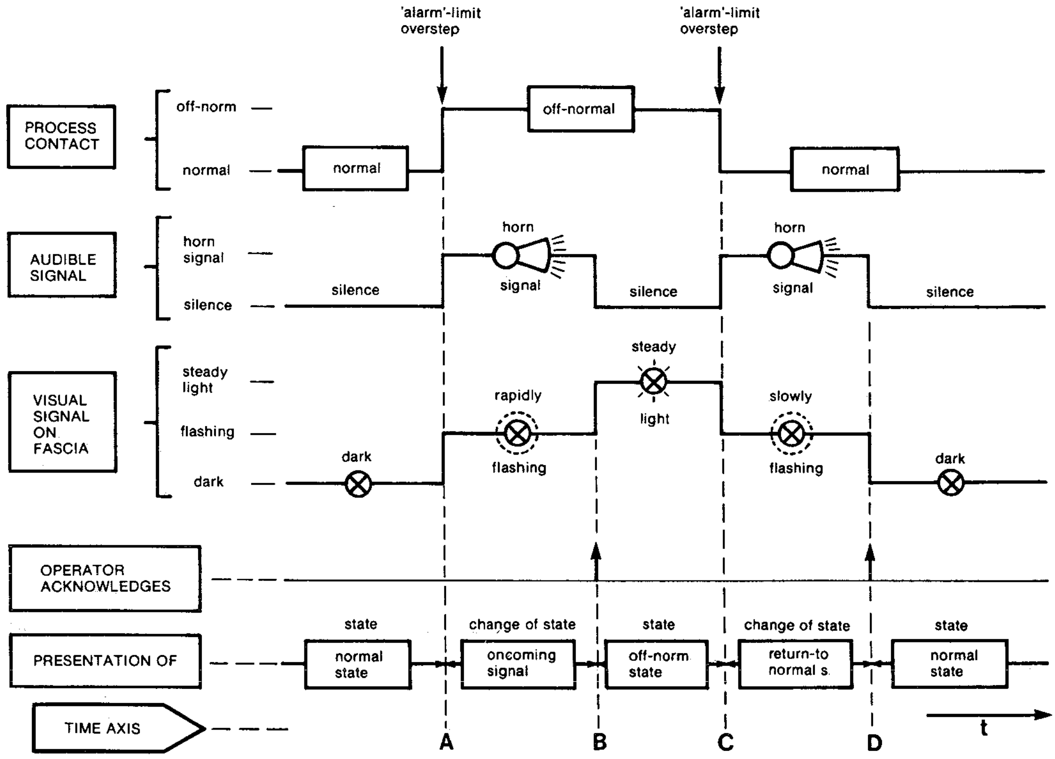

Fig. 1. Time sequence of PF annunciator system.

B. The Processing of a Warning Signal in a PF System

To clarify the processing of a warning signal, the time sequence of the appropriate signals and the related acts of acknowledgment are presented in Fig. 1. A process variable exceeds the alarm limit at point A. Hence the binary state of the associated process contact is inverted.

At that moment an audible signal can be heard in the control room and the light that belongs to the process contact starts flashing. When the operator hears the audible signal, he looks for the flashing light (detection), the associated process variable (discrimination), and the reason for the change in this variable (interpretation). Based on this information he can predict what will happen if no action is taken, and then he has to decide whether or not action is necessary. If action is required, he has to decide what it must be. The operator will acknowledge the warning signal at some moment after discrimination (point B), but not necessarily after interpretation. In some systems, when a process variable returns to normal (point C), a second signal occurs. At point D the light goes out.

In the next section we present some ideas resulting from the study of the descriptions and specifications of (modern) process-alarm systems. Based on these ideas, we will formulate some hypothetical relations between events, signals, signal ratings, and (control) actions by the operator.

C. Model and Hypotheses

As stated in Section II-A, the attention of the operator must be directed to changes in the state of the process as soon as they are taking place so that he will not be faced with undesirable results. Such changes can be divided into expected and unexpected events.

Unexpected events in general are disturbances. They move the process into an off-normal state where process variables exceed their alarm limits, production machines are stopped, emergency apparatuses are started, etc. The warning signals that occur in such a case are called oncoming signals. They are presented to the operator both audibly and visually (see Fig. 1). The operator cannot ignore these signals as he is not sure about what is happening. Therefore he will rate these signals as requiring an urgent notice, and he will take action in order to minimize the consequences of the disturbances and if possible to eliminate their causes. We formulate the following as an hypothesis.

Hypothesis A: Signals not resulting from operator action are oncoming ones; they will be rated as unexpected and urgent, and will be followed by action.

Expected events usually result from operator actions. After a disturbance the operator brings the process back into the normal state. As a result, return-to-normal signals occur. Even when no disturbances or machine troubles occur, the annunciator system generates signals (both oncoming and return-to-normal) as a consequence of operator actions such as switching the machines on or off, readjusting set values, etc. Because the operator himself changes the state of the process, the accompanying warning signals will give him hardly any information and so they will not require an urgent notice. This is the reason that the return-to-normal signals are not presented audibly in many systems; in some systems, they are not even

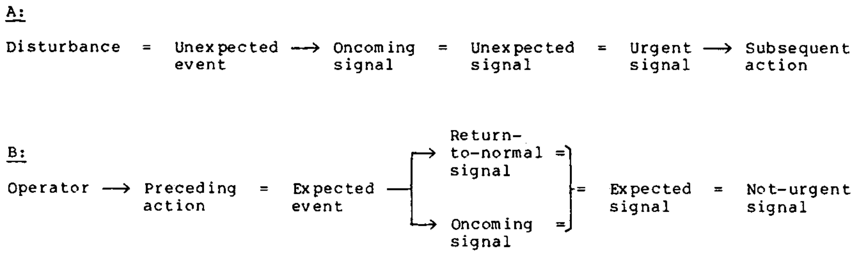

Fig. 2. Hypotheses about ratings of warning signals.

TABLE I
TABLE BASED ON THE HYPOTHESES ABOUT RATINGS

SIGNAL TYPE	ACTION	Not urgent: Unexpected	Not urgent: Expected	Urgent: Unexpected	Urgent: Expected
Oncoming	Preceding	-	B	-	-
	Subsequent	-	-	A	-
Return-to-normal	Preceding	-	B	-	-
	Subsequent	-	-	-	-

presented at all! With these ideas in mind one can formulate the following hypothesis.

Hypothesis B: Signals resulting from operator action will be rated as expected and not urgent, and will not be followed by action.

Both hypotheses are shown schematically in Fig. 2; this figure can also be presented in tabular form (Table I). According to the hypotheses, all signals not resulting from operator action will be found in the cell marked A; all signals caused by operator actions will be found in the two cells marked B. In the remaining cells, no signals will be found. In Section V, we examine these hypotheses in relation to the actual data in the fertilizer plant.

III. THE OPERATOR-PROCESS SITUATION

A. The Plant

The plant under consideration produces fertilizer grains. In most of the process sections, solids (grains and powders) are present; in a few sections only, fluids are present. Temperatures are fairly low (mostly under 100°C). High pressures and vacua do not occur, and strongly poisonous chemicals are not used. Most of the operations are mechanical (like sieving, mixing, turning over, blowing, etc.) or physical (drying, etc.).

The plant itself is very large and consists of many machines and pieces of apparatus. Set-value adjustments and on-and-off switching of machines generally result in a change in the value of the process variables within three min. It is not necessary to check afterwards as there will be no further reaction.

Several process units can be distinguished in the plant. Each process unit consists of a functional group of machines and apparatuses. At least two units of each type have been installed. Connected in parallel, they form a "process group." The transportation system (mostly conveyor belts, ropes, and feed-scrolls) is made in such a way that one or more process units of a group can be connected with one or more of the next group. This arrangement enables the operator to stop individual machines and apparatuses (e.g., for maintenance) without stopping or seriously interrupting the whole process.

Plant operators make such connections between the units of the successive groups, either on the orders of the control room operator or on their own initiative. The plant operators are the people who most often switch the machines and pieces of apparatus on and off. A few machines can also be switched directly from the control room. The amount of end-product is adapted to large fluctuations in demand and/or other circumstances (e.g., maintenance), by starting or stopping one or more process units. Automatic shut-down systems are used for the safety of the people and for safeguarding of equipment.

B. The Annunciator System

The control room is equipped with a control board, a graphic panel, and a console (see Fig. 3). The graphic panel is placed over the control board and extends over its whole length. It contains 357 lights of the PF annunciator system. Each light has been placed in a schematic picture of an apparatus or machine. The other 225 annunciator lights are placed in matrices on the vertical part of the console.

Process variables are either analog or binary. In general the analog variables have a value which lies somewhere between the physically possible minimum and maximum. Between these two extremes the designers have defined the so-called alarm limits. Examples of such analog process-variables are temperature, pressure, level, and material composition. The binary variables have two possible values; examples are as follows: a motor runs or is out of operation, a valve is open or closed, and a pipe is clean or clogged.

The lights on the graphic panel are in light-field; the majority of them represent binary variables. The lights on

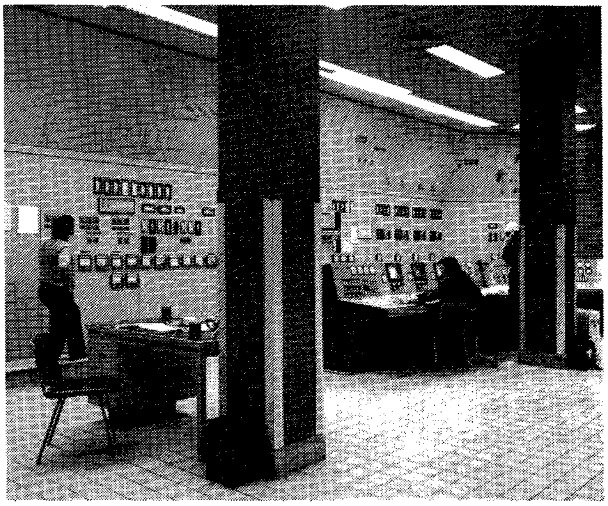

Fig. 3. Control room of fertilizer plant.

the console are in dark-field; the majority of them represent analog variables. The annunciator system presents both the oncoming and return-to-normal signals. The annunciator system is subdivided into five acknowledgment groups. Each group monitors one or more process groups. The operator can easily see the corresponding parts of each acknowledgment group on the graphic panel, on the console, and also on the control board because these parts have been placed vertically in line. He acknowledges each warning signal in such a group, both from the graphic panel and from the console by using the same acknowledgment button that is placed on the horizontal part of the console. Each of the five buttons has a light for indicating the occurrence of a warning signal in its group. There is only one audible signal (a two-tone bell) for all warning signals.

C. Clusters and Oscillations

Starting or stopping a process unit is accompanied by many warning signals from both the analog and the binary process variables. These signals come in rapid succession. We call such a group of signals a *cluster*. (We recorded 133 clusters in 63 h. The average duration of a cluster was 5 min with a standard deviation of 6.5 min. The average number of warning signals in a cluster was 12.) The operator is familiar with the signals in a cluster. In fact he usually initiates them himself. Even so, he has to acknowledge all the warning signals separately. Since he has to be near the controls in such circumstances, he often has to walk back and forth between the control board and the console (see Fig. 3). Hence, during a cluster the annunciator system demands more attention and causes more stress than seems necessary.

Occasionally, due to fluctuation of the value of a process variable, a process contact will be constantly switching on and off. As a consequence, the associated annunciator constantly generates warning signals. This is quite irritating because all these signals also have to be acknowledged. We called such an accumulation of signals an *oscillation*. (We recorded 50 oscillations in 63 h. The average duration of an oscillation was 8.5 min with a standard deviation of 8.5 min. The average number of warning signals in an oscillation was 12.)

When the control room operator is dealing with cluster or oscillation signals, it is quite possible that in other process parts, signals not belonging to the cluster or oscillation (single signals) will occur. At such moments these single signals can very easily be overlooked. Hence we postulate the following.

Hypothesis C: Single warning signals occurring during a cluster or an oscillation will be rated differently (e.g., more often "urgent") from those occurring alone.

IV. Methods and Techniques

A. Observations

One of the aims of the study was to gain insight into the way the annunciator system in the fertilizer plant was actually used. Therefore we wanted to know whether hypotheses A and B, formulated in Section II-C, really covered the situation. In order to get an idea as to how busy the operator is in dealing with the system, we wanted to have more detailed information about the distribution of signals in time, and the alternation of the periods that have many signals with those that have few signals. For this purpose the warning signals were recorded by the investigator and rated by an operator. Special observation forms were designed in conjunction with the operators (see Fig. 4). The investigator, on his part of the form, noted the following for each signal:

- the exact time of occurrence;
- the name of the annunciator;
- whether the signal was oncoming or return-to-normal;
- the state of the process units at that moment.

The operator, on his part of the form, rated the following aspects *immediately after* the occurrence of the warning signal.

Expectation: Did he expect the warning signal or not? If so, on which was it based: data or action? (As postulated in the hypotheses, an unexpected warning signal will be rated as urgent; an expected one as not urgent.)

Urgency: Was it, in retrospect, necessary that the warning signal had to be regarded immediately or could it have been disregarded for some time?

During the training and familiarization of the operator with the observation forms, it appeared to be necessary to add the categories "less urgent" and "no information"; in contrast to the model, there were several signals that were rated as such by the operator. These categories were initially supposed to be minor ones. So, the following distinction was useful during the observations:

1) *The Urgent Signals*: after detection, these signals must be regarded immediately;
2) *The Less-Urgent Signals*: a delay of response of about one min is admissible. In our opinion, one min delay

IN OPERATION: COATING 1,3 | SIEVES 1,2,3,4 | DRYING 1,2,5,6 | M+P 1+5 3+7 | MILLS 1,2 | M.C. 2 — PAGE = 3

DATE = [redacted] SHIFT = Morn. OPERATOR = [redacted] OBSERVER = [redacted]

TIME	ANNUNCIATOR	SIGNAL		CLUSTER + OSCILL.	EXPECTED			URGENCY				ACTION				ACTION PLACE			REMARKS
		ON-COMING	RETURN-TO-NORM.		AFTER ACTION	ON BASE OF DATA	UN-EXP.	URGENT	LESS URGENT	NOT URGENT	NO INFO	PRECEDING	SUBSEQ. STANDA	SUBSEQ. NON STANDA	NO ACTION	INSIDE C. ROOM	OUTSIDE C.ROOM	VIA PHONE	
9.50.30	Rawbunker 1	X				X				X			X			X			
52.20	"		X		X					X		X				X			
54.25	Cyclone 4B		X				X			X		X					X		Maintenance, because of blockage
54.55	B 12		X	X			X				X	X					X		HHT ////
55.18	Cyclone 4B	X					X			X		X					X		Maintenance
56.50	Start mill 3			X															HHT HHT /
56.53	A21	X		X			X		X						X				HHT HHT //
58.01	B12 end oscill.		X	X															
58.47	Dryer fan 4		X		X						X	X				X			
59.02	A21 end oscill.		X	X															
10.00.24	E 35	X			X				X			X						X	Change head for cleaning
10.00.26	N23	X					X		X					X				X	
TIME	ANNUNCIATOR	ON-COMING	RETURN-TO-NORMAL	CLUST + OSCILL.	EXP. AFTER ACTION	EXP. ON DATA	UN-EXP.	URGENT	LESS URGENT	NOT URGENT	NO INFO	ACTION PRECED.	SUBSEQ. STANDA	SUBSEQ. NON STANDA	NO ACTION	INSIDE C. ROOM	OUTSIDE C.ROOM	VIA PHONE	REMARKS
10.03.40	End Start mill 3																		
05.31	E 15	X				X			X						X				
07.12	E 36		X		X				X			X						X	
09.08	J23	X				X			X						X				
10.25	Filter Scroll 3	X		X			X	X					X					X	
11.29	Filter scroll 3		X		X			X				X						X	
15.01	J23		X			X			X						X				
15.57	Cyclone 4B		X				X			X		X					X		Maintenance
16.05	Stop coat 1																		HHT HHT HHT ///
18.14	Motor Dryer 6	X			X					X		X						X	
18.24	Speed Dryer 6	X			X					X		X						X	
21.22	End Stop coat 1			X															

Fig. 4. Observation form.

is relatively quite a long time; therefore we use the words "less urgent";

3) *The Not-Urgent Signals*: a delay of response of about ten min is admissible;
4) *The Signals Without Information*: these signals contain no information for the operator.

In the remainder of this article, 3) and 4) have been added together.

Action: Which operator action (subsequent or preceding) had accompanied the warning signal and was it taken inside or outside the control room? In contrast to the model, we had to add the category "no action." Just like the categories less urgent and no information, this category was supposed to be a minor one.

Not all signals belonging to clusters and oscillations (Section III-C) could be recorded and rated, as they occurred in rapid succession. Moreover the operator is familiar with such a group of signals. So, for clusters and oscillations, only the exact time of the first and the last warning signal was recorded. The number of signals was counted and noted on the observation form. Warning signals not belonging to a cluster or an oscillation were recorded and rated as such. These signals, called "*single warning signals*," are the ones on which most of the results are based.

At the beginning we thought every control room operator could participate in the investigation regardless of his experience. During the testing of the observation forms, however, it appeared that there were more signals when less experienced operators were on duty. This we ascribed to the way in which they controlled the process. We decided to carry out the actual observations with experienced operators because we wanted to use only one category. The group of operators with whom we did the investigations could be considered to be representative of those who are able to control the process on their own. As it was impossible for an operator in the fertilizer plant to control the process and fill out the forms at the same time, another operator (the "observer") was asked to fill them out. To do this the observer had to try to follow the reasoning of the controlling operator. The observer was sitting beside the investigator; both had a form in front of them. The observer rated the signal that he had either noted himself or had read from the form of the investigator. Both forms were checked regularly with regard to the noted signals.

TABLE II
SUMMARY OF OBSERVATION DATA

	1	2	3	4	5	6	7	8
Total	816	280	133	50	1148	266	960	62^50'
Morning	265	92	42	16	485	59	330	17^40'
Afternoon	300	113	58	16	422	115	420	25^07'
Night	251	75	33	18	241	92	210	20^03'

1 is the number of single warning signals not occurring in a cluster or oscillation.
2 is the number of single warning signals occurring in a cluster or oscillation.
3 is the number of clusters.
4 is the number of oscillations.
5 is the number of signals counted as belonging to clusters.
6 is the number of signals counted as belonging to oscillations.
7 is the estimated number of nonrecorded signals belonging to clusters and oscillations.
8 is the observation time (= h, ′ = min).

In each shift of operators (crew) we used two operators who were used to working together; in total: four crews × two operators equals eight operators. For half of an observation period one of these two operators controlled the process and the other rated the warning signals. For the other half the roles were reversed.

Before carrying out the actual observations, we spent some time on training and familiarizing the operators with the observation situation. The observations were carried out during 14 shift periods, viz., five morning, five afternoon and four night, totaling 63 h during normal plant operation (i.e., no total start-up or break-down).

B. *Interviews*

We agree with Bainbridge [8] that interviews may be the best verbal method for getting an idea of the operator's knowledge of and experience in process technology. By interviewing operators, we expected to record their knowledge and opinions about the annunciator system. If carefully organized, interviews are also suitable for discovering human errors and the possible situational and individual factors causing them [9].

All of the eight operators who took part in the research were interviewed. We chose the personal interview (outside the control room) so as to collect a personal opinion from each operator, and because people are more inclined to talk about their mistakes in a personal interview than in a group.

Anonymity being guaranteed, nobody objected to the use of a tape recorder. Moreover since the operators already knew the researchers from on-the-job training of the latter, the interviewer could focus his mind fully on the interviews. All interviews were done by the first author; they lasted from 45 to 90 min. The subjects of these semi-structured interviews (open-ended questions) were the advantages and disadvantages of the annunciator system, and human errors (critical incidents, [10]).

V. RESULTS OF OBSERVATIONS

The numbers of signals collected in the observations are listed in Table II. The analyses concern the following:

1) ratings of single warning signals (Section IV-A);
2) time intervals between consecutive single warning signals;
3) clusters and oscillations.

A. *Ratings of Single Signals*

Before discussing the results, we present in Fig. 5 both the percentages of the response alternatives of each (rated) aspect and those of the signal type. The following findings are worth mentioning.

- The number of signals followed by operator action was small (7.5 percent).[2] An explanation that fits our hypotheses would be that rather few disturbances occurred during the observation period.
- 42 percent of the warning signals were unexpected. According to our hypotheses this would mean that quite a lot of disturbances occurred, rather more than in the case mentioned above.
- 13 percent of the signals required urgent attention.

Thus, there are rather great differences (7.5 percent, 42 percent, and 13 percent) among these three figures. We therefore suspect that the model is wrong. We come to the same conclusion if we consider the categories "no-action signals" (45 percent) and "less-urgent signals" (36 percent), both of which we had suspected to be minor ones.

1) Data Versus Hypotheses: We examine to what extent the relations as given in Fig. 2 (and Table I) are present in the data. Therefore we consider Table III in more detail.

According to hypothesis A, signals not resulting from operator action would be oncoming ones, rated as unexpected and urgent, and would be followed by action. In Table IV (extracted from Table III) all the 624 signals not resulting from operator action are classified according to the other aspects. From this table we see that only 25 out of 624 signals fit this hypothesis.

The second implication in hypothesis A is that oncoming, unexpected, and urgent signals would be followed by

[2]Approximately the same percentage was found in the polyethylene plant [10].

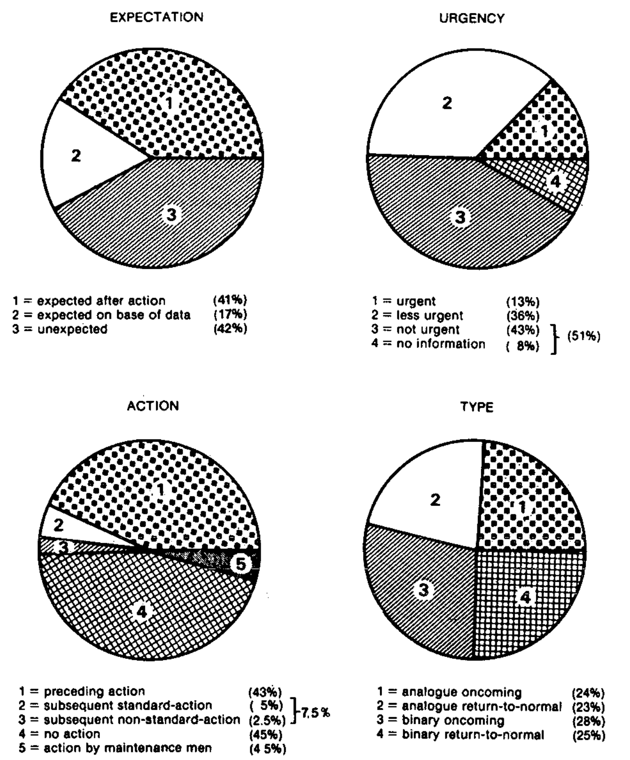

Fig. 5. Percentages of response alternatives for each aspect.

TABLE III
ACTUAL NUMBER OF SIGNALS FOR EACH COMBINATION OF ASPECT CATEGORIES

Signal type	Action	No information + Not urgent: Unexpected	No information + Not urgent: Expected	Less urgent: Unexpected	Less urgent: Expected	Urgent: Unexpected	Urgent: Expected	
Oncoming	Preceding	44	73	12	69	5	12	215
	Subsequent	4	2	14	4	25	10	59
	No action	118	66	38	38	21	14	295
Return-to-normal	Preceding	30	56	7	129	1	34	257
	Subsequent	3	3	2	2	3	9	22
	No action	102	54	33	50	2	7	248
		301	254	106	292	57	86	1096

No action means no *operator* action; so, actions performed by the maintenance men are included.

action. In Table IV we see that for 25 signals this is true, but for 21 signals, not true.

According to hypothesis B, signals caused by the operator would be rated as expected and not urgent. In Table V (also extracted from Table III) the 472 signals with a preceding action are classified according to the other aspects. Out of these signals only 129 (26 percent) belong to the predicted category. The greater part of these signals does not fit the hypothesis, however.

TABLE IV
SIGNALS NOT RESULTING FROM OPERATOR ACTION (CF HYPOTHESIS A); SUBSET DERIVED FROM TABLE III

Signal type	Action	Others: Unexpected	Others: Expected	Urgent: Unexpected	Urgent: Expected	
Oncoming	Subsequent	18	6	25	10	59
	No action	156	104	21	14	295
Return-to-normal	Subsequent	5	5	3	9	22
	No action	135	104	2	7	248
		314	219	51	40	624

Others mean less urgent, not urgent, and no information.

TABLE V
SIGNALS CAUSED BY THE OPERATOR (CF HYPOTHESIS B); SUBSET DERIVED FROM TABLE III

Urgency	Unexpected	Expected	
Urgent + Less urgent	25	244	269
Not urgent + No information	74	129	203
	99	373	472

In conclusion, we state that hypotheses A and B do not cover the situation. First of all, there is the existence of the categories no-action signals (45 percent) and less-urgent signals (36 percent). Secondly, the relations are by no means as obvious as was expected.

What are the reasons for the discrepancies? Why are so many signals rated differently from what was postulated in the model? From further analysis of the data we gained some insight into the way the annunciator system in the fertilizer plant was actually used. In the following we consider successively both hypotheses, and mention the most important findings.

a) Signals not resulting from operator action (hypothesis A): Table IV shows us that most of the signals not resulting from operator action, contrary to what was supposed in hypothesis A, are rated as no action and/or less urgent/not urgent/no information. Also return-to-normal signals are included.

i) Signals not followed by action (543): 44 of these signals were rated as urgent and 159 as less urgent (Table III). Analysis of these signals showed that the operator often used the annunciator system as a tool for *monitoring the changes* in the process. For a good supervision of the process he wanted to observe the following:

- disturbances in the process which did not require an action directly ("wait and see");

- whether or not an analog variable would return to its desired value of its own accord;
- whether or not some of the apparatuses started up automatically when the process required it.

From the other 340 signals with no action, 280 were rated as not urgent, e.g., because the changes concerned took place slowly; 60 signals were rated as no information (for the operator they might have been omitted).

ii) Return-to-normal signals (270): 21 of these signals were rated as urgent and 87 as less urgent (Table III); 22 return-to-normal signals caused a subsequent action, three of them were even "alarming" (unexpected and urgent). In several cases the operator had to wait for a return-to-normal signal when he really wished to carry out an action immediately after noticing the signal, e.g., starting up a pump.

So, return-to-normal signals are sometimes very important to the operator. We will discuss this in Section V-A2.

b) Signals Caused by the Operator (Hypothesis B): From Table V we learn that operator actions not only caused signals that were expected and not urgent (according to hypothesis B), but also signals which were rated as urgent/less urgent and unexpected.

i) Urgent and less-urgent signals (269): 244 of these signals were expected. Obviously the operator wanted to be informed rather soon about the results of his actions (control actions or the commands to the plant operator), and therefore he used the annunciator system. In 46 cases (Table III) he even wanted to know *immediately* whether an action had had the desired result, for instance, whether the plant operator had performed his task correctly.

So, in contrast to the model, not only the unexpected events urgently required notice, but sometimes also the expected ones.

Analysis of the above-mentioned 244 signals showed us that also included in this subset were the few (six) signals generated by a plant operator who wished to inform the control room operator of his whereabouts by switching a motor off and on. In these cases the annunciator system was used as a kind of communication system.

ii) Unexpected signals (99): 74 of these signals were rated as not urgent/no information. These signals were caused by the plant operator acting on his own initiative (cleaning, little repairs, maintenance, etc.). The remaining 25 signals were rated as urgent/less urgent; six of them were caused by wrong actions. The model does not start from the assumption that the operator is unaware of the action taken by others. In the fertilizer plant, however, the control room operator was sometimes faced with signals that he did not expect at that particular moment and that were caused by other people.

2) Return-to-Normal Signals in General: Let us consider Table III in more detail with regard to return-to-normal signals. When dealing with the hypotheses in the foregoing section, we have already seen that not only the oncoming signal, but also the return-to-normal signal, meant "information" for the operator. For instance, a return-to-normal signal sometimes meant that the operator should start an action. In other cases it gave him feedback about actions which had been carried out by the plant operator.

TABLE VI
URGENCY VERSUS TYPE OF SIGNAL; DERIVED FROM TABLE III

URGENCY → / SIGNAL TYPE ↓	No information + Not urgent	Less urgent	Urgent	
Oncoming	307	175	87	569
Return-to-normal	248	223	56	527
	555	398	143	1096

In Section II-C it was said that in some annunciator systems, however, return-to-normal signals are not presented to the operator. What would that mean for the operator in the fertilizer plant?

The reason for omitting return-to-normal signals is that these signals would already be known to the operator. But this is not always true as we can see in Table III. There were 183 unexpected signals of which 48 were rated as urgent/less urgent. Also, return-to-normal signals were not always caused by the operator himself as was assumed in the model. There were 248 signals not related to any of his actions; 92 of them were rated as urgent/less urgent. It concerned signals belonging to variables in a process section that returned to the required values of their own accord and of which the operator wished to be reminded when dealing, for instance, with another section.

Finally, we compare the return-to-normal signals with the oncoming ones on the rating aspect, urgency. Table VI shows us the numbers. From this we conclude there is no meaningful difference in the rating between the two types of signals.

The total number of warning signals could be decreased by nonpresentation of the return-to-normal signals. But the findings mentioned above suggest that we should be very careful of merely omitting them in the fertilizer plant. At least 279 signals rated as useful (urgent and less urgent) would then be lost (25 percent of the total number of signals and 53 percent of the return-to-normal signals).

3) Summarizing the Ratings: The hypotheses A and B do not cover the situation. The control room operator in the fertilizer plant used the annunciator system to ascertain whether

- disturbances occurred in the process, and if so, what kind of disturbances;
- disturbances disappeared of their own accord;
- (or not) apparatuses started up automatically when the process required it;
- his actions had the desired results;
- an event (action or disturbance) occurred that he expected;
- the plant operator had performed his task correctly;

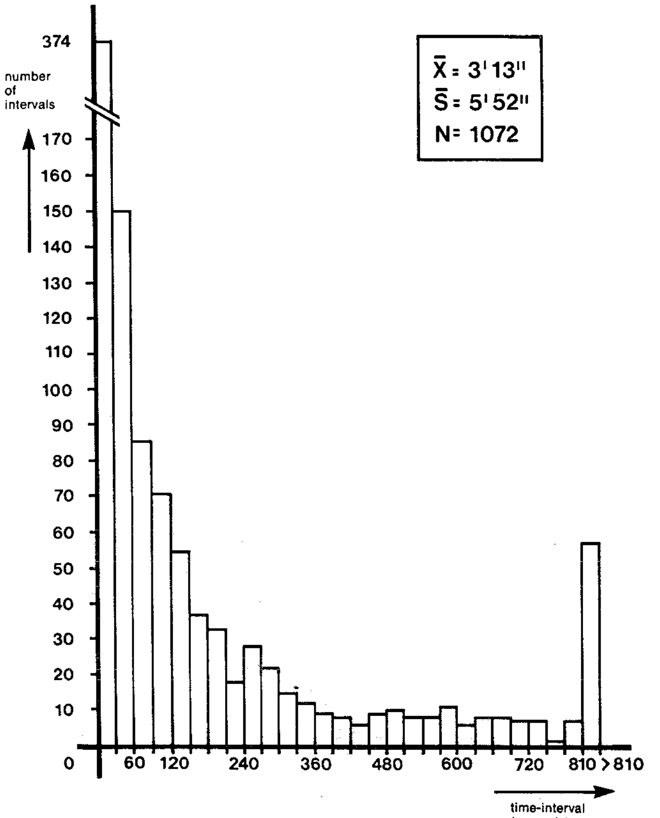

Fig. 6. Histogram of time intervals.

- the plant operator had acted on his own initiative;
- the plant operator had reached his place of destination in the plant.

By analyzing the ratings, we got an idea as to how the annunciator system is actually used. In the following sections we deal with the subject of "busyness."

B. Time Intervals Between Consecutive Single Warning Signals

To get an idea of how busy the operator is in dealing with the single signals of the annunciator system, we wanted to have more information about the distribution of single signals in time and the alternation between the periods with many, and those with few signals.

The frequency distribution of the time intervals between the consecutive single signals is given in Fig. 6. This figure shows that there were many short and few long time intervals—a phenomenon we also found in the polyethylene plant [11].

We cannot yet see a pattern in the distribution of busy and quiet periods. This point was tackled by taking the autocorrelation function into consideration. The autocorrelation was calculated for the various values of the lag ($u = 1$ to 10; [12]). These correlations were smaller than 0.15. From this result we cannot deduce a regularity in the sequence of consecutive time intervals. Similar results were found for the time intervals of the three shifts separately as well as when we took into account the first signal of each cluster and oscillation (see Section V-C). In conclusion, these results indicate that with regard to *single* signals within a particular shift, busy periods versus quiet periods cannot be clearly indicated. These signals occurred almost at random. (In the Appendix the three types of shifts—morning, afternoon, and night—are compared with regard to "busyness" based on the number of signals per unit of time.)

C. Cluster and Oscillations

As mentioned in Section III-A, process units have to be started and stopped very frequently. This is accompanied by many warning signals (cluster; Section III-C).

Often the control room operator had only to give one or two orders to the plant operator. Once the procedure had been started, the plant operator managed its continuation and termination alone. Based on the information from the annunciator system, the control room operator could see how far the plant operator was in performing his task, and whether a machine that had been switched on had already reached the right temperature, etc. Using this information, he adjusted the set values of the appropriate controllers (this is a type of manual "feed-forward control").

An oscillation is generated by the fluctuation of the value of a process variable (Section III-C). After an oscillation or cluster had been started and identified, the signals belonging to an oscillation-string or a cluster-string could be predicted very accurately.

Part (approximately 75 percent) of the total observation time, viz., 47 h and 42 min out of 62 h and 50 min, did not contain any cluster or oscillation. In the remaining part quite a lot of signals had to be acknowledged. Table II shows that during 15 h and 8 min at least 1414 (1148 + 266) signals belonging to clusters and oscillations, and 280 single signals occurred.

In Section III-C we postulated that *single* signals occurring during a cluster or oscillation will be rated differently (e.g., more often as urgent) from those occurring alone because of the fear of overlooking them (hypothesis C). We examined this in Table VII.

It was found that single warning signals occurring during a cluster or an oscillation were rated as more urgent and more expected than the others ($\chi^2(3) = 22.9$, $p < 0.05$ and $\chi^2(2) = 13.6$, $p < 0.05$). How can this be explained? In analysing the data, it was found that in the fertilizer plant a cluster itself sometimes caused a single signal in the same process unit (a so-called induced single signal). Hence, in dealing with a particular cluster the experienced operator will expect this induced single signal if it occurs. There are situations in which such a single signal could be followed by serious trouble. In that case he will rate the induced single signal as urgent. In total we recorded 90 induced single signals. When these were excluded, the χ^2-test gave the following results: single signals occurring during a cluster or oscillation (but not induced by it) are more urgent than those occurring alone ($\chi^2(3) = 20.37$, $p < 0.05$); and, these single signals are *not* more expected than those occurring alone ($\chi^2(2) = 2.31$, $p < 0.05$).

TABLE VII
RATINGS OF SINGLE SIGNALS AS SUCH, AS WELL AS DURING CLUSTER AND OSCILLATION

Aspect	Response alternatives	Signals not in clus/osc. number	%	Signals in clus/osc. number	%	χ^2
(Total	-	816	100.0	280	100.0	-)
Expectation	Expected after action	332	40.7	116	41.4	χ^2 13.6
	Expected on base of data	119	14.6	65	23.2	χ^2 (0.05)
	Unexpected	365	44.7	99	35.4	= 5.99
Urgency	Urgent	97	11.9	46	16.4	
	Less urgent	273	33.5	125	44.6	χ^2 22.9
	Not urgent	368	45.1	97	34.6	χ^2 (0.05)
	No information	78	9.6	12	4.3	= 7.81
Action	Preceding	348	42.7	124	44.3	
	Subsequent standard	45	5.5	10	3.6	χ^2 4.1
	Subsequent non-standard	16	2.0	10	3.6	χ^2 (0.05)
	No action	370	45.3	123	43.9	= 9.49
	By maintenance-men	37	4.5	13	4.6	
Type	Analogue oncoming	195	23.9	64	22.9	
	Analogue return-to-norm.	192	23.5	58	20.7	χ^2 1.4
	Binary oncoming	227	27.8	83	29.6	χ^2 (0.05)
	Binary return-to-normal	202	24.8	75	26.8	= 7.81

For each aspect, we tested the independency between the (response) alternatives and the fact, whether or not the signals occurred during a cluster or oscillation. (The χ^2 statistics were based on the columns with the raw frequencies.)

The explanation for rating these signals as more urgent is due to the fact that operators could easily have missed them in the middle of the clusters and the oscillations, which confirms hypothesis C. (The operators also reported this problem in the interviews, Section VI-B).

In conclusion, we would emphasize that clusters and oscillations should be made less dominant. In Section VII-B we deal with measures that will reduce these kinds of signals.

VI. RESULTS OF INTERVIEWS

The operators were asked to give their opinions about favorable and less favorable aspects of the annunciator system (Section VI-A) and also their errors, if any, while processing the signals (Section VI-B). The main points are mentioned in this section.

A. The Annunciator System

1) General Aspects: The annunciator system concerned (Section III-B) presents *all* the return-to-normal signals. In the operators' opinion they should be presented because the operator needs to know whether the process variables have returned to the required state in one part of the process while he is dealing with another part. He also likes to know whether the plant operator performs the task he has been set, and what stage the process has reached (reduction of uncertainty).

2) Audible Subsystem: In the opinion of the operators the audible signal was irritating. They said that sometimes they acknowledged as soon as possible to get rid of the signal! They thought that their irritation was due to the great number of signals which were sometimes audibly presented. In the case of an automatic start or stop procedure in one of the process groups, only the beginning and the end of the procedure were presented audibly. All the other signals were visual ones. This kind of noise reduction was considered to be an improvement.

3) Visual Subsystem: It was not seen as a problem that one part of the system had been designed in light field (graphic panel) and the other one in dark field (console). An explanation for this attitude could be the physical and functional separation of both systems.

In the opinion of the operators, a part of the dark-field system had not been designed logically. The running lights of seven motors that were not always in operation were unlit when their motors were not running. The lights of the other motors that were placed on the same console were unlit when they were working. This was understandably found to be rather confusing. They suggested putting them all in the light-field system because they thought that something that is working should be lit.

The matrices on the console were easy to observe (see also Fig. 3). No discrimination problems were mentioned because the text of the annunciator had been placed on the "light-window" and not above, below, or beside it. The characters on the light-window were found to be too small. If more text is needed, well-chosen abbreviations should be used.

The graphic panel was seen as a useful tool because it gives an overall picture of the following:

- the state of the process (which part is working; how the process units are linked together);
- a breakdown (what is happening);
- the work outside the control room (which part is the plant operator dealing with).

4) Acknowledgment Subsystem: Group acknowledgment was considered to be inferior to the individual acknowledgment with which most of the operators were familiar. As possible reasons the following were mentioned: the signals that are overlooked can be "acknowledged" unseen (see also Section VI-B); another signal occurs *while* an acknowledgment push-button is being pressed, and then this signal is lost! (Although the probability of the latter occurring is low, it nevertheless exists.)

Group acknowledgment also has disadvantages when oscillation and cluster signals occur (Section V-C). While holding the finger on the push-button, the operator will not notice single signals in the same acknowledgment group.

If group acknowledgment has to be applied, e.g., in some of the more advanced systems or when a part of the system has been placed above reaching height (see Fig. 3), then the acknowledgment system must be designed in such a way that only a very short trigger-pulse is given when a button is pressed, and not a continuous pulse that lasts as long as the button is pressed. In the first case a signal that is coming on during pressing cannot then be acknowledged.

B. Errors Made/Critical Incidents

The most important incidents are mentioned in this section.

Incident A: Failure to notice a particular signal when several annunciators start flashing at the same moment.

Cause: The annunciator system concerned had group acknowledgment. Therefore the signal was acknowledged without a visual check.

Consequence: The light of the annunciator concerned stayed on (unseen by the operator) and some time later a process part stopped.

Incident B: Failure to notice that process unit *B* had stopped during the start-up of another unit *A*.

Causes: The operator did not notice and did not acknowledge the annunciator system because he had the idea the signals all belonged to unit *A*.

The operator kept on acknowledging in order to get rid of the audible signal, not adequately noticing the visual system.

Consequence: Production flow was disturbed.

Incident C: The signal was incorrectly assessed.

Causes: The attention of the control room operator was distracted by other duties/tasks (other process units, telephone calls, the presence of maintenance people, and so on).

The operator was not yet well-informed about the process.

Consequence: A part of the process stopped and a dangerous situation occurred for the plant operator.

In most cases distraction seems to be the cause of wrong actions and commands. We quote one of the operators in the following: "... Mostly these events happen when we are busy, ... when there is a crowded control room, ... much maintenance work to be done, etc. ..."

Incident D: The stopping of a piece of apparatus was presented audibly, but the annunciator concerned on the graphic panel did not flash. The operator did not see anything, guessed that it was an unimportant signal, and merely pressed the button.

Cause: The light of the annunciator was defective.

Consequence: The process unit stopped.

Incident E: Looking at the graphic panel from his seat, the control room operator instructed the plant operator by telephone to start a particular conveyor-belt. Later it appeared that the wrong conveyor-belt had been started.

Causes: The black apparatus numbers on the graphic panel were too small[3] and it was difficult to perceive the black numbers correctly on a blue background.

Consequence: The plant operator corrected the control room operator and asked by telephone which conveyor-belt should be started.

VII. Conclusion and Recommendations

A. Functions of the Process-Alarm System

Our findings indicate that in the fertilizer plant the process-alarm system is mainly used as a monitoring tool in process control and not as an alarm system requiring action (Sections V-A, V-C and VI-A). Both changes in the process state (attention function) and the state itself (memory function) are monitored.

Consequently, the effects postulated in hypotheses A and B (Section II-C) could not be proved. In view of the results of our study, we prefer to use the term annunciator system instead of the usual—alarm system. The term alarm system suggests an alarming situation in which action had to be taken. In reality, however, we found that the warning signal in many cases merely confirms the action of the operator. It gives feedback to him (reduction of uncertainty). Only 7.5 percent of the signals was followed by operator action. Sometimes the operators in the fertilizer plant even used the annunciator system as a communication system (Section V-A1).

Another important function of the annunciator system is its memory function. A review is given of the state of the process contacts, which is necessary for monitoring and identifying the actual state of the process.

Because of these various functions, it seems advisable to investigate whether an alarm system could be designed (in addition to the annunciator system), which would give only the actual alarms (fatalities and equipment-danger alarms). These signals would not permit easy acknowledgment as was discovered in the interviews (Section VI-B).

B. Reduction of the Number of Signals

The number of *single* warning signals we recorded in about 64 h was surprisingly high, as was the percentage of not-urgent signals (51 percent; both oncoming ones and return-to-normal). In our opinion there are two ways of

[3]Text must be easily legible. The size of the letter symbols on the graphic panel must follow the (ergonomic) rule: minimum size of the symbols is the reading distance/143 [13].

helping the operator with the burden of so many signals: off-line analysis and real-time analysis. For off-line analysis, staff and operators should consider the implemented alarm points. One might ask the question: Are all these points necessary for a good control of the process? Real-time analysis could assist the operator in diagnosis [14].

One should be very careful about decreasing the number of signals by the nonpresentation of the return-to-normal signals (with the idea of not burdening the operator with unnecessary information). From the interviews we learned that in the operators' opinion, return-to-normal signals needed to be presented (Section VI-A). We have to keep in mind that the operators in the fertilizer plant were only familiar with a system which includes the return-to-normal signals. On the basis of the ratings of all single signals (Section V-A), it is surprising why in so many other systems (in other companies) return-to-normal signals are not presented audibly (no attention function) and in some systems not at all (no feedback function). From the observation data we learned that in the fertilizer plant, a return-to-normal signal (with the light flashing more slowly) did not mean no information. Sometimes it was even very important, e.g., when after noticing it the operator had to carry out an action immediately.

In about a quarter of the observation time the operator was burdened with a great number of signals which he knew would come (*clusters* and *oscillations*, Section V-C). Also, during clusters and oscillations, single signals occurred. These signals were rated as more urgent than those occurring alone because these signals could easily be overlooked by the operator (Section V-C). Such events have occurred as was stated in the interviews (Section VI-B).

In the design phase of an annunciator system in a particular plant, one should investigate when clusters and oscillations will occur, and what measures can be taken to decrease the number of these signals.

For the fertilizer plant we recommended the following.

1) Clusters should be made less dominant. It is not advisable to suppress the cluster signals totally. First, the operator has to identify a particular cluster and second, in the fertilizer plant, he needs to check it visually. Some simple methods to make clusters less dominant are as follows.

A Suppression of the Audible Signal: At the beginning of a cluster, the operator throws a switch so that the signals of that cluster are only presented visually. When the cluster has finished, the switch must be thrown back, either manually or automatically.

Cluster Acknowledgment: This is a kind of group acknowledgment for all the annunciators that give a signal during a particular cluster. Apart from this, the normal acknowledgment system for these annunciators remains (Fig. 7).

In the fertilizer plant, one can tell from which particular annunciators the signals of the clusters are coming and therefore can easily separate them electrically from the other signals.

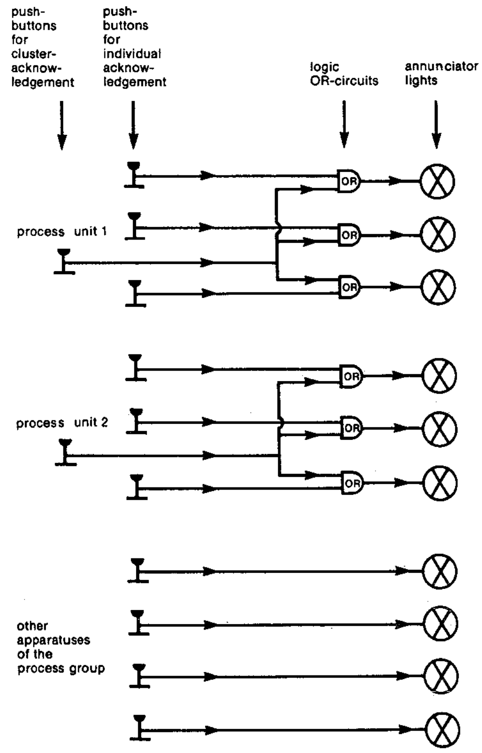

Fig. 7. Scheme of cluster acknowledgment.

2) The number of oscillations must be decreased. Oscillations occur when a process variable is continually passing the alarm limit. This can be suppressed by the following:

- the introduction of a "hysteresis" around the alarm limit;
- the changing of the value of the alarm limit (This is appropriate when the process variable oscillates around that point only);
- the introduction of a time delay. (This is only useful in rather fast oscillations.)

Not only did the cluster and oscillation signals give rise to a busy atmosphere in the control room, but the maintenance that was carried out during the morning shift did also (see Appendix). This busyness should be limited as much as possible.

C. Suggestions for Further Research

In Section II-A we dealt with the audible, visual, and acknowledgment subsystem of the annunciator system in more detail. These systems are interesting from an ergonomic point of view because they form a part of the "interface" between the human operator and (in our case) the chemical process.

The methods and techniques developed and used in this study allowed us to gain insight into the actual use of the annunciator system. These methods, however, are rather time consuming, but nevertheless necessary for a good understanding of the situation (see Sections V-A3, VI-A, and VI-B). They also provide us with a framework on which further research can be built.

TABLE VIII
INFLUENCE OF MAINTENANCE

Number of single signals caused by maintenance actions:	59	16.5 %	(n=265+92)
Number of clusters and oscillations caused by maintenance actions:	8	14 %	(n=42+16)
Number of counted signals in these clusters and oscillations:	176	32 %	(n=485+59)

Maintenance actions are actions done by the maintenance men and actions done by the operators in preparing the apparatuses and machines for maintenance.

This study also taught us that in our control room the operator sometimes acknowledges only to get rid of the *audible* signal (Sections VI-A and VI-B). In theory this is a strange reaction because the operator is made aware of a change in the process state by means of this signal (attention function). In practice, however, it is necessary to know which requirements the audible system has to meet in order to avoid the above reaction (see also [15]).

Moreover one should investigate, under laboratory conditions (simulation experiments), whether it is the signal itself or the number of warning signals per unit of time that determines the impression made.

It was said that in the fertilizer plant, with its conventional system, the *visual* system was easy to observe. In a push-button system for fascia lights, the operator can see at a glance which process variables are off-normal. He simply recognizes the light by its position. In the more advanced systems, however, the different (warning) signals are all presented on one or more visual display units and printers. In these systems information about the state or the change of state is not immediately available and can only be obtained after a request; thus, the operator has to search for information. Moreover in these systems the operator must always read the information, which is mostly given in text, and must acknowledge on a separate keyboard. This way takes time and could cause human errors. We know that operators sometimes complain about the lack of a good overall view in these systems. Attention and memory functions seem to be inferior to those of a conventional system. Therefore we think it is necessary to set up a simulation experiment. In this experiment different ways of presenting the information to (trainee) operators in the same process situation should be compared systematically, both objectively (performance measures, errors, and so on) and subjectively (ratings). Studies of this kind will lead to the formulation of design rules. In our opinion one should incorporate as much as possible the favorable aspects of the old conventional systems in the flexible new ones.

In field research, one can trace the favorable and less favorable aspects (Sections VI-A and VI-B), but sometimes one has to verify opinions under laboratory conditions. The following will illustrate this statement. In applying *group acknowledgment* (Section II-A), also often used in the more advanced systems), it was said that the operator sometimes dealt inadvertently with a signal that he had not even noticed because it occurred simultaneously with other signals. Therefore it should be better to acknowledge each signal individually. We think it necessary, in addition to the operators' opinion and common sense, to have data gained from simulation experiments with which to prove that group acknowledgment should not be applied.

APPENDIX

In Section V-B we concluded that within a particular shift, busy periods versus quiet periods cannot be clearly indicated. A comparison of the shifts with regard to "busyness" can however be based on the number of signals per unit of time.

The number of signals recorded and the total observation time in each shift are shown in Table II. By analysing these data (single signals during clusters and oscillations and those outside clusters and oscillations added together) with the χ^2-test, we concluded that more single signals per unit of time occur in the morning shift than in the other two shifts ($\chi^2(2) = 11.01$, $p < 0.05$).

In the above calculation, clusters and oscillations themselves were not included. Some data concerning them are also shown in Table II. When included, the χ^2-test gave the following results:

- in the morning shift, more signals per unit of time are counted than in the other two shifts ($\chi^2(2) = 82.94$, $p < 0.05$);
- in the morning shift, the estimated number of non-recorded signals is greater per unit of time than in the other two shifts ($\chi^2(2) = 47.41$, $p < 0.05$);
- the number of clusters and oscillations per unit of time is not significantly higher ($\chi^2(2) = 1.81$, $p < 0.05$).

The first two results indicate that more signals occurred during the morning shift than during the other two shifts. In the process industry, one has the impression that the morning shift is busier than the other two shifts. The reason is that besides the operators many other people are present then and much maintenance work is being done. The operators in the fertilizer plant were of the same opinion. In order to test whether or not the extra number of signals mentioned above was really caused by maintenance actions (only carried out during *morning* shifts), we drew Table VIII (to follow).

When the numbers of Table VIII were subtracted from those in Table II, the following χ^2 values were calculated: $\chi^2 = 11.01$ became 0.25, $\chi^2 = 82.94$ became 9.24, and $\chi^2 = 1.81$ became 0.67. So, we found none of the χ^2 values significant. From this result, it can be concluded that maintenance did cause most of the additional warning-signals.

There are two other ways of explaining the operators' busy morning shift: the presence of maintenance men and other (staff) people in the control room contribute to a busy atmosphere and could have distracted the operator; and the signals caused *and* acknowledged by a maintenance man (e.g., during testing a circuit) were not taken into account. Of course these signals added to the busy atmosphere.

Acknowledgment

The authors are very grateful to Professor J. E. Rijnsdorp, Professor M. J. M. Daniëls, Dr. H. Kuipers, Mr. E. Piso, and Mr. T. White for their valuable comments. The authors wish to thank the Dutch chemical industry (DSM) for their permission to publish the article and Mr. J. Praagman for his advice concerning the statistical analyses. Thanks are also due to the operators in the fertilizer plant and to Mr. J. van Dijk.

References

[1] P. K. Andow and F. P. Lees, "Process-plant alarm-systems: General considerations," in *Loss Prevention and Safety Promotion in the Process Industries.* Amsterdam: Elsevier, 1974, pp. 299–306.

[2] E. Edwards and F. P. Lees, *The Human Operator in Process Control.* London, England: Taylor and Francis Ltd., 1974.

[3] T. J. Williams, "Interface problems for process control," presented at the 1974 IFAC/IFIP Symp., Zürich.

[4] Purdue-Europe, "The operator interface in process control in European industries," *TC-6 Man–Machine Commun.*, SINTEF, Trondheim, Norway, May 1977.

[5] *The Accident at Three Mile Island*, Rep. President's Commission, Washington, DC, Oct. 1979.

[6] T. B. Sheridan, "Human error in nuclear power plants," *Technol. Rev.*, pp. 22–33, Feb. 1980.

[7] H. Kragt and D. Kortlandt, "Ergonomics in the struggle against 'alarm inflation' in process-control systems," in *Automation for Safety in Shipping and Offshore Petroleum Operations*, A. B. Aune and J. Vlietstra Eds. New York: North-Holland, 1980, pp. 231–238.

[8] L. Bainbridge, "Verbal reports as evidence of the process-operator's knowledge," *Int. J. Man–Machine Studies*, vol. 11, pp. 411–436, 1979.

[9] H. Kragt, "Human reliability engineering," *IEEE Trans. Rel.*, vol. R-27, pp. 195–201, 1978.

[10] J. C. Flanagan, "The critical-incident technique," *Psychol. Bull.*, vol. 51, pp. 327–358, July 1954.

[11] D. Kortlandt and H. Kragt, "Process-alarm systems as a monitoring tool for the operator," in *Proc. 3rd Int. Symp. Loss Prevention and Safety Promotion in Process Industries*, Basel, Switzerland, vol. 10, pp. 804–814, 1980.

[12] G. M. Jenkins and D. G. Watts, *Spectral Analysis and its Applications.* San Francisco, CA: Holden-Day, 1968.

[13] S. L. Smith, "Letter size and legibility," *Human Factors*, vol. 21, no. 6, pp. 661–670, 1979.

[14] P. K. Andow, "Real-time analysis of process-plant alarms using a mini-computer," *Comput. and Chem. Eng.*, vol. 4, pp. 143–155, 1980.

[15] J. Wheale, "*Auditory Warnings: Signal Variations and their Effect on the Operator*," presented at the 30th Annual Conference of the Ergonomics Society, St. Catherine's College, Oxford, Apr. 1979.