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Publication date:
2005

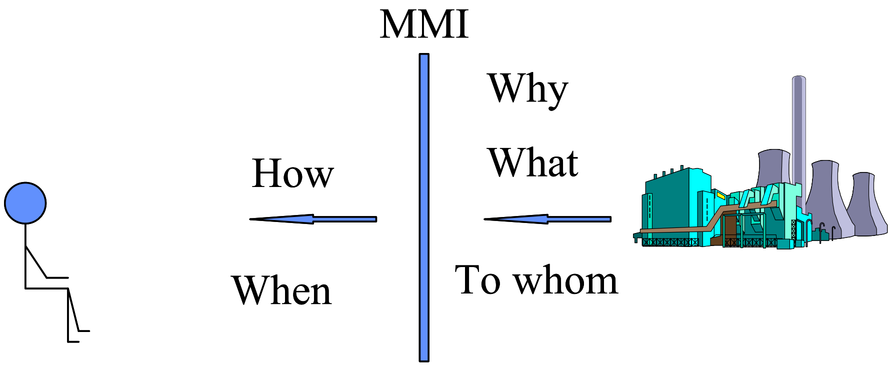
Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Paulsen, J. L., & Lind, M. (2005). Design of Process Displays based on Risk Analysis Techniques. Risø National Laboratory. (Risø-PhD; No. 8(EN)).

Risø-PhD-8(EN)

Design of Process Displays based on Risk Analysis Techniques

Jette Lundtang Paulsen



Risø National Laboratory
Roskilde
Denmark
May 2004

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This thesis is submitted in partial fulfilment of the requirements for the Ph.D. degree at The Technical University of Denmark and Risø National Laboratory

Abstract :
This thesis deals with the problems of designing display systems for process plants. We state the reasons why it is important to discuss information systems for operators in a control room, especially in view of the enormous amount of information available in computer-based supervision systems. The state of the art is discussed: How are supervision systems designed today and why? Which strategies are used? What kind of research is going on? Four different plants and their display systems, designed by the author, are described and discussed. Next we outline different methods for eliciting knowledge of a plant, particularly the risks, which is necessary information for the display designer. A chapter presents an overview of the various types of operation references: constitutive equations, set points, design parameters, component characteristics etc., and their validity in different situations. On the basis of her experience with the design of display systems; with risk analysis methods and from 8 years, as an engineer-on-shift at a research reactor, the author developed a method to elicit necessary information to the operator. The method, a combination of a Goal-Tree and a Fault-Tree, is described in some detail. Finally we address the problem of where to put the dot and the lines: when all information is 'on the table', how should it be presented most adequately. Included, as an appendix is a paper concerning the analysis of maintenance reports and visualization of their information. The purpose was to develop a software tool for maintenance supervision of components in a nuclear power plant.

Resume Denne afhandling drejer sig om problemerne med design af display systemer til procesanlæg. På grund af de store mængder af information der er til rådighed med computerbaserede systemer er det nødvendigt at fastlægge hvilke informationer operatøren behøver for kunne udføre sit job. State of the art bliver også diskuteret: Hvordan designes overvågningssystemer i dag? Hvilke strategier bruges til designet? Hvad foregår der på forskningsområdet? Fire forskellige display-systemer, som forfatteren har udviklet, beskrives og diskuteres. Dernæst beskrives fra hvilke kilder designeren kan få oplysninger om anlægget. Der lægges vægt på hvilke risici der kan forekomme med anlægget. Et kapitel beskriver hvilke grænseværdier der kan benyttes ved display design, såsom konstitutive ligninger, setpunkter, komponentkarakteristikker, design parametre, samt deres validitet i forskellige situationer. På baggrund af forfatterens erfaring som designer af display systemer, som forsker inden for risikoanalyse og ud fra 8 års erfaring som driftsingeniør på en forsøgsreaktor, har hun udviklet en metodik til at fastlægge hvilke informationer en operatør *skal* have for at kunne overvåge et anlæg på en sikker måde. Metoden, der bygger på en kombination af et goal-træ og et fejl-træ beskrives i detaljer. Til sidst beskrives hvordan de nødvendige informationer kan analyseres, og hvordan de bedst præsenteres på skærmen. En artikel om informationssystemer til vedligeholdsplanlæggere er medtaget som et appendix. Formålet med dette arbejde var at udvikle et software program for vedligeholdsovervågning på nukleare anlæg.

Risø-Phd-8(EN)
May 2004

ISSN 0106-2840
ISBN ISBN 87-550-3253-2
87-550-3254-0 (Internet)

Contract no.:

Group's own reg. no.:

Sponsorship:

Cover :

Pages: 144
Tables: 14
Figures: 73
References: 53

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Preface

This thesis is the result of a PhD study performed at Risø National Laboratory and the Technical University of Denmark. The study forms a part of the research carried out in the OECD Halden Reactor Project (HRP) in Norway and in the Nordic Nuclear Safety (NKS) Projects. For the authors part of the research, the HRP concerns development of display systems to operator in nuclear power plants and the NKS, information systems for maintenance planners. During earlier project work within HRP and NKS I found there was a gap between research on the design of display systems and practical experience and knowledge. The designers, often operators with practical experience and knowledge on the other hand do not know about the research going on in the field. It is this gap I want to bridge with the thesis.

There are two main subjects to treat: What to present to the operator, and how to present it. These are also the main subjects for the thesis.

The displays developed for nuclear power plants have been tested on full-scale simulators at the Halden Reactor Project. A software tool for maintenance supervision has been further developed at Risø and is now installed at the central office in Stockholm, where all maintenance and failure reports for the Nordic nuclear reactors are collected: a tool to which all the involved power plants have access.

Acknowledgement

I would like to thank Risø National Laboratory, The Technical University of Denmark, The Halden Reactor Project and the Nordic Nuclear Safety Project, for supporting my Ph.D. project.

Thanks are due to Prof. Professor Morten Lind, DTU for supervising my study as well as to Assist. Prof. Johannes Petersen, DTU and my colleagues at Risø for advice and helpful discussions. Linguistic assistance was kindly provided by Poul Einer Hansen.

Part I

1. Introduction

To operate a process plant one must be familiar not only with the plant and the process but also with the safety aspects of the operation. Particularly in abnormal situations the operator must have access to key information so that he can observe the state of the plant quickly and interpret the situation. Only then will he be able to convert unwanted situations and to take action and lead the plant into a safe state.

1.1.1 Content and form

In order to assist the operator in carrying out his tasks and to support his situation awareness, the plant must be furnished with an appropriate *information system*. And it is not enough that the displays of the information system show all relevant information: they must present it in a way that makes it easy for the operator to observe if the state of the plant has deviated from the expected; to find out what has happened; and to decide what to do about it.

Thus the problem of designing a process plant information system has two sides: on one hand, to select the information content of the displays; on the other, to choose the form in which to present the information.

This work focuses on process plants where an early detection of failures has an impact both on the economy and on the safety of the plant. In particular we shall also study *condition monitoring* which relates to the 'health' of a component or a system. The condition of a component may have been reduced by degradation or by a defect, but this does not necessarily influence the function of the component directly because a control system may compensate for the failure. The function is disturbed only when the control system is no more able to compensate. The purpose of the condition monitoring is to be aware of incipient failures before they disturb the function of the system or the plant. Besides, condition monitoring is a valuable tool for maintenance planning.

1.1.2 The design problem

When an interactive screen-based information system is installed in the control room of a process plant, the operator may be provided with almost unlimited access to information. It seems fair to expect that the designers of such information systems should not just be concerned with assessing the content of the information, but should also develop a strategy on how to present this information to the user. Yet only some few general methods have been developed to support the design of such systems, and general, strategic considerations are scarce.

How is the design carried out in practice? Who are the designers? And which strategies do they apply? To enlighten questions like these a study of recently installed, screen-based control rooms was carried out, Paulsen and Weber [36]. The over-all conclusion of the study was that at the four plants in question the screen-based information systems present the information in a rather unsophisticated form based mainly on *mimic diagrams*, with measured parameters displayed as digits.

To establish if some design strategy had been followed, both regarding content and form of the information, a questionnaire was handed out. The persons who had designed the displays filled in the questionnaires; at three of the plants these were operators and at the fourth one it was an employee from the electricity department. At the three plants where an operator had been in charge of the design the display design was mainly based on experience; at the fourth one the displays merely copied the PI diagram (Piping and Instrumentation diagrams). Hence, it came out that strategies were almost entirely absent.

1.1.3 Why this lack of a strategy?

One reason could be that little work has been done in the field, especially with strategies that can be applied by non-scientific staff. Besides the software for display design tends to focus on mimic diagrams; these are well known and it is fairly easy to copy the PI diagrams.

The mimic-diagram approach in the design of information systems means that the possibilities inherent in the computer-based systems are not utilised to the full. Much relevant information about the operation and condition of the plant can be extracted by the computer systems. For example one may calculate illustrative parameters such as energy flow, efficiencies of heat exchangers, fouling factors, conditions of components, system functions and characteristics, and various indicators of a deviation from expected behaviour.

Information systems still tend to be based on a one-to-one relation between measurement and information unit presented, just as in the control rooms of former days where the mimic diagrams were painted on the wall and an instrument was typically located just at the measuring point in the mimic diagram. In the old control rooms, though, there was a variation as to how the measurements were presented: some were shown on meters, others were presented as functions of time, and others again were shown as bars (temperature, pressure). But it was difficult to see which information was more important than other, and this is still the case in rather many recently installed control rooms.

A number of guidelines exist for the design and evaluation of Human Computer Interfaces, but they are of general nature [11] in the sense that they put up numerous requirements to the content of the information system, but they do not indicate where and how this information is acquired. Researchers within different disciplines have worked on how to improve on display design, especially the forms of presentation. Very few have worked on the content needed for early detection of failures and diagnostic purposes. The most well known research is done by J. Rasmussen [40] who has developed the Abstraction Hierarchy (AH), which is a framework for organizing knowledge of goals and functions based on a means end analysis. The AH is further used in the theory of Ecological Interface Design (EID) of Vicente and Rasmussen [51]. Some of the research in presentation forms has been included in the NUREG-0700 rev.2 guideline for nuclear power plants. There is still a lack of practically useful methods for determining information to be presented for the operator so he is able to observe incipient failures and be able to perform a diagnoses task.

1.1.4 Goal for the thesis

A main goal for the author of this thesis has been to develop strategies for design of display systems, both regarding the content and the presentation form. The thesis has its main focus on the diagnostic tasks and how to observe incipient failures and disturbances in plant performance. The goal is pursued in two ways: firstly by carrying out a literature study of the methods developed, stressing their use and the tests that have been made of them and discussing at some length the most important works in the field; secondly by giving an account of the author's own contributions to display design, including the use and tests of these displays, combined with her experience with maintenance planning, plant design and risk analysis methods. Four specific display systems created by the author are thoroughly discussed in Chapters 3-6, thus constituting a core matter of the work and this together with other researchers work are the background for the development of a strategy for display design. The strategy is based on a combination of a Goal-Tree and a Fault-Tree for determining the content of the display. The presentation form is based the different graphical elements described in this report and a description of where and how to use them for different purposes.

1.1.5 Composition of the thesis

The thesis is organised in three parts.

Part I, Chap. 1 – 2, explains the problem and looks into what has been done about it. Chap. 1 is the present introduction, which describes the background for the work and outlines how it is composed. Chap. 2 is an account of the ‘state of the art’ of display systems design, including existing standards and guidelines as well as recent and ongoing research, and concluding with a discussion of problems to be solved.

Part II, Chap. 3 – 8, is mainly concerned with the four specific display systems designed by the author: for a pipe reactor system (Chap. 3); for a pressurised nuclear reactor (Chap. 4); for a waste incineration plant (Chap. 5); and for a condenser (Chap. 6). Each of the four systems is treated in detail including a process description, the background for the design, its use and test, and an evaluation of the design. The development of these systems gave rise to the idea of using risk analysis as a structured method to determine the information content of the displays. The design of a display system requires a thorough knowledge of the system in question; therefore the treatment of the four specific systems is supplemented with a general discussion (Chap. 7-8) of structured methods to give information to the designer.

Chap.8 describes different kinds of references for the functions and the conditions of the plant. This regarding constitutive equations, design parameters, empirical rules etc. and their validities in different situations

Part III of the thesis, Chap. 9 – 10, treats three aspects of the theoretical framework, as conceived by the author, for the design of display systems for supervision of plants and for condition monitoring of components.

Chap. 9 describes the development of the Goal-Tree Fault-Tree (GTFT) method and discusses in a comparative study the difference from the Abstraction Hierarchy.

Chap.10 concerns the presentation of the information, and gives a strategy on how this can be done on the basis of different known graphical elements and a structured method for the presentation.

Chap.11 is a discussion of methods and how the new strategies contribute to the ongoing research and the guidelines.

Chap.12 is the conclusion

Appendix A is a paper attached concerning visualisation of outcomes from failure reports.

2. Display Systems: State of the Art

In a description of the state of the art of new display systems and ongoing work, it seems appropriate to narrow the scope to design principles that can be used within technical systems.

Some of the literature we have studied were chosen because they focus on *technical systems*; others because they explain and illustrate how *visualisation of information* has been realised in different areas. Not all of the references are of direct interest for the research of the author because the purposes of the various ways to visualise information may be different from ours, sometimes also because the work domains differ. For the present thesis, the most interesting work domains are those pertaining to control of safety critical process plants, where *dynamic* information is presented to the operators. The operators must observe changes in the dynamic system and interpret these changes. Therefore it is appropriate already at this point to distinguish between dynamic and static work domains.

Still, the presentation of static information can be relevant at technical plants for some purposes, such as (1) studying the failure history of certain components; (2) updating the risk analysis; and (3) optimising maintenance. A chapter on these issues is included in the thesis (Appendix A), but compared with the dynamic work domain they are of minor interest.

Judging from the literature on the design of display systems including review papers, quite a few researchers have worked with the visualisation of information from dynamic systems such as process plants. Rasmussen[40], Beltracci[4], Lindsay[22], Woods[53],Vicente[51] have developed new ideas for strategies for the design of displays. Sanderson [23], Jamieson [17], Han Ham[13] have used and tested some of the ideas. These people and their groups have made the most well known research in the field of dynamic work-domains. Many of the display systems that have been described elsewhere e.g. Tufte and Sears[43][41], concern the presentation of static data from databases. Indeed one can get good ideas from the static presentation modes also on how to present information about dynamic systems, provided the presentation mode can meet the requirements for dynamic presentations; in particular it must be easy to observe and easy to understand.

One difference between presenting static data and dynamic data is exposed when asking who or what may activate the presentation, cf. Vicente [49].

When searching information from static data, it is the user who decides when to do the search, and sometimes also how to do it. There is no time pressure and therefore no need for fast observations and actions. Looking for a house to buy, wanting to know the relationship between the number of bathrooms and the price, is not the same as supervising a nuclear reactor. The same goes for historic data on components, cf. Paulsen et al.[Appendix A] where the data can be presented in 10 different ways to get the required information and an extra search can be done if required for the long time maintenance planning.

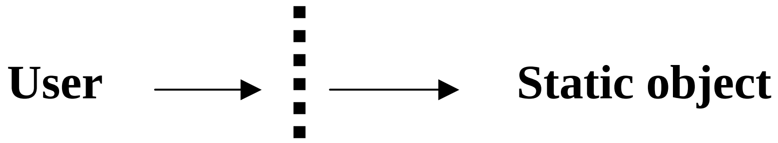


Figure 1 The user is the initiator to get information

For dynamic systems such as process control, it is the plant supervision system that draws the operators' attention to the fact that something in operating condition is not as it ought to be. To utilise this information, the user must act on them very quickly to find the disturbance in the plant. The operator has no influence as to when the system wants his attention.

Diagnosing a failure requires that the user can find the appropiate information for the system in question and that the presentation is easily understood, so that he is able to act in time before the failure propagates into a serious event.

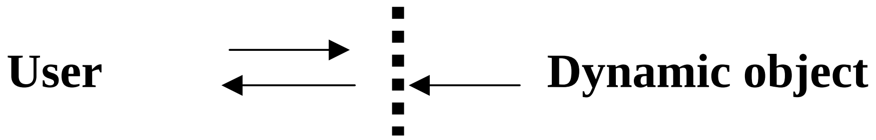


Figure 2 The dynamic object is the initiator to give information

In the dynamic case, the design of a display system must be more stringent than in the static case. The reasons are (1) the time pressure problem and (2) the consequences in case of a misunderstanding of the information.

2.1 Guidelines and Standards

In this chapter of state of the art, existing standards and guidelines for display design will be described. Especially the recommendations from USNRC (United Nations Nuclear Regulatory Committee) guidelines will be explained in more detail.

Guidelines and standards exist for design of new control rooms. The Human Computer Interface Guidelines are e.g.
NUREG[44], ISO[16], IEEE[15], EPRI[10]

The guidelines specify tasks to be done by the designer when developing a new control room. This concerns ergonomic issues such as the choice of furniture, light, distance to displays, size of fonts on the display, colours, where to place important information, where to place the desks, the chairs etc.

About the displays, design recommendations are given for

- General display guidelines
- Display formats
- Display elements
- Data quality
- Display devices

The NUREG-0700 [44] Human System interface Design review Guidelines and the NUREG –0711[46] Human factors Engineering Program Review model for nuclear power plants, describe all issues to take into account when designing a new control room to meet the requirement for the final review by NRC. This also concerns test of the systems and training programs for the users. The EPRI and the IEEE follow the same guidance as the NUREG guidelines recommend and therefore in brief the NUREG guidelines concerning the content of the displays will shortly be described.

The requirements are described on a general level and concerning the detailed design and integration the guideline NUREG-0711 recommend that the applicants should develop their own specific and detailed guideline for new HSI (Human System Interface) based on the generic guideline as the present. The NUREG-0700 review guideline is based on the design recommendation in NUREG-0711 and NUREG/CR 6633

They also emphasize that the specific guideline should be written so it can be readily understood be designers.

2.1.1 Content of the display System

In the process of designing a display system, the first and most important task is to assess the information content of the displays.

For the determination of what to be presented the NUREG guidelines recommend to do an *information requirement analysis*. The information required is expressed as:

Information requirements refer to what information operators need to safely and efficiently operate the plant.

The guidelines describe the Information requirement analysis to emphasize

- Operating experience:
  Lessons learned from other complex human-machine systems, especially predecessor designs.
- Functional requirement analysis and function allocations:
  Support of the operators role in the plant, e.g. appropriate levels of automation and manual control.
- Task analysis:
  Tasks that are necessary to control the plant, detailed information and control requirement for normal and accident conditions. Possibility to get detailed information.
- System requirement:
  Constraints imposed by the instrumentation and control systems.
- Regulatory requirements:
  Applicable regulatory requirement should be identified as input to the HIS design process.
- Other Requirement:
  The applicant should identify other requirements.

The NUREG guidelines are updated frequently and new proven methods are included in the updated issues.

The ISO 9241-3 most concerning the ergonomic requirement for new control rooms are a part of the ISO 9000 requirements.

NUREG/CR 6633
About “Advanced Information Systems Design” describes new research going on and a discussion of the new research. The report describes e.g. the alternative new approach for information extraction using the Abstraction Hierarchy [40] and EID[51] (Ecological interface design). Both methods will be described later in the chapter. The word Advanced means in this connection screen based information systems.

The conclusion from studying the guidelines is that the guidelines give an overall emphasizing description of what a detailed guideline for a specific plant must take into account and include. The guidelines do not recommend specific analysis methods for e.g. operator tasks or for systems requirements.

2.1.2 Presentation of the information

Standards for design of PI- diagrams, ISO[16], has been widely used in many years for the production of drawings. These standards specify icons for all components. These icons can also be used in the design of mimic diagrams.

The information formats described in the NUREG-0700 Rev.1 guidelines describe the following types of visualization techniques to use for presentation of information on the displays. Some of them shown on Figure 3

- Mimic diagrams to present the plant layout
- Text to give information
- Digits for information of single values
- Trend curves to follow measured values in time
- Bar graphs for information of single values
- Pie charts can be used to compare values.

The NUREG-0700 Rev.2 has extended the types of visualization techniques with the following shown on Figure 4

- Polar plots
- Linear profile chart
- Configural displays
- Integral displays

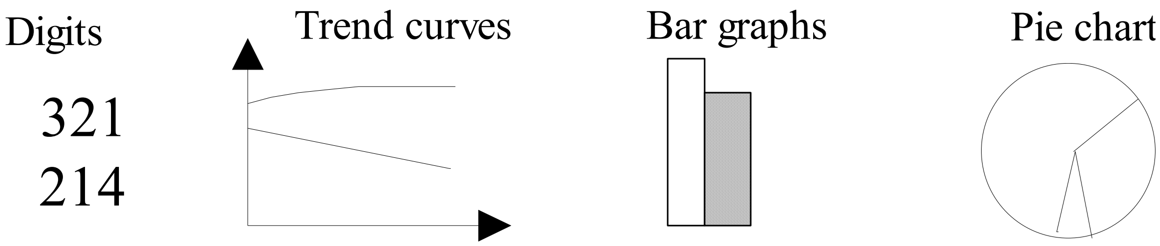


Figure 3 Common used forms for single sensor single indications

The NUREG-0700 rev.2 gives very few examples, but refer to NUREG/CR 6633 and 5908 for further information about the use of the display techniques.

The 6633 recommend that, configural displays may be used when operators must make rapid transition between high-level functions and parameter values. Integral displays are mentioned to be used to communicate high-levels, status-at-a-glance information where the user may not need information on individual parameters to interpret the display.

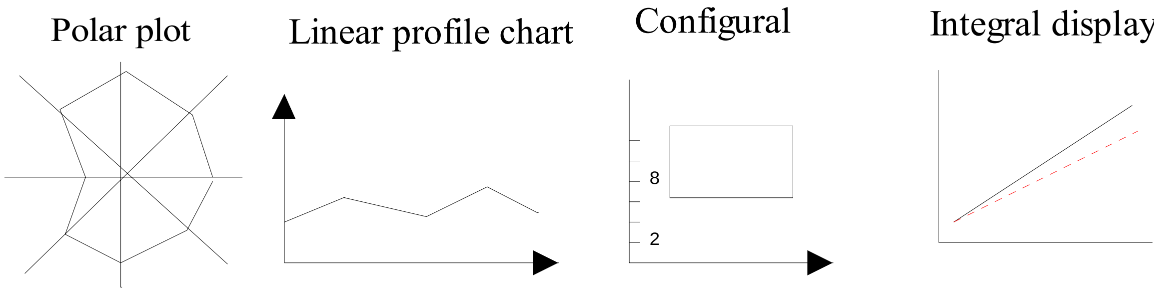


Figure 4 Advanced visualization forms for multiple variables

2.2 Ongoing research

In different disciplines such as engineering, psychology and computer science, research has been done to improve the information presentation systems, both regarding the content of the display system and the presentation of the information to the operators.

Some of the work described are implemented in the NUREG-0700 rev.2 guideline and some have still not proven their usability and further research is recommended to be done.

The research interest in improved display design for industrial applications has mainly focused on display systems for nuclear power plants. The Three Mile Island event in 1979 led to focus on human errors and behaviour and thereby on the information needs of the operator.

2.2.1 Content of the information System

2.2.2 The Abstraction Hierarchy

A serious challenge when designing display systems for safety critical plants is: How can the display be designed to meet the requirement in the guidelines that the operator must be able control the plant during normal and accident conditions. What will happen if the plant system designer has not foreseen the accident situation?

Is it possible to specify an information system that copes with this problem of unexpected events? Especially, how will the information system help to prevent a problem to develop into an accident situation

A framework for the design of interface systems, with the scope to meet this requirement, is the *Abstraction Hierarchy* suggested by Rasmussen [40].

The Abstraction Hierarchy (AH) is a framework for representing knowledge of a working domain on several abstraction levels. Such a hierarchy describes bottom-up what components and functions can be used for, how they may serve higher-level purposes, and top-down, how purposes can be implemented by functions and components. For each layer of the abstraction hierarchy information must be extracted which can give information to the operator about available goals and functions and failed goals and functions. If a goal has failed the operator should be able to find the lower level function or functions failed and be able to re-establish the goal and thereafter find the root causes for the event. This is the main purpose of using the AH framework. The splitting up into abstraction layers is called a means-end analysis of a physical system.

Each layer in the AH describes the functions and the constraints belonging to this layer. The constraints in this functional hierarchy are process limitations, constitutive equations, component characteristics, physical properties etc. The constraints for the different levels help in detecting if a function is unavailable, or partly unavailable. The AH is goal oriented, that is, each layer is a goal for the layer below and a necessary function for the goal above. The AH is a general principle and does not focus on specified events. The method can be used at all levels of a process. The following table provides a description of the five levels of representation in the AH:

LEVELS	
Functional Purpose	Production flow models, system objectives, constraints, etc.
Abstract Function	Causal structures: Mass-, energy- and information flow topology, etc.
Generalised Function	“Standard” functions and processes: Feed back loops, heat transfer, etc.
Physical Function	Electrical, mechanical, chemical processes of component and equipment.
Physical Form	Physical appearance and anatomy; material and form; locations, etc.

Table 1 The Abstraction Hierarchy

2.2.3 Ecological Interface design (EID)

During the 1990’s, particularly Rasmussen together with Vicente [51] have further developed the abstraction hierarchy principle to what has been termed Ecological Interface Design (EID), comprising a model of human behaviour too. Human behaviour in process control is described with three different modes [40] skill based, rule based and knowledge based behaviour.

- Skill based behaviour: The operator act on what he observes.
- Rule based behaviour: The operator use rules or procedures to act on what he observes
- Knowledge based behaviour: The operator must interpret what he observe and take a decision based on his knowledge.

The knowledge-based behaviour is used in unforeseen situations and requires more support from the display system while the situation is not trained and no procedures exist. The purpose of EID is to change the knowledge-based behaviour into skill based or rule based behaviour. As is the case with the AH, the EID framework is a general principle, but not a guidance of how to do it in a concrete case.Vicente used the EID principle for development of the DURESS display [50], which will be explained later in the presentation part of this chapter.

2.2.4 Multi level Flow Modelling (MFM)

Another example of research in process plant modelling is the development of Multilevel Flow Modelling (MFM) by Lind [21] and his research group (1994) also on the basis of a means-end part-whole hierarchy. The MFM model has as its main objective to be used in the conceptual design of industrial automation systems. The MFM model divides the flows in mass-flows and energy-flows and uses different symbols for the functions in a process plants, such as symbols for: goal, transport, storage, source, sink, balance and barrier, Figure 5.

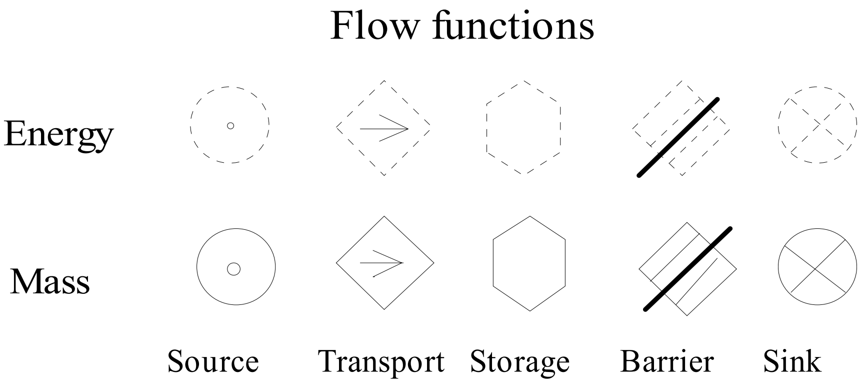


Figure 5 Multi Level Flow symbols

The MFM model focuses at the conservation of mass and energy. Each symbol is presented by its own constraint e.g. a transport function has the constraint that the input flow should be equal to the output flow. If a deviation occurs the system in the lower level of the hierarchy, which has the transport function as its goal, must be examined. This lower system also consists of a flow diagram of the MFM symbols. The information to get from a MFM model is the constraints on mass and energy on several abstraction levels. As for the abstraction hierarchy the model can be used for diagnoses of disturbed goals[21]. See also Larsson [19]

2.2.5 Application of the Abstraction Hierarchy

In his PhD project Dong Han Ham [13] has modelled the secondary circuit of a pressurised water reactor according to the AH. On the basis of the result, a display containing the required information was made. Dong Han Ham mentions that he focuses on the content of the display, not how to present the content. He uses bar graphs and numbers for presenting the information. He tested 3 different display contents: the display with the usual information measured, such as flows and temperatures; one based on the AH with high-level information such as mass and energy balances; and one with some more information. The second display with the content determined using the AH showed a better operator performance than the first one, but the third display, the one with some further information was even better. The control system of the plant was not included in the modelling.

2.2.6 Test of the Abstraction Hierarchy for other domains

The AH is developed for man-made technical systems, but this is not the same as saying that it cannot be used for other domains.

In their work concerning patient monitoring systems in Intensive Care Units (ICU), Miller and Sanderson[23] discuss the use of the AH framework for modelling “deranged” physiological systems for the ICU information systems design. The work domain is the patient.

Miller and Sanderson refer to a work of Sharp [42], concerning neonatal intensive care units. Sharp attempts to use the AH levels as defined for other domains, but he quickly concludes that these are not appropriate for this purpose; therefore Sharp modifies the AH formalism. Likewise Miller and Sanderson refer to a work of Hadjukiewicz [12] who, in a context of anaesthesia, further modifies the AH by removing control; however Hadjukiewicz admits that the conventional medical representation of the human body mixes different levels of abstraction.

Miller and Sanderson claim it is important that modelling of ICU patients includes biological control systems and makes them visible. Miller and Sanderson conclude that the AH is not appropriate for modelling biological systems.

Morten Lind [20] has in a study of the primary side of a pressurised water reactor discussed the conceptual problems in the AH.

2.2.7 Presentation of Information

A good presentation of the required information makes the difficult interpretation task easier for the operator. It is necessary that the operator from the displays understands what is going on in the plant. Therefore the problem of how to present data has also been a subject for research and tests. Below we shall describe some of the presentation methods.

2.2.8 Polar Plot

Woods [53] tested the effect of using a *polar plot* to show the variables in the primary loop of a pressurised water reactor (PWR). In a polar plot the selected variables are normalised and each normalised value is a vector starting at the centre of a unit circle.

A special feature of the presentation method is that the shape of the polar graph becomes asymmetric in case of a deviation in plant behaviour. The asymmetry makes it easy to detect that something is not as it should be. In the polar display the values can be structured due to the part of the system they belong to, so that the asymmetric shape also tells the operator where in the system the deviation has occurred. The polar plot supports the monitoring and acts as overview information and shows the operator that something has to be observed in more detail. The polar plot takes up little space on the screen; yet it shows many variables.

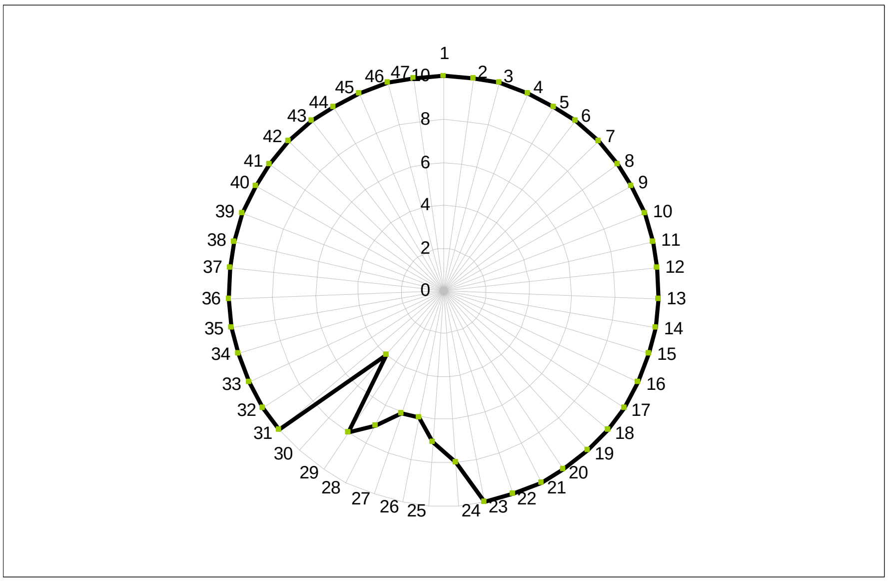


Figure 6 Polar plot of normalised variable values

Several other researchers (Bennett&Flach [**5**], Barnes& Suantak[**2**], Coury&Boulette [**8**], Hurts [**14**], Montgomery& Bivona [**26**]), have made tests of displays, both with regard to content and to form. Most of the tests compare different ways to show the single measured parameters.

We shall describe some few displays in more detail because they represent new ideas in display design and two of them also suggest the design of an entire display system.

2.2.9 Rankine cycle display

Beltracchi [**4**] designed, for a nuclear power plant, a display concept based on the Mollier diagram (water-steam conditions) where the Rankine cycle of the plant is plotted in the diagram, using entropy as abscissa and temperature as ordinate. The purpose is to show the state of the water-steam cycle and to be able to observe deviations from the expected thermodynamic states and thereby be able to make a diagnosis of what had happened. The diagram for a pressurised nuclear reactor is shown on Figure 7,

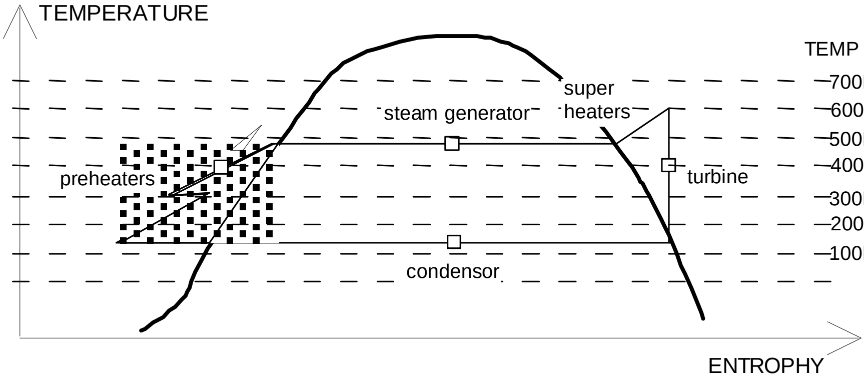


Figure 7 Rankine cycle display for a power plant

The diagram mainly shows what happens on the secondary side of the PWR plant while the primary side is represented by a small triangle to the left of the saturation line. The distance between the triangle and the saturation line is the safety margin for the pressure on the primary side.

Beltracchi was not quite satisfied with the way the primary side was shown. The pressure margin is an important safety parameter and in view of that, the presentation is not sufficiently focused. Besides, the temperature difference between the primary and the secondary side is not shown although it is an important quantity too. As mentioned above, the Ranking cycle focuses on the secondary side; for safety purposes it has less importance than the primary side.

The interesting feature of this display is that it uses a well known thermodynamic diagram as basis for the display and place the working points from different places in the plant on the diagram and get thereby the dynamic figure for the Ranking cycle. The display had not really success in its test in a simulator. The operators did not like it. Perhaps the information they got out of the display was of minor interest and furthermore is entropy an awkward parameter that the operators do not have a relation to. That was the explanation the author got from the test persons. The test persons were all operators at nuclear power plants.

2.2.10 Configural display

Based on the work of Beltracchi, Lindsay [**22**] designed a display for a sodium cooled nuclear reactor where the temperatures in the plant are presented in a polygonal graph. The Mollier diagram is shown in the display in the same way it was in the Beltracchi display for the secondary side of the reactor plant (is not shown on Figure 8)

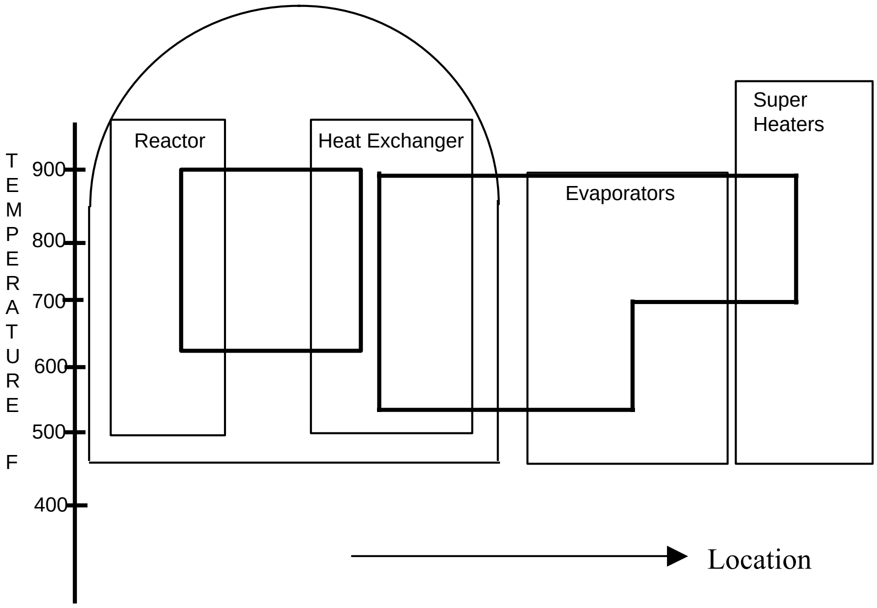


Figure 8 Lindsay's display for a sodium cooled reactor

Lindsay designed an entire display system for the reactor, but the display shown in the figure is the most innovative feature of his work on how to present the temperatures in the system. The figure shows a simple drawing of the different main systems of the plant, namely

- the reactor, which is cooled by sodium
- the heat exchanger, transporting the heat to a sodium loop
- evaporators (steam generators), using the heat from the sodium loop
- super heaters, also using the heat from the sodium loop

The bold line figures show, in their corners, plots of temperature against position of measurement. In addition to presenting the temperatures, these plots also give information about the coolant increases and decreases in the three systems. Besides, it is easy to follow the difference in temperature between the secondary and the primary side. The figure for the secondary side must show a lower temperature than the one for the primary side, because this indicates that the secondary side is able to transport the heat away from the primary side. The difference in temperature did not come forward in the Beltracchi-display although it is just as important as the pressure margin in the water-based, pressurised reactors. Test of the display was a success and the operators were very satisfied with the display.

The displays of Beltracci and Lindsay were both called Configural displays and are now included the NUREG-0700 guideline from 2002 as a form recommended to use. The displays were made around 1987.

2.2.11 Dynamic interface design (Paulsen Display)

Paulsen [33] presents the design of a display system for pipe reactors where the variation across the plant in temperature as well as in pressure is shown by means of connected lines. The idea is inspired by the Lindsay's and Beltracchi's displays, using the saturation curve as a lower limit for the pressure, to warn against a situation where the water could start boiling in the pipes. The system, which has been implemented at a pipe reactor plant and has been in use for several years, is described in detail elsewhere in this work. No strategy for selection of the information to show was used. The news was just to show the measured variables in a graphical manner and add the calculated saturation pressures from the measured temperatures.

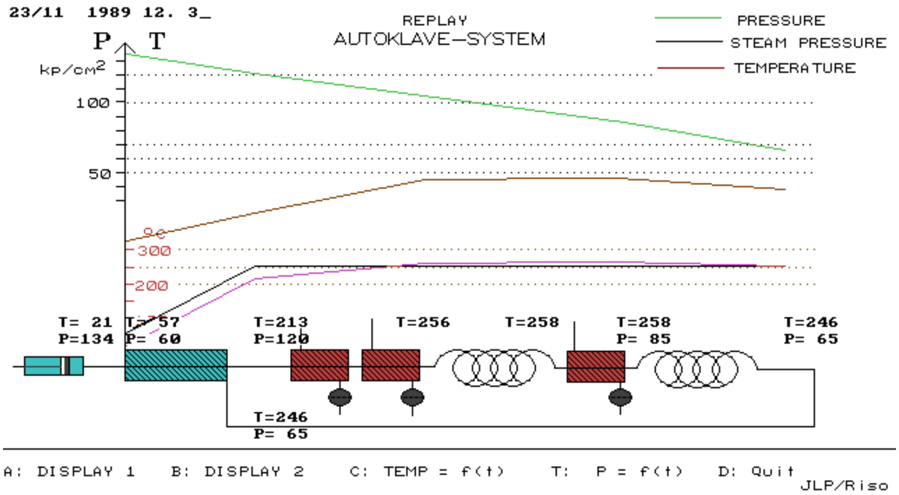


Figure 9 Paulsens' display for a pipe autoclave

The display technique is the same as for Lindsays' display with a position in the plant as the x-axis and a scale for the measured variables on the y-axis. Upon this drawing are the working points for different places in the plant placed and the points for the saturation pressure for each of these points.

2.2.12 Pressure margin on a Pressurised Water Reactor (PWR)

Weisang (in [48]) has created the display shown on Figure 10 to support the monitoring of the pressuriser in a PWR or especially the pressure margin for the reactor pressure. The display is implemented on a simulation model of an advanced reactor type in Korea.

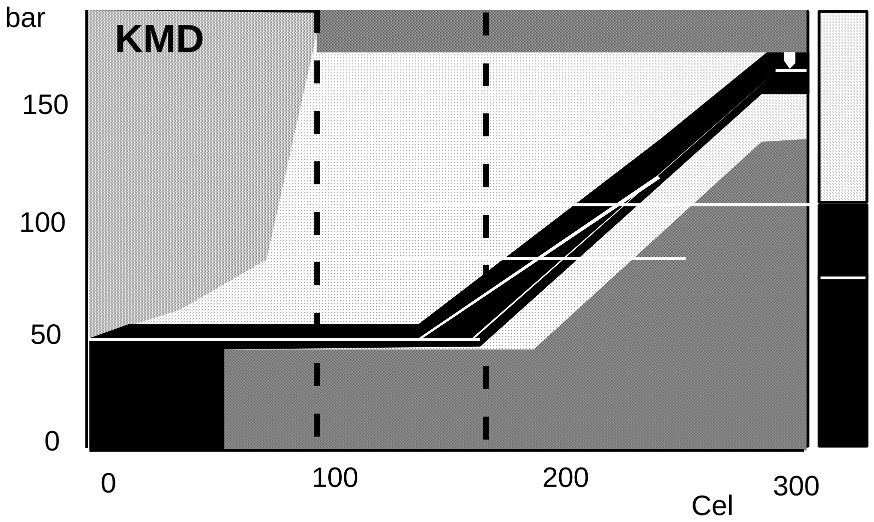


Figure 10 Implemented display for a pressuriser

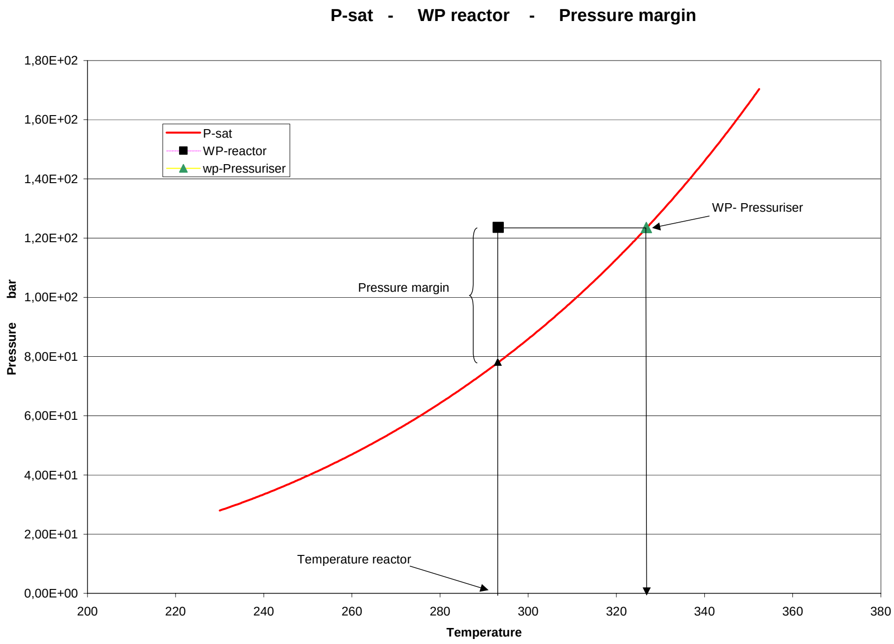


Figure 11 Illustrate the idea behind fig.10

In a PWR the pressure in the reactor must be above the saturation pressure, to prevent boiling in the core. This is ensured in the following way:

The pressuriser is equipped with heating elements that keep the temperature at a higher level than in the reactor tank; consequently the pressure is also higher than the saturation pressure in the reactor tank. The pressuriser contains water and saturated steam, that i.e., the working point for the pressuriser is on the saturation curve. The display shows the saturation curve and the working point of the pressuriser. The working point of the reactor is shown too; it lies above the saturation curve.

If a line is drawn from the temperature of the reactor on the x-axis to the pressure of the pressuriser, the pressure margin can be seen as the vertical distance between the working point of the reactor and the saturation curve. The display is a good illustration of how to use a reference, in this case the saturation curve for steam, in the display design. The display shows the primary operating objective of the pressuriser, which is to keep the reactor pressure above the saturation pressure. The information to show comes from the knowledge of the whole purpose of the pressuriser: Keep the pressure in the reactor above saturation pressure. The display technique is based on the steam saturation curve, which is the characteristic for the pressuriser behaviour, but it is also the critical lower limit curve for the pressure in the reactor. The actual working points of the pressuriser and the reactor are shown on display too. The technique is the same as for Beltraccis' display with the basis display showing the saturation curve and the working point for the whole plant.

2.2.13 The DURESS display

Vicente designed a display for a dual tank water system [52] to support the control of the system, Figure 12

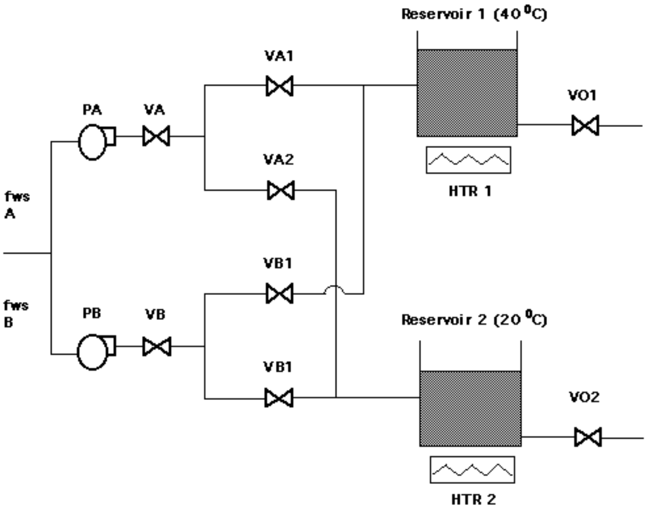


Figure 12 Mimic diagram of the dual water tank system

The content in Vicente’s presentation is based on an application of the Abstraction Hierarchy. The equation

ENERGY = MASS x SPECIFIC HEAT x TEMPERATURE

$$E = M * \rho * T$$

is used for the presentation in the following way:

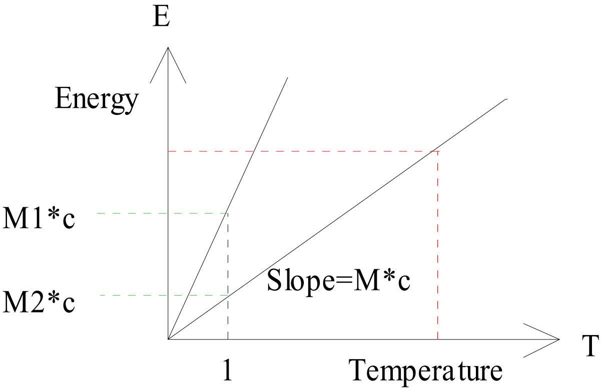


Figure 13 Principle of the DURESS display

The mass inventory of a system multiplied by the specific heat M*c equals the slope of the line representing the energy E of the system as function of the temperature T. A change in temperature will change the energy according to the line. In case the mass inventory changes, the slope of the line will change too as seen on the Figure 13, for mass inventory values M1 and M2. The presentation of the principle is rearranged accordingly, as shown in Figure 14.

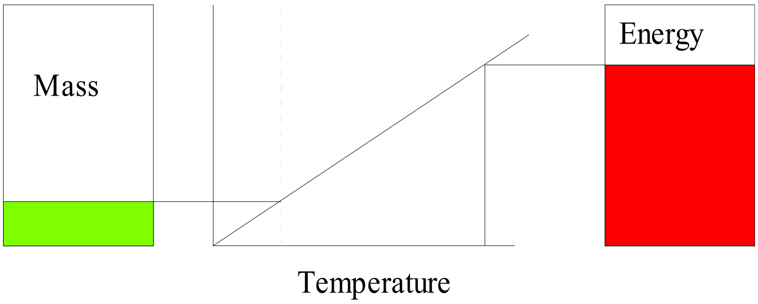
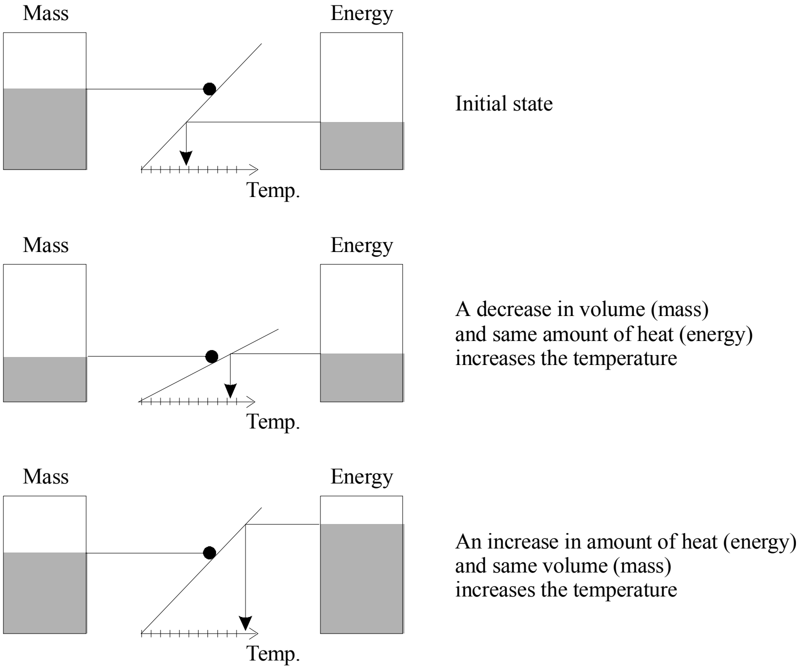


Figure 14 Rearranged presentation

The following figures show different applications of the principle.



Initial state

A decrease in volume (mass)
and same amount of heat (energy)
increases the temperature

An increase in amount of heat (energy)
and same volume (mass)
increases the temperature

*Figure 15 Use of the equation E=M*T*ρ*
ρ=specific heat

The following representation showing inventory changes is also used for the advanced DURESS display.

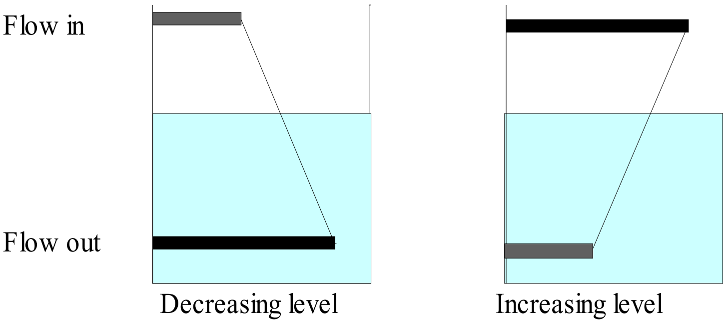


Figure 16 Change of inventory

The principle in *Figure 16* is that inflow and outflow are shown as horizontal bars and a line connects the endpoints of the two bars. If the line has a negative slope the mass inventory is decreasing, and a positive slope indicates an increasing mass inventory.

The final display, using the two principles is shown in *Figure 17*

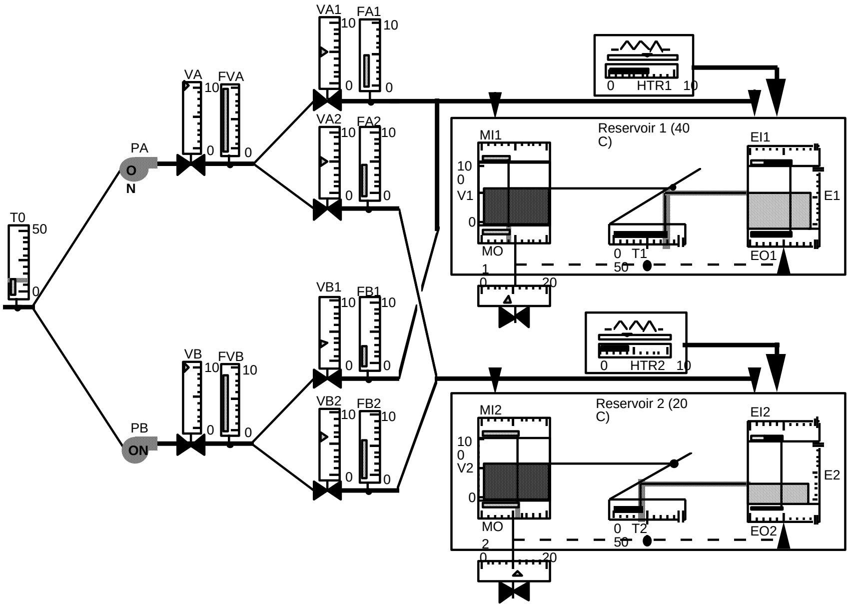


Figure 17 Display for a dual tank water system

The display has been tested on a simulator over a two-year period. The use of the AH strategy and the display design has led to positive results such as a faster diagnosis of an initiating event.

The content in Vicente's presentation is as described earlier based on an application of the Abstraction Hierarchy.

The presentation technique is very complex and does not fit into the types described in the guidelines. The technique of using a linear equation connecting two values, in this case the mass and energy, can be adopted as an idea for similar equations.

2.2.14 Multi Level Flow Displays

Prætorius [**38**] elaborates the concept of *Multi Level Flow Modelling (MFM)*, developed by Lind [**21**] to facilitate the design of displays for a pressurised nuclear power plant to be used for diagnoses purposes.

Figure 18 shows the flow of energy through the plant from its source, the reactor system, through the primary and secondary systems to the turbines or cooling tower. The display is one of the 12 displays in the system.

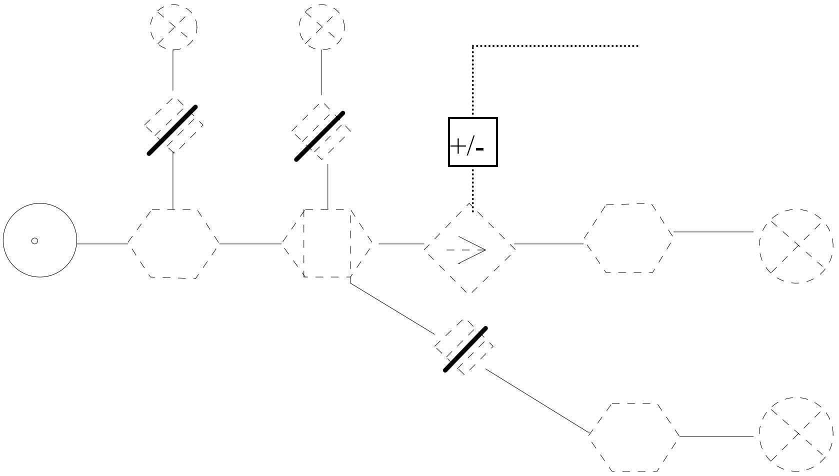


Figure 18 MFM used for interface design.

Symbols such as a '+' sign and '–' sign were included in the control system on the display, for example to show whether a valve is opening or closing, or whether a pump is speeding up or slowing down. The +/- was indicated on the diagram in a box shown above the function controlled. Such indications are supposed to appear when the control system tries to compensate for a failure, and it can be most helpful in diagnosing a fault because the indication turns up before the goals has been disturbed. The displays were tested on a simulator. The time it took to diagnose a fault in the plant using two different devices: either a conventional mimic diagram with the measured variables as digits, or the displays based on the MFM. The result of the test was clearly in favour of the MFM model; the diagnoses of the initiating event was faster using the MFM display than using the mimic diagram display (the present author was one of the test persons). The indications of the control system activities also quickly made it clear that the control system started to compensate for an event in an early phase. The content of the display is based on a means-end hierarchy.

The flow structures are based on the MFM icons, which could be called functional mimic diagrams.

2.2.15 Mass data display

Beutel *et al.* [6] developed a *mass data display* for a power plant to support monitoring of the plant, Figure 19

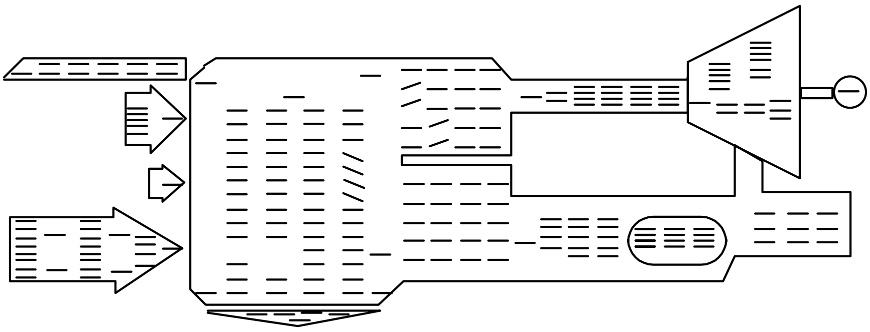


Figure 19 Mass data display for a power plant

The display shows, in a simple way, the systems of a pressurised nuclear power plant. On the display we can see a number of small lines, each representing a measured value in the plant; the values are grouped according to the system in which they were measured. In steady state, all lines are horizontal. A change in the measured variables will result in a change in the lines representing these variables: now they appear as sloping lines. As with the polar plot, the operator gets an indication of a deviation in a specific system, and propagation of a failure can be followed.

The mass display can be used as an overall display like the polar plot, telling the operator that a deviation in the measured data has occurred, and also where in the process it happened. About the content of the display no strategies has been used, but all measured values can be included. The display technique is not described in the guidelines.

2.2.16 Use of the design principles

Paassen [47] uses a combination of MFM and the IED design principles for designing a display for a cement mill.

Monta et al. [25] use the idea from the DURESS display in a design for displays for a nuclear power plant.

Jamieson and Vicente [17] treat display design for petrochemical applications; their work is discussed here because they use several of the design ideas described in this chapter in their design, in order to present the information in an optimal way. The paper describes the use of the AH for a fluid catalytic cracking unit (FCCU)[Figure 20] and the display is designed on the basis of the outcome from the AH.

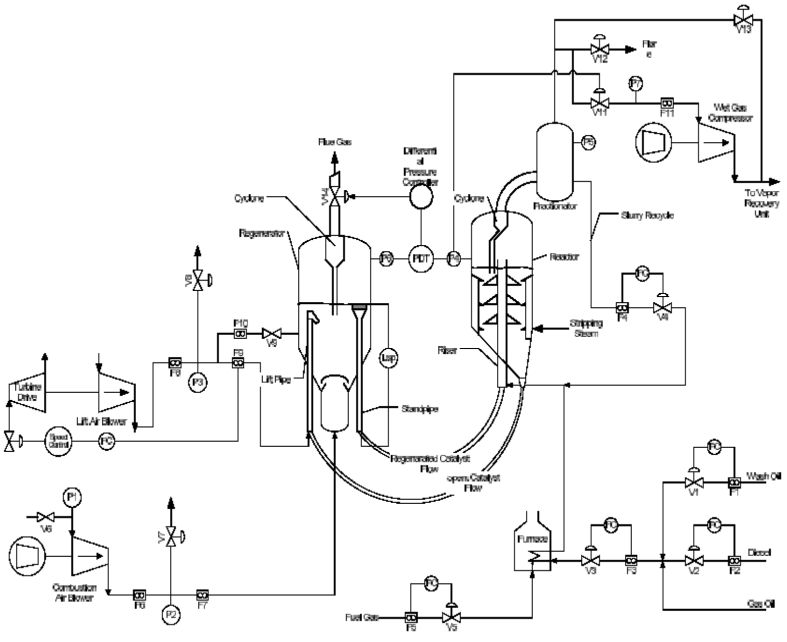


Figure 20 Cracking unit

The final display is separated in 8 windows of different size, called view ports. Each view port presents a specific part of the information required by the AH, and using different methods for visualizing the information.

Content of the display seen on Figure 22 Display for a cracking unit

View port 1 Use of the Paulsen display. The Paulsen type display is used for supervising the temperature and the pressure distribution across the plant	View port 4 Use of the mass data display. The Mass data display is used for supervising the single measured variables and thereby detecting a deviation from normal state	View port 7 Polar graphs for supervising selected variables.
View port 2 Use of the polar graph. Air supply unit and valve detail display	View port 5 Balance	View port 8 Use of the ideas from the Duress display.
View port 3 Use of the polar graph. Air supply unit and valve detail display	View port 6 Use of the DURESS display. The DURESS type display for supervision of energy and mass inventory etc.	

The display has not been tested by operators, but would be interesting to see if operators can cope with the different ways of presenting information.

It is difficult to see if the requirements from AH are fulfilled, because a description of the goal of the plant and of the processes is missing.

There are two separate processes: One is cracking the input, but to what? The other is the regenerating process of the catalyst. A description of the mechanisms is necessary for an evaluation of the display. Furthermore there is no analysis identifying the problems that must be avoided.

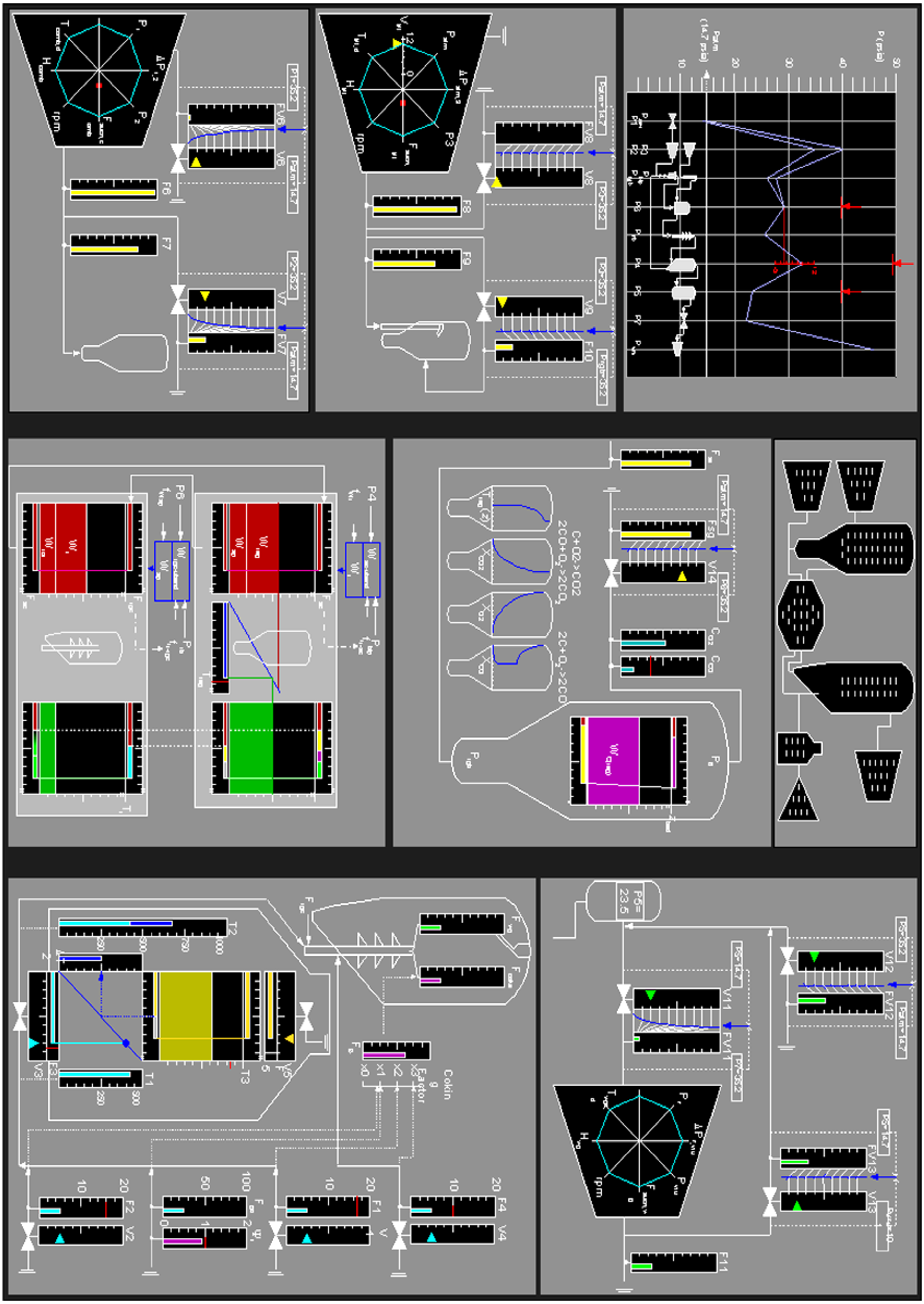


Figure 21 Display for a cracking unit

2.2.17 Reviews of advanced displays and ongoing research

Burns and Vicente [48] describe 13 new types of displays and evaluate them to see how many of the requirements of the AH they fulfil. The displays described in the paper are the most well known among new ideas for the design to process plants. The 13 displays are not evaluated according to test results, but for some of the displays the results are described.

Vicente [50] gives an account of state of the art for the development and use of Ecological Interface Design, EID. The article describes tests from different work domains where EID has been used. The conclusion is that in almost all of the tests, the displays developed due to EID yield faster fault diagnoses than conventional displays. Still, more work has to be done to improve the design.

U.S. Nuclear Regulatory Commission [1] discusses new design methodologies such as EID. The conclusion is, that the methods based on the AH and EID have not yet proven to be satisfactory for nuclear power plants.

2.2.18 State of the art in power plant industry

The introduction and use of screen based displays and especially of large screen displays in new control rooms has been a study object concerning the use of methods used to extract information and how to present the information for the operators, see Paulsen and Weber [36]. It was investigated (1) how the large screens are used, (2) what they are used for, and (3) whether or not a methodology was applied when designing the displays. Shortly before the study took place, two new conventional power plants had been put into operation, and at one old conventional power plant a new screen-based control room had replaced the old control room. Besides, an older nuclear power plant had a screen-based control room under design. At all four plants, the control room was supplied with large screen displays.

The study carried out at the four power plants showed that all the screen-based information systems are based on mimic diagrams, with the measured parameters displayed as digits. To examine the possible use of a strategy in the design of the information system, a questionnaire was applied; it showed that such strategies were almost entirely absent, except for the nuclear power plant that followed the NUREG 0700 rev.1 guideline principles.

When the design had been decided by an operator, as was the case at three of the four plants, it was mainly based on piping and instrumentation diagrams (PI-diagrams); but their experience on which measured variables would be necessary to see on the display played a role in the choice of data to be presented. Acting as a designer, the experienced operator asked himself questions like: What are the most frequent problems in this system? And: Which information do I need to observe these problems? At the fourth plant, where a control room designer chose the design, the diagrams on the screen were merely copies of the PI-diagrams showing all measured values in the same format.

The displays were made with tools from ABB, Siemens and Hartmann & Brown. The tools are developed to use mimic diagrams as their main display form. The systems have several nice features and there are a number of possibilities for information about the plant and the components in these systems; possibilities that were utilised at all four plants, e.g. component run time and control system sequence information.

However, at none of the plants did the design include displays that are more advanced than mimic diagrams and trend curves. The designers of the display systems at the four power plants had not seen or heard anything about what has been going on in the academic world regarding the improvement of displays. The designers had travelled around and visited several plants in Europe to learn about their experience with screen-based displays and about the tools they use. It should be noted that a group that also included human-factors people such as psychologists supported the designers in the layout and choice of colours for the displays.

2.3 Discussion of state of the art

Valuable new ideas have emerged – why have, as yet, none of them been implemented at the real-world process plants?

One reason could be that only little work has been done in the field, especially with strategies that can be used by non-scientific staff. Besides the process control software tends to focus on mimic diagrams; these are well known and it is fairly easy to create them from PI diagrams.

The mimic diagram approach means that the possibilities inherent in the computer-based systems are not utilised to the full in the design of display systems. Much other relevant information about the plant operation and condition can be extracted from the computer systems, in particular information about the condition of the components. Condition monitoring of components can be carried out using the same measured variables that appear in the mimic diagram, but displayed otherwise. For example: measurements of flow and temperatures in a heat exchanger system can be used to calculate the heat exchanger efficiency which can in turn be compared with the expected efficiency. Such information is valuable for maintenance planning. The display showing the pressure margin on a PWR (Figure 10) is a nice example of presenting critical information for the operator in an easy way using a physical property, in this case the steam saturation curve, and the distance to the actual working point.

In addition, some of the display elements still tend to be based on a one-to-one relation between measurement and information unit, as was the case in the old control rooms where the mimic diagrams were painted on the wall and the indicator instruments were typically located just at the relevant points in the mimic diagram.

In the old control rooms there was at least a difference in how the measured values were presented: some were shown on indicating instruments, others were printed on paper-plotters as functions of time. But it was difficult to see which information was more important than other. In many new control rooms this is still the case, only there the information is shown on computer displays instead. The reason could be that we want the information we are used to, and the designers of the displays do not know all they can get with the new computerised system. Who has told them? Perhaps: A link is missing between the people doing research in the area, the companies developing the software for display design and the end-users.

2.3.1 What has to be done?

It is the view of the author that the academic field in display design has not taken the question of the *purposes of the displays into* account. The need is obvious because any designer of a display system must ask himself: "This display I am designing – what is it for, basically?"

Looking at the various displays suggested by Lindsay, Beltracchi, Prætorius, Vicente, and Paulsen, one must draw the conclusion that none of them have described, unambiguously the purpose of their displays.

The following is the present authors' explanation of the purposes of some of the described displays.

- Beltracchi wants to give information about the thermodynamic states in the plant.
- Lindsay wants to show how the temperature levels, increases and decreases in the plant, and he uses polygons to give the operator an overview and enable him to see what is happening in the plant.
- Paulsen, expanding the idea of Lindsay to include the pressures in the plant and their lower limit, wants to alert the operator if the function in some component is not as intended, or if there is a boiling somewhere in the system.
- Vicente, by developing the DURESS display, wants to supply the operator with information that, in case of an unwanted event, assists him in getting the system back into a safe and normal state.
- Prætorius, by developing her display based on the MFM model, wants to construct a sort of advanced alarm display that tells the operator which function has been disturbed and then do a diagnoses task.
- Similarly, both the polar display and the Mass Data Display can be characterised as overview displays that may inform the operator of a deviation from normal state in some area of a plant.

Another piece of work that needs to be done by the designer when the content of a display system is determined, is to give an exhaustive classification and identification of the various *variables* in the display systems considered here. A first attempt to do this could be to record as many variables as possible, describe them briefly and classify them as 'very important' over 'important' to 'less important'. This should be done in a specified way, according to operation, safety, economy, or maintenance criteria. Some of the measured variables cannot be singled out but must be compared to others, to give relevant information to the operator. This is for example the case for temperature measurements across a district-heating pipe. On the other hand, some variables may stand-alone, for example the actual power production at a power plant.

The identification and classification of variables have an influence on how they are presented in the various displays. For example, information about the production at a power plant is not important for evaluating the condition of components and does not have to be shown in a condition monitoring display, but should of course appear in some way in the display for operating the entire plant.

There is also a need for a strategy or some advices on how to present information. There are as described earlier some recommendations in the new NUREG guideline.

The four following chapters describe in more details, display systems that the author has developed, which gives the clue to the developed strategy, which pay regard to the display goals and operator tasks.

Part II

3. Display System for a Pipe Reactor

This chapter describes the development of a display system for a chemical pipe reactor, and experience with the system is reported. The background for the development of the displays was that at the end of the 1970's it was decided to install a pipe reactor pilot plant at Risø National Laboratory.

The pilot plant was built in 1980, and it was planned to be running 24 hours a day for a longer period. At that time, computer based information systems were not available for this kind of projects. But after some years the situation had changed, and it became possible to design and test different types of pipe reactor displays. The display system was developed in 1989 by the present author and it was used until the pipe reactor was closed in 1997.

3.1 Description of the Process

The chemical pipe reactor was built to test a new method for the extraction of uranium by wet oxidation. The system was developed at Risø National Laboratory, and the aim was to test the method on an industrial scale. The uranium ore was provided from Kvanefjeld, Greenland. The wet oxidation process for the uranium includes the following steps:

- Creation of a slurry of grinded ore and an alcaline liquid, which was a mixture of water, NaHCO and NaCO. (In the pilot plant, the solid content was 50% .)
- The slurry is heated to approx. 260 ^{o}C.
- Oxygen is injected.
- A reaction time of about 30 min is observed.
- The slurry is cooled down, to below 90^{o} C.
- The slurry goes to a filter.

During the process the uranium content of the ore is dissolved in the liquid and can be extracted from the liquid as Yellow Cake by a chemical precipitation method.

3.2 Description of the Pipe Reactor

A pipe reactor concept was chosen for the process. The actual type of pipe reactor had been developed previously by the German company Lurgi for the treatment of bauxite for aluminium production. A pilot reactor, to be used for experiments within aluminium production, was built in Germany; it was used for the first tests with the uranium ore, and due to the promising results a similar reactor was built at Risø National Laboratory in 1980.

As mentioned above, the wet oxidation of uranium requires a temperature of approx. 260^{o}C. To prevent boiling the pressure must be above the saturation pressure for water at this temperature. A certain flow is also necessary in the pipes in order to keep the solid floating. The requirement to the flow was one of the main reasons to choose the pipe reactor concept. Another reason was the rather simple construction consisting of industrial standard high-pressure pipes instead of high-pressure tanks.

The system consists of a tank with stirring, a pre-pressure pump, a high-pressure slurry pump, a heating system, an oxygen injection system, 2 km of reaction pipes and a cooling system. The slurry pump has a maximum capacity of 3 m^3 per hour and a maximum pressure of 160 bar.

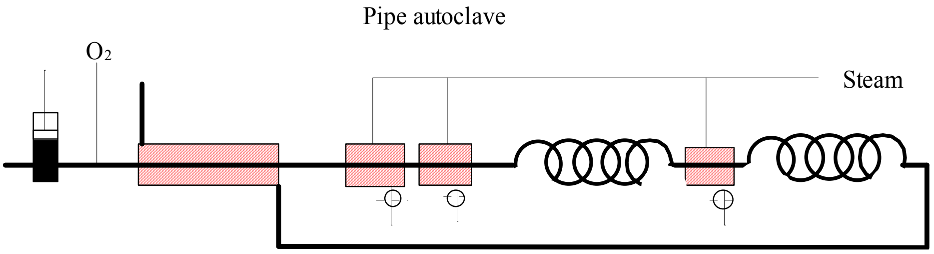


Figure 23 Sketch of a pipe autoclave system

The heating system consists of four heat exchangers with concentric tubes. The first one is a pre-heater where the in-going slurry is pre-heated by the processed slurry. This pre-heater is 185 m long, its inner tube having a diameter of 20 mm.

To increase the temperature of the slurry to the level required for the process, two heat exchangers of 35 m each were installed; they heat the slurry using condensing steam. The heated slurry passes through 1000 m of pipe, then another heat exchanger with steam to compensate for the temperature loss in the pipe, then again 1000 m of pipe, and finally the cooling in the secondary side of the pre-heater.

The plant is located partly inside a building, partly outside. The tank is at the ground floor of the building, and the pump is placed in the basement. The heat exchangers and pipes are situated on a field outside the building. The filter system is located at the ground floor of the building, and so is the control room.

The system is equipped with sensors to measure temperatures, pressures and the speed of the pump and the indicators are placed on a panel beside the high-pressure pump in the basement of the building. The presentation is as single sensors single indicators each on its own instrument. There are 7 temperature indicators and 5 pressure indicators. The speed of the pump is not measured, but a set point is given to the control system of the pump. The control room also gives room for two plotters with trend curves for the temperatures, respectively for the pressures. The system was designed for manual operation, in order to keep it as simple as possible. In the system, two variables are adjustable: the speed of the pump and the amount of steam for heating the slurry. Thereby the velocity of the slurry and the temperature of the medium can be controlled.

3.3 Process design requirements

The requirement to the system was that it should be able to process 3 m3 of slurry (with 50% solid) per hour. The process should be performed at 260°C, with a reaction time of 0.5 hour.

To get a sufficient mixture with the oxygen a fully developed turbulent flow is necessary; i.e. the Reynolds number must be high. Besides, the transport of slurry requires a certain velocity to keep the particles floating. To secure a sufficient lift of particles, pipes with a diameter of 28 mm were chosen; they should ensure the required turbulent flow and a velocity over the critical value, that is, the lowest velocity at which the solid stays floating in the liquid. Operation below the critical velocity will result in a severe wear of the pipes.

Aiming at a reaction time of 0.5 hours, the length of the reaction pipes was set to 2000 m.

To prevent boiling in the system at a process temperature at 260°C, the pressure must be higher than the saturation pressure for water in the entire reactor. Boiling in the system will decrease the slurry temperature, increase the speed of the slurry and thereby reduce the reaction time. The pipe autoclave has therefore been provided with a pressure reduction pipe in the last part of the autoclave to keep the pressure inside sufficiently high. The depressurisation is performed in a 50 m long pipe with a small inner diameter, 10mm, at the exit of the secondary side of the pre-heater.

A high-pressure diaphragm slurry pump was chosen for pumping the slurry. The pump has a maximum capacity of 3 m3/h and a maximum pressure of 160 bars. For safety reasons the pump automatically stops if the pressure reaches 145 bars. The pressure drop across the reactor is expected to increase during operation due to scaling on the surfaces of the pipes.

Heating of the slurry takes place in heat exchangers, as described earlier.

3.4 Operational requirements

During a wet oxidation process in a pipe autoclave, the operator must meet several requirements. In this chapter we shall merely discuss those requirements that were known before the initial start-up of the plant.

The requirements are the following:

- Start up requirement
- Requirement to normal operation
- Requirements for closing down the plant

3.4.1 Start up requirement

The first task is to start up the system, which is done by operating the process with water, without ore, until the desired process temperature has been reached in the reaction pipes. At that point, the slurry, or what else has to be processed, is pumped into the autoclave.

During start up it is important to overview that the temperatures measured in the system are continuously increasing. Furthermore it is important to ensure that the pressure is sufficiently high to prevent boiling in the autoclave. To monitor the build-up of scaling in the pipes during steady state operation it is important to provide the information system with a reference value, which could be the pressure drop across the systems, when no scaling is available, Figure 20. The reference value could also be the pressure drop measured at the start of the process in question. During shut down of the plant, also operating with water, comparable measurements are used to calculate the average scaling thickness in the pipes.

Information that must be presented to the operator during start-up in order to meet requirements:

To follow that the temperature is continuously increasing all over the autoclave, *the temperatures* measured, shown as trend curves was needed. These curves show if the temperature increase in time in the reactor were as expected. It is not easy to make a reference curve while the speed of the increase of temperature is very dependent of the outside temperature and the wind speed, but the temperature should increase in time.

To follow that the heat exchangers behave as intended, the *temperature increase* across each heat exchanger must be present too.

To overview if the pressure in the autoclave is sufficiently high to prevent boiling, the *pressure* must be present together with the *saturation pressure*, calculated for each measuring point of temperature.

To make it clear when the required reaction temperature is reached, the set point *Tset* must be present.

Task during start-up	**Variables**	**Information**	**Presentation**
Follow the temperatures during start up. Follow each heat exchanger	All T's	Rate of change	Temperatures as function of time. Temperature increase across each heat exchanger Tset
Overview pressures and saturation pressure	All P's and P_{sat}	Margin to critical pressure.	Bars on a mimic diagram or curves.
End of start up	T and T_{set}	Goal state	Comparable presentation of T and T_{set}

Figure 24 Start-up information

3.4.2 Requirements to normal operation

During normal steady state operation there are two main requirements that should be meet. Firstly, it must be ensured that the state in the autoclave fulfils the conditions for the chemical process to take place. This has three implications: (1) the *temperature in the reaction pipes* must be maintained at levels required for the process, (2) the *pressure after the pump* must be kept sufficiently high, and (3) the *velocity of the fluid* must be kept above the lower limit for the fluid in question. Regarding (1), it should be added that during steady state operation it is particularly necessary to keep watching the temperature in the reaction pipes. If it becomes too high or too low, the steam supply must be regulated accordingly.

Secondly, the *pressure drop* across the autoclave must be followed closely. An increase of the pressure drop is expected due to scaling on the pipe surfaces. The pressure after the pump must not exceed a maximum of 145 bars; if it does, the operator may decide to reduce the speed of the pump and thereby the velocity of the fluid as well as the pressure drop across the system. However he must also be careful not to reduce the velocity of the fluid below the critical velocity for the slurry so that the solid keeps floating and the requirements for a full turbulent flow are still met.

If the pressure decreases unexpectedly, the usual cause is a reduced velocity of the medium. This can be due to problems with the pump or to a leak in the system. The operator must make a diagnosis of the problem, and he must also decide when to clean the autoclave to get rid of the scaling.

Information that must be presented to the operator in normal condition:

To overview that the required reaction temperatures are present in the reaction pipes, the temperatures in the reaction pipes as well as T_{set} must be shown. It is only the temperatures in the reaction pipes that have an interest, while the pressure is of interest in all points of the autoclave.

To monitor that the pressures in the autoclave are sufficiently high to prevent boiling, the pressures measured as well as the saturation pressure, calculated for each measuring point, must be shown.

To ensure that the fluid velocity V is above the critical velocity V_{crit}, these two quantities must be available, and so must the Reynolds number, to check it is sufficiently high. The actual velocity V and Reynolds number are continuously calculated from the flow measurements while the critical velocity V_{crit} for the slurry in question is calculated before the operation starts.

To follow the build-up of scaling, the pressure drop across each part of the autoclave must be monitored and compared to the initial pressure drops for a clean system.

To be aware of when the maximum pressure for the pump is reached, the pressure just after the pump must be followed.

Tasks in Normal operation	**Variables**	**Information**	**Presentation**
Sufficient reaction temperature	T and T_{set} in reaction pipes	Temperature margin.	Trend curves or overview curves
Sufficient pressure	P and P_{set} all over the autoclave	Pressure margin.	Overview curves
Sufficient velocity	Flows, F_{crit}, Re	Safety for the system. Availability of turbulent flow	Shown on the pump display
Pressure drops	dPs' and dP_{clean}	Availability of scaling	Bar graphs
Maximal pump pressure	P_{pump} and P_{max}	Safety margin for the pump	Pmax as an upper limit for the pressure.

Table 2 Information needs during normal operation

3.4.3 Requirement when closing down the plant.

When the plant is closed down, the system is cooled by water until the temperature is below 100°C, so that the system is below the boiling point and the pump can be stopped. The task in this situation is to change the feeding from the slurry to water, close the steam supply and monitor the temperature decrease in the system. During this period the pressure drops across the heat exchanger and the diameter of the reaction pipes must be measured, to be able to calculate the thickness of the scaling that has been built up during the process.

Data that must be presented to the operator:

During cooling down of the plant the highest temperature will be just after the pre-heater, while the incoming water is still heated in the pre-heater. The temperature must be below 100°C before the pump can be stopped.

Tasks during shut down	**Variables**	**Information**	**Presentation**
Overview the max. temperature	Tmax	Closing down status	All temperatures

Table 3 Information needs during closing down the plant

3.5 Experience with Operating the Plant

Operation of the plant was rather simple during normal conditions, but the problems with scaling occurred very fast and caused the pressure drop across the system to increase, primarily in the heat exchangers and in the first 300 meters of the reaction pipes. When the pressure reaches 140 bars, a decrease in the velocity of the slurry is necessary to continue operation, if possible, due to critical velocity. If it is not possible to continue operation, a cleaning of the pipes is necessary. The pressure after the pump in the beginning of the operation with slurry was about 120 bars.

In normal condition, the velocity of the slurry is proportional to the speed of the pump; therefore the velocity of the slurry can be reduced by slowing down the pump. The same technique is used to prolong the reaction time. Uncontrolled decrease of the velocity of the slurry happened often due to problems with the suction valves and other problems with the suction side of the pump system. The velocity of the slurry in these situations was not known. The pressure drop across the depressurisation pipe could to some extent act as an indicator of the flow.

Due to a limited amount of steam, problems with heating the system also occurred during cold weather where the heat loss to the surroundings increased.

With the ‘single-sensor single-indicators’ indication system it was hard to get an overview of what was happening in the system when something went wrong or did not behave as expected. Even that all operators of the system had participated in the development and building of the plant, so they knew it well, but that is not the same as knowing the behaviour of the plant during operation.

The chemical experiments were successful, but mechanical problems must be solved and effective cleaning methods must be developed before an industrial plant can be built.

In 1989, the plant was used in a test concerning wet oxidation of polluted soil. The main pollution was organic material. Due to the development of simple graphical PC systems and data acquisition systems, it was decided in 1989 to install an on-line PC-based interface to the system. The interface project was also an opportunity to test and develop new ideas on how to present information appropriately to the operators. During the operation, various displays were designed and tested. Experience clearly showed that it was important to monitor the condition of the components, because scaling was expected, but not at that speed that it was actually building up during operation. Pump problems had not been foreseen to the extent that they appeared.

3.6 Display Design for the Pipe Reactor

The display system ended up with including five displays:

1. An overview display showing the *temperature- and pressure distribution* across the pipe autoclave.
2. A condition monitoring display showing the *pressure drops* across different parts of the autoclave.
3. A display with trend curves for *temperatures*.
4. A display with trend curves for *pressure drops.*
5. A display for *condition monitoring of the pump.*

All five displays were developed mainly on the basis of the experience the participants got, during operation of the plant in 1980-81, with chemical as well as with mechanical and fouling problems. The displays (the text of which is in Danish) were shown on a single computer screen in the control room.

3.6.1 Display No. 1

The idea for the first display originates from the work of Lindsay [22] who designed the display system for a Sodium Cooled reactor.

Due to the temperature requirements for the chemical process, it is important to know the temperatures in the reactor, especially the temperature before the reaction pipes. The three lines in the display (Figure 25) shows the distribution across the reactor of, respectively, the temperature (lower line), the pressure (upper line) and the saturation pressure (middle line). The saturation pressure is calculated from the measured temperatures in the reactor; it must be considered a lower limit for the pressure in the pipes. In the bottom of the display is inserted a mimic diagram of the pipe reactor, with the temperatures and pressures shown digitally.

During the development of the display, it has been the main scope to give the operator an easy overview of the temperatures and pressures in the system, including the possibility to check if the heat exchangers do provide the intended temperature increase. The mimic diagram helps the operator to recall in which components the different functions occur; thereby it is made easier for him to fast observe if a component does not function as intended.

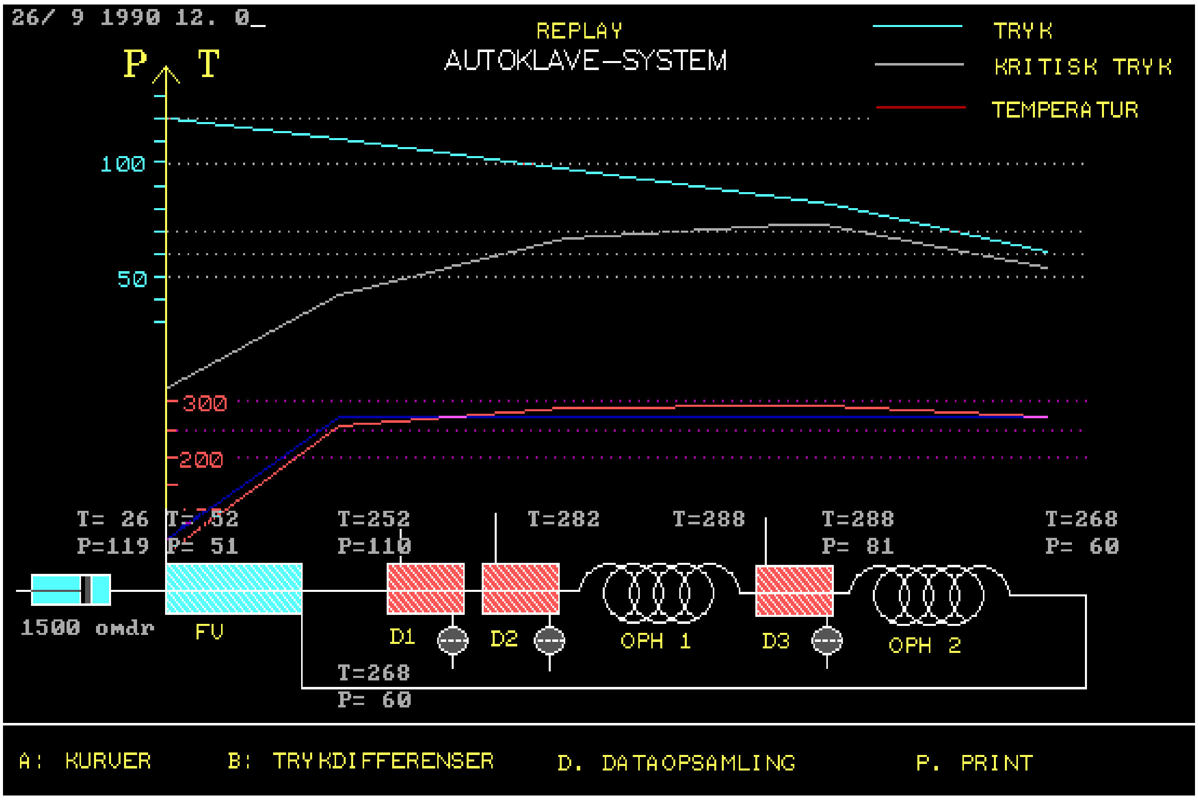


Figure 25 Display 1

Experience has proved that the display shows the information needed and provides a suitable overview of the system and the process. Actually it turned out to contain even more information than it was designed for. This is perhaps not surprising in view of the fact that the information level in the former control room was fairly low, although the plotters did give some information about stability of the pressures and temperatures during steady state operation.

It is the authors' judgement that Display No.1 presents the data in a most informative way. The shape of the temperature distribution informs about the state of the process, and whether the system is operating satisfactorily. The saturation pressure curve can be used in two ways: to check the safety margin from the boiling point, and to get an alert when the reaction time had to be prolonged, which is effectuated by decreasing the velocity of the slurry. In case where the velocity has to be reduced it is easy on the display to follow when the process approaches the boiling point and thereby just reduce the flow so boiling still is avoided. The pressure distribution diagram includes information about the distance to the lower limit. It is also easy to observe the increase in the total pressure drop across the autoclave, that is, the increase in the pressure measured on the pressure side of the pump. Such an increase could be the result of an increased fouling in the pipes. The display points directly to this problem when it arises, and by observing the steepness of the pressure curve the operator can see where the maximum fouling occurs. A pressure increase could also arise as a consequence of a partly blocked pipe, but this would be observed as an increased pressure drop in just one of the reactor parts in between the pressure measurements

That the diaphragm pump is running smoothly is checked in the display by looking at the pressure after the pump and judge if it is stable. In case of problems with the suction valves the pressure will drop because of the decrease in flow.

To check that the steam generator works as intended the operator just has to look at the temperature increase across the heat exchangers.

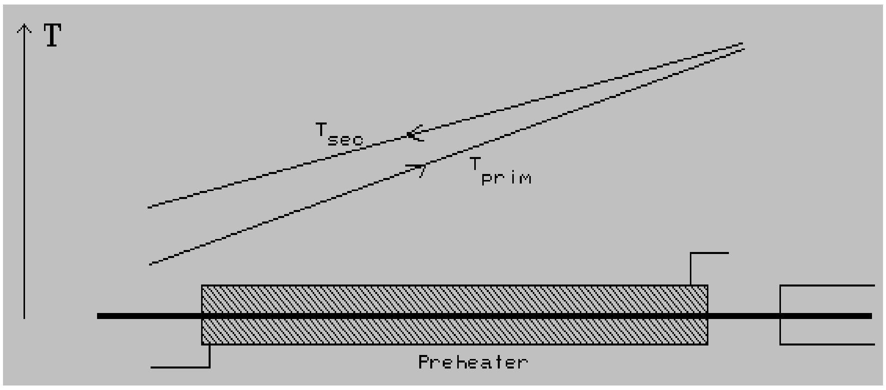


Figure 26 Exothermal reaction in the pre heater

In the pre heater, where the incoming slurry is heated by the out coming and processed slurry, it is expected that the temperature increase for the incoming slurry is equivalent with the temperature decrease of the out coming slurry. The flows are the same on both sides of the heat exchanger. On the display the two lines showing this increase and decrease of temperatures will be parallel, but during operation with polluted soil in the development phase of the display system, it was observed that the two temperature lines were not parallel. What was observed, were exothermal reactions starting in the pre-heater, which added some extra energy to the incoming slurry and with the consequence that the temperature increase were larger than the temperature decrease on the outgoing slurry (Figure 26, which is a part of Figure 25).

$$\Delta E_{\text{primary}} = \Delta E_{\text{secondary}} + E_{\text{exotherm}}$$

This observation gave the information that an exothermal process starts below 220°C, which is the maximum temperature the incoming slurry gets in the pre heater. In the same manner exothermal reactions could be observed in the reaction pipe. The reaction heat and the amount of organics oxidised can both be calculated from these observations. It had not been planned to quantify the oxidation by measuring the temperature, just by taking out samples now and then. The flow of the slurry was measured directly, but due to large uncertainties the measurements were not usable. Instead the flow was calculated from the speed of the pump but that can be done only if there are no problems with the pump. A better indicator of the flow, and thereby the velocity of the slurry supply, was the pressure drop across the drossel pipe (depressurising section). No scaling occurred in this pipe. During start up and closing down of the plant the dynamics could be seen on the display as well.

After having worked with the display over a period, the operators stated that the display made them able to understand much better what was going on in the plant. It had become easy to be aware of problems, to observe them at an early stage, and to diagnose them once they had occurred.

A replay of data from a uranium extraction operation in the past, during which it had become difficult to reach the required process temperatures, showed what the reason was: boiling had occurred in the reaction pipe. Boiling forces the temperature to decrease with the pressure drop, and the preheating becomes inefficient. This event could have been avoided if the display had been available during the uranium extraction process; and there were other similar findings. – Part of the display (Figure 25) that indicated boiling in the autoclave during the uranium extraction operation is shown in Figure 27

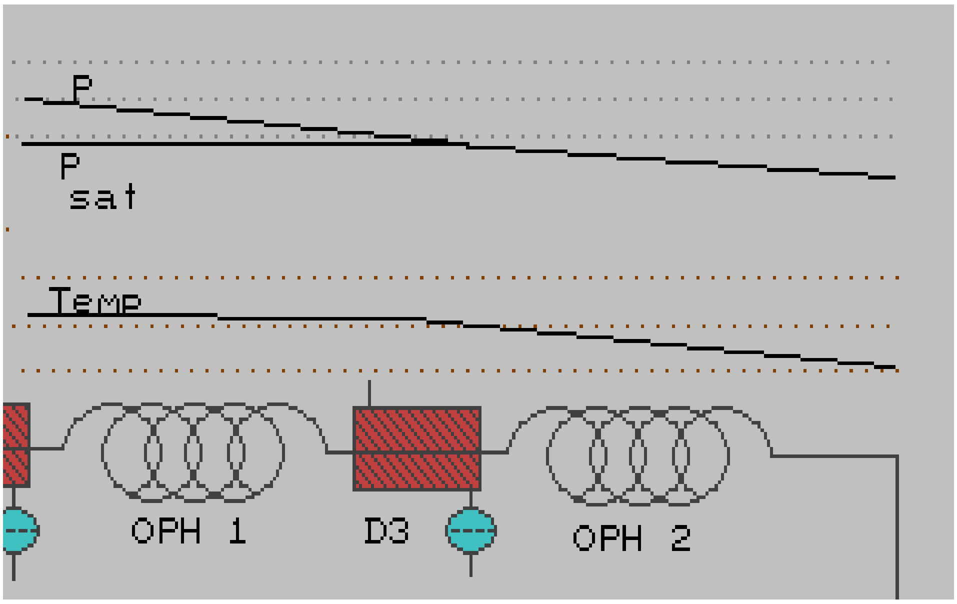


Figure 27 Boiling in the Pipe Reactor

3.6.2 Displays No. 2

The second display [Figure 28], having the same mimic diagram as on Display No.1 [Figure 25], shows the pressure drops across the different components of the pipe reactor: The Pre-heater, both the primary and secondary side, three heat exchangers, the one reaction pipe and the second reaction pipe. It was not possible to measure the pressure drop across each heat exchanger and the first reaction pipe, while measuring points were not installed for measuring the pressure drop for each of these components. Coloured bar graphs indicate the actual pressure drops during operation, green if below or equal reference pressure and red colour if above. The non-coloured bar graphs show the corresponding reference pressure drops for a clean plant; the temperature distribution is shown as in Display No. 1.

Display No. 2 was developed to enable the operator to readily observe a scaling problem when it occurred, and to decide when and where to clean the system. Later the data were used in another program to calculate the average thickness of the scaling. It was part of the aim of the project to determine where scaling happened in the reactor, and to calculate the scaling rate. The end task was to be able to calculate the appropriate time interval between cleaning of an industrial reactor with a greater diameter than the pilot reactor.

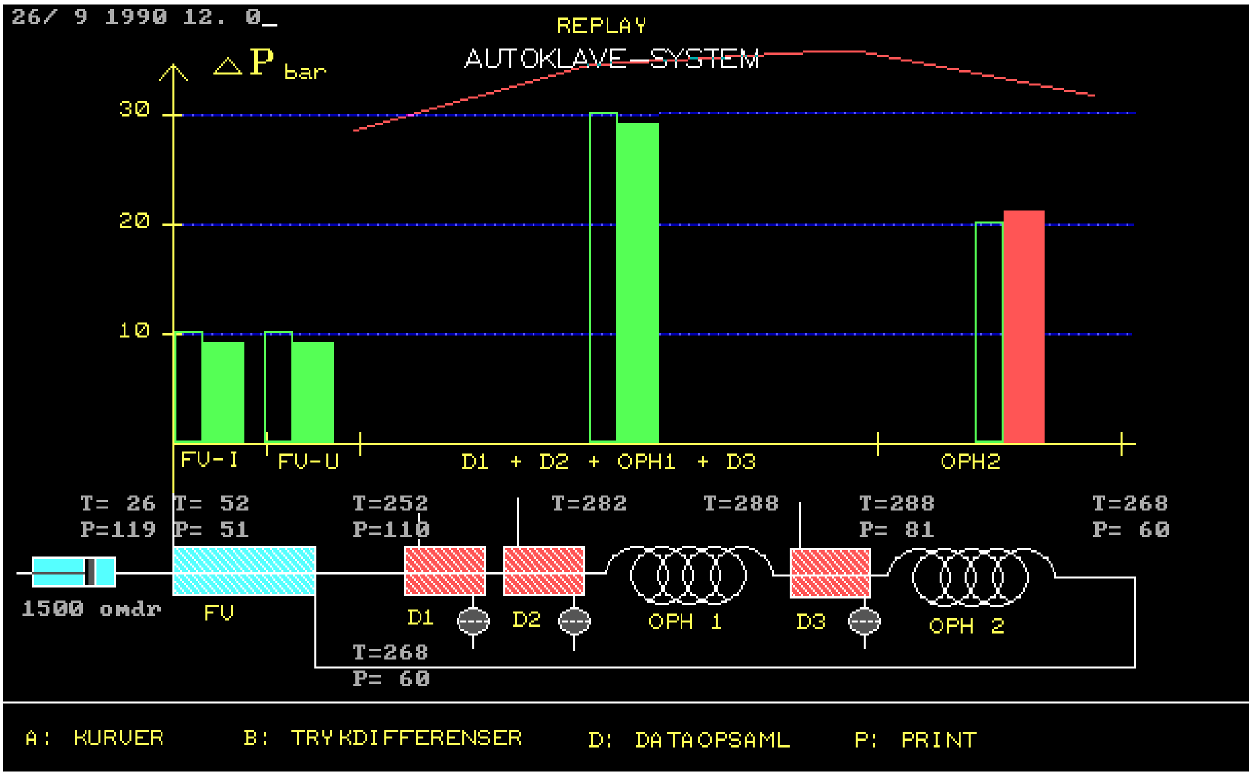


Figure 28 Display No.2

The use of Display No. 2 during operation turned out to be scarce. One reason is that one could not see the pressure distribution across the reactor and the lower limit for the pressure, especially not the pressure after the pump. The monitoring of the pressures had a higher priority than the monitoring of temperature. The pressure can suddenly fail due to pump failure, but the temperature does not change so fast due to the high heat capacity in the system.

Discussions with Leo Beltracchi also made it clear to the author that while Display No. 1 shows the function of the system, Display No. 2 shows the condition of the heat exchanger and the reaction pipes or more precisely their degradation due to fouling. Maintenance people must look at the condition of the system from time to time; those who operate the system here and now do not have to. Still, the condition information is valuable for the operator too, to see how close the plant is to the point where a cleaning is necessary, and to use this information in his operation planning.

3.6.3 Displays No. 3

The third display [Figure 29] shows the trend curves for the temperatures and they are useful during start up because it allows the operator to check if all heat exchangers function as intended, which mean that the temperature increase across each heat exchanger is as expected. The heat exchangers, using condensing steam, consist of concentric pipes. The condensed water is released during steam traps. Because the plant was placed outside and some of the experiments took place during winter, it sometimes occurred that the steam traps were frozen. However it was only observed when the condensed water reached the level of the inner pipe, causing the heat rate to decrease and, when the pipes were covered with water, to stop. This situation was detected rather easily looking at the trend curves where the temperature increase across one or more heat exchangers stops.

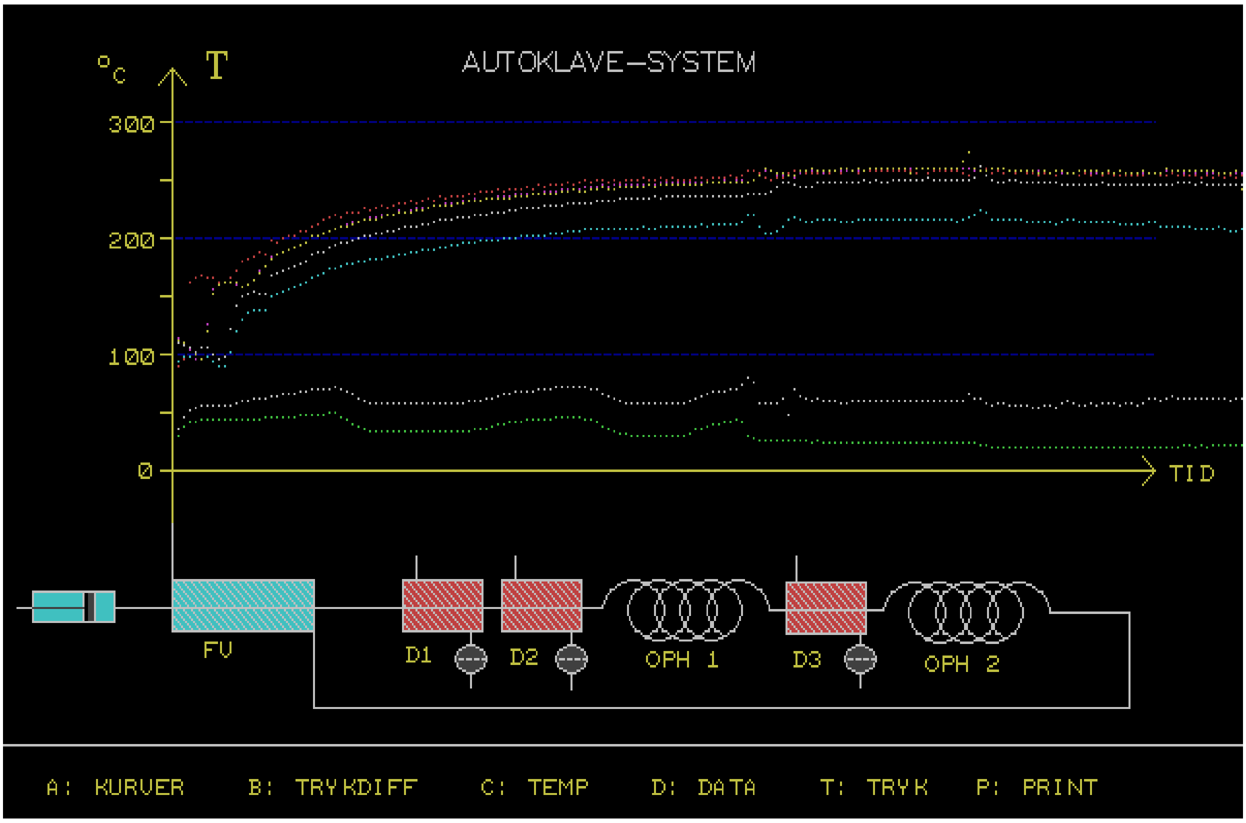


Figure 29 Display No. 3

3.6.4 Display no. 4

The fourth display [Figure 30] shows the trend curves for the pressure drops across different sections of the pipe autoclave. The purpose of the display was to follow the pressure increase due to scaling across each section of the system, and thereby get information about where and at what temperatures the scaling occurred. This information is important when designing a large industrial plant, where cleaning facilities must be planned before the building of the plant and not as in a pilot project with rather primitive hoses and portable acid tanks were sufficient. However the display suffers from the lack of information of the flow, which has a great influence on the pressure drop. A change in the pressure drops could be a result of a decrease in speed of the pump but it could also be a result of a failure in the suction valves.

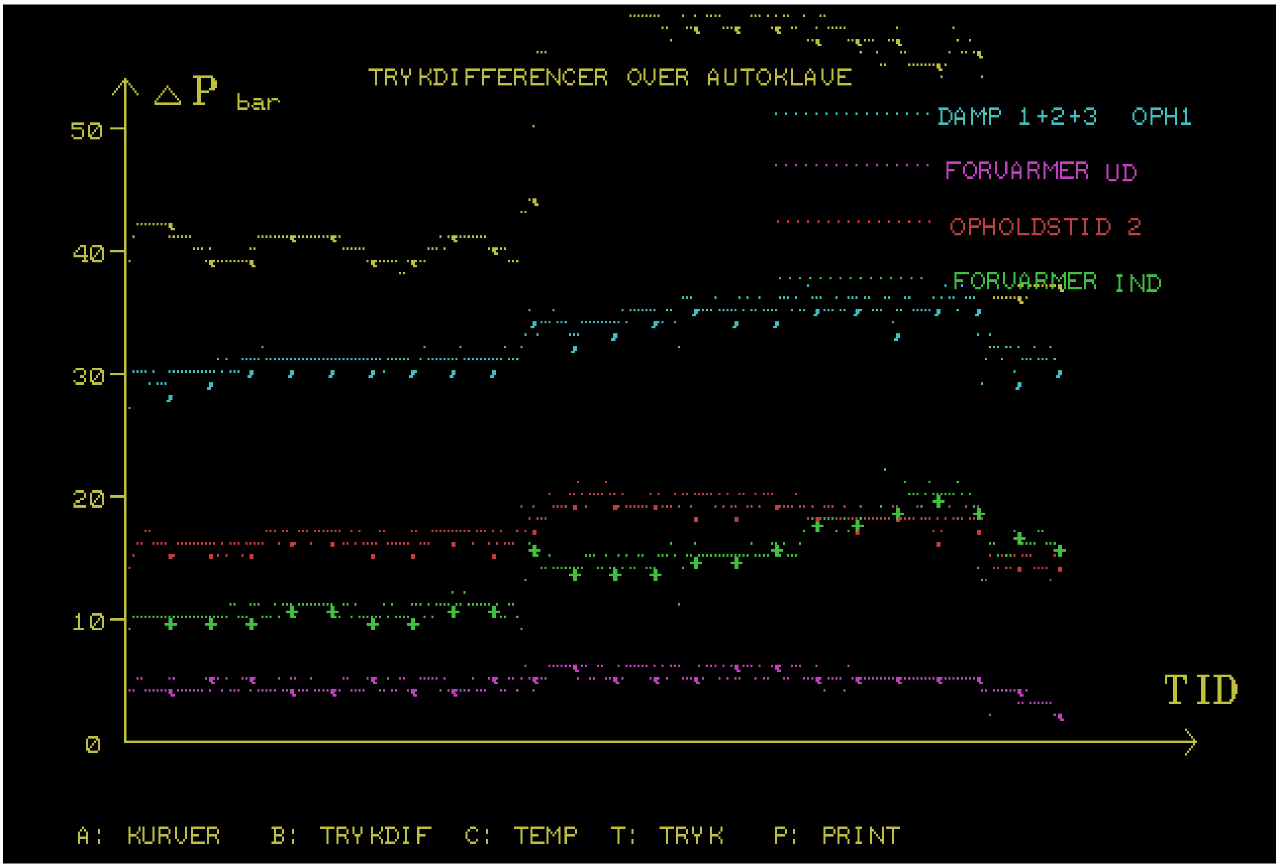


Figure 30 Display No.4

On this display the pressure drop across the depressurising pipe is the yellow curve. This pressure drop could be used as an indicator for changes in the flow, while no scaling appeared in that pipe, which would have changed the pressure drop even with constant flow. This pressure drop was used in the calculation afterward for estimating the scaling thickness.

3.6.5 Display No. 5

The fifth display [Figure 31] summarises the condition of the slurry pump. The purpose of the display is to check if the pump is operating on its characteristic and to follow the distance of its speed to the lower limit for the speed, which could be the critical velocity for the slurry. Besides, the display gives an alert if either the Reynolds number or the pressure in the reactor has become too low.

The display presents all operation limits as well as the pump characteristic. Unfortunately the display did not come into use, due to faulty flow measuring equipment.

The display for the pump is an example on how different component characteristics can be used in combination. The pump is a positive displacement pump of the type diaphragm pump with three pistons. The pump is developed for slurry transport at high pressures. The flow through a positive displacement pump is proportional to the speed of the pump and therefore is the characteristic for the pump a straight line.

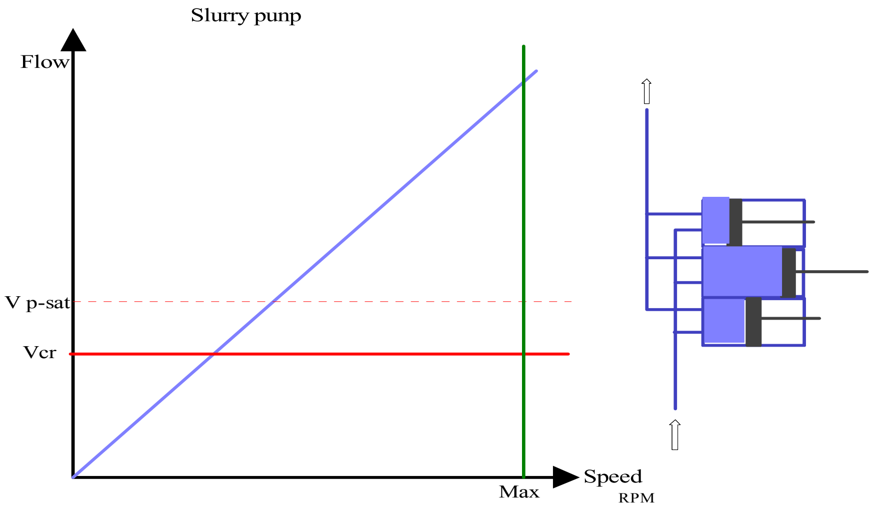


Figure 31 Display No.5

As discussed above, the transport of slurry requires a certain velocity of the fluid to keep the solid particles floating. Therefore there is a lower limit for the flow rate. This critical velocity depends on (1) the pipe diameter of the connected system, (2) the percentage of solid in the slurry, (3) the particle size, (4) the specific weight of the solid and the fluid, (5) the flow of the slurry, etc.

The critical velocity is an absolute lower limit for the velocity of the slurry. If it gets below the critical velocity, severe wear and damage of the pipes may be the outcome.

Operation at the critical velocity proved to lead to a Reynolds number higher than required; therefore it is hardly necessary to show the lower limit of the Reynolds number in the display.

There is also an upper limit to the flow rate, viz. the one caused by maximal speed of the pump.

Due to the velocity requirements and the problems with the pump, which can lead to flow problems, a display for condition monitoring like the one in Figure 31 will help the operator and the maintenance planners in their decisions about when to take action to prevent failures. The problems experienced with this type of pump are typically concerned with the tightness of the suction valves or with air in the suction line. In both cases the consequence is a reduced flow, resulting in a working point below the pump characteristic. If the pump is automatically regulated, the control will compensate for the deviation in flow and increase the speed of the pump. The pump has a maximum speed corresponding to the maximum flow on the display.

The result of these considerations is that there is a triangle of accessible points in the diagram for the operation of the pump. Depending on the connected system and the process, yet other limits can be implemented in the display. For example, the pressure in the system is subject to a lower limit because the slurry will start boiling in the pipes in case the pressure gets below the saturation pressure. Similarly, to keep the process temperature at 260°C requires a certain pressure and therefore also a certain flow which can be shown in the diagram as another lower limit for the flow.

3.6.6 Discussion of the pipe reactor displays

The 1st and the 5th displays are the most valuable displays of the five displays.

The first display gives quite a lot of information about system and components functions, but it is difficult to observe degrated condition in the components by observing the steepness of the pressure curve. For this observation the 2nd display can be used. Changes in time cannot be observed on the or display 1 or 2 and therefore the display must be supported by trend curves. Even that trend curves are necessary to have to follow deviations on measured and calculated information, is it difficult to get and overview of the plant situation from trend curves alone.

The 5th display is a display for condition monitoring of the pump. The display use the same ’format’ as Beltracci use with a reference curve, here the pump characteristic, as the basis display and then the actual working point and limits can be plotted on the display. This type of displays can be recommended for condition monitoring of also other components.

4. Overview Display for a Pressurised Water Reactor

The positive experience with graphical displays for a pipe reactor led to a cooperation with the OECD Halden reactor project in Norway concerning the development of a graphical overview display for a pressurised water reactor simulator in Halden.

4.1 Description of a Pressurised Water Reactor

A pressurised water reactor (in the sequel: PWR) consists of a primary and a secondary side, each with a separated closed loop water system, Figure 32. An electrical generator system is attached to the secondary system.

The reactor in the primary side produces hot water, approx. 300°C. A steam generator separates the primary and the secondary side. In the steam generator the water on the secondary is converted into steam, which is next converted into mechanical energy in the turbines by a rotating shaft. This rotating shaft rotates a electrical generator and the mechanical energy is converted into electrical energy. This is a common energy conversion system for power plants, independently of the fuel type used. Schematically, the process can be depicted like this:

Thermal energy → Mechanical energy → Electrical energy

In the following way:

Water → Hot water → Steam → Rotation → Electricity

In most thermal plants the steam is produced in a boiler, not in a separate secondary system, as is the case as in the PWR. But the energy conversion principle is still the same as for the secondary side of a PWR.

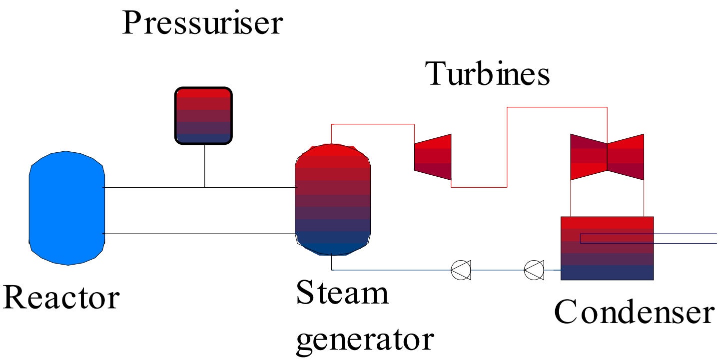


Figure 32 PWR plant

Regarding its purpose, the steam generator can be compared with the boiler in a conventional power plant, and also with the reactor in a boiling water nuclear plant, but the PWR steam generator uses hot water produced on the primary side in the reactor as source of energy. The most common fuels are gas, coal, oil, and uranium.

The primary side consists of the reactor with control rods, a closed cooling system and a pressuriser system as the main components. The secondary side contains a feed water system with pumps and heat exchanger, steam generators, high-pressure turbines, low-pressure turbines and condensers.

In a PWR, the reactor is totally filled up with pressurised water. To avoid boiling in the system, the pressure, maintained by the pressuriser, is kept above the point of saturation. Boiling in the reactor would reduce the heat transfer from the core to the water and could result in a severe damage of the core.

The pressuriser is equipped with heating elements to increase the temperature in the pressuriser above the temperature in the reactor, and thereby increase the pressure of the whole primary system above the point of saturation. The difference between (1) the actual pressure in the reactor and (2) the saturation pressure at the actual temperature in the reactor is an essential quantity and must be supervised: it is the *safety margin for the pressure* Alternatively, one might measure the difference between (1') the actual temperature and (2') the saturation temperature at the actual pressure; indeed this so-called *temperature safety margin* is used for supervision at some nuclear power plants.

Water is heated in the reactor and transported into the steam generators where it cools off during the process and is returned to the reactor. The primary system is provided with a number of high-pressure injection pumps, used during normal operation for the injection of boron for control of the neutron flux. In case of a leak in the primary system the system is used to maintain the water inventory in the system. In normal operation one pump is running, but in emergency situations up to four pumps can go into duty to maintain the water inventory. The most common leaks arise between the primary and the secondary side in the steam generators.

On the secondary side of a PWR, feed water is heated and evaporates in the steam generators. Steam from the generators drives the high-pressure and the low-pressure turbines. The low-pressure outlet steam from the turbines is condensed in the condenser, which is cooled with seawater, or with water from cooling towers. Next, the condensed water is pumped through the feed water system where it is heated by drain from the turbines before it enters the steam generators.

There are not any serious safety problems on the secondary side itself, but the water flow through the secondary side of the steam generators must be able to transport away the heat produced in the reactor. If the secondary side cooling in the steam generators is failing, it can cause severe damage on the core, in particular if no emergency systems are available on the primary side. For this reason, the mean temperature difference between the primary side and the secondary side of the steam generator is an essential quantity to supervise too while the heat transfer depends on the temperature difference. The temperature on the secondary side must be lower than the temperature on the primary side to be able to transport heat away from the primary side.

4.2 Description of the overview display.

The main idea behind the display is to show the measured main parameters, and thereby the main functions that are taking place in a plant, in an direct graphical way by drawing lines and polygons, like in the Lindsay display but in addition showing flow and pressure distributions across the plant. Main parameters in the case of a PWR plant are temperature, pressure, and flows. By main functions in meant: Temperature increases and decreases, pressure increases and decreases and the flow changes in the system. Furthermore the calculated value for the lower limit for the pressure in the primary system must be shown. Energy flows can be calculated and shown in the same way. The measure parameters and the functions are indicated on a compressed mimic diagram of the plant, as for the pipe reactor where other plant parameters can be shown too, such as water levels, valve position, flow paths, pump status etc.

The first draft for an overview display for the PWR was inspired by the pipe autoclave display. The idea was to split up the secondary side just after the condenser and start in the left side of the display with the preheating system followed by the steam generators, the turbines and finally the condenser. The primary system is placed as shown in Figure 33.

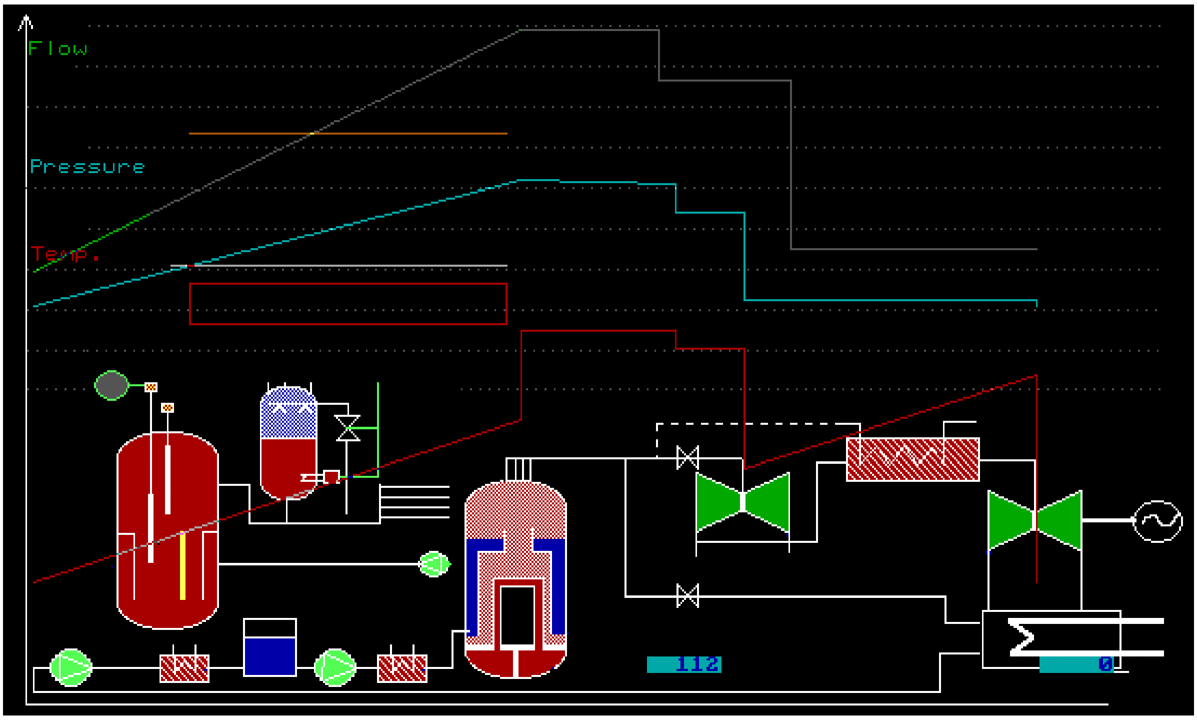


Figure 33 Overview display for a PWR, 1. draft

The curves show the temperatures, the pressures, the saturation pressures and the flows of the primary, the secondary and the tertiary loop of the plant. The tertiary loop is the cooling loop for the condenser e.g. seawater loop or water from a cooling tower. The polygon consists of straight lines connecting the points in the coordinate system representing the values of the measured parameters. The position of the connecting points of the curves is vertically correlated to the mimic diagram and the position of the sensors in question. Only vertical movements of the polygons can take place.

When the draft was presented to the operators, they were not enthusiastic. It looked quite different from what they were used to. For example, they thought that the preheating system should be placed below the turbine system, as it had been up to then. This is shown on the mimic diagrams on Figure 34, which is the conventional mimic diagram of a simulator and on the simplified diagram on *Figure 35*.

The display systems were developed in the framework of a simulated PWR plant, originally made as a model of the Three Mile Island nuclear power plant, Larsen [18]; the model had been used in connection with the Multi Level Flow

Model, Lind [21] for a series of experiments the purpose of which was to find out how the incident at the Three Mile Island plant could have been prevented if it had been equipped with better display systems, Prætorius [38], as described in Chapter 2.

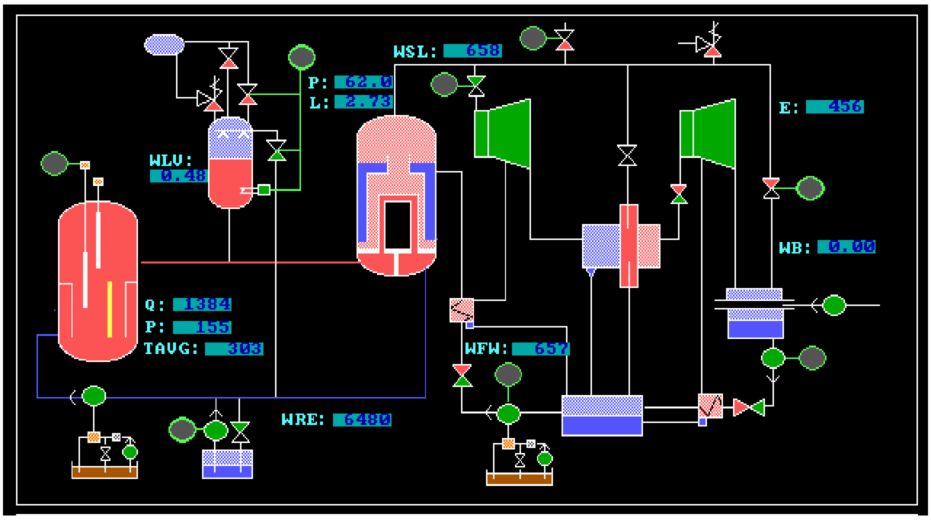


Figure 34 Mimic diagram of the PWR simulator

In the second draft of the display system, the systems were placed as the operators were used to, with the primary system to the left and the secondary system to the right, as in Figure 35. To avoid confusion about which part of the curves belongs to the pre-heater system and which to the turbine system, the pre-heater curves are drawn as a dotted line in the same colour as the curve through the turbine side.

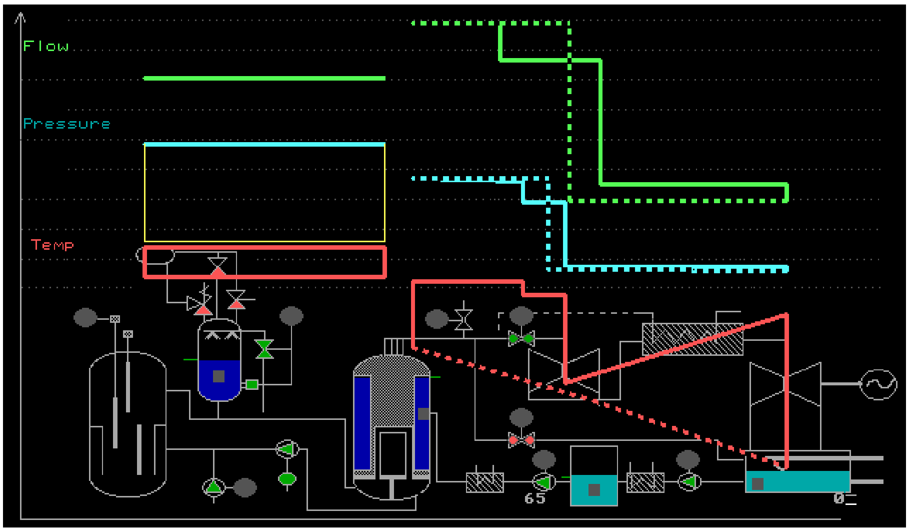


Figure 35 Overview display, draft 2

For the second draft, it was decided that it should be implemented on a full-scale PWR simulator, to show, as also was the case for the first draft, the measured parameters and others that can be calculated from them. For example, the saturation pressure in the reactor is calculated from the temperature and shown on the display, with a yellow line indicating the lower limit for the pressure, which means that the pressure margin is always present for the operator.

The reason why it was decided not to show estimated values is that these, for example the flow through turbines (not measured) which should equal the feed water flow (measured), are reliable only in normal situation, while they can be misleading in case of an abnormal event, for example a pipe rupture before the turbines. But the most important challenge of the display system is precisely that it should conceive an abnormal event and make the operator aware of it.

One problem about using polygons to show the measured variables is that there are more than one train in the pre-heater system, the steam generator system and the turbine system in a real plant. The small simulator used for draft 1 and 2 have only one train, both for pre-heating, steam generation and for the turbine system. To separate the trains the polygons are displaced from each other at a distance of 5 pixels in horizontal direction, to make it clear which train deviates from the others in an event situation. One polygon represents the steady state condition, so it is possible to see deviations from the intended condition as well.

The levels of the pressuriser, the steam generators, the feed water tanks and the condensers are shown as levels in the mimic diagram. The same method is used for levels as for the polygons described above, with the levels placed beside each other in such a way that it is possible to see the levels in the four-steam generator and a reference level too. The small simulator has only two generators and therefore only two levels are presented. If a level starts to increase, an up-arrow is shown for the level in question, and similarly a decreasing level is indicated by a down-arrow so that the operator is made aware that the situation is changing. Key values of the parameters are shown digitally too in the mimic diagram, as tradition has it: at the point where the values are measured.

4.2.1 The control system

The control system is interesting both for the diagnosis of an event and for maintenance purposes. As discussed earlier, the control system has a tendency of hiding incipient failures, so the observation of the activity in the control system could be a way to reveal such failures. Similarly, the control system compensates for the effect of wear in components. In both cases the plant functions are still normal, but the condition of the plant has changed. Actions in the control system are shown in the overview display in the same way as changes in the water levels. If the control system speeds up a pump, an up-arrow is shown in a box beside the pump in the mimic diagram. This idea was adapted from Prætorius [38] in *Figure 35* . The display implemented on the full-scale simulator is shown below. This display still suffers from the lack of a lower limit for the pressure in the reactor and the arrows at the controllers. A special problem about the display is: how should the pumps be presented as components, and how should their status be shown. Letting each pump correspond to an arrow in the display solved the problem: when the pump is running the arrow is white, and when it is idle the arrow is grey. White and grey are the colours that were chosen in the full-scale simulator for components operating, respectively not operating. Incidentally, to register the status of a component can be a task in itself; for example, that the power has been switched on to open a magnetic valve is not the same as to say that the valve is in fact open.

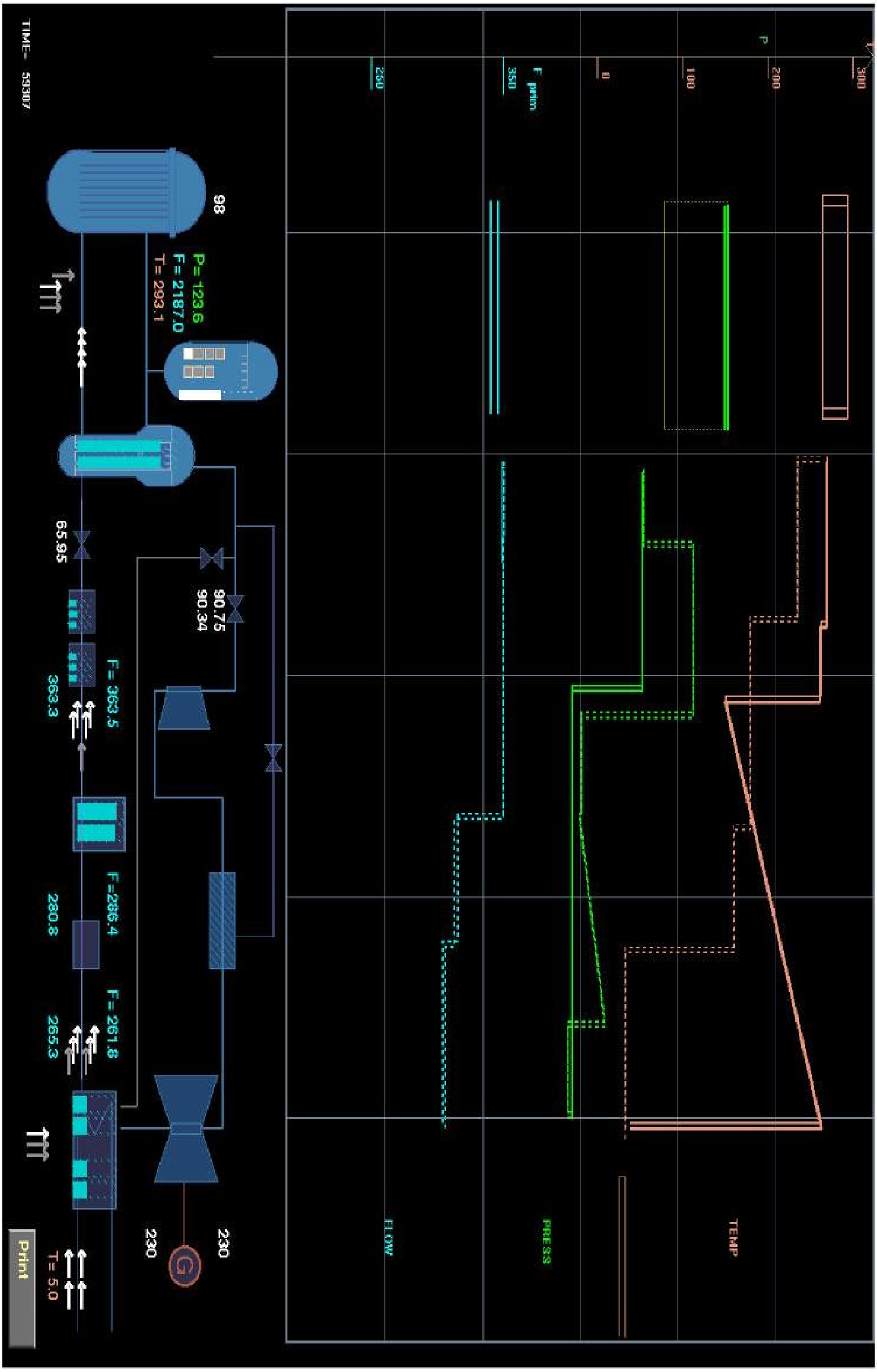


Figure 36 Final Display for the PWR full scale simulator

4.3 Evaluation of the design

The PWR overview display was designed with a view to the display for the pipe reactor: the idea was to try out if the way the measured variables were presented for the pipe reactor could be applicable and valuable in the case of a nuclear reactor too.

At the time the PWR display was developed, it was not intended to fulfil all the requirements to a display. The aim was merely to show the measured variables not just digitally but also in other ways. To evaluate the design and estimate its ability to fulfil the requirements will be valuable for further work. It should be added that it is not the purpose of an overview display to fulfil *all* requirements for an entire system.

The information required in the overview display was the following:

- *Layout* of the plant
- Types of *components*
- *Goals* of the plant
- *Functions* of the plant
- *Reference values* included for both goals and functions.
- Important *safety* requirements

The requirements for an overview display must focus on the main systems and the main components.

4.3.1 Layout and components

The layout follows the layout used for piping and instrumentation diagrams (PI-diagrams) for this type of plant, unless that the symbols for the pumps do not follow symbols, which are used for PI diagrams and only the main pipes and components are present.

4.3.2 Goals of the plant

The overall goal of the plant is to produce a specified amount of power in a safe way. This goal does not appear in the overview display. One way to represent the goal would be to show it as an energy flow through the entire plant; however the energy flow through the turbine system cannot be calculated from measured variables, since the flow on the steam side is normally not measured.

Still, the power output must of course be shown on the screen, and so must the reactor power and the overall efficiency: they are among the key parameters. The efficiency can change from day to night due to the cooling water temperature, but even then it is an indicator, e.g. for condenser problems.

4.3.3 Functions of the plant

The functions of the plant are: temperature, flow and pressure increases and decreases. They are all presented in the overview display whereas the references, that is, the set points for power and other quantities, are not presented.

4.3.4 Condition of the plant

There is no presentation of conditions of the plant in the overview display because this is not the purpose of an overview display. However, a quantity such as the difference (or the ratio) between actual and expected efficiency of the plant is an overall indicator of its condition, and it might be appropriate to include this quantity in the overview display.

4.3.5 Safety

When the pipe reactor display was designed we knew the safety problems inherent in the plant, and what to be aware of during operation. Now, when we are addressing the problem of providing information related to safety on a PWR, the following questions must be answered:

- What are the safety problems of the plant?
- Which situations must be avoided?
- How can these situations occur?
- How can these situations be identified/recognized?

As mentioned in the beginning of the chapter, there are at least two main safety problems when trying to avoid any risk of a core melt down in a PWR: (1) to keep the secondary system able to remove the heat from the primary system (for this task, the temperature difference between the primary and the secondary side is an important safety parameter); (2) to prevent boiling in the primary system.

Both these problems can be managed in the present overview display. The temperature difference between the primary and the secondary system can easily be checked, Figure 37. It is also easy to see if the primary pressure is higher than saturation pressure.

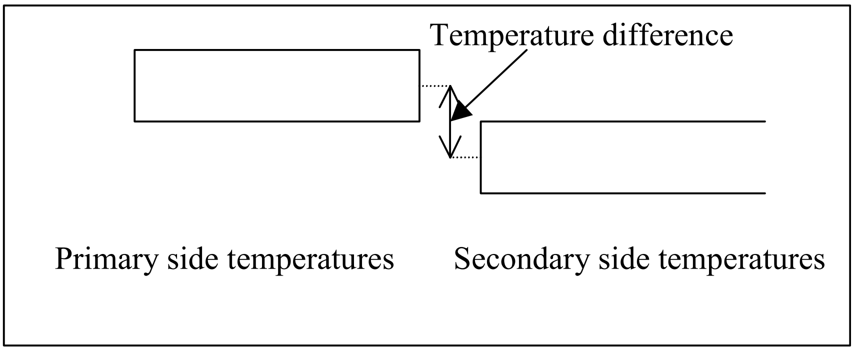


Figure 37 Temperature difference primary-secondary

The unwanted situations are caused by leaks and failures of pumps. In both situations, the control system tries to compensate for the leak or the failure. The implemented supervision of the activity in the control system, makes it possible to follow compensatory actions. The idea was tested first on the small-scale simulator; the test pointed to up- and down-arrows to represent actuator activities as being valuable in the overview display and even in lower level displays.

4.4 Tests of the overview display

The first tests of the PWR overview display were performed on the-small scale simulator during the development of the display. Next, a series of three tests were made on the full-scale simulator at the Halden Reactor Project, Norway, in order to see how the display would behave during different transients. The full-scale simulator models the reactor at the nuclear power plant in Loviisa, Finland.

The overview display was implemented at the Loviisa simulator according to the design rules that have been followed in all other displays at this simulator: rules for how to represent open/close valves, which symbols to use for pumps, which colours to use etc. We shall now give a brief account of the three tests made at the Loviisa full-scale simulator.

Test no. 1 – Trip of one turbine

Observations. The first observation on the display after the trip was a drop of mass flow before the low-pressure heaters. This means that the condenser pumps are running but the flow is by-passed back to the condenser. The flow in the condenser pumps is maintained. – It was rather easy to follow the steps in the automatic regulation of the flow into a stable operation with one turbine train.

What to be done. The curves need to be supplemented with references. It should be easier to see if a curve has moved up or down: small changes are hardly observed without some kind of reference curve. On the other hand, the pressure and the temperature distribution across the tripped turbine train have no interest, and parts, which are not in operation should not be represented.

Test no. 2 – Leak in the high pressure heat exchanger

Another not un-normal event is a leak in one of the high-pressure pre-heaters. There are two types of leak: a leak in the plate between the inlet chamber and the outlet chamber and a leak in a pipe between the primary and secondary side of the heat exchanger. Test no. 2 was a leak in a pipe.

Observations. This leak could not be observed with the present measured parameters.

What to be done. There is a need to present additional measurements on the display.

Test no. 3 – Leakage in a steam generator from the primary to the secondary side

Observations. The level in the pressuriser goes down. The charging pumps are activated. The valve on the feed-water control on the secondary side starts to decrease the feed-water flow.

What to be done. Again, some reference curves or points would be appropriate because they would make it easier to observe a change in flow, a temperature or a pressure.

4.5 Conclusions from the tests

Experience from running various events on the simulators using the new overview display yielded valuable information about the dynamics of the plant and about the sensitivity of the measured parameters to the events in question.

A quantity which turned out to react quite slowly and with delay to an event is the temperature. In contrast, the flow reacts almost immediately. This difference in behaviour is hardly a surprise since the temperature in the system must depend on the temperature of the structure material and is in fact often a secondary effect of a change in flow. Paulsen et al.[31](It can be added that the control system acts very fast on an event too, and again this is of course not a surprise.)

Even in case the flow stops completely, the temperature remains almost the same for a rather long time. This is explained by the fact that the main actuators in the control system are the pumps and the valves. A stop of a pump or the closing of a valve causes an immediate stop of the flow; just a decrease in pump speed or a partial closing of a valve has an effect on the flow at once, but does not influence the temperature before much later. Such observations are useful for future work on specifying which parameters must be shown in the overview display in order to make the operator aware of incipient failures. This kind of information also indicates which parameters should be alert and which may be kept more in the background.

The following conclusions can be drawn from the three tests of events at the full-scale simulator using configurable displays:

- In case the feed flow is disturbed, as was the case for the turbine trip and the leak in the steam generator, the configural displays shows the event very well and the operator can quickly observe that something has changed.
- A leak in the pre-heater is not observable. Such a leak can be detected by checking the valve that controls the water level in the pre-heater. Some events require a study, preferably an FMEA analysis, of failure modes and their consequences.
- By some of the events the polygons totally overlap each other Figure 38 and Figure 39,, and this leads to a confusion when trying to understand what is going on.

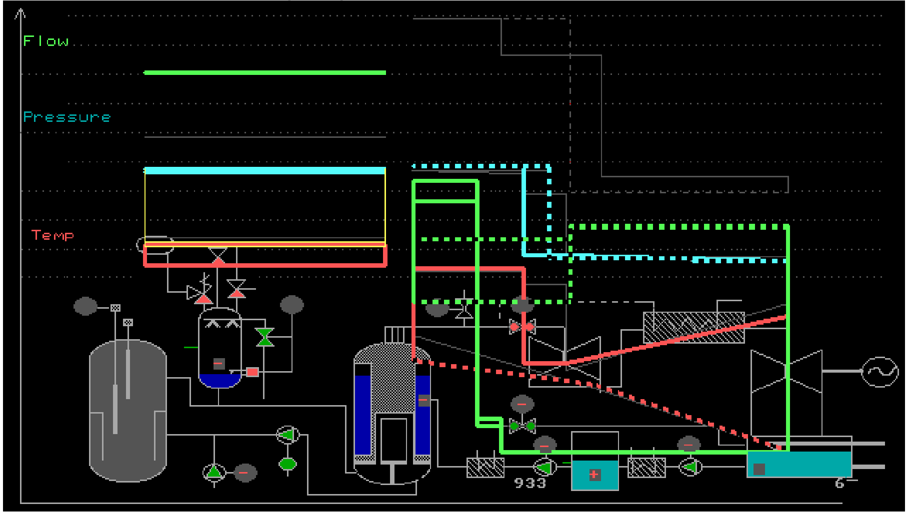


Figure 38 After a scram- overlapping polygons

Or a normal situation

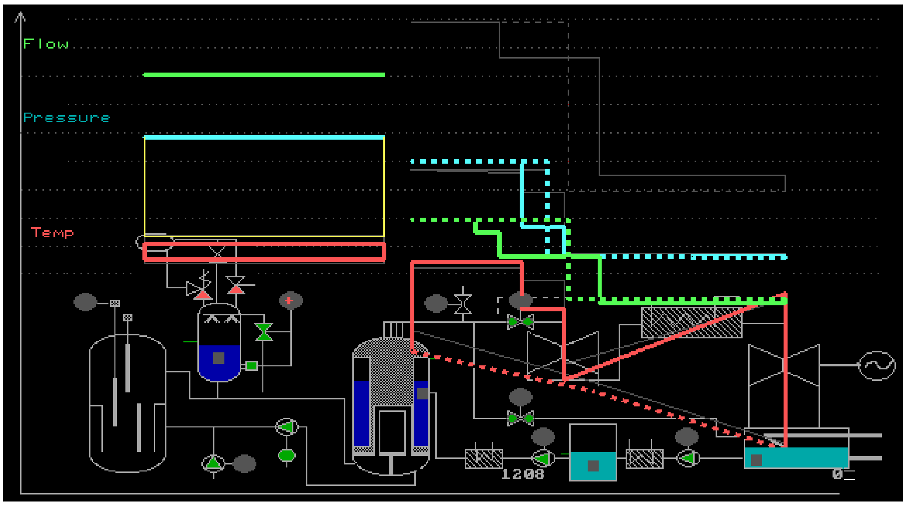


Figure 39 Plant at half power- also overlapping polygons

- In case of a failed sensor the situation is the same: the polygon will be confusing and not helpful Figure 40.

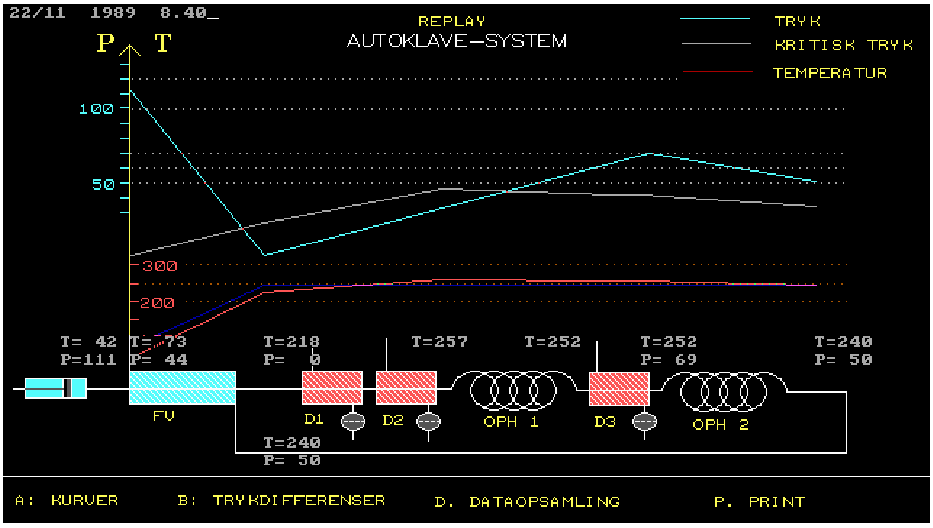


Figure 40 Sensor failure in the pipe reactor

The last three pictures show the weakness of Configural displays. If more than one type of variables are shown on the same display they can in specific situations overlap each other and the display will be confusing. A sensor failure disturb the picture a can make the display nearly useless. Concerning the up and down arrows on the small simulator, a wish for a future display is to make it visible from where controller has its input. Could be done by dotted lines on the mimic diagram.

5. Design of an Overview Display for a Waste Incineration Plant

During an EU project (CLEAN) with the main goal to reduce the emission from waste incineration plants, it became appropriate to take up the challenge of developing an overview display for such a plant, see Paulsen and Weber [36]

To achieve the goal of the project and indicate practicable ways to reduce the emission, it was attempted to optimise the control system. For this task, a neural net controller was constructed based on experience from a particular plant. The overview display was developed in order to test the neural network controller; besides it would be useful for the training of the operators.

Waste incineration plants present a very interesting problem compared to other energy producing plants, viz. that the operator does not know in advance what the burning value and the moisture content of the waste is. This is why solely adjusting the airflow cannot control the burning process; the operator also has to make a visual inspection of the burning process.

The operator should be considered part of the control system. The information to the operator about the plant status must be very precise so that he is able at any time to take the right decision about which actions he should carry out. This feature of the plant makes certain claims to the selection of information to the operator, and to the way it is presented.

5.1 Description of a waste incineration plant

The purpose of a waste incineration plant is, simply, to get rid of the waste. In most plants the energy produced by the incineration is utilised directly for domestic heating, but in some cases also for the production of electricity.

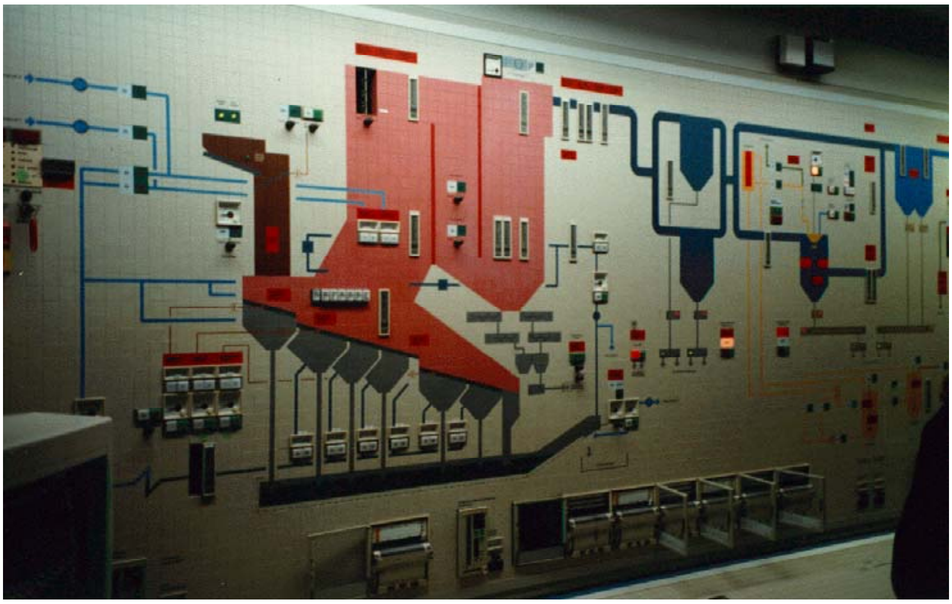


Figure 41 Waste incineration plant. 1.generation display

Waste, of mixed domestic and industrial origin, is delivered to the plant by road transport and unloaded into a waste pit; the pit is usually sized for a capacity of several days in order to guarantee a continuous treatment of the waste, regardless of possible fluctuations in delivery. Specially designed waste cranes feed the incinerator.

The incineration of the waste takes place on a stoker type grate. The slag's produced during this treatment are removed through a slag quench tank and an extractor placed underneath the grate. The boiler located above the grate produces live steam by cooling the flue gas from an initial temperature of at least 850°C down to about 230°C at the boiler outlet.

To get an efficient burnout, it is necessary that during the start-up phase the minimum temperature of the flue gas in the post combustion zone is 850°C, even when taking the temperature fluctuations at normal operation into regard. In order to ensure this, start up and/or support burners are installed.

Part of the combustion air is drawn from the waste pit, preheated and injected through the grate and the waste layer into the combustion chamber (primary air). Additional air is drawn above the slag extractor and injected into the combustion chamber above the grate (secondary air), in order to achieve a complete post-combustion of the flue gas.

The steam produced in the boiler proceeds to a condensing turbine, which is used for the generation of electric power.

A flue gas cleaning is performed before the gases are released into the atmosphere.

5.2 The information required for building the display

What is an optimal process? First of all, the requirements for the process to be optimal must be known; and so must the problems during normal operation as well as the risks connected to the process and the plant

A simple strategy based on some questions used in risk analysis work was used to extract the information to display to the operator:

- What is the goal?
- What is the problem?
- Why does it occur?
- How is it observed?
- How to control it
- How to present it

Addressing these questions leads to an identification of the relevant process variables to present to the operator.

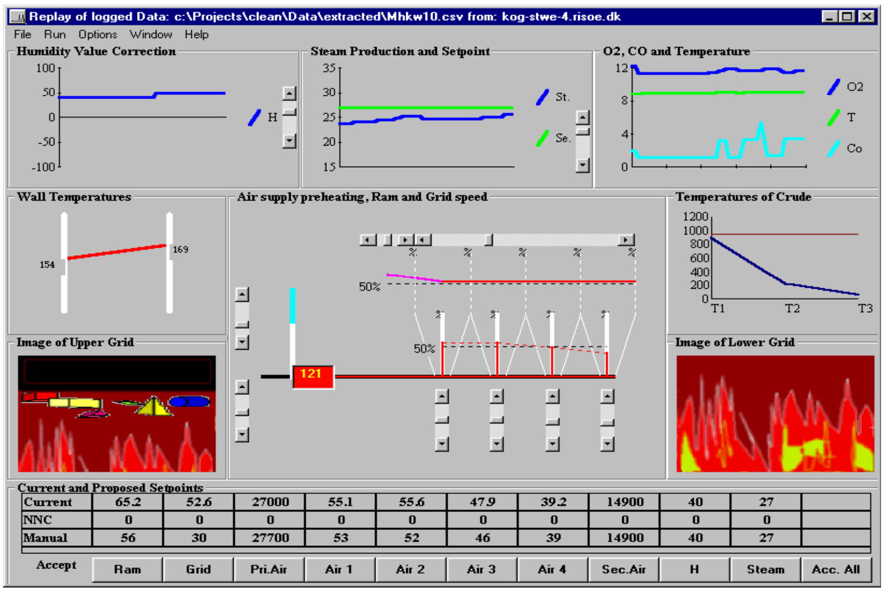
Typical problems in the project dealt with here is the emission of unwanted elements in the crude gas, for example a too high levels of carbon monoxide and of dioxin. These problems can be avoided by maintaining a sufficiently high temperature in the incineration chamber and a sufficient airflow to the incineration process.

Due to the considerable variation in humidity and heating value of the waste, it is difficult to estimate the necessary airflow. The optimal way of running the process is to keep the energy output constant corresponding to a constant flow of steam, but this is difficult to realise because of the variation in heating value of the waste input. The same strategy as described above – asking why, what to observe, and what to do – can be used to analyse the problem of deviation from normal energy output:

Using the strategy		
QUESTION		**EXAMPLE**
What is the goal?	→	Minimise release products
What is the problem?	→	Incomplete burnout of waste
Why does it occur?	→	Variation in characteristics of input waste (burning value and humidity) Too low temperature in the second incineration chamber. Problems with the waste distribution on the grate
How is it observed?	→	Unstable steam production CO and O2 levels in the flue gas are increasing or decreasing. Values below or above limits for acceptable operation. The temperature in secondary chamber is lower that set-point, Tsec <Tset
How to control it	→	Change the amount of input waste, primary air, secondary air, grid speed, or the preheating
How to present it	→	Depends on what to observe. A mixture of different presentation forms as trend curves, graphical representation of process variables and video of the drying and burning zones will be used.

Table 4 The analysis

Figure 42 shows the resulting overview display, with the various types of information it was decided to have on it.



Current	65.2	52.6	27000	55.1	55.6	47.9	39.2	14900	40	27	
NNC	0	0	0	0	0	0	0	0	0	0	
Manual	56	30	27700	53	52	46	39	14900	40	27	
Accept	Ram	Grid	Pri.Air	Air 1	Air 2	Air 3	Air 4	Sec.Air	H	Steam	Acc. All

Figure 42 Overview display for a waste incineration plant, 3. generation

The production goal of the plant has been set to a production of 25 ton of steam per hour. Since it is important to take measures against *variation in steam flow*, the steam production is shown in the display as a trend curve. Another problem, a possibly *incomplete incineration*, appears from the O_2 and the CO content in the flue gas; therefore they are presented as trend curves too, as for the steam production to be aware of the tendencies in the variation.

An *uneven distribution of waste* on the grid can, to some degree, be detected by observing the wall temperatures along the grid. These temperatures are shown on two vertical axes representing the walls. A line connects the two temperatures, making it easier to see a deviation from optimal function, which would mean the same temperature at the same position on both sides, that is, a horizontal line.

The middle part of the display informs about *the grate*: the grate velocity in % of maximal velocity; the openings of the primary air throttle valves; the temperature of the primary air; and control bars for manual control of the grate velocity and air throttle valve openings.

In the middle to the right, *three important temperatures* are shown: the flue gas temperature in the second incineration chamber T1 supplemented with the set point value (the horizontal line); the temperature before the flue gas cleaning system T2; and the exhaust temperature T3. The three temperatures are connected with lines to observe changes better. This line also shows the temperature drop in the boiler, T1-T2, corresponding to the energy delivered to the district heating system. A decrease in the temperature drop across the boiler will indicate scaling problems on the heat transmission surfaces in the boiler.

On the display is also made room for real-time presentation of the pictures from two *video cameras*, one showing an image from the upper grid to supervise what is coming in of waste, the other an image from the lower grid with information of e.g. unburned waste

In the upper left corner is a graph showing the *Humidity Value Correction*. The operator can adjust the humidity in the incineration chamber if he finds that the humidity and thereby the burning value of the waste has changed. The crane operator keeps the operator informed about the type of waste he is loading into the system; from this and other information the operator estimates the humidity value.

As it can be seen in the figure, almost all the variables are presented in a graphical form, making it easier for the operator to see if the operation of the plant is normal or a deviation is occurring.

5.2.1 Test of the display

During the initial implementation of the neural network controller, the operator is regarded as part of the controller. The operator has to perform the actions manually that the controller, after it has been finally implemented, will carry out automatically. The initial implementation is therefore a test of the neural network controller. The display must present, besides the information about plant condition, advice to the operator about manual adjustment of set points

The neural network controller has been tested at a incineration plant in Darmstadt, using the display we have developed. The display turned out to be able to supply all the graphical information required. The neural network control part was not fully finished at that time.

During the test, the steam production suddenly and unintentionally decreased to a level much below what was normal during steady state operation. The normal production would vary between 20 to 30 ton/hour; this rather high variation was caused by the changing burning value of the input, and it was the main reason why the management wanted to optimise the control system. The operator discovered the decrease while he was looking at the new display; clearly he was sceptical and thought that there has to be something wrong with what it showed. He went to the traditional Siemens display system, Figure 43, and looked at a lot of screens whereby he found out that the grate has stopped to move. The interesting thing is that all the variables he was looking for were present in the new display: it was rather easy to see in this new display – on one screen – what had happened, and the consequences of the event were.

Figure 43 Second generation displays

The incident reported here is not claimed to be a proof that the system described above fulfils all requirements to an optimal overview display. Still, it seems to extract the essential key parameters, and it does so by utilising the philosophy in risk analysis thinking. The simple strategy that was applied has proved to facilitate the elicitation of the sub-goals necessary for the goal to be fulfilled

6. Condition Monitoring of a Power Plant Condenser

This chapter deals with the development of displays to be used for power plants. One specific system is studied as an example: a *condenser system*. The condenser is of particular interest because it has an impact on the economy of thermal power plants, and it was a wish at several plants to install condition monitoring which could give an early indication of problems in the condenser and, if possible, information about the type of problem that had occurred.

6.1 Description of a Condenser

The performance of the condenser system is essential for the efficiency of the power generation and thereby for the overall economy of the power production. The condenser has as its main purpose to keep the pressure as low as possible on the secondary side of the low-pressure turbine. Its operation influences directly the plant efficiency, because the efficiency of the plant depends on the quantity P_{turb}/P_{cond}, that is, the ratio between the pressures before and after the turbine. A cooling system is used to condense the steam and to keep the temperature, and thereby the pressure in the condenser, as low as possible. An ejector system removes the non-condensable gases from the condenser. Disturbances and degradations in these two systems influence the pressure in the condenser.

The condenser is also used for other purposes: to receive dump of steam, drainage, re-circulation from condenser pumps etc.[28]. These systems have a connection to the condenser and therefore they may influence the pressure in the condenser.

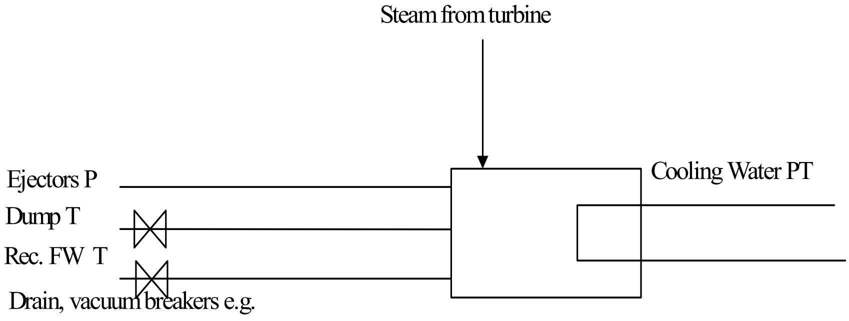


Figure 44 Condenser system

To illustrate the influence of variation in pressure, a measured dependency between generator power and condenser pressure at the Barsebäck Nuclear Power Plant is shown in Figure 45. It illustrates the variation from January to August 1997 due to the increase in seawater temperature. The corresponding increase in pressure leads to a decrease in generator power of 50Mw, from 617 Mw to 567 Mw.

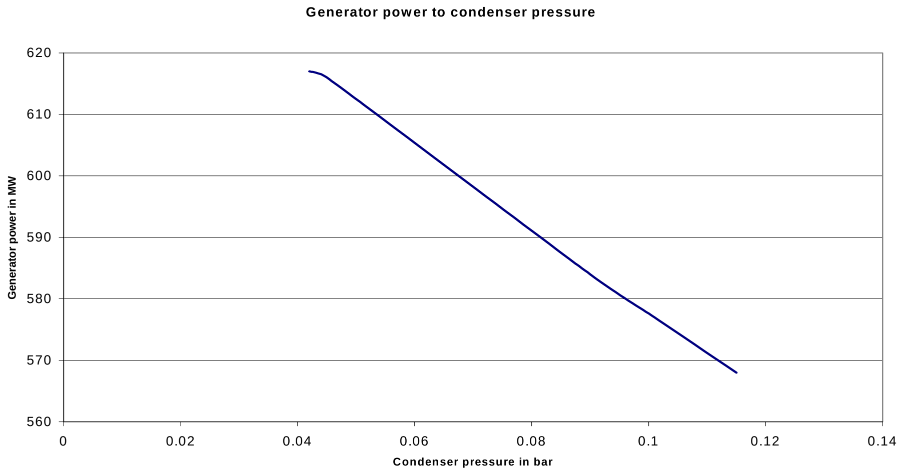


Figure 45 The Influence of Condenser Pressure on Generator Power.

The change in the sea-water temperature is a natural phenomenon and nothing can be done about that. But the same consequence results from failures in the systems that are connected to the condenser and exert an influence on the pressure in the condenser. This is why power companies are interested in condenser behaviour.

6.2 The simple strategy applied to the condenser

An account of how the strategy is applied to the condenser system is presented in Table 5.

QUESTIONS	**Answers**	**Information to show**	**References**
What is the purpose of the display ?	To distinguish between the different failure modes in the condenser that gives increased pressure.		
What is the problem?	Temperature increase in the condenser Non-condensable gasses in condenser	Tcond Tcooling Pcond	Tcond expected Pcond = f(Tcond)
How does the problem occur?	Ejector problems Cooling problems Incoming air Fission gasses		
How is the problem observed?	Decrease in expected power Increase in condenser pressure Increase in air flow from ejector	Power Pcond Flow-air	Expected power
Invariants and physical laws in the process?	The condition is saturated steam => Working point on the steam saturation curve Daltons law P=Pa+Pb+…+Pn (sum of partial pressures)	Saturation curve and working point Pmeas	Expected working point on saturation curve Psat
Design parameters?	ΔT= Tcondenser-Tcooling water = constant at normal operation	ΔT	
Characteristics?	Saturation curve	Saturation curve	
Specific properties?			
How to present the problem?	Actual working point and expected working point relative to the steam saturation curve Trend curves for Tsea,Tcond, Pcond, Psat…		

Table 5 : Strategy Applied to a Condenser.

The information identified from applying the strategy described above is necessary when designing a display for efficient condition monitoring of a condenser. This is explained in the following.

The purpose of the display is to inform the operator about the condition of the condenser and to assist him in distinguishing between different failures in the condenser, especially failures that lead to an increased pressure.

As described above, the condenser pressure depends on the temperature in the condenser and thereby on the coolant water temperature. The lower the pressure, the better is the economy for the power plant. A change in pressure leads to a change in generated power; the latter is often observed first. A change in generated power can happen due to a change in the condenser, or to other changes in the plant. If the change in power were due to a change in the condenser performance it would be advantageous to look at the generated power and pressure as function of time in the same diagram. In this way deviation of pressure from a constant value can be observed as a cause to decreased production. As the naturally change in cooling water temperature can be the cause to the increase in condenser pressure, the cooling water temperature value must be present as a trend curve too. At the Barsebäck nuclear power plant, small fluctuations also occur in the condenser temperature due to addition to the system of fresh water with a temperature lower than the one in the condenser.

In general, one of *the design parameters* is the temperature difference between the coolant water and the condenser. The expected pressure in the condenser can be calculated as a function of the coolant temperature, and the working point can be plotted on the *characteristic*, i.e., the steam saturated curve, which is to be considered an *invariant* for the condenser performance. When the measured working point is plotted in the diagram too, it is easy to see the deviation from the *expected working point.*

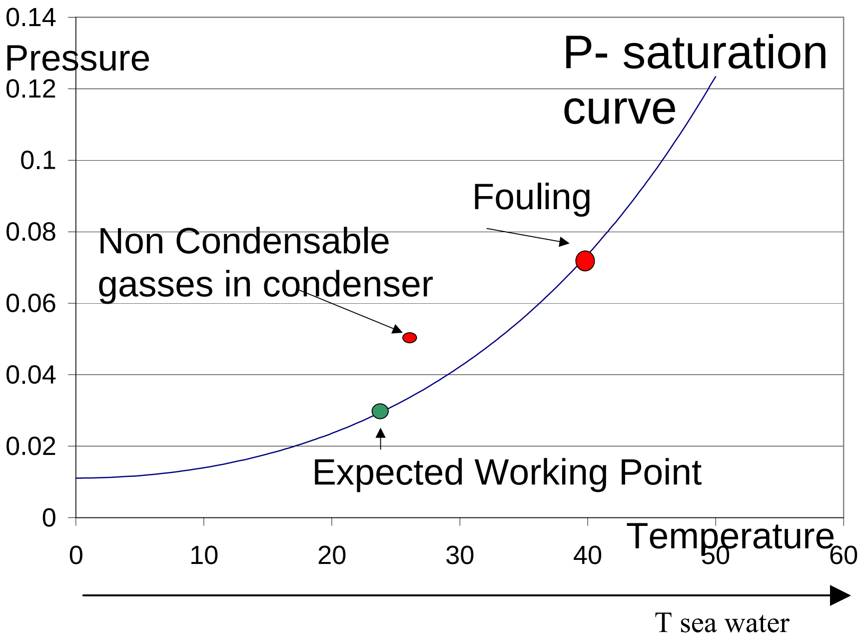


Figure 46 Display for condition monitoring of a Condenser.

The display developed for the condenser is shown in Figure 46. The purpose of the display is to indicate deviations of the actual working point of the condenser from the expected working point; besides the display should be able to show which type of degradation or failure that has occurred.

Cooling problems and fouling on the heat transmission surfaces cause an increase in the condenser temperature and thereby in the pressure, but the working point will still lie on the saturation curve. Non-condensable gases are expected to increase the pressure in such a way that the working point moves up above the saturation curve, but the gases also give rise to an increase in temperature due to a decrease in heat transmission.

Fouling on the heat transmission surfaces is expected to increase the pressure in the condenser more slowly than is the case when a failure has happened in the ejector system, or when leaks of air have entered into the condenser. Tests at a Danish power plant where the ejector system was stopped for half an hour showed a fast increase in pressure due to the formation of non-condensable gases. The present display has therefore importance for the maintenance planning of the condenser and for optimisation of the thermal performance of the entire plant.

The display has been implemented for tests at the HAMBO simulator at the Halden Reactor Project. The idea of involving the component characteristics is also used for condition monitoring of other types of components in the ongoing Halden reactor Project. Tests of the displays will show if this type of presentation is well understood by the operators and if it is sensitive enough to be able to observe incipient failures. Replaying data from Barsebäck has given promising results, Figure 47

The display developed for the condenser must be supported by *trend curves* for the relevant variables.

6.3 Test of the Condenser Display

The condenser display was implemented on a PC to test its functionality. The programming language used for this demo was Visual Basic. The display was used for replaying data from two thermal power plants, one nuclear and one gas fired, and data from the HAMBO simulator.

From the nuclear power plant, both data for a cold winter period and data for a hot summer period were replayed, Figure 47. The operation was performed with a constant reactor power and it showed a difference in generator effect between the winter and the summer period of nearly 60 MW, due to the difference in cooling water temperature. The working point remained on the saturation curve,

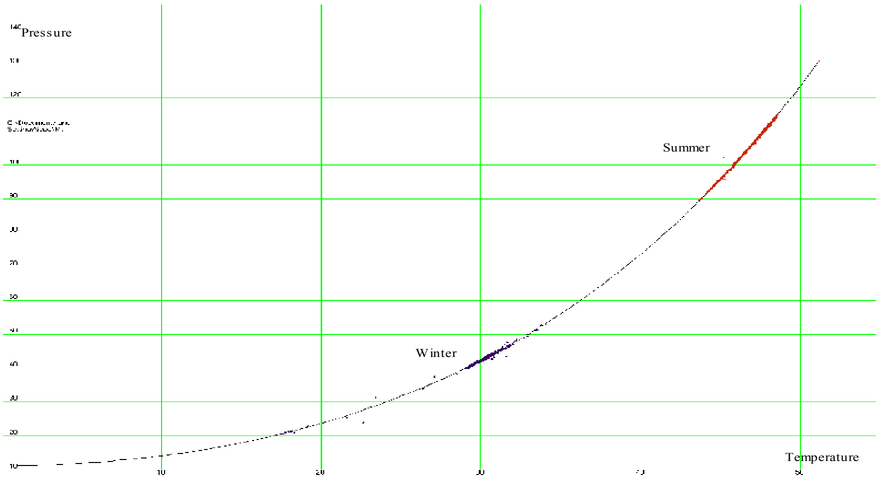


Figure 47 Replay of Data from Barsebäck

The display was implemented on the HAMBO simulator and three tests were made, one simulating an air leakage into the condenser, one with a stop of a main cooling pump and one with a stop of the ejector system; the latter event might have similar consequence as fouling on the heat transmission surfaces. Both tests are shown on Figure 48.

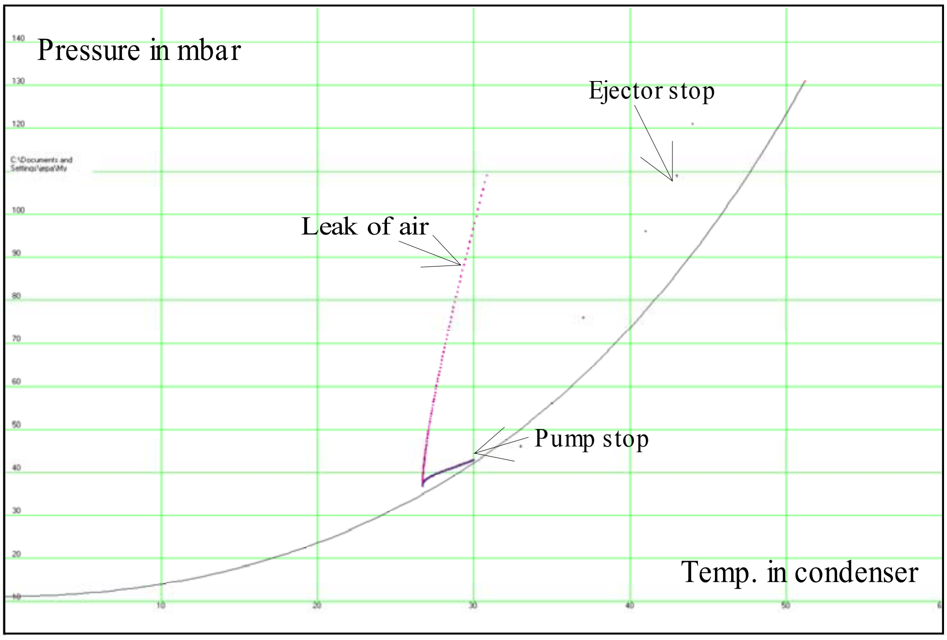


Figure 48 Test on HAMBO of the Condenser Display.

In general, the results of the tests were as expected. In the case of an air leak into the condenser, the working point of the condenser deviates from the saturation curve, showing a pressure higher than at saturation. This points to other gases than just steam having been introduced into the condenser. In the case of a pump stop the working point is expected to end up on the saturation curve after the system has stabilised; it seems to be exactly what happens.

The condenser display can be supplemented with the curve that shows the effect of variation in the condenser pressure on the generator power. The result would look similar to the Figure 49 display replayed with data from the pump stop on the HAMBO simulator.

The display shown on Figure 49 is a combination of two characteristics for the plant. The one to the left is the curve showing the generator effect as function of the condenser pressure, but with the pressure shown on the y-axis and the effect on the x-axis. The one to the right is the same as for the condenser display also with the pressure as the y-axis.

- The working point of the condenser (T,P) is plotted into the right side display
- A horizontal line is drawn to the characteristic in the left side display.
- The x- value is then the generator effect
- Eventual loss in effect due to increased pressure in the condenser can be observed from the x-axis of the left display as seen on the figure.

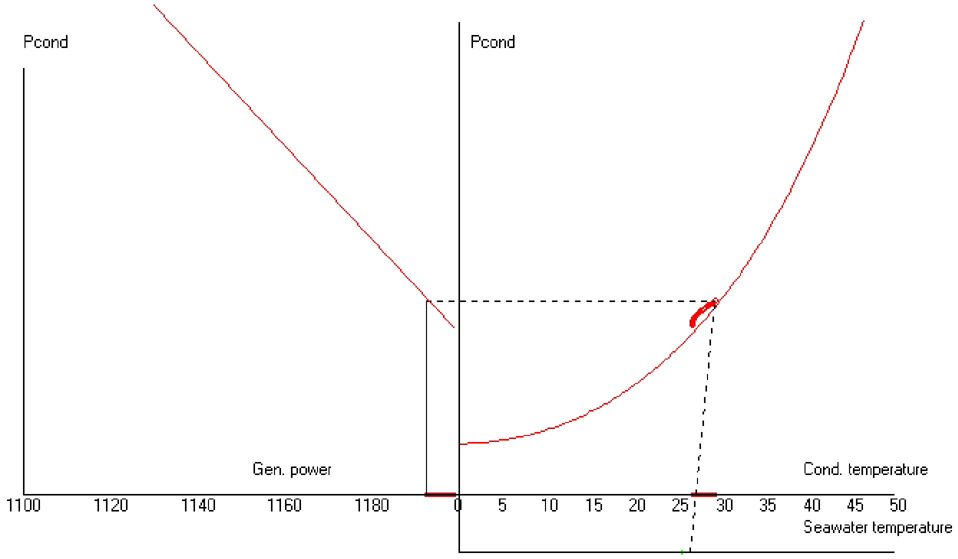


Figure 49: A Combined Display Showing the Consequences of a Pressure Increase in the Condenser.

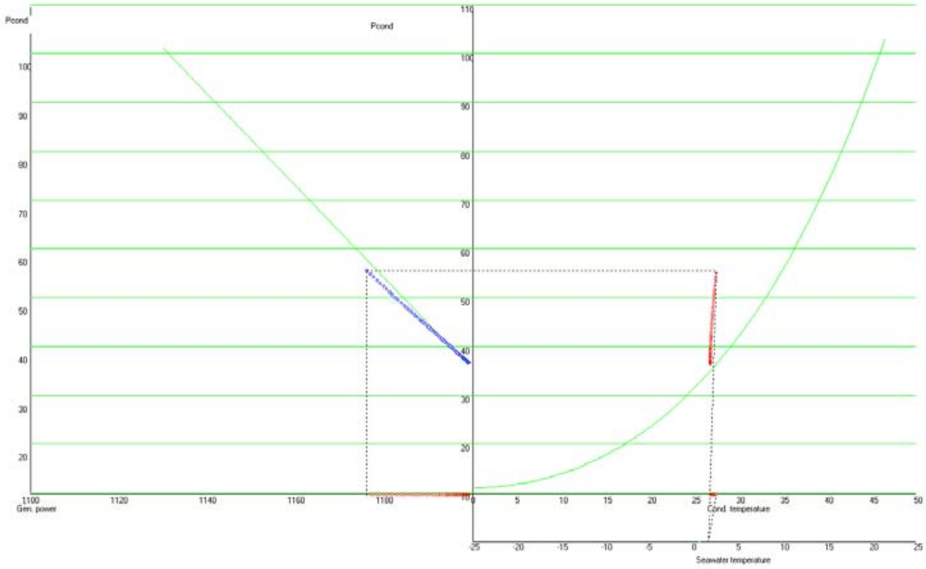


Figure 50 The same display, but with an air leak (new version of the display)

The test was performed in the mode with a constant reactor power. In the case of constant generator power the consequences of an increasing condenser pressure would be an increasing reactor power, while a control system will increase the reactor power to compensate for the decreased generator power of the plant. The efficiency will decrease as for the constant reactor power mode.

The condenser display showed that the display fulfilled its purpose namely to distinguish between the different failure modes for the condenser. Furthermore also the influence of the effect of the plant can be seen.

Certainly other information can be put into the present display, but the task was just to show, that there is a difference in behaviour of the condenser, dependent of which situation that occur.

7. Systems Analysis

Lessons learned from the guidelines, state of the art on design of displays and own experiences are that the designer must have a deep knowledge of the plant and its functions to be able to assess which information is necessary for the operator. It both concerns the normal functions and safety aspects of the plant. How do the designer get this knowledge? A comprehensive and structured *systems analysis* may give the designer the required knowledge. This chapter describes how knowledge about the plant originates from different sources and/or analysis. The content of the chapter can be summarized as follows.

We set out with a brief discussion of the *design specifications* for the plant and its *control system*, but the item that is treated most thoroughly is *risk analysis*, including aspects such as hazard identification, root cause identification and human errors.

7.1 Plant design

During the initial design of a process plant for making a specified product, the decisions are taken on how to carry out the production. Usually this can be done in more than one way. For example, in the case of a nuclear power plant, one may choose between a large numbers of reactor types. Similarly, in chemical plants there are different methods to make the same product, and for each method there may even be different components to choose among in the design of the whole plant.

For the designer of the information system it could be valuable to have access to information from this stage of the design process, in particular to the arguments for choosing a specific process among the various possibilities. Of course not all arguments are relevant in this connection; for example an argument for reasons of prize is not as valid as an argument for safety reasons. Still, the various arguments have been intertwined in the initial decision process. To inform the designer about these arguments is to enable him better to understand the problems connected to the process – to realise what to be aware of, and what to avoid with the chosen process. Likewise it could be informative to know the reasons for the choice of components: why was a specific component selected from a set of various possible ones? Here, too, the economic aspects are not as interesting as the positive and negative functional aspects involved in the choice of a component. It could have been decisive that the component had a specific characteristic, which would fit to the process; but it could also have been safety reasons that closed the matter, for example the wish to use redundant systems.

The following flow diagram, Figure 51, gives very short some of the questions asked when designing a plant.

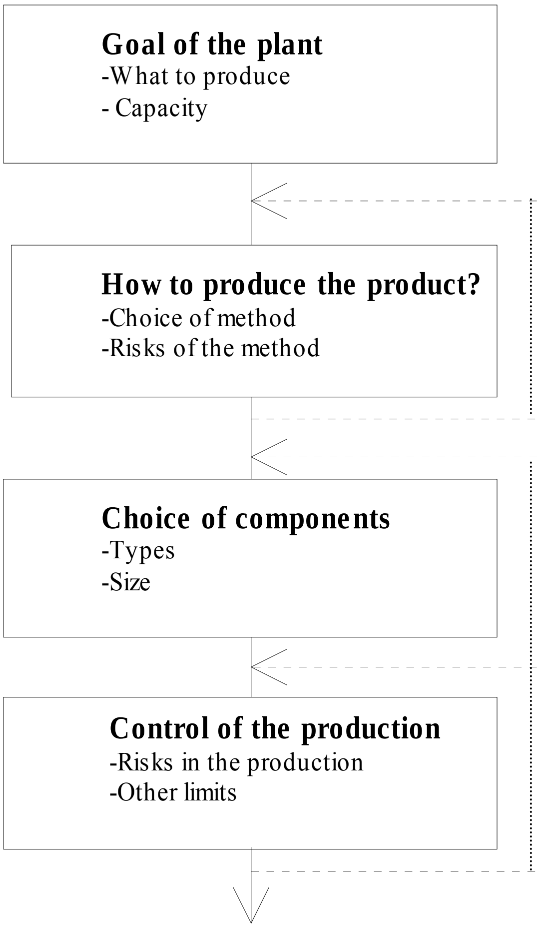


Figure 51 Simplified flow diagram of a design process

7.2 Design of the Control System

The purpose of the control system is to ensure that the intended operating goals of the plant are met. And there are goals at all levels of the plant: to keep up production is a goal; to keep a certain water level in a tank is a goal, too, although at a lower level. As a consequence, the control system must supervise different goals of the plant and react to deviations from them.

One important operating goal is to ascertain the protection of the process and the plant. Protection of the process means for example to a chemical production process below a certain temperature, to prevent the product from being ruined. The control system should react to e.g. deviations from the normal operation temperature, and maintain the temperature within given limits.

Protection of the components, means for example to ensure liquid at a certain pressure on the suction side a pump to prevent it from breaking down. Then it is a task for the control system to assure that liquid is at hand where it should be, for example by keeping a certain level of liquid in a tank on the suction side of the pump.

Protection of the process and the plant itself can give rise to the installation of *interlocks*. The demand to do so can also result from a risk analysis of the production process. Included in the specifications of the control system, besides information of operating goals to achieve and problems to avoid in normal conditions, also information about possible interlocks should appear. The installation of interlocks is sometimes necessary, e.g., to prevent human errors, but interlocks also restrict the possibilities to rearrange the process in an emergency situation where the absence of the interlocks might have been more convenient.

As, by nature, the control system tends to hide incipient failures, a supervision of the actions of the control system would be informative for the operator. He is himself a part of the control system. Therefore, when deciding how to design the control system, one of the important questions is: what must be automatically controlled, and what the operator must control?

In safety critical plants and in complex plants the automation level is very high. However during emergency conditions, a number of operations are still based on manual control. For nuclear power plants, it has been decided that the operator should control certain situations. In these cases the operator makes use of Emergency Operating Procedures (EOP), as a source of advise about his tasks and decisions during abnormal conditions. This practice resulted from the possibility of an unforeseen event that might cause difficulties for the control system to function as intended. Using his general process insight, an operator would probably have a better possibility to cope with the situation.

Conclusively and in brief, the purpose of the information system is to support the operator in his tasks during normal operation, but especially in emergency situations.

7.3 Sensor analysis

There is only one source from which dynamic information about the plant can be extracted for use in display systems: the *sensors*. These are placed in the plant for different reasons:

- To perform automatic control of the plant and its processes, it is necessary to install sensors at a number of different places in the plant.
- Similarly, to ensure sufficient supervision of the goals of the plant, of the plant behaviour, of its safety and its processes, it is necessary to install sensors in the process.
- Finally, requirements from the authorities can give rise to further sensors. For example, it may be necessary to supervise the pressure in tanks and to control the content of exhaust gases.

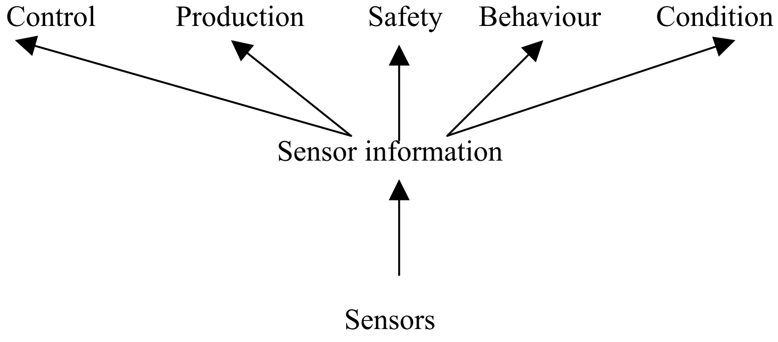


Figure 52 Purposes for the sensors installed in a process plant

A *sensor analysis* is a description of the purpose of each sensor in the system in question. The aim of the study is to support the design of the information system on how to show the information that has been collected. The following examples illustrate the relevance of such a study.

- Suppose that a sensor is installed to show the temperature variation in the seawater. Obviously, it is more informative to show the temperature as a function of time than just to show it digitally, as is common today.
- In the case of a sensor measuring the production of power, we have a somewhat different situation. It is obvious, and in most situations also sufficient, to present the instantaneous value; however for specific purposes a presentation of power output as a function of time may be relevant. Knowledge of a certain temperature in the pre-heating system in a power plant is only useful if the temperature 'before and after' is indicated too, that is, one must be able to see if the temperature in the heat exchanger is going up or down; a stand-alone temperature yields little information because prediction is important for supervision.

7.4 Risk Analysis

A *risk analysis* is a structured examination of a system and its functions, with a view to identifying causes and consequences of unwanted events and thus to reducing risks by taking precautions.

The risk analysis deals with selected *emergency situations* as well as with other unwanted events; and it provides information about the root causes for these events. In other words, the risk analysis points out the 'hot spots' in the plant and thereby gives input to the designer of the information system: what must the operator be aware of during operation of the plant?

A further outcome of the risk analysis is that it identifies important sensors in the system.

Carrying out a risk analysis requires the use of a number of systematic methods, each of them with different purposes. Among the most used methods are [37]:

Functional modelling for risk analysis.
Fault tree analysis
Human error description.
FMEA (Failure Mode and Effect Analysis)
HAZOP Analysis (HAZard and OPerability)

The five methods have different approaches:

A common feature of Functional modelling and the HAZOP method is to identify the hazards that are consequences of faults in the plant.

The Fault tree analysis considers these hazards as top events and finds the root causes for them. Using the fault tree method the probability of the top event can be calculated, if the failure rates for the root causes can be found. Fault tree analysis is used in probabilistic safety analysis where the probability of the top event is a part of decision criteria for safe operation of the plant.

The FMEA focuses on failure modes of the single components; it analyses the consequences of these failure and identifies the root causes for them.

A more detailed description follows below.

7.4.1 Functional modelling for risk analysis.

Among different techniques for functional modelling we shall briefly describe a widely used technique based on SADT [7] ,Structured Analysis and Design Technique, and further developed in the EU-project Tomhid [39].

Functional modelling aims at identifying and assessing possible hazards or unwanted events. An identification of hazards can be made on the basis of a description of the different functions that are performed in the plant.

The purpose of the functional model is to work out a sufficient description of the functional units of the plant, for example the stages of the process or procedure, or the single operations. The model describes the operational and technical circumstances that are significant for the operation and the safety of the plant, resulting in a coherent description of human actions and technical processes.

Use of the method implies that each unit is analysed by asking questions such as:

What goes into the function?
What comes out of the function?
What is the aim of the function?
What is done to implement the function?
Which control functions are being contemplated, and why?

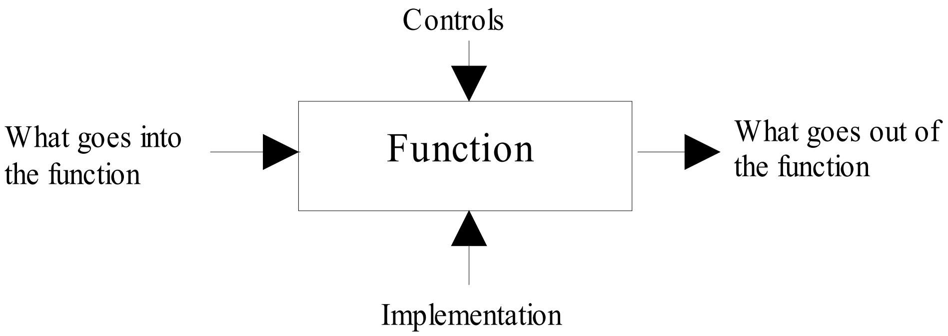


Figure 53 SADT functional modelling concept

When the functions of the plant have been identified, a checklist is applied to analyse the function. The checklist describes:

The function in question
The unwanted events of the function
The possible consequence of a failing control function
An assessment of the function, and of the possible precautionary measures, that should be taken.

Function	Unwanted event	Consequences	Control measures	Assessment

Table 6 Functional modelling checklist from the Tomhid project development

7.4.2 Fault tree analysis

A *fault tree analysis* is used when the unwanted events are already identified and there is a need to throw light on the logical connections between the causes of these events. The result of the analysis is presented in a fault-tree as shown in Figure 54 .The method is best explained and illustrated by giving an example.

The method:

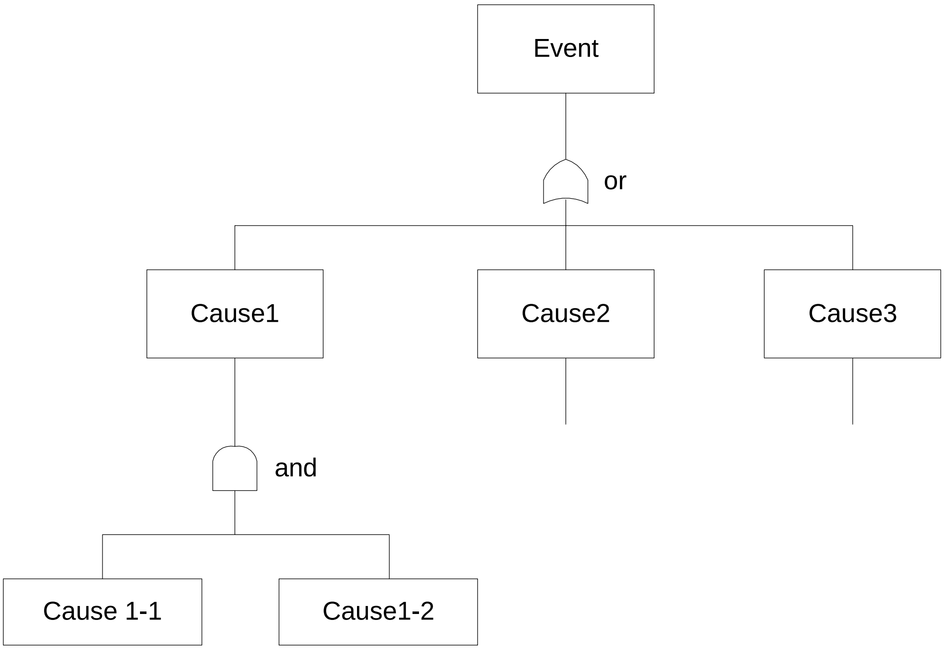


Figure 54 Fault tree structure

Example:

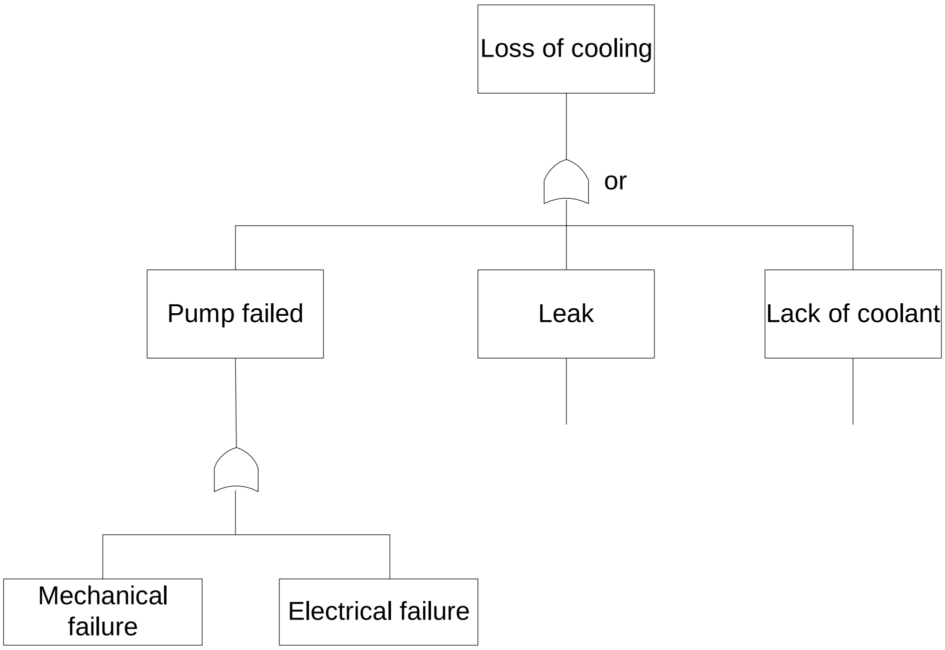


Figure 55 Example on use of a fault tree

7.4.3 Human error description

An analysis of *human errors* can reveal inappropriate elements in the procedures and in the system that the operator must adjust. Furthermore the analysis can point to the consequences of human errors.

In each specific situation, for example when analysing procedures, it is useful to compile a list containing the most common human failures that the risk analyst must be aware of.

Human errors can be divided roughly into three main categories :

- The operator fails to do what has been pre-scribed
- The operator does what has been prescribed but does it incorrectly
- The operator does something that has not been prescribed.

Going slightly more in detail, one or more of the following labels may be attached to the error:

- Operation carried out incorrectly
- Operation carried out correctly but at the wrong time
- Unnecessary operation - not prescribed or not learnt by heart
- Operation carried out correctly but on the wrong unit, system or component
- Operations carried out correctly but in the wrong order
- Failing communication or misunderstanding.

Finally, let us mention that "operator" is a broad term that can include such people as:

- Control room operators
- Operation staff
- Maintenance staff.

7.4.4 Failure Mode and Effect Analysis (FMEA)

This type of risk analysis is used to reveal the consequences and the causes of failing components. In a table as seen in the example in Table 7 , the components are listed. For each components its failure modes are listed, and for each failure mode the causes and consequences for the failure. The last column describes if actions have to betaken to prevent some of the failures or the consequences of a failure. Below is an example for stop of a cooling pump.

Component	Failure mode	Cause	Consequence	Actions
Cooling pump	Stops	Electrical failure	Lack of cooling	None or should be examined

Table 7 FMEA example

When carrying out an FMEA, it is convenient to have access to a list of possible component failures, Table 8.

Control system	**Failure mode**
Pumps	Do not start/stop Unintended start/stop Ageing
Valves	Do not open/close Unintended opening/closing Internal leakage
Sensors	Not correct measurement
Transmitters	No function Partly defect
Heat elements	Do not start /stop heating Unintended function
Operators	Human errors
Passive systems	
Pipes	Leaks Fouling Blocked/partly blocked
Heat exchangers	Internal/external leakage Fouling
Safety valves	Do not open/close Unintended opening
Bursting disks	Do not break Break unintended

Table 8 Failure mode of different components

7.4.5 Hazop analysis

The Hazop analysis aims at identifying (1) the *consequences* of deviations in process variables, that is, pressure, temperature, flow, etc., and (2) the significance of these consequences for the safety and the operation of the plant. The result of the analysis will appear in a table, exemplified in Table 9

System	Variable	Deviation	Cause	Consequence	Actions
Cooling system	Flow	Too low	Pump failure	Insufficient cooling	None or should be examined
			Valve failure	Insufficient cooling	None or should be examined

Table 9 Hazop analysis example

7.5 Which information is retrieved from the analysis and how can the information be used?

The information obtained from the design process of the system itself and the control system should give the display designer knowledge about intended functions of the plant.

The information obtained from the risk analysis are the events that can happen in the process in question and the root causes for these events, both technical faults and human errors. Furthermore information on how the failures propagate through the system is obtained. The final display system must enable the operator to detect these failures.

Even it is said that such an analysis will not find all failures, the analysis will give a deep understanding of the behaviour and functions in the process and what to take special care of during display design. In the theory all possible failures should be found in a risk analysis, but such an analysis must also from the beginning make some assumptions e.g. as not to include multiple failures. The analysis described should give a sufficient knowledge of the ‘perfect’ plant, but for old plants the operators experience must also be taken into account.

The next chapter will discuss different references for the process, the components and systems, which can be added to the designers “knowledge base”.

8. References for Functions and Conditions

In the design of display systems, one of the tasks is to find references or norms for normal operation. The main focus in the design is to facilitate monitoring of deviations caused by incipient failures so that they can be detected before the goals of the system are disturbed. Many incipient failures are hidden by compensatory control. An example is wear in a pump: if no control system were at hand, the wear would result in a decreased flow; however in case a control system has been installed including feed back control of the flow, the control system will increase the speed of the pump to compensate for the wear and keep the flow at the desired level. How are such failures observed? And which kind of references can be used?

This chapter discusses different types of references to be used for observing deviations in processes and in equipment. Examples are given in order to illustrate the references and to suggest how they may be classified with respect to validity in different situations

From the design phase, reference information concerning the component, the system and the medium can contribute to the information system. Deviations from normal operation and other failures can be observed as deviations from those specifications. This information originates (1) from the component characteristics, (2) from the specific properties of the material, such as thermal conductivity and specific weight, and (3) from physical laws, such as Dalton’s law for gases. The constraints express the laws of mass and energy conservation, the flow equations, the temperature and pressure dependencies for saturated steam and other relevant equations for the process and system in question.

The references described in the following are:

- Component characteristics
- Design specifications
- Material specific properties
- Physical laws
- Empirical rules and models
- Limits for the process and the plant

8.1.1 Component Characteristics

Components such as pumps and valves have working characteristics, which give information about their function in different operating modes. A positive displacement pump Figure 56a has a linear characteristic, which means that the flow is proportional to the speed of the pump. A change of speed in a pump leads to a changed flow due to the operating characteristic. The characteristics for a centrifugal pump are a number of ‘parallel’ curves. Each curve corresponds to one certain speed of the pump as show in Figure 56b. The characteristic shows the dependency between the flow through of the pump and the pressure increase across the pump.

In designing a process plant, these characteristics are used to choose the right component for the desired use.

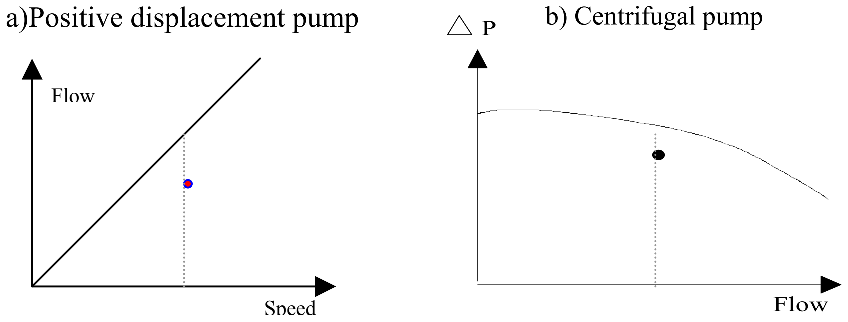


Figure 56 a, b Examples of characteristics from two different pump. Also showing the working points deviations from the pump characteristics

The characteristic of the component does not change because of a change in operation mode of the plant, but the working point on the characteristic can move.

If degradation takes place in a component, a deviation from its characteristic will result. The reason could be wear of the component, for example in the seat of a valve resulting in a higher flow through the valve than expected. Another example is leaking suction valves on a positive displacement pump, as described for the pump display for the pipe autoclave. A leak will here result in a flow lower than expected at that specific speed of the pump, due to back flush through the suction valves.

8.1.2 Design Specifications

By *design specifications* we understand a specific working mode at normal working conditions. An example is a heat exchanger designed to maintain, at normal operation, a certain temperature difference between the primary and the secondary side at the terminals, and – more importantly – to transmit a certain amount of energy.

Fouling on the heat transmission surfaces will increase the Terminal Temperature Difference (TTD) due to a decreased heat transmission coefficient; this in turn leads to a decrease in the efficiency of a heat exchanger which is specified during the design phase; and the expected efficiency can be used as a reference parameter.

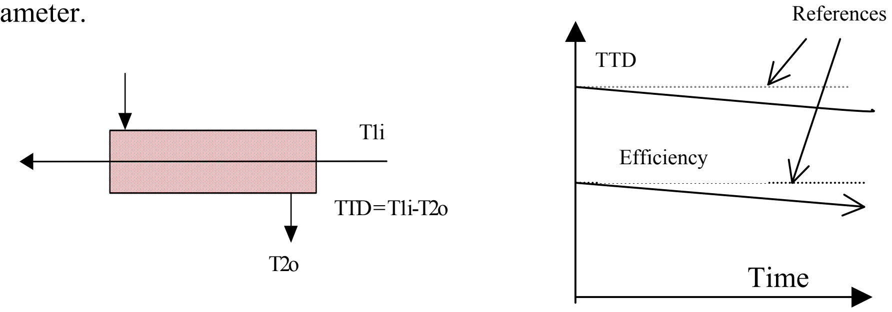


Figure 57 Heat exchanger. The figure shows the terminals for measurement of the terminal temperature difference, TTD, and a trend curve with reference value for the TTD and efficiency e.

In a condenser, one of the design specifications is the temperature difference between the steam and the inlet liquid. The temperature difference is constant *only* at design conditions as is true for the TTD for heat exchangers.

8.1.3 Material Specific Properties

Specific properties are properties connected to materials, fluids and gases. Examples: specific weight, specific volume, specific heat, viscosity, thermal conductivity, specific properties of water and steam. Whenever possible, these quantities can be calculated using measured thermodynamic state variables and can be compared with the expected properties acting as reference values. For instance, we could calculate the actual thermal conductivity for the material in a heat exchanger. In that situation, fouling could be detected by a decrease in the value of the expected conductivity.

8.1.4 Physical Laws

Examples of physical laws are: (1) the relation $P = f(T)$ between pressure and temperature for saturated steam, (2) Dalton's law. Let us recall the latter: Consider a container with mixture of gases, and denote by 'partial presssure' of a gas in the container the pressure that would be exerted by that gas if it were present alone; then the total pressure in the container equals the sum of the partial pressures. Laws like these two are always valid, and they may serve as references in systems where these laws are relevant for the process that takes place.

Even if steam is not an ideal gas, the presence of other gases in a condenser can be observed by a pressure exceeding the pressure of the saturated steam:

$$\text{Pcondenser} = \text{Psat} + \text{Pgas}$$

$$P = P1 + P2 + \ldots.. + Pn$$

Additional examples of physical laws are the mass and energy conservation laws, Ohm's law, the relation $V = R \times I$ between voltage, resistance and currant in an electrical circuit, and other laws from the theory of electricity e.g. Kirchhoff's law.

8.1.5 Empirical Rules and Models

Empirical rules and models are 'equations' developed on the basis of experiments and experience. An example is wear in a pipe leading to a decrease in the pressure drop across the pipe. This is a consequence of an increased pipe diameter: the pressure drop is given by the formula

$$\Delta p = \lambda * L * Q^2 * v^2 / D$$

where:

λ is Fannings' factor, a coefficient which depends on the roughness of the pipe, the viscosity of the fluid and Reynolds' number. The Fannings' factor is a factor based on experiments.

L is the length of the pipe
Q is the volume flow
V is the velocity
D is the diameter of the pipe

This expression is for Newtonian fluids and not for complex fluids such as slurries.

The pressure drop can be used to calculate how much the diameter has increased due to wear, but also to calculate the thickness of fouling if this is the problem. In systems with no wear and with clean water, the pressure drop can be used to calculate the water flow. This method was used for the pipe autoclave where the last 50 m of pipes had a diameter of 10 mm. It turned out later that the wear was in fact a problem in that pipe, and it had resulted in a leak in a bending.

8.1.6 Limits for the process and the plant

Limits are references expressing lower and upper limits for certain process parameters. Every process and every plant is subject to certain limitations. These limitations are implemented and used for control in various ways, in particular by limit values applied in the automatic control system or by the operator. It could be limits on levels in tanks; pressures and temperatures in systems; pressures and temperatures in the process; flow of the medium treated; reaction time; difference between pressures across filters etc.

Such limits can be used in the display, to show how far the process is from reaching this or that limitation. For example, an alarm could be installed to appear when the control system of a pump has reached 95% of full speed, where normal operation with a recently maintained pump is 65%. These two numbers could be of importance for the operator who must be alert about a possible degradation of the pump or of the connected clutch.

8.1.7 Validity of the reference

As the references are important for the observation of deviations in goals, functions and conditions of the plant, the question of relevant references must be part of a questionnaire to the designer of the display system. The quality of the information sources used as references must be analysed with respect to validity as it is done in the following table.

Source of knowledge	**Classification**	**Example**
Component characteristics	Always valid	Pump characteristic
Design parameters	Valid only under design conditions	Terminal temperature difference (TTD) in heat exchangers
Physical laws	Always valid	Gas equation. P=f(T)for saturated steam
Fundamental natural laws	Always valid	Mass and energy conservation
Specific properties of matters	Always valid	Thermal conductivity of materials
Empirical rules and models Indicators	?	Pressure drop across a well known pipe.
Limits	Some can be changed during operation and as a fault during maintenance.	Upper limit for a pressure to protect the components.

Table 10 Classification scheme for references

References, which are invariant regardless of the operating conditions, are more valid than those, which are valid only under design conditions, such as TTD, the terminal temperature difference in a heat exchanger. This quantity, TTD, could be measured at different operating conditions and thereby act as a characteristic for the heat exchanger, but it is normally not used that way. Design parameters are useful under design condition, to look for degradation in the components. References, which are valid just under certain operation conditions, can sometimes be used as other information in other operating condition. E.g. The calculated pressure drop across a pipe with a flow of clean water will always be lower than the pressure drop across the same pipe if the medium is slurry at the same flow, but the value for clean water gives at least an information about the lowest pressure drop across the pipe.

Now we postulate that the designer knows everything possible to obtain about the process, the plant, the behaviour of the plant, the risks connected to the plant and how they occur but:

The knowledge of the plant is not a specification of what to present, because the knowledge have to be structured due to a strategy. The next chapter describes a strategy for determining the content of the display.

Part III

9. Content of Information. The Goal-Tree Fault-Tree (GTFT) method.

The design of the pipe autoclave display system, using the configural display method and other well known presentations forms, the positive experience of using the displays during operation and the experience with the overview displays, using the same types of presentations, for (1) the nuclear reactor, (2) the waste incineration plant and (3) the condenser, gave inspiration to develop a guide for the design of displays for process plants.

The term ‘guide’ is to be taken in a practical sense, that is, the guide should be a tool that provides the designer with advice about how to extract the necessary information, and how to present it.

Experience from the operation of the pipe reactor showed, among others, that it would have been valuable to know the results from a risk analysis of the plant before the initial start up. If a risk analysis had been performed on the pipe autoclave system, the operators would have been more aware of the problems that might occur during operation; and they would also have been better prepared for deviations in operation and for how to detect them in time.

In the development of the guide, methods from risk analysis of process plants are taken into account, and the same questions that were used for the waste incineration plant and the condenser are posed:

- What is the purpose?
- What are the problems?
- How do the problems occur?
- How are the problems detected?
- How should the problems be presented?

These questions constitute the main ‘body’ of the strategy, and for small, well-known parts of a plant they will in many cases be sufficient. But to form a precise and exhaustive guide they must be enhanced. The aim of the strategy described in the sequel is to enable the operator to detect incipient failures on the displays before the goals are disturbed.

9.1 The Goal-Tree Fault-Tree method (GTFT)

The proposed guide/strategy is mainly based on a fault-tree analysis, which compared with the Abstraction Hierarchy (AH) framework described in Chapter 2, is more problem-oriented. The fault-tree is in this context used as a qualitative analysis tool. A strategy where a tree structure can be used to extract knowledge gives a good overview of how a break of constraints, or just a deviation from the intended, propagates through the system. The fault tree is a structured description of how a failure or a coincidence of failures can propagate into a number of higher-level functions, which if broken, will lead to an unwanted top event. The detection of early failures that can result in disturbances of functions and goals is also important knowledge when deciding how to present information on the displays.

The fault-tree analysis is normally an analysis of a known unwanted event on a lower level than e.g. stop of production, but an event that can lead to a stop of the production or to an unsafe situation. The author found it was natural to combine a Goal-Tree, to achieve the higher-level functions, with a Fault-Tree that describes the events influencing such higher-level functions as well as the goals. The Goal-tree in this context describes goal and sub-goals. The number of layers with sub-goals is not determined. The failed sub-goals are then taken as the top-events for the fault-tree analysis. The information obtained from this analysis gives also the information required for using the AH structure, if this structured functional hierarchy is found appropriate when the design the display has to be assessed. The Fault-Tree part includes the control systems and the safety systems, just like it includes any other type of equipment. It is not quite obvious where to place control systems and passive safety systems in the AH. The root causes found using the fault tree will also give input to the requirements to condition monitoring of systems and components. Condition monitoring is in the AH placed on the Physical Function level.

Another problem to take care of is to distinguish between the purpose of the process and the purpose of the process equipment. We shall illustrate this by an example: extraction of Uranium in an alkaline process from ore, following a specific chemical reaction.

To extract Uranium is the purpose of the chemical process. The purpose of the plant is to establish the conditions for this process to take place.

The questionnaire used in the GTFT method is shown below in a short version; it poses more or less the same questions that are used for the Goal-tree-Success-tree, GTST, method [24] where a Goal-Tree is applied, but for the GTFT method both on the process level and on the equipment level. It is recommended to use the GTFT on the process itself to analyse unwanted reactions such as run-away reactions.

As soon as the sub-goals for the system are identified, the analysis proceeds by means of a Fault-Tree analysis to identify the problems in achieving these sub-goals.

OVERALL DESIGN PURPOSES:
    What are the purposes of the displays?

GOAL TREE:
    The process
    What is the goal of the process (the medium)?
    What are the requirements for the process goal?
    Which problems are connected with the process?

    The plant or system
    What is the goal of the plant or system (equipment)?
    What are the sub-goals for the goal to be achieved?

FAULT TREE:
    What are the problems associated with the sub-goals?
    How do the problems occur?

PRESENTATION OF THE GOALS, FUNCTIONS AND PROBLEMS
    How are the goals and functions observed?
    How are the problems detected?
    How to present the goals, functions and problems to the operator?

In the following, the different aspects of the strategy are elaborated.

What are the purposes of the displays?

A display system for a process plant contains many displays, each of them with a specific purpose that must be assessed before the system can be designed. Examples of the different purposes of displays, or rather: of the information they present to the operator, is that it should make him able to:

- Supervise various goals and functions in the plant, e.g., heating and cooling functions.
- Monitor the condition of a specific component.
- Supervise the control system.
- Get an overview of the entire plant

What is the goal of the process?

There is often more than one goal in a process plant, e.g., the goal of the process and the goal of the plant. In the sector of chemical production, the same plant is sometimes used for making different products, each of them being produced according to a specific chemical reaction; and each reaction gives rise to specific problems that influence the sub-goals of the process system. To analyse the total production, it might be appropriate to distinguish between the process problems and the system problems.

Which hazards or risks are connected with the process?

Hazards and risks may arise as the result of, among other, the following events: exothermal processes; pollution of the product (e.g. during the production of medicine); radioactive radiation (e.g. at nuclear power plants); toxic emissions (e.g. during the production of weed control chemicals); explosions.

Such hazards are the top events for a fault tree analysis for analysing the root causes for such an event to happen. The hazards are identified by means of a hazard analysis of the process. A hazard analysis often forms part of the design criteria for the control system for a process plant, but also for the equipment chosen for the process plant.

What are the requirements for achieving the process goal?

For power production it is the processes of phase changes of water ending up with high pressure steam to be used for the turbine function of converting thermal energy into mechanical energy. For chemical processes it can be a demand to temperature, pressure, additives etc.

What is the goal of the system?

The goal of the system is to establish the right conditions for the process to happen in a safe and economical way.

Concerning condition monitoring, it can be a requirement for a component for optimal function, the latter signifying that the component works at the intended part of its characteristic, or rather: the deviation from this characteristic is acceptable.

What are the sub-goals for the goal to be achieved?

The sub-goals are the requirements on a lower level to the system necessary for the top goal.

What are the problems of the sub-goals?

For a goal or sub-goal, the problems are (1) failures in the supporting functions on several levels, or (2) a failed state, e.g. pressure not established. The failed functions and states for a specific goal can be elicited using the fault tree analyses.

How do the problems occur?

A problem may arise gradually from wear in components, but can also be caused by a sudden breakdown of components, e.g. a broken shaft of a valve or a pipe rupture. 'Breakdown of components' includes the breakdown of the control system such as instability due to parameter drift. The information on this level can be extracted from the fault tree analysis.

How are the problems detected?

The aim of this strategy for display design is to enable the operator to detect incipient failures before the goals are disturbed. An analysis must be made to reveal how functional failures are detected as early as possible. The detection of deviations requires that two questions must be addressed: What is the situation? and: How should it be? More specifically we may ask:

Which references exist in the process and in the plant?

The use of references is essential in the detection of deviations, and should be presented on the displays.

Deviations from operating characteristics for components and systems must be examined; and so must any observation that seems to represent a deviation from physical principles and invariants that the process should follow or should have as a constraint.

When answering this item in the strategy, it may be necessary to take some of the higher levels information into regard, such as the conservation laws for mass and energy.

- The conservation laws for mass can be used to keep control of mass inventory and for the detection of leaks in pipes, e.g. pipe lines for oil and gas. The energy conservation law is used e.g. when calculating efficiencies on power plants.

- For condition monitoring it is valuable to have access to characteristics for the component. Even if the condition of a component has decreased, the component may still be able to achieve its purpose e.g. due to the feed back control. For condition monitoring, a deviation from the intended condition must be supervised, e.g. it should be detected if the working point for a pump deviates from the pump characteristic.

- It may also be helpful to consider the physical characteristics of the process itself, e.g. the saturation curve used on the display for the condenser. Similar characteristics exist for other media such as ammonia and metals, e.g. phase-diagrams.

How to present the problem for the operator?

The presentation of information must be clear and has as one of the purposes to decrease the complexity of interpretation task in case of a disturbance in the plant. This is also the aim for the Ecological Interface Design. The question will be discussed in chapter 10

9.1.1 Illustration of the method and a questionnaire

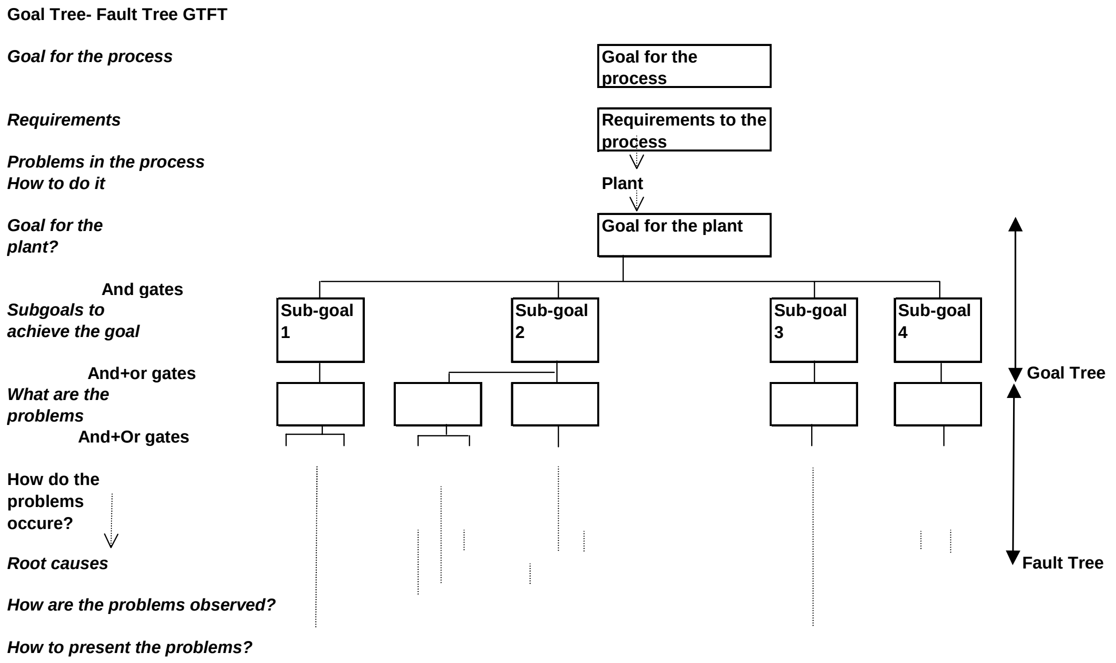


Figure 58 Goal-Tree Fault-Tree

The graphical method can be supplemented with a questionnaire, which may clarify the problems of how to observe goals and functions and how to detect deviations from intended operation.

Questions	**Answers**	**Data**
What is the purpose of the display?		
What is the goal of the system/process?		
What are the sub-goals?		
What are the problems?		
How do the problems occur?		
How are the problems detected?		
Which references can be used:		
Invariants and physical laws in the process?		
Design parameters?		
Characteristics?		
Controls:		
Control actions?		
Presentation:		
How to present the goals, the functions and the problem?		

9.1.2 Discussion of the method

At this point of the proposed method it is appropriate to discuss if there are limitations to the use of the GTFT method? What can it be used for? How many layers are necessary? Who can use the method?

The method is top-goal based which means that it starts with a goal and the analysis is based on requirements for maintaining this top goal. This means that a change in top goal will require another analysis e.g. efficiency, production and safety as different top goals will give different inputs to what the operator has to observe to fulfil the goal. In case the top goal is efficiency of a power plant, the pressure in the condenser is one of the most important parameters to overview, but this parameter is not important if safe production is the top goal. This problem is also relevant to the Abstraction Hierarchy.

The overall goal for both the AH and the GTFT method is to specify important information to supervise for the operator to be able to prevent serious accidents and therefore are the top goals related to safety and that is what both methods are developed to cope with.

A fault tree analysis is a well-known method for calculating the probability of the top event to happen. The lowest levels in the analysis are the ones where data are available such as failure frequency of pump. The failures could be due to wear or to maintenance failures. The fault tree method used in the GTFT method has its main purpose to give an overview on the important sub-goals, functions and root causes to be observed and how they are dependent of each other. The next phase concerning the content of the displays is to determine how to follow the status and changes of these goals, functions and incipient root causes online.

Failures due to maintenance failures will not occur especially as a maintenance failure but as the online measured consequence of a maintenance failure.

9.1.3 Summary of the method

The GTFT is a dynamic presentation of degradation and faults in a plant and the propagation of these events upwards in the system.

There is no exact number of layers neither of sub-goals nor of layers in the fault tree. It depends on the plant.

A display designer must have a good knowledge of the plant, its behaviour and the possible risks, which can occur in case the control system and the safety system fail. The designer or usually the design team will then be able to make a sufficient GTFT analysis for a qualitative analysis.

9.2 Example: Uranium extraction in a pipe autoclave.

The Goal-Tree-Fault-Tree method and the AH will now be illustrated using the example: extraction of uranium from ore in a pipe reactor.

9.2.1 The Process

For the chemical process itself the goal is to extract uranium from ore following a specific chemical reaction equation. The requirements to the process are: sufficient oxygen must be present; the pH value must be above a certain level; similarly, the temperature must be above a certain level; and the reaction must be allowed to continue for sufficiently long time.

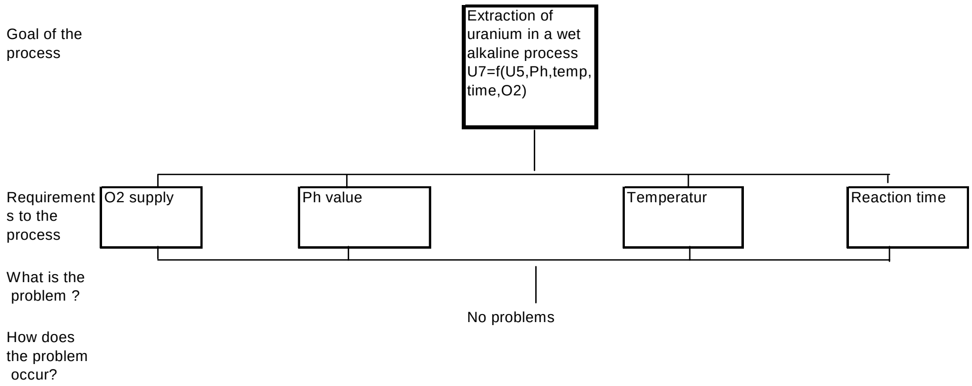


Figure 59 GTFT analysis of the process

In case these conditions are not fulfilled, the efficiency of the process is not optimal or is zero, but not unsafe.

The oxygen supply can be measured; the pH value in the prepared slurry is measured; the temperature in the reactor is measured; and finally, the length of the reactor, together with the maximum flow of the pump, determine the minimum reaction time.

If the reaction was exothermal and there were a risk of a runaway reaction, one of the requirements would be to avoid such a reaction. To keep a process on the safe side of a runaway reaction is to keep it within certain temperature constraints or/and to keep the ingredients of a mixture within certain limits. The information about what to avoid must appear clearly on the displays.

9.2.2 The Plant

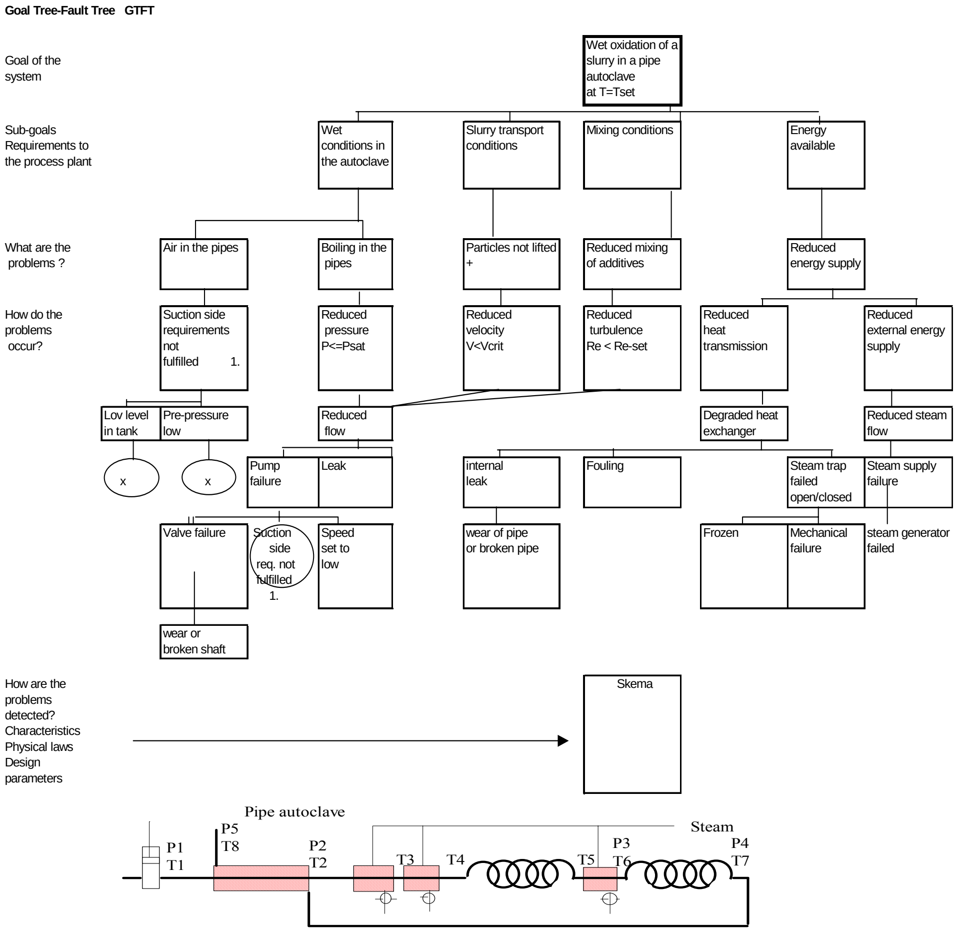


Figure 60 GTFT method applied to the pipe reactor

In the presentation of information about the operation, goals, functions and condition of the plant, the method will attach importance to the use of references. The references can be taken from the design of the plant, the physical laws the process has to follow, the invariants in the process, the component characteristics and, of course, the assessed upper and lower limits for some of the variable.

The questionnaire filled in according to the GTFT:

Questions	**Answers**	**Observations and detections**
What is the purpose of the display?	Overview the purpose and functions of the autoclave.	
What is the goal of the system?	Wet oxidation of uranium in a pipe reactor at temperature $T=275^{o}C$ according to the equation: $U7=f(U5,Ph,temp,time,O_2)$	Show the temperatures T at the inlet of the reaction pipes and the set point temperature $T_{set}=275^{o}C$
What are the sub-goals?	Wet conditions in the pipe reactor Slurry transport conditions Mixing conditions Energy available	
What are the problems?	Boiling in the pipes Air in the pipes Sliding particles Reduced mixing Reduced energy	
How do the problems occur?	Pressure in the pipes too low due to: *Pump failure* *Leak* Pre-pressure too low due to *pre-pressure pump problems.* *Storage tank level L to low* Velocity V of the slurry too low due to: *Pump failure and leak* Reduced turbulent flow due to: *Flow too low* Reduced energy supply due to: *Steam system failure* *Steam trap failure* *Fouling* Leak	P equal to the saturation pressure P_{sat} Deviation from intended flow at that speed Mass balance: $Flow_{in} = Flow_{out}$ Pre-pressure< $P_{pre-min}$ L lower than L_{min} V lower than V_{crit} Flow F lower than required flow for the slurry Re too low E less than required E Flow < $Flow_{(Re-min)}$ Steam flow too low Steam temperature too low Temperature increase across HE too low. Thermal conductivity of the material decreased => Heat transmission coefficient too low => Temperature increase across HE too low. Pressure drop increased Mass balance not fulfilled. Change in Flow

How are the problems detected?	By observation of the deviation between expected values and measured values, or values calculated from measurements	
Which references can be used:		
Invariants and physical laws in the process?	The saturation pressure Psat for steam at temperature T The pressure drop across a pipe Other thermal equations Mass- and energy balance	Psat=f(T) dP=f(Q,D…..) E=UA(Ti-Ty) etc.
Design parameters?	Terminal Temperature Difference (TTD) for condensing Heat Exchangers = Constant for design conditions TTD for liquid-liquid heat exchangers = Constant Temperature increase across each heat exchanger = Constant	Tsteam-Tind = constant $T_{primary\text{-}out} - T_{secondary\text{-}in}$ = constant $T_{n-1} - T_n$ = constant
Characteristics?	Pump characteristic	Flow=constant*speed
Controls:		
Control actions?	Manual pump control Automatic control of steam	T_{steam} and set point for the steam temperature $T_{steam\text{-}set}$
Presentation:		
How to present the goals, the functions and the problems?	Presentation of goals, intended goals and deviations. Presentation of intended functions and deviations. Presentation of described consequences of the faults and failure by use of measured data, calculated information, references and different types of drawings according to an analysis of the deviation from normal.	Drawings Trend curves Graphical presentation According to an analysis of the measured data and what the operator has to observe and how.

Table 11 Information listed according to the GTFT method

9.3 Use of the Abstraction Hierarchy to compare the information determined by the GTFT method

In this section we first use the Abstraction Hierarchy (AH) to specify information for displays for the pipe reactor; thereafter we evaluate the information specified by the GTFT method.

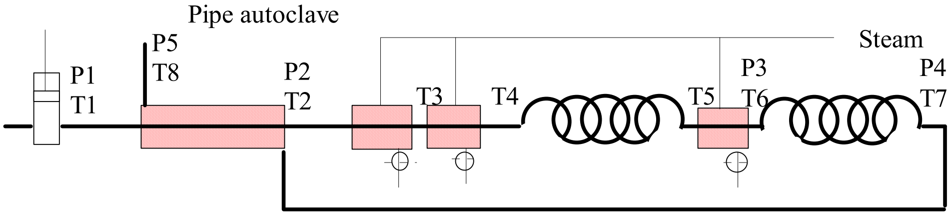


Figure 61 Pipe reactor system

The main purpose of the Abstraction Hierarchy is to represent information from all levels of the function of the plant in question according to the means-end relations. The detailed information for each level is provided by a part-whole analysis.

Functional Purpose: *Production flow models, system objectives, constraints, etc.*
The functional purpose of the pipe autoclave is to increase the temperature of the slurry T4 to 275°C and to keep the slurry at this temperature for 0.5 hours.

Abstract Function: *Causal structures: Mass-, energy- and information flow topology, etc.*
Mass flow and energy flow
Constraints:

- The velocity V of the slurry must be above the critical velocity $_{\text{Vcrit}}$ for the particles, to prevent the particles from sliding in the pipes, i.e., there must be lift on the particles.
- Mass- and energy conservation laws.

Generalised Function: *"Standard" functions and processes: Feed back loops, heat transfer, etc.*
The standard functions are
Condensation, heat transfer, heating, cooling and transport.

Physical Function*: Electrical, mechanical, chemical processes of component and equipment.*
Pump function

Physical Form: *Physical appearance and anatomy; material and form; locations, etc.*
Pump, heat exchangers, reaction pipes, steam supply system etc.

The information to be presented from the different levels is listed in the table below.

Levels	Functions	**Information to show**
Functional Purpose	Safe autoclaving of slurry at temperature T= T_{set} in a pipe autoclave in a safe way.	T, T_{set}
Abstract Function	Energy flow Mass Flow	Supply of energy Flow of slurry Velocity higher than critical velocity, V> Vcrit
	Conservation of Energy and mass	Flow $_{in}$= Flow $_{out}$ Energy balance
Generalised Function	Condensation Heat transfer Heating Cooling	dE_{steam}, dE_{slurry} T2-T1 T3-T2 T4-T3 T6-T5 T7-T8
	Mass Transport	Flow
Physical Function	Pump Function	Working point on the pump characteristic
Physical Form	Pump Heat exchangers Reaction pipes Steam supply system	Pictograms

Table 12 Information required using the AH

When the table for the GTFT method is compared with the one for the AH, we can see that the information required from the AH framework is also determined by the GTFT method, but the reverse is not true: applying the Abstraction Hierarchy does not point to the necessity of a pressure above the point of saturation; at least it is difficult to find out where to introduce it. The GTFT also specify root causes, but the AH does not.

It is not a surprise that the information revealed using the GTFT method fulfils the requirements from the AH framework. The difference between a means-end hierarchy and the GTFT method is that the former specifies layers that are either necessary requirements to the upper layer or goals for the layers below, while the latter (the fault tree) describes the sub-goals, the failed goals and the failed functions.

Rasmussen and Vicente claim that also unexpected events are detected using the AH for the analysis since the AH looks for breaks of constraints on goals and functions. The GTFT method can just as well be claimed to detect unexpected events, since all the sub-goals necessary for the process and the plant to succeed are analysed in the GTFT method.

9.4 Information on the pipe reactor display

The actual pipe reactor display presents some of the information that is required using the GTFT method. The following table lists the required information and shows which parts are presented on the displays Figure 25, Figure 28, Figure 29, Figure 30 and Figure 31.

Observations and detections		
Show the temperatures T at the inlet of the reaction pipes and the set point temperature T_{set}	YES	
P equal to the saturation pressure P_{sat}	YES	
Deviation from intended flow at that speed	YES	
Mass balance: $Flow_{in} = Flow_{out}$	NO	$Flow_{out}$ not measured
Pre-pressure< $P_{pre-min}$	NO	
L lower than L_{min}	NO	not measured
V lower than V_{crit}	YES	
Flow F lower than required flow for the slurry		
Re too low	YES	
E less than required E	NO	
Flow < $Flow_{(Re-min)}$	YES	
Steam flow too low	NO	Not measured
Steam temperature too low		
Temperature increase across HE too low.	YES	
Thermal conductivity of the material decreased => Heat transmission coefficient too low => Temperature increase across HE too low.	NO	
Pressure drop increased	YES	
Mass balance not fulfilled.	NO	
Change in Flow	YES	
Psat=f(T)	YES	
dP=f(Q,D…..)	YES	
E=UA(Ti-Ty) etc.	NO	
Tsteam-Tind - The constant	NO	

$T_{primary\text{-}out} - T_{secondary\text{-}in}$ = constant $T_{n-1} - T_n$ = constant	YES YES	
Flow=constant*speed	YES	
T_{steam} and set point for the steam temperature $T_{steam\text{-}set}$	NO	The measured values not available for the display
Drawings Trend curves Graphical presentation According to an analysis of the measured data and what the operator has to observe and how.	YES	

Even if the pipe reactor displays were designed before any strategy was available it appears from the above table that the displays do show most of the information required from the strategy.

Among the problems that have not been discussed are the following: which quantities can we measure – and which of them are in fact measured? For example, in the case of the pipe reactor, the energy and the mass balance cannot be calculated, due to a lack of flow measurements. The flow substance changes during the process: first cold slurry, later a hot mixture of slurry and gas which is, at any rate, difficult to measure. A leak in the pipe reactor system does not show in the mass balance but by a loss of pressure; therefore the operator needs an analysis of how different events can be detected so he can act as soon as it is indicated that something is not as it should be.

10. Presentation of the Information. A Practical Guide

Once it has been decided which information must be made available for the operator to supervise the plant, the next problem arises: how to present this information in a clear and appropriate way so that deviations from normal operation can be observed and interpreted without ambiguity and in time.

Various ways to present information have already been discussed in chapters 2-6. We shall now address the question of generalisation: is it possible to formulate some general rules or proposals on how to present the information for the operator? The rules must be based on existing knowledge about different plants and about the information that was found to be necessary in the specific cases. Another question we must address is this: how can different levels of abstraction be presented according to the Goal-Tree Fault-Tree analysis.

This chapter describes the different graphical elements and their use and presents, on this basis, some examples on how to visualize the decomposition of the goals and functions. We start out with describing four basic presentation forms

- Single sensors- Single indications
- Grouped presentations
- Integrated presentation
- Complex presentations

10.1 Single Sensors – Single Indications Presentation

The most common ways to present information of a single numerical quantity are: 1) by *digits*, 2) by an *instrument*, 3) by a *bar* graph. Each of them can be visualized on a mimic diagram, anchored to the position where the measurement is made. Besides we may include 4) *trend curves* which are usually shown on separate displays.

The principle is ‘single sensors - single indications’ presentation on a mimic diagram, like in the old control room with the mimic diagram painted on the wall.

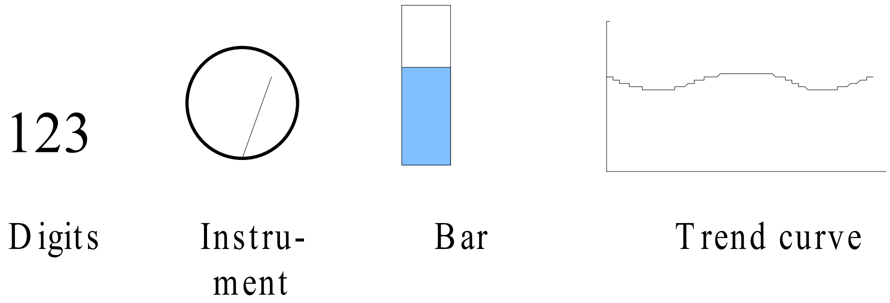


Figure 62 Single sensors - single indication presentations

A mimic diagram including the variable values is the most common way of presenting the information. A mimic diagram is often just a copy of a PI- diagram. All values are original measured values and often no calculated values are present, but the calculated values could be presented the same way. The trend curves are of course a presentation of two variables, the measured or calculated plant variable and the time.

10.2 Grouped Presentation.

Even if a number of numerical quantities are presented individually by way of single sensors – single indications, they may as a supplement be shown grouped, e.g., in a *polar diagram*. We shall look at two such polar diagrams, or as they are phrased in the spreadsheet program Excel: 'radar diagrams': a non-normalized plot of 11 variables, and a normalized plot showing the same variables:

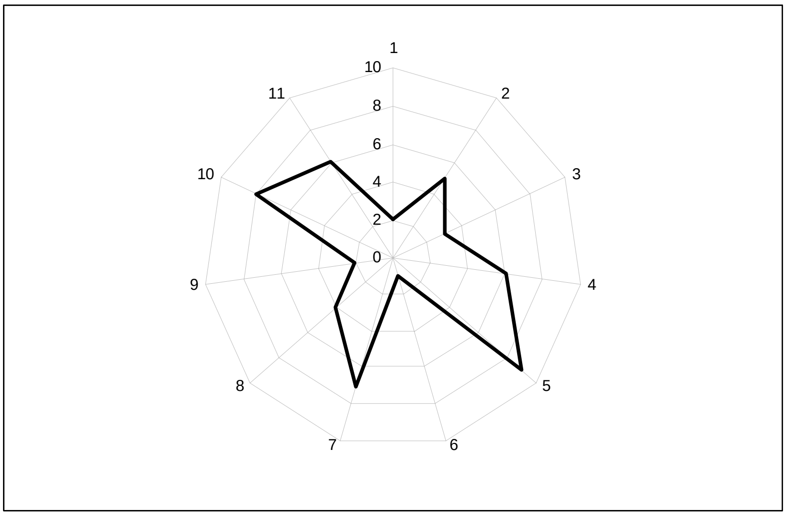


Figure 63 Non-normalized radar diagram (Excell version)

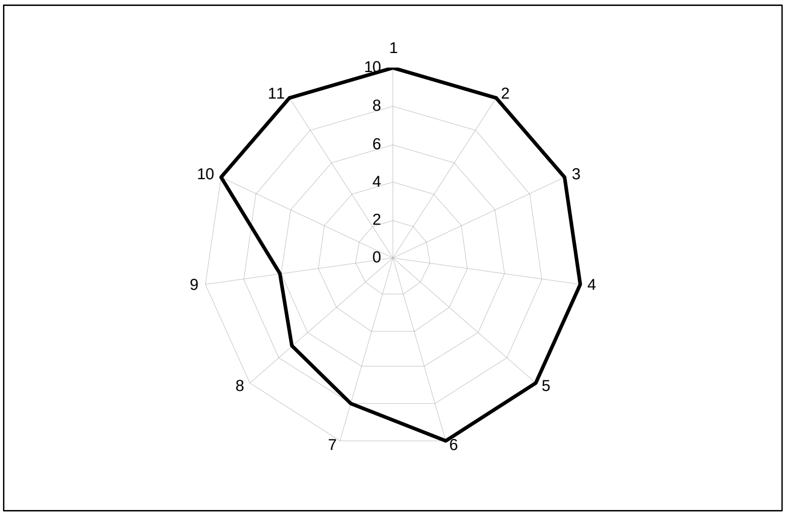
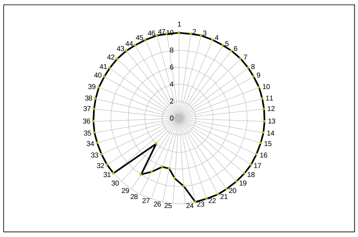


Figure 64 Normalized radar diagram

The normalized plot uses the outer regular (symmetrical) polygon as a fixed reference for variables presented and it just requires a glance at the plot to observe deviations from the reference polygon. In the non-normalized plot this is less easy even if the figure is supplemented with a reference polygon. Even at a smaller size and with many variables included, the normalized polar diagram is quite often able of clearly indicating that something has changed. By contrast, the non-normalized polar diagram may be useful for other purposes but it is of little use for a plant operator in his supervision task: the shape of the polygon pertaining to normal operation can be very complex to remember, and therefore it is difficult to observe when a deviation has occurred.



The normalised polar diagram may serve as a first indication that something is happening somewhere in the plant. However the variables must be arranged adequately in the display, for example in groups according to sub-systems of the plant. The polar plot can be combined with the mimic diagram.

10.3 Integrated presentation

Screen-based process control offers a number of possibilities, such as: to use curves, to use a combination of several displays, each with its own purpose; to have figures moving on the screen. The last option, moving figures, should be used for showing the dynamics of a process, as is the case for the pipe autoclave displays.

In computer based systems one may also choose to change reference curves automatically, as in the case of condition monitoring of a centrifugal pump where the characteristic depends on the speed of the pump. Again, we emphasize that the use of references is always valuable for observing a deviation in the operation of a plant.

Below find some examples of how such an *integrated presentation* can be utilised. We have to distinguish between the process going on in the plant and the system itself.

The process

For an optimal production, the process itself, e.g., energy conversion or a chemical process going on in the plant is presupposed to take place in a certain well-defined manner. Everywhere in the plant the process is assumed to be in a well-defined state or in a transition to a well-defined state. In water-based power plants the state of the water can be: fluid water, steam, superheated steam etc. The state of the water can be assessed from measuring the pressure and the temperature. In a state diagram, as the Mollier diagram, the actual states, different places in the plant can be plotted in the shape of actual *working points (WP),* as did Beltracci to get the Rankine cycle display[4]

For a thermal state in a plant, the working point can either lie on a reference curve, below the curve, or above it. For example, the reference curve for saturated steam is the so-called saturation curve, and if the WP for a condenser deviates from the saturation curve there is a deviation from the expected situation. It can also happen that the working point lies on the curve but at a wrong place, which indicates another type of non-expected situation. Examples of deviations and their interpretations are provided by the displays for the pressuriser and for the condenser Figure 10 and Figure 46.

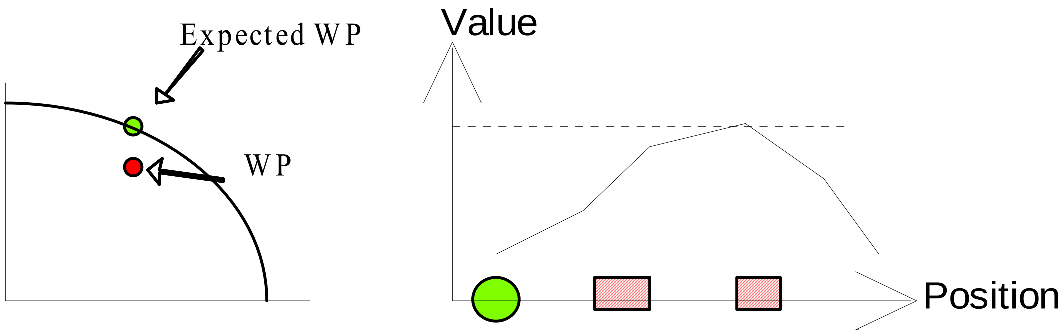
A visualisation of the deviation between the WP and the set point, can be used to quickly indicate that the temperature or the pressure does not have the desired value, which means that something is not as it should be and we have to find the reason why. The temperature increase, due to exothermal reactions, should in principle follow a specific curve, either due to time or to chemicals added. Deviation from this curve, especially if the temperature increase is too fast, means that action must be taken to prevent an uncontrolled exothermal reaction, which could otherwise result in an explosion.

The system

The goal of the plant is to establish the right conditions for the process in the plant. The conditions can differ from process to process and references and set points are different for each process. Many chemical plants are used for different processes, which can change every day. Furthermore the plant component and systems itself has also some references and set points, which are fixed and determined during the design process. These references are connected to the protection of the components and thereby also the safety of the plant and the process. The references can be:

- Pressure and temperature allowed for the components.
- Levels in tanks.
- The working points for pumps.

10.3.1 Examples on presentations



Reference curve
+ Working Point
+Expected WP

Mimic diagram
+Configural curve
+Reference

Figure 65 Types of integrated information

The examples shown on *Figure 65* apply to many different situations. The presence of a reference curve together with the actual WP and the expected WP is useful, both for e.g. the thermal states of a plant and for condition monitoring for components. The display can also include the acceptable limits for deviation from the references.

Configural curves are curves connecting WP's in an xy-diagram, where the x is the position of a variable anchored to a mimic diagram, and the y is the value a variables to be shown.

Configural curves are valuable for showing dependent variables such as the temperatures across a plant, or the pressure and the energy distribution across part of a plant. Such curves can make it easier to supervise district-heating systems, both for the energy loss and the energy consumption, and even to observe leakages. For long distance pipe-lines, configural displays for supervision of the pressure would be informative, to control both the pressure drops and the pressure increase in each pump station.

Figure 66 shows a presentation of the energy flow for a power plant. The presentation can be combined with an overview display for the plant and with some references for normal energy flow. For each flow, a calculation in % of the original energy would also be informative since it would indicate the efficiency in each step of energy conversion.

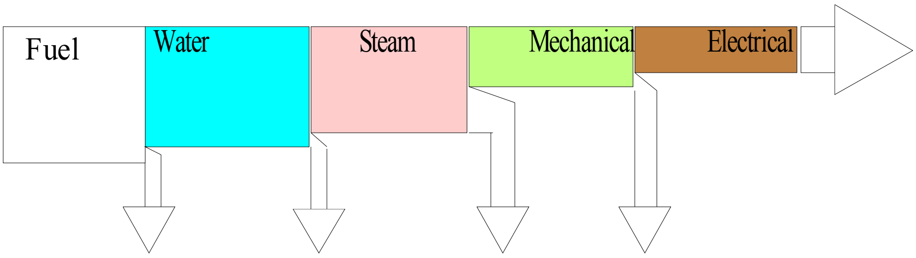


Figure 66 Energy flow in a power plant

This type of information could also be used for other types of flow, e.g. a flow of mass or a flow of production units.

For condition monitoring of components, it is obvious to use integrated graphical presentation, as exemplified by the pump, the condenser and the autoclave pipe.

One detail of the DURESS display, shown in *Figure 67* could be used as an integrated display too. It shows very clearly whether the content in the tank, with an input and output, (mass or energy) is increasing or decreasing.

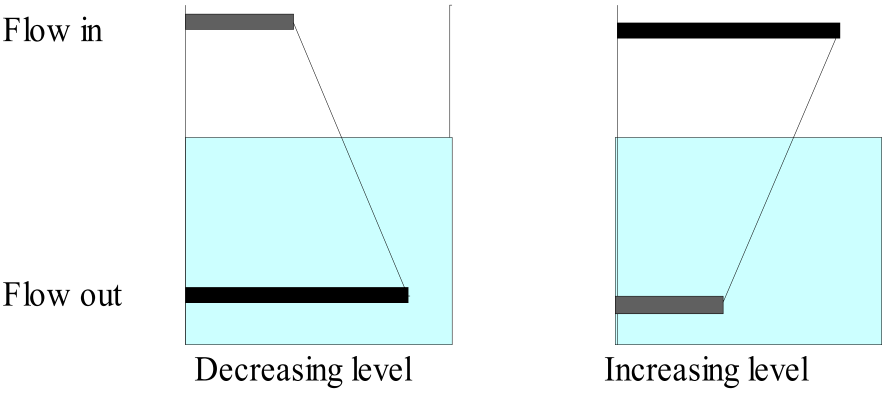


Figure 67 Tank information

10.4 Complex integrated Information

The most complex integrated displays are often specific to the purposes to which they have been developed: they may be packed with good ideas, but at the same time these ideas are sometimes so specific that they cannot be recommended for general purposes. A typical example is the DURESS display developed by K. Vicente, described in Chapter 2. It is indeed a complex integrated display including various devices which may be quite useful in special situations but are difficult to include in a general guideline.

In a project concerning information from an unmanned *submarine*, the author designed, a.o., the displays in *Figure 68*. A combination of different values is compressed into a part of a submarine conning display. The example shows how several different variables can be presented together in an easy a simple way (Paulsen [30])

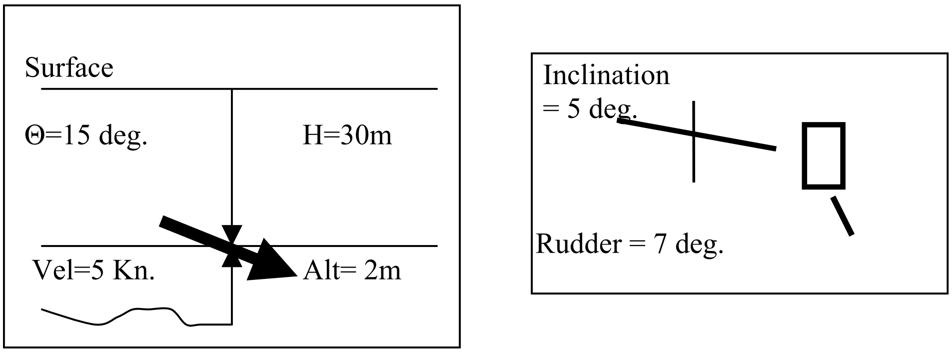


Figure 68 Displays for an UAV

The length of the arrow represents the velocity of the submarine, the direction of the arrow its direction of movement. The depths H under sea level as well as the altitude A above the sea floor are shown too, and so is the shape of the sea floor hitherto passed. Θ denotes the angle of inclination, that is, the vertical direction of movement. Even the inclination and the rudder position of the craft are visualised in the display. As a supplement, colours could be used to indicate if the position above the sea floor is within a required limit, and similarly for the inclination.

What we have described is merely a part of the information in the submarine conning display, not all of it – just to exemplify how information can be combined graphically.

10.4.1 Presentation of control system

If a control system had been used for the pipe reactor in chapter 3 it would have looked like the one on the figure 67. A set point for the temperature at the inlet to the reaction pipes controls a steam valve and thereby the amount of steam. A set point for the flow controls the speed of the pump. A safety critical set point for minimum flow will change the process flow from slurry to water to prevent the slurry from damaging the pipes or blocking the pipes.

A proposal for presentation of the control system, also known from PI diagrams, is presented in the figure.

A + or a – sign indicates if the controller is in action, or the controlled component change speed, position or power. What are measured depends on what can be measured. The dotted lines show the input to the controller. Trend curves of the information must be present too, e.g. the controller position or, for a pump, the percentage of maximum speed.

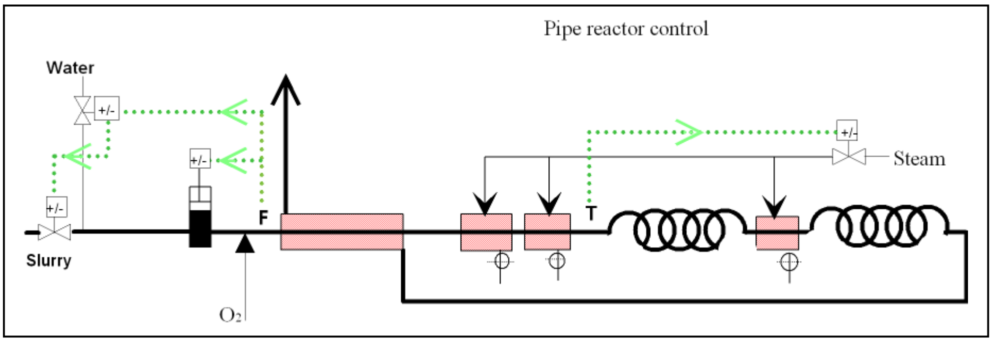


Figure 69 Pipe reactor with control system

10.5 Display design

The results obtained from the GTFT analysis are requirements for supervision of component behaviour, system functions, sub-goals and plant goals. How can the graphical elements described in the previous chapter be used for this supervision?

Supervision of components must take into regard both the condition of the components and their functions. Condition monitoring is a measure of degraded behaviour, i.e.,of the deviation from intended behaviour, which corresponds to the design parameters or characteristics in the actual situation. In this case it is convenient to have an integrated display based on the component characteristic or design parameters, and on this plot the expected WP and the actual WP as shown in [Figure 46]a . Set points and limits can be shown on this type of displays too as seen on [Figure 31]. On this display the deviation from expected condition can be seen, as well as distance to the limits. The information is also valuable for the maintenance planning.

To supervise the functions of the components it would be appropriate to have a mimic diagram showing where the components are placed, while the function of a component is dependent of where in the system the component is installed. Anchored to this mimic diagram, configural curves show what happens in the component, e.g. heating, cooling, flow, pressure increases and decreases. These curves give the operator a visual indication of what is going on in the plant. References, goals and limits can be shown on the display, too. This type of display was used for the pipe reactor Figure 25 and for Lindsays' display *Figure 8*. The control system can be shown on the mimic diagram cf. .

Goals, principles and sub-goals can be more specific and therefore they are harder to present in a general format. Still, the goal of a plant can often be shown digitally.

It is also recommended to have trend curves on the measured and calculated values.

A Graphical Guide is the following:

Subject	Graphical method recommended
Goal	Digits - trend curves
Principles	
Sub goals	
Plant function	
Component functions	Configural curves
Components condition	Characteristics + WP's
Plant layout	Mimic diagram + digits incl. Controls +safety systems

Table 13 GUIDE for presentation of graphical information

Basically the guide follows the principle of the Abstraction Hierarchy, only other names are used for the content, and recommendations are given on how to present the information on different levels of functions and goals. No fixed number of layers is laid down.

Below, three examples are presented: a simple heat exchanger, the pipe reactor and the pressurised water reactor.

10.5.1 A heat exchanger

A heat exchanger is shown in this figure.

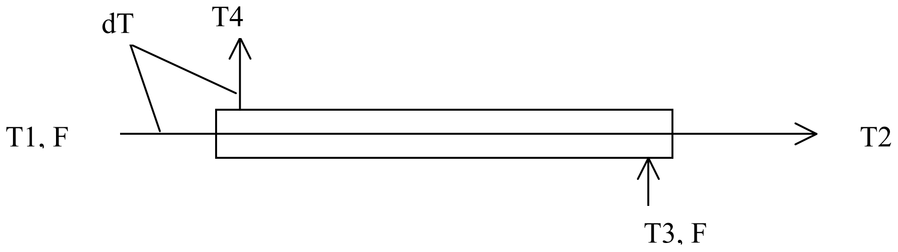


Figure 70 Heat exchanger

The purpose of the heat exchanger in a system is to heat a certain amount of fluid to a temperature T_{set}.

The principle used is Newton's 2^{nd} law on energy conservation.

The design of the heat exchanger has specified a Terminal Temperature Difference, dT. This quantity is known, the expected heat transmission coefficient k is known and the design efficiency is known, all of them in 'clean condition'. Besides it is assumed for this example, that there is the same flow of the same medium on both sides.

The problems of such a heat exchanger are fouling, internal leaks and external leaks.

In the following guide are listed how presentation of the condition, functions and goals are recommended.

GUIDE

Functional levels	**Visualized functions**	**Constraints**	**Graphical elements to use**
Goal	Reach temperature T2	Tset	Digit or trend curve
Principle	Energy conservation Mass conservation	Energy balance Flow balance	Bar graphs
Function	Heating, Cooling, Flows	$T_3 > T_{set} + TTD$	Configural element
Condition	K-value (Heat transmission coefficient) TTD (terminal temperature difference Efficiency	Design parameters	Trend curves
Plant lay-out	Mimic diagram		Symbols digits

Next, Figure 71 shows how the heat exchanger and its functions may be presented, according to the graphical guide, on different levels of information.

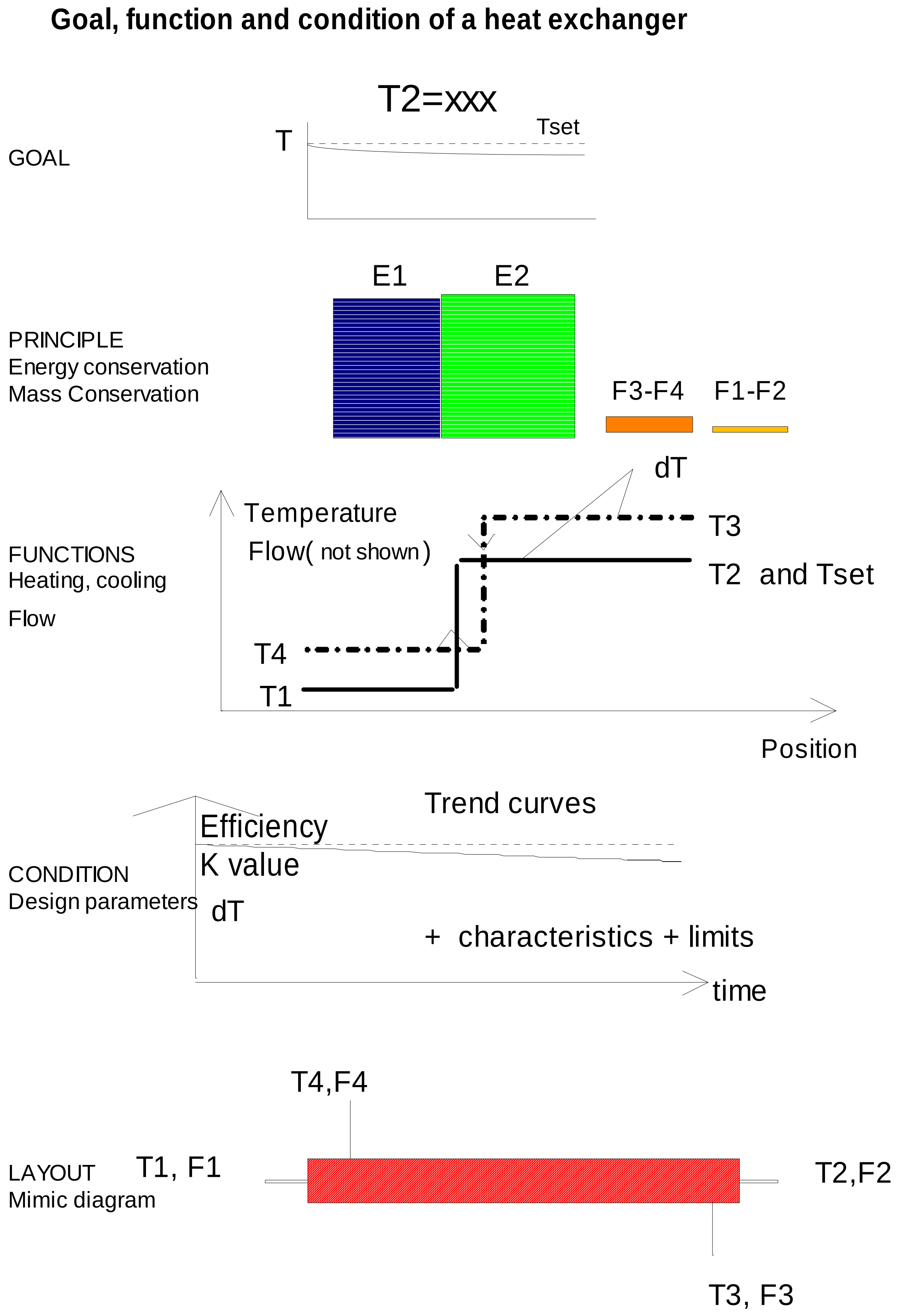


Figure 71 Presentation according to the Graphical Guide

10.5.2 The pipe reactor

Looking at the displays for the pipe reactor one can observe that the information presented on the different displays is in accordance with the Graphical Guide.

The following table specifies, for the different tasks of the pipe reactor, the displays on which the information is presented and the graphical elements used.

Display number	**Functional levels**	**Visualized functions**	**Constraints**	**Graphical elements used**
1, 3	Goal	Temperature T1	Tset	Digit+trend curve
5	Principle	(Flow)	Mixing by turbulent flow.	Integrated display
1	Functions	Heating, Cooling, pressure drops	Steam saturation curve as lower limit for the pressure	Configural element
2, 4, 5	Conditions For pipes and heat exchangers and the pump	Pressure drops. Pump characteristic+WP	Expected and Max. pressure drops Max pump pressure Min. flow Max. pump speed	Bar graphs+ Integrated display with characteristic
1, 2	Layout	Mimic diagram		Symbols digits

A principle of a pipe reactor is to give the chemical reaction a specific reaction time. A principle is also to mix chemical substances using a turbulent flow

Energy- and mass conservation are important constraints for the pipe reactor. However these constraints are not visualized. For example, it would have been useful to be able to observe on the display if a leak of steam to the environment had occurred, but due to the lack of information of steam flow this was not possible. Similarly, in the case of a leak of slurry it would have been an advantage to be able to show it on the display. The use of the conservation laws require some more instrumentation than is normally seen on process plants. Power plants do not have measurements of flow on the turbine side, nor on the drains from the turbines used for preheating. This means that with existing instrumentation is it not possible to follow the energy flow through the turbine system.

Display for the pipe reactor according to the Graphical Guide

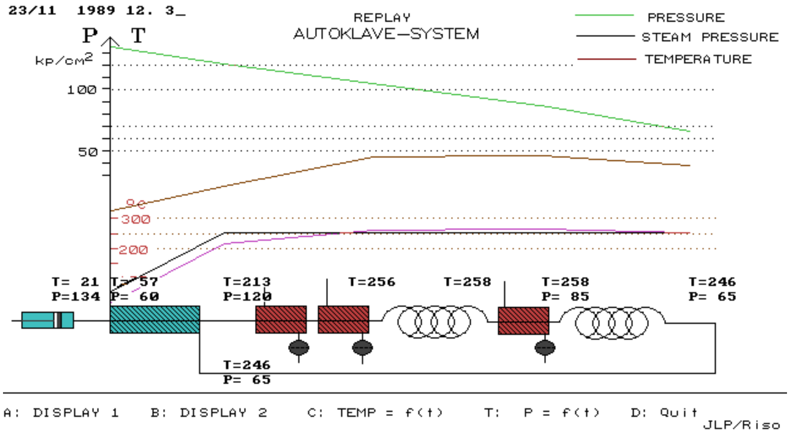
GOAL

$$T = 256\ ^{o}\mathrm{C}$$

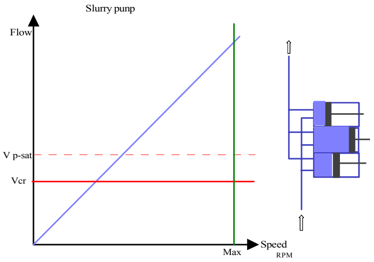
$$T_{set} = 260\ ^{o}\mathrm{C}$$

FUNCTIONS

LAYOUT



CONDITIONS



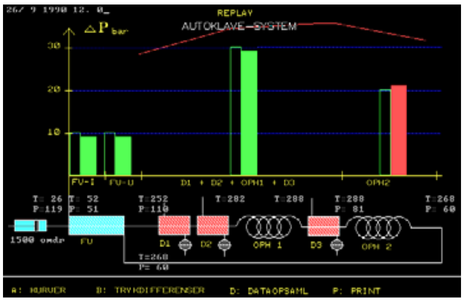


Figure 72 Presentation forms for a pipe reactor

10.5.3 The pressurized water reactor

Looking at the overview display for the PWR and comparing the content with the requirements from the Graphical Guide, we can see that the layout and the general functions such as cooling, heating, heat transfer, pressure increase and pressure drops are present on the display.

Figure 66 in this chapter is an example of how to present energy transport and it satisfies the level of principle. The example on condition monitoring of the condenser is placed on the level of condition. On this level all other displays for component conditions must be placed too- among them the pressuriser display of Wiesang [in 48]. The functional purpose, i.e. the amount of power the plant produce can be visualized digitally, together with the set point.

Display	Functional levels	Visualised functions	Constraints	Graphical elements used
	Goal	Power	Set point	Digits
Example	Principle	Energy flow	Energy conservation	Bar graphs
Overview	Functions	Heating, cooling Mass flow Pressure increase Pressure decrease	DT between primary and secondary side.	Configural displays
Condenser Pressuriser	Condition	Condenser pressure Reactor pressure	Steam saturation Pressure margin in the reactor	Integrated displays
Overview	Layout	Mimic diagram		Symbols and digits

Table 14 Graphical elements used for a PWR

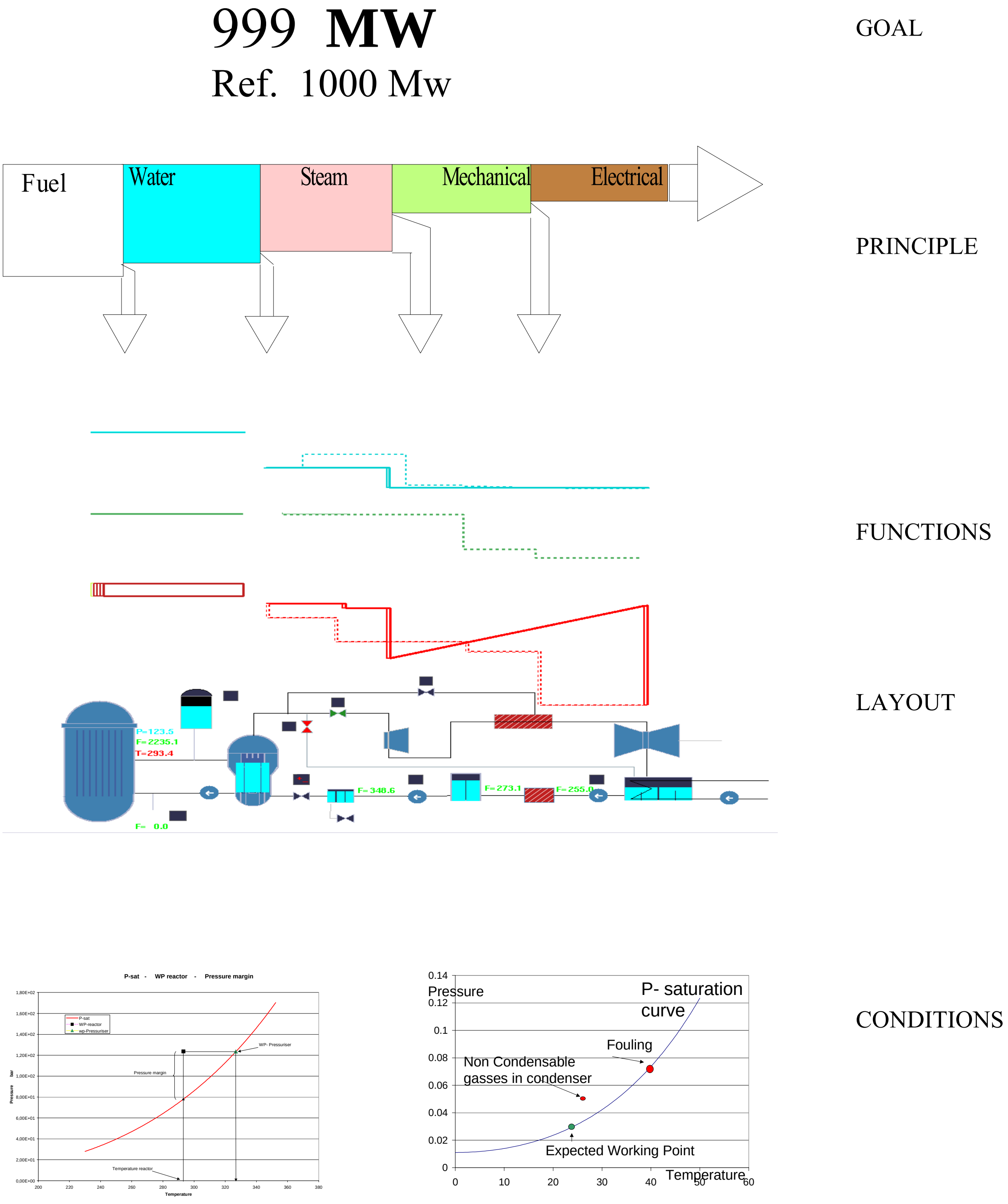


Figure 73 Some presentation for a PWR

This overall graphical information must be supplemented with trend curves and more detailed information for each subsystem.

11. Discussion of the methods

The author of this thesis claims to have developed a number of novel methods and features that can improve the design of display systems for the supervision of a process plant. In order to support the claim we must both outline the design methods that existed previously and assess what the new methods have contributed.

As discussed in Chap. 1, Introduction and Chap. 2, State of the Art, there are virtually no written-down practical methods for the design of display systems for process plants – at least, no such methods exist that pay regard to the form-versus content discussion. For many years, there has been a request for methods and principles aiming specifically at 'how to place the dots and the lines'. The research in the field has mainly consisted of theoretical considerations; one example is the development of Ecological Interface Design [51], EID. There are some applications of EID, but it seems difficult to generalize these applications into a method of what the designer wants show in his display and how to present the information. The Graphical Guide is a guide for designing EID using more well known methods.

Rasmussen's Abstraction Hierarchy, AH, has been conceived by many as a method to lay down the content of a display system. However it is rather a framework based on the engineering-oriented way of designing a process plant, asking questions such as:

- What is to be produced?
- What are the principles for the production?
- Which processes are needed?
- Which properties must the systems possess?
- How are the systems combined into a plant?

The Abstraction Hierarchy puts focus on the demand on the display system for containing information from all layers in the structure. When this demand is fulfilled, it is claimed that it is possible to locate a failure and plan how to re-establish the state.

The AH has not been described particularly well in the literature as a practical tool and has not, up to now, been used convincingly as a guide. To be able to provide information in each of the AH layers, one must, in our opinion, carry out a thorough risk analysis in order to expose the necessary functions, control measures, redundant systems and safety systems. The designer must know what are the hazards in the plant. For example, if energy conservation is used as a surveillance parameter for leakages, and the designer does not know that certain exothermic reactions in the process can develop into run-away reactions, then a serious problem may arise. The GTFT method takes care of this problem.

Presently applied design tools recommend that a mimic diagram of the plant is drawn, and that variables are shown either digitally or by a bar graph. The mimic diagram may be supported by trend curves. Admittedly, these tools have fine facilities for following the control sequence diagrams. But there is no superstructure to combine them, and no guide to doing it. This is what the author's methods, the Goal-Tree Fault-Tree method (GTFT) and the Graphical Guide, contribute. The GTFT method specifies which information must be present in the display systems, and how it is structured in 1) goals, 2) functions and 3) conditions. The structure is closely related to that of the AH, and this is no surprise since every process plant contains components with certain properties and functions, sub-systems with functions and goals to serve, the plant goal itself and a method on how to achieve this goal. These properties are inherent in process plants and cannot be changed. Subsequently, the Graphical Guide offers a guide to designing an appropriate structured graphical presentation, both concerning conditions, functions, goals and constraints.

The official guidelines, too, contain some recommendations on the content and presentation elements in display systems, but there is no guidance as to how to provide the information or how to specifically apply the graphical elements. This is precisely what the two above-mentioned methods offer. Indeed, it is our long-term hope that the methods may be incorporated in the official guidelines when they have proved to be good, simple and robust. – The graphical elements used in the Graphical Guide are illustrated in NUREG-0700 rev.2 too, but not for specific purposes.

12. Conclusion

This thesis treats various topics connected with the design of display sys-tems for process plant operation. The work falls into three parts:

Part I, Chap. 1-2	Introduction; State of the art
Part II, Chap 3-8	The author's own designs; Systems analysis methods
Part III, Chap 9-12	Design guides; Discussion of methods; Conclusion

Part I

The Introduction (Chap. 1) briefly states the reasons why it is important to have a high quality display system in a control room, both with respect to the content of the single displays and to the way the information is shown. Investigations at recently established power plants have shown that these still mainly rely on mimic diagrams, with measured variables indicated digitally. The mimic diagrams are supplemented with trend curves showing the time variation of selected variable. Data from an inquiry form investigation of design strategies showed that no such strategies had been applied, and the designers had no knowledge of the recent research in the area.

Why is the research being ignored? And what can be done to enhance the utilisation of novel technique? To answer these questions, a literature study was carried out on practice today as well as on actual research in control room information systems.

The State of the Art account (Chap. 2) has two main points of view. Firstly, it outlines what the existing guidelines say about the content and form of display systems, and what they claim the systems must do. The guidelines specify a list of demands on the information systems in order for the operator to be able to carry out his tasks, and they point out that one must use the experience from the actual and similar plants. But there is no indication as to how the demands could be met. In short: the guidelines do not provide methods, they merely state a number of demands.

Secondly, the chapter discusses the research in the area in the period 1980-2000 and argues that here, too, indications of methods are sparse. The only well-known method, Rasmussen's Abstraction Hierarchy, AH [ref.], is mainly a general framework describing a means-end hierarchy of functions and goals and stating that the operator must have information at each hierarchic level: from top level elements as well as from their constraints.

The AH framework seems quite evident and convincing but has turned out to be difficult to apply in practice. Also, users have pointed out certain drawbacks of the AH, and there is a lack of a practical guide to its use as well as of illustrative examples hereof. Thus, the reason why strategies and methods have hardly been applied could be that the designers did not have access to such strategies and methods, at least not in an applicable form.

Finally, the chapter provides a number of examples of graphic display form that might form part of a structured guide to information presentation – which is among the very purposes of the thesis.

Part II

The core matter of this part is a thorough description of four display systems developed by the author. The first one is a full display system for a pipe re-actor (Chap. 3) used for wet-oxydation processes at high temperatures. The experience with the use of the system were convincing and led to an invitation from the OECD Halden Reactor Project to develop an overview display for a pressurised water reactor (Chap. 4), which was tested on a full-scale simulator and proved to supply useful information to the user, both during normal operation and in abnormal situations.

An overview display developed for a waste incineration plant in Germany (Chap. 5) illustrates that a rather simple design strategy, aiming at the needs, may lead to a better result than what would have come out if no strategy had been applied.

The last display was developed for a condenser (Chap. 6) and concerns condition monitoring, a valuable tool to observe incipient failures or wear in a component and, for such a reason, to take it out of operation be-fore its function is influenced. Control systems are connected to components and are usually able to compensate for the degradation of a component. The condenser display was tested on a simulator and by replaying data from a nuclear plant; the test showed that it was possible to distinguish between different types of degradation – and that the condenser functioned OK.

The experience with the design and use of the waste incineration display enhanced the development of the strategy (Chap. 9) that resulted from the work in the PhD project. Other important factors in the development process were: risk analysis, thermodynamics and component theory.

Chap. 7-8 outline the relevant systems analysis methods and point out the references that may be used in a process plant.

Part III

An account is given of general methods that the author has developed, taking into regard what the guidelines prescribe; what other researchers have done; and what the author has done herself.

As mentioned above, the AH has some inconveniences and drawbacks, but the means-end point-of-view may be supported in an obvious way by combining a goal-tree with a fault-tree (Chap. 9).

The goal-tree describes the primary goal of the plant and the method used to achieve it. Sub-goals point out the processes needed to reach the goal, and similarly for sub-sub-goals. Next, certain functions are needed, but at this step it is natural to pass on to a fault tree, describing how and why a failure may occur in these functions. By using a fault-tree one may include failures in both control functions, safety systems and component states. The outcome is a qualitative mapping of failures and their consequences in the plant, useful in the analysis of what must be supervised.

A comparative test of the goal-tree fault-tree method (GTFT) against AH showed that GTFT provides not only the information claimed by the AH, but also information on necessary conditions, The GTFT method will also take controls and safety systems into account. In addition, GTFT provides a useful general view of the situation.

While Chap. 9 is concerned with the content of the displays, Chap. 10 treats the presentation form. A key notion is the author's 'Graphical Guide', summarised in Table 13. Based on normal graphical elements, the Graphical Guide gives a compact account of how one may show, in an illustrative way, important features such as

- Goals
- Functions
- Conditions
- Plant layout

The Graphical Guide was built up using 1) the NUREG guidelines and reports, 2) the displays described in Chap. 2 (State of the art), and 3) the author's own displays. The use of the guide is illustrated by examples, in particular for the pipe reactor display treated in Chap. 3.

Chap. 11 contains a discussion of methods, with emphasis on the author's own contributions: the Goal-Tree Fault-Tree method for determining the content and the Graphical Guide for presenting the information.

What are the limitations of the two new methods? If the GTFT method is applied for a specific plant, the results will point at the information the operator must have to be able to diagnose a failure and to observe an incipient failure. The method aims at normal operation and not at, say, start or closing down situations. – The Graphical Guide does not specify how to present alarms nor how to take control actions from the screen.

Still, it is the hope of the author that the two methods may contribute to the design of better display systems; that they may inspire new research in the field; and that they may perhaps even influence recommendations in future official guidelines.

The present Chap. 12 draws the conclusion of the thesis and Chap. 13 lists the references to literature.

An *Appendix* about graphical presentation of information from maintenance reports is included; to show that other strategies are applied for these purposes when users decide which information they want for their special needs. Another difference is the lack of a time pressure that is the problem in real time systems.

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Appendix A

Graphical Illustration of Information from Maintenance Reports

The present paper describes the development and test of a computer tool aiming at safety and maintenance. The tool is based on the Nordic common failure reporting system containing data from 14 nuclear power blocks. The reports were collected over the years 1975-1995.

As an example on how to use such a tool, a study of the high pressure charging pump on a PWR was done, and the result are reported below. The project forms part of the Nordic Nuclear Safety research program NKS and is carried out in collaboration with Sydkraft, Barsebäck, Swedish Nuclear Inspectorate (SKI), The Data Base Office (TUD-Kansliet) and Delft Technical University.

Background and Scope of the Research

As process plants grow older, the equipment reaches an age where the failure data may be observed to deviate from those predicted by the manufacturer. Ageing problems start to show up in the equipment, and it is time to reconsider the maintenance performance with the purpose of re-optimizing safety and productivity.

Nuclear equipment, e.g. safety systems, are complex high-technology systems that must operate for long periods of time without serious failures, and must be very durable. A great amount of redundancy and diversity is aimed at in nuclear facilities, to ensure the safety of the plant. Repairs, inspections and overhaul of equipment are usually done at specific time intervals, when the plant is down for refuelling. This process generally follows a pattern of increasing complexity, depending on the operating times accumulated by the system.

The physical environment in which the equipment operates is most straining and can have serious detrimental effect on the complex mechanical and electronic components of the equipment. High temperatures, strong vibrations, a high humidity and the presence of radiation all take their toll. This is why the reliability characteristics, throughout the operating phase, may deviate from those specified by the supplier.

The nuclear power plants in the Nordic countries have established a common data-base to which all repairs of components are reported. Of the nuclear power blocks in Sweden and Finland, 14 have joined this data-base. Another database containing reports from safety related failures, the so-called Licensee Event Reports, has also been established. The purpose of these data-bases is safety related and they are mainly used in the calculation of the reliability of components involved in safety studies.

The aim of the work reported in this chapter is to use the data bases for ageing and maintenance assessment of the components, since good maintenance is necessary for a high safety and also for good economy. The development of statistical methods to support the different users with information for use in their daily work is part of the work.

The personnel at the power plants have access to the data bases from terminals. Thereby they may use the data for their own purposes.

The investigation of well-known methods and the above-mentioned development of new statistical methods form the main part of the work.

The users of the final tool are primarily meant to be
- Maintenance planners
- Safety departments
- Authorities
- Craftsmen
- Managers
- Utilities
- Operators

and

The users need for information can be divided into the following main topics.
- Maintenance
- Ageing and condition
- Safety
- Economy

To extract the right information, we must address such questions as:
- What is good maintenance?
- How do we measure maintenance quality?
- Which data are available for the purpose?
- How to present the results for the users?

In nuclear power plants, safety has an important role in all questions, so one answers to what good maintenance is could be
- Minimize maintenance costs but keep safety high.

In order to fulfil this goal, that is: minimize costs without reducing the demands to safety, it is necessary to combine high quality components, high quality repair work, and punctual preventive repairs. In order to check if this combination has been achieved, let us list some possible *indicators* to measure or to calculate:

-The amount of early failures after repair is low.
-The amount of unplanned repairs is low.
-The relation between preventive and corrective repairs is reasonable.
-The failure rate is not increasing.
-The time used for maintenance is not increasing.
-The unavailability due to repair is low.
-The repair rate is not larger than for identical components from other manufacturers.
-The repair rate is not larger than for identical components elsewhere at the plant, or at other plants.

One thing is what the users want to measure, another is whether this information can be extracted from the available data.

A failure report contains information about the failure and the repair, but it also provides a classification of the failure type by describing how the failure was detected, by indicating the failure type and mode, and by giving a brief account of what has been done during repair.

To treat the information in the reports, including statistical analysis, a *computer program* was developed. An important objective in the design of the program was that it must be possible to pool data in several ways: from selected plants; from selected components; for a specified failure mode; or for a specified time interval. Thus the user at one plant may, e.g., pool data from a selected group of other plants and compare the results with data from his own plant.

To elicit a given problem, a large number of graphs can be retrieved. The graphs can be organised as a hierarchical system where the user starts with overview graphs and then dives deeper and deeper into his problem.

A Pilot Study of Charging Pumps

In this pilot study we have focused on three charging pumps at the Swedish nuclear power plant Ringhals 2 (# 334CSAPCH-01,-02,-03) to show which kind of information can be extracted from the TUD reports.

We did not read the reports in detail but rely on their time indication and coding. At any rate, the system is meant to give indicators rather than exact answers and the user is supposed to find the more precise answers by using his own knowledge, other experts and perhaps other data sources.

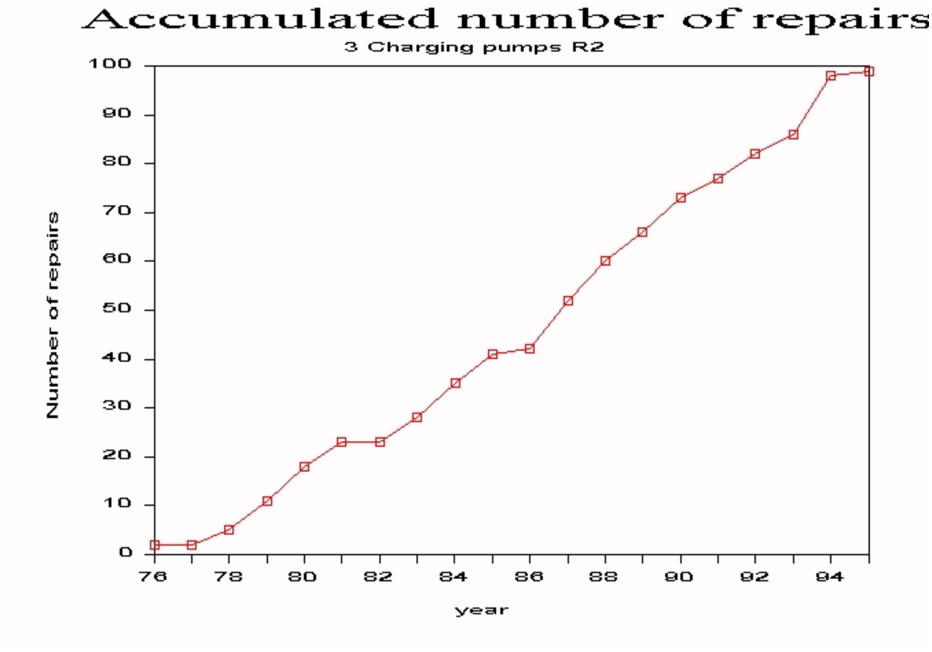
Twelve graphs are drawn, each of them followed by an interpretation of what the graph may tell the user. The twelve graphs illustrate:

1. The accumulated number of repairs
2. The accumulated number of repair hours
3. The mean unavailability due to repairs *(not included here)*
4. The accumulated number of repairs for each pump
5. The accumulated number of repair hours for each pump

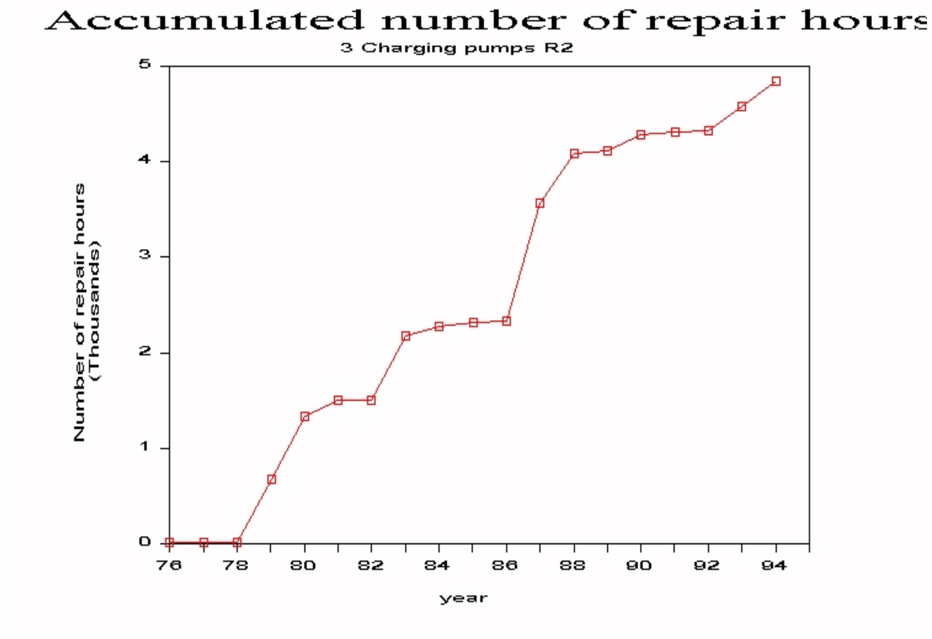
The total number of failures (functional; non-functional; and early)

7. The number of repairs due to time between repairs.
8. Subsurvival functions (observation modes)
9. Conditional subsurvival function (observation modes)
10. Subsurvival functions (failure modes)
11. Conditional subsurvival function (failure modes)
12. Time average failure rate bound

The first graph shows the *accumulated number of repairs* for all pumps. This graph tells the user if there is an increasing or a decreasing tendency in the number of failures over the years of operation. The graph does not depart markedly from a straight line, meaning that on average for the three pumps, nearly the same amount of failures happen every year.



That the number of failures per year is fairly constant is not the same as to say that no ageing effects occur. This is illustrated by the next graph, the *accumulated number of repair hours* over the operating years.

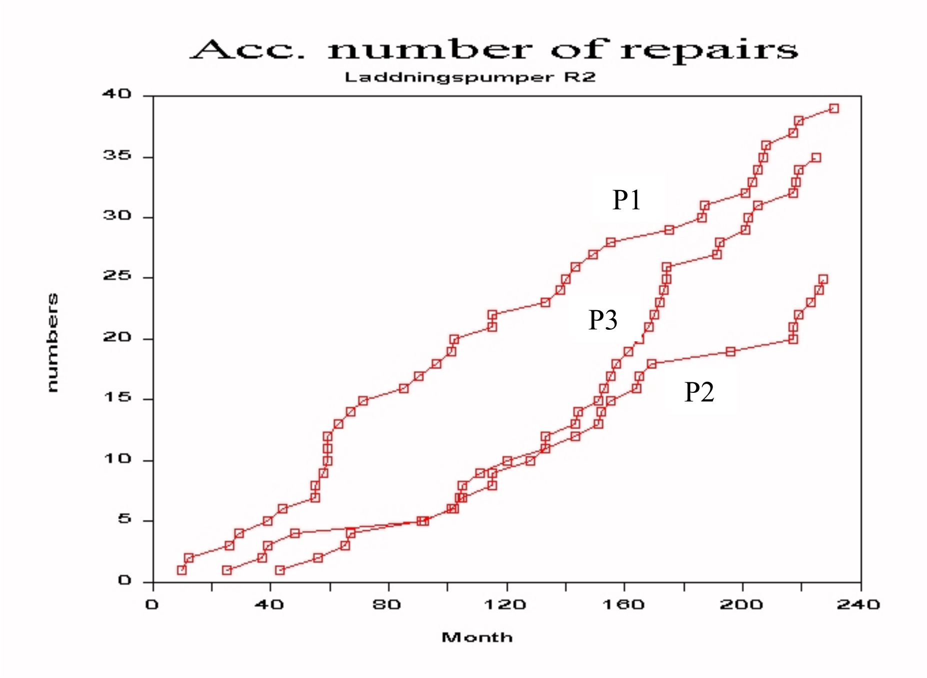


(The graph of a related quantity, the *mean unavailability due to repair*, no. 3 in the above list, is not shown here).

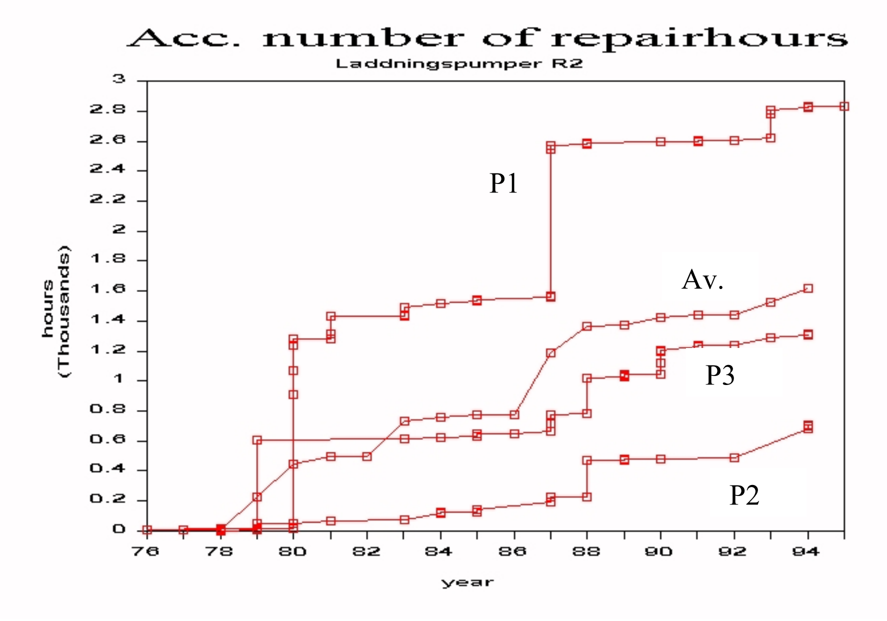
If there are ageing effects, they should cause the number of repair hours to increase, that is, the repair hours curve should generally tend to curve upwards (convex curve). However there is no clear indication of this in the graph. It shows that there has been certain periods with unusually many repair hours. After 1988 the curve flattens out but then it starts to increase faster again, even if only slightly, from about 1993.

If we want, for example, to look at the individual pump and compare it with the average of all three, this can easily be done.

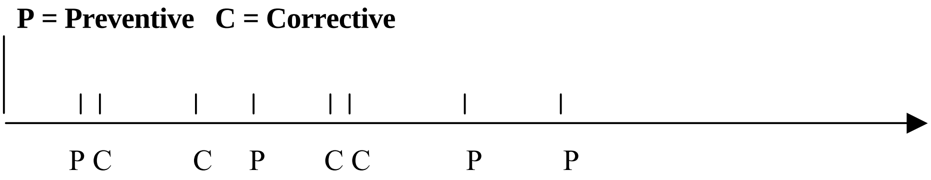
The graph fig. shows the accumulated number of *repairs for each pump*. As we can see, there is a marked difference between P1 and the two others in the beginning, however P3 seems to have had some problems between month 150 and 180, a 2.5 years period in 1987-1989, and that brings it closer to P1. For the same reason, when looking at the entire 20 year period, the repair number for P3 has a vaguely increasing tendency while P1 and P2 show a rather constant repair rate.



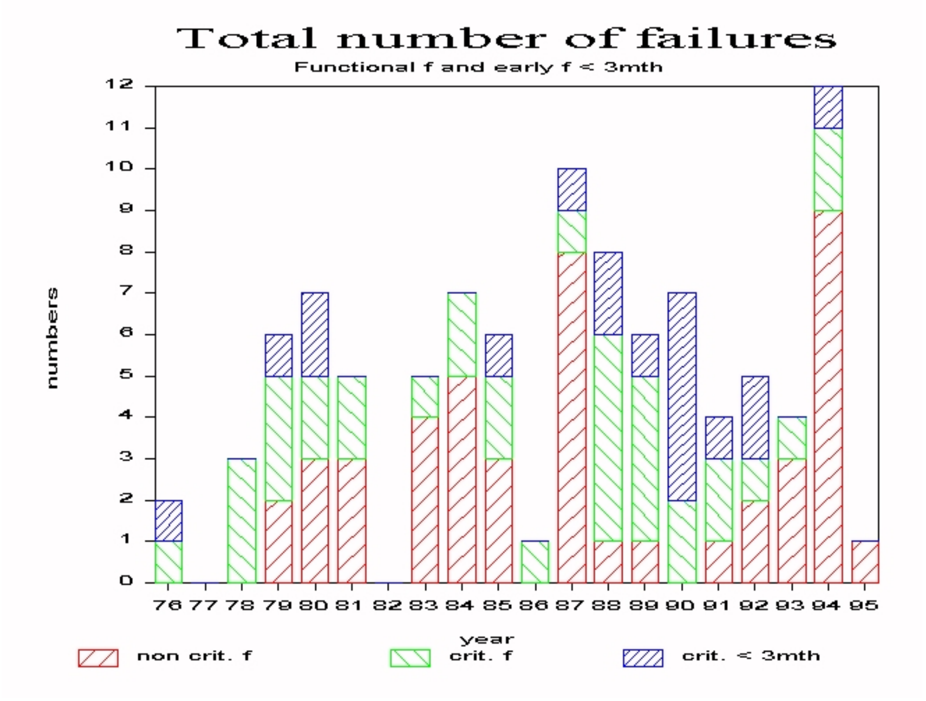
The graph on fig. shows the accumulated number of *repair hours for each pump*, supplemented with average accumulated hours for all three pumps (curve # 2 from above to the right in the diagram. Such a graph can be of some help to a user who wants to study the difference between pumps. For example, the diagram to the left showed that P2 has increasingly many repairs in the last couple of years, but the diagram to the right reveals that it must have been mostly minor repairs.



The next step is to split up the investigation according to types of failures, such as critical and non-critical failures. We also want to look for early failures after repair. The drawing below (not in the 12 item list) is a simple rendering of how the repairs are distributed over the period. It is easy to observe the unwanted situations: the early failures after repair.



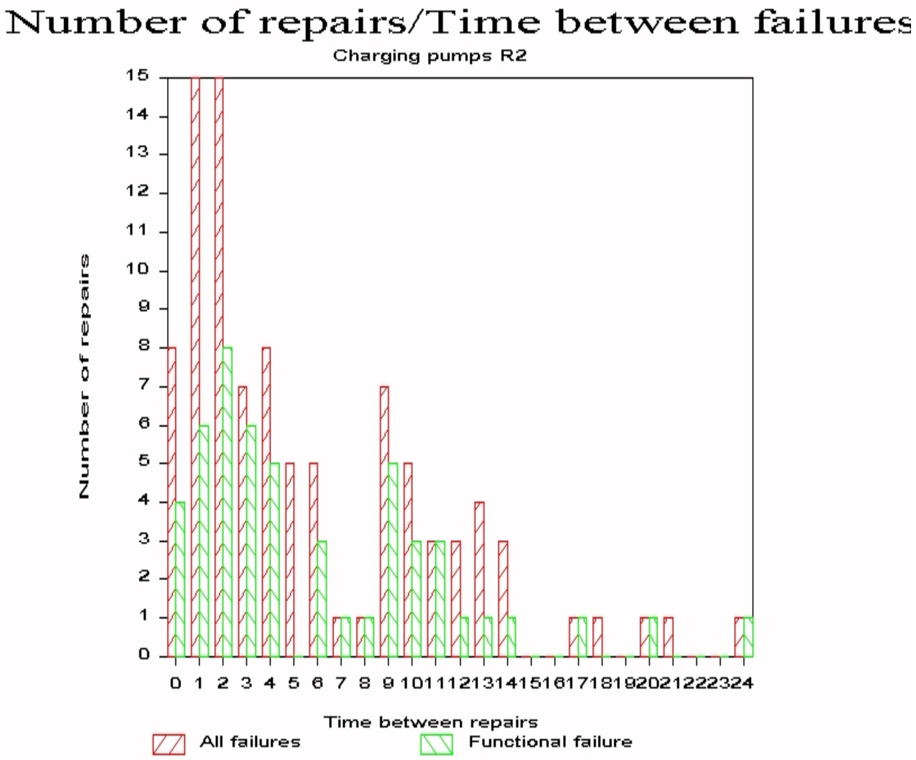
The following two graphs illustrate, a.o., the question of early failure after repair.. Let us first take a look at the *total number of failures*.



The histogram on the figure shows, by the height of each bar, the total amount of repairs per year for all pumps. The bar is divided into repairs due to (1) non-critical failures, (2) non-early critical failures and (3) early critical failures, that is, those that happened less than 3 months after the last repair on that pump.

As an example, consider the year 1994 in which 12 repairs were performed at the pumps. Of these repairs, 9 were due to non-critical failures; 3 were due to critical failures; and one of them happened less than 3 month after the last repair. This means that the 12-unit bar for 1994 is split up in (from below) segments of 9, 2 and 1 units, respectively.

In 1990 there were 7 repairs, but 5 of them were due to critical failures and all happened less than 3 month after the last repair. The red, green and blue segments of the 1990 bar therefore have lengths 2, 0 and 5, respectively.



Now, look at another graph, the one shown on the figure above . It is a histogram which illustrates the distribution of time between repairs: the length of the first bar (column) from the left indicates the number of repairs that have happened within 0-1 months from last repair of the component; the second bar indicates the number of repairs within 1-2 months from last repiar; etc. Each bar consists of two, the left part (in red) indicating the total number of failures of the type, the right part (in green) the number of 'functional', that is, critical failures.

As an example, consider the bar with "9" below it; it carries the information that 7 repairs were done on components that had been repaired last time between 9 and 10 months ago; and of those 7 repairs, 5 were due to critical failures. Whether early repairs are in fact re-repairs cannot be seen from the graph, but there are some indications of this phenomenon in that we have noted rather many re-repairs taking place in the first 1-3 months after a repair. However less than half of them are due to a critical failure.

A drawback of a graph like the one just described is that it does not contain any information about when these early failures occurred: was it in 1978? – or was it in 1994? Neither does the graph tell us which components it was that gave rise to particularly fast re-repairs. One of the graphs already described, the one showing the accumulated number of repairs per month, might be a good supplement in this question.

One reason for the plant management to be interested in early failures is that knowledge about this aspect may help to discover bad quality of (1) the repair, (2) the spare parts or perhaps (3) repair instructions.

Conclusion

This graphs are an illustration of using non-dynamic sources, where the user can determine how he can use the information and present them in a way that he gets an answer on his question

The aim of the pilot study was not primarily to study the behaviour of the pumps but rather to address the question whether the failure reports can give valuable information to the users.

This chapter has described some simple graphs that can be produced without making assumptions and without using mathematical formalism. Nearly all the graphs give rise to new questions; and new graphs can be produced to try to find the new answers. The users of the system themselves must inform the system about their needs.

However at this stage of the development of the program, we may conclude that some information can be extracted from the reports.

Before drawing a final conclusion of the study, it is necessary to discuss it with relevant staff at the Ringhals 2 plant that know the pumps, and to hear their opinion of the results.

The TUD data are not perfect, but it is hoped that the output may provide at least some indications on ‘good or bad behaviour’ in the area. The same methods combined with advanced statistical methods can be used on the local data bases, probably leading to more reliable results.

When the results from using the TUD data base are compared with results from the local data base, the uncertainty of using the TUD data base only can be estimated

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