Cognitive
Engineering
Laboratory

Research on Factors Influencing Human Cognitive Behaviour (II)

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CEL 95-08, Volume 1

Final Contract Report
September, 1995

Prepared for
Japan Atomic Energy Research Institute

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ABSTRACT

This final contract report describes the findings from the work conducted under the second year of a 3 year research program on factors that influence human cognitive behaviour in nuclear power plants (NPPs). Two work items were addressed in this second year. First, a literature review of some of the important factors affecting the design of the visual form of an interface was conducted. The review illustrates the design principles found in the literature with copious example displays. In addition to these design examples, another outcome of the literature review was a proposed experiment, to be conducted in the third year of the research program. This proposed experiment will investigate the principle of visual momentum (Woods, 1984) in the context of the DURESS II thermal-hydraulic system simulation. The results of this first work item are presented in volume 1 of this final report. Second, an experiment was conducted to investigate the interaction between interface design and "theoretical" (i.e., model-based) training in terms of their respective effects on operator adaptation. A longitudinal experiment was conducted in the context of DURESS II with two interfaces, one based on the principles of ecological interface design (EID) and another based on a more traditional piping and instrumentation diagram (P&ID) format (these were the same interfaces that were evaluated in the first year of the research program). In addition, there were two training conditions, one with essentially No Training and one with Training based on an abstraction hierarchy representation of DURESS II. These two factors were factorially crossed in a 2 x 2 between-subjects experimental design. The experimental findings revealed that the EID interface groups consistently outperformed the P&ID groups, thereby replicating the results obtained in earlier evaluations of EID. Also, the Training groups improved more than the No Training groups on most performance measures, suggesting that training based on the abstraction hierarchy can lead to improved performance. As far as we know, this is the first time that the value of the abstraction hierarchy for training has been empirically demonstrated. Finally, there was little evidence of an interaction between interface design and training. The results of this second work item are presented in volume 2 of this final report.

ACKNOWLEDGEMENTS

This research project was sponsored by a contract from the Japan Atomic Energy Research Institute (Dr. Fumiya Tanabe, Contract Monitor), as well as research and equipment grants from the Natural Sciences and Engineering Research Council of Canada. We would like to thank Dimitrios Nastos and Dr. Tanabe for their contributions to the research presented in this volume of the report.

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OVERVIEW

A predictive model of human cognitive behaviour, including the mental strategies used in emergency situations, is needed in the design and evaluation of nuclear power plants (NPPs). Existing models, however, suffer from several significant limitations. One of the major problems is the lack of deep understanding of human operators' adaptation processes, and especially the critical factors that influence such adaptation. This research project is intended to be a three year research program that is devoted to empirically investigating this topic. The impact of four factors on adaptation will be investigated: the interface content; training; the visual form of the interface; and operators' pre-existing competencies. The results obtained will be useful to the development of a model of human cognitive behaviour and to the development of criteria for the design and evaluation of complex human-machine systems.

This final contract report describes the work conducted under the second year of the research program. In the first year, the impact of interface content and form on adaptation was empirically investigated (Christoffersen, Hunter, & Vicente, 1994). In this second year, two work items were completed. A literature review of the issues pertaining to the design of the visual form of the interface was conducted. This, in turn, led to a proposed experiment to be conducted during the third year of the project. The literature review and the proposed experiment are described in this volume. The second work item completed this year was an investigation of the impact of training on operator adaptation. A longitudinal experiment investigating the interaction between interface design and training based on the abstraction hierarchy was conducted. The results of this experiment, representing the bulk of the effort in this year’s contract, are presented separately in volume 2 of this final contract report.

INTRODUCTION

Visual forms are invaluable for illustrating concepts, both concrete and abstract. Descriptive geometry simplified the production of engineering drawings, without which, designs would be quite difficult to communicate accurately. The integration of geometry and physical laws facilitated the proof of theorems and the solution of practical problems. Many areas of knowledge use some kind of graphic representation to convey information accurately in a concise, unambiguous manner, including chemistry, electrical engineering, music, and architecture.

This literature review deals with the design of visual form in human-computer interfaces for NPPs. The following topics are covered: classification of visual elements, elementary graphical perception, non-data ink, visual search, perceptual segmentation, emergent features, nomograms, and visual momentum. Rather than just verbally describing the theoretical basis for each of these topics, as is normally done in literature reviews, we have decided to adopt a different approach instead. Following the model and rationale put forth by Rasmussen, Pejtersen, and Goodstein (1994), each principle is illustrated by one or more examples. Some of these examples are based on the existing EID interface for DURESS II, illustrated in Figure 0 (see Christoffersen et al., 1994 for a description). Most, however, are newly created examples that show how the principles in question can be used to design visual forms for certain subsets of the DURESS II system, and in one case, another process control system. The remainder of the examples are based on visual representations that have been developed over the years for teaching and representing engineering systems. In this way, the otherwise abstract principles can be illustrated in a very concrete fashion. The examples, if adapted, also serve as a basis for designing novel displays for NPPs. In some cases, they also provide ideas whose merits can be evaluated in future experiments.

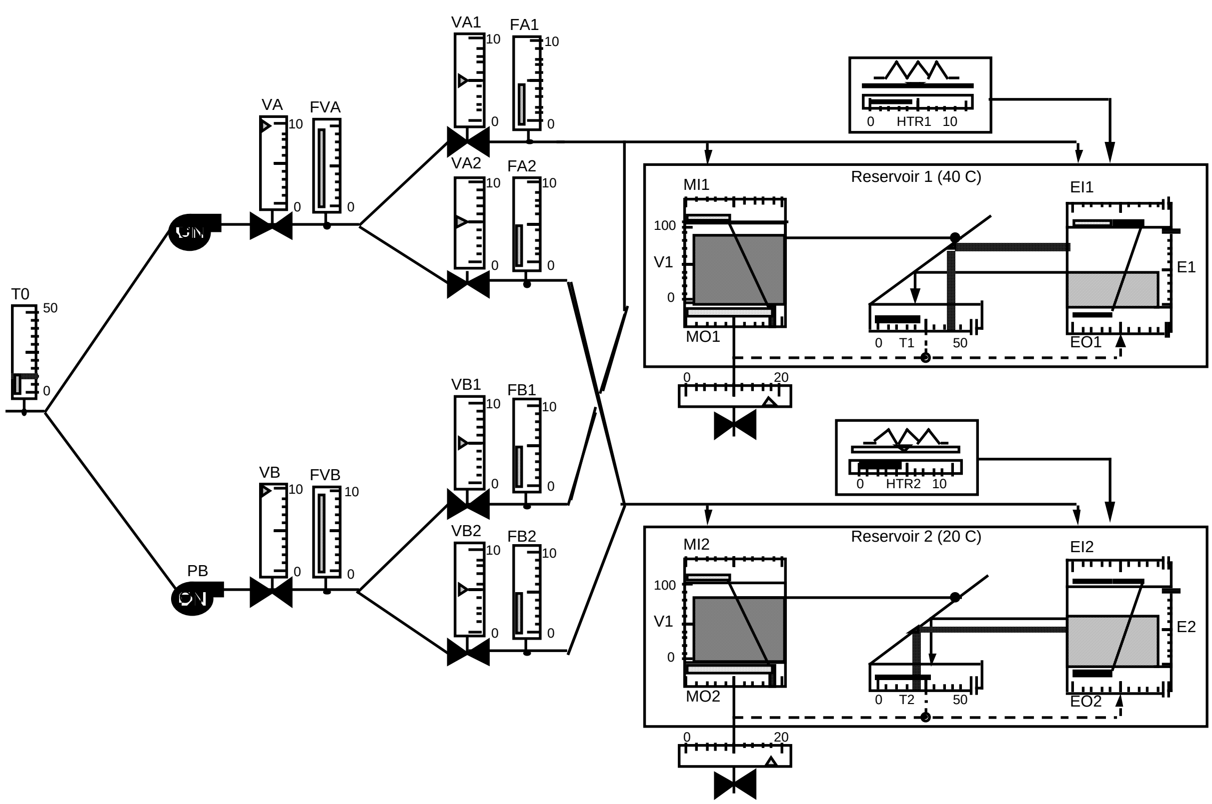


Figure 0. Existing EID interface for DURESS II.

The literature review ends by briefly describing an experiment addressing one particular visual form issue, visual momentum. This experiment is proposed for the third year of this research program.

CLASSIFICATION OF ELEMENTS

This section describes some basic distinctions to classify elements of a visual display. These definitions provide a set of basic concepts, and therefore, a terminological basis for the remainder of the literature review.

Viewports + Process Views = Workspace

Woods (1991) has made a number of distinctions which are important to consider in the design of visual forms. He defines a process view as a representation of the system that can be displayed to the operator. In contrast, a viewport is an area on a video display terminal (VDT) that can be used to display one or more process views. A viewport can be a window, a subset of the area available on a single VDT, or even an entire VDT. The computer workspace is defined by all of the process views that are available to operators, the viewports that they can use to display these process views, and also the mappings between process views and viewports (i.e., the rules that govern which process views can be displayed on which viewports). These basic concepts are important to consider, especially when it comes to improving visual momentum (see below).

Pictographs vs. Graphics

Bertin (1981) distinguishes between two types of displays:

i) Pictographs require a single stage of perception: what does the sign signify? (e.g., stop sign.)

ii) Graphics require two stages of perception: what are the elements; and what is the relationship between them? (e.g., bar chart.)

He also makes an analogy between graphics and mathematics: "Graphics create relationships among a set of elements of pictography. Graphics uses the three dimensions of the image (x,y,z). It is a spatial 'sign system' independent of time. Mathematics creates relationships among a set of elements of language. Math uses the two dimensions of sound (t, f(t)). It is a linear 'sign system' defined by time." (p.178)

Bertin fails to mention that mathematical relationships can be represented not only by equations (a function of time), but also as a graphic (a function of space). Thus, perception of a mathematical function can be as immediate as any other graphic, and is not constrained by the time which would be required to read an equation, as he suggests.

In the existing EID interface for DURESS II, most of the displays are graphics showing the relationship (through analogical reference) of a quantity against its scale. The mathematical (geometric) relationship between mass, energy and temperature is represented graphically. This should allow immediate perception of relationships. The dynamics of this graphic, however, require explanation, or observation over time.

Iconic, Propositional and Analogical Reference

According to Woods (1991), display elements may use one of three types of reference:

i) Iconic displays resemble the objects they represent (e.g., 'falling rock' road sign). These are pictographs, since they require one stage of perception.

ii) Propositional displays are arbitrary representations which do not resemble what they represent (e.g., language, digits, 'yield' sign). These are also pictographs.

iii) Analogical displays have a structure and behaviour related through some natural mapping to the structure and behaviour of what is being represented (e.g., thermometer). Since analogical displays are usually measured against a scale, a relationship is shown, making them graphics, in Bertin's terms.

All three types of reference are used in the DURESS II EID interface. The pump icons resemble pumps, and all the displays use propositional labels. Most of the displays use analogical reference to display volume flows, heat flows, temperature, or energy. The mass display is iconic as well as analogical. By its shape, it resembles a reservoir filling up with water, which is what it represents. The energy display, though, also resembles a reservoir filling up with water, which is not what it represents. Thus, there may be some initial confusion, until the operator learns that it is an energy display.

> *At the lowest level of abstraction, it is useful to have iconic reference so that the system may be represented as it appears.*
>
> *Most of the quantified information (flows, inventory) are best represented by analogical reference.*
>
> *Propositional reference is useful for labeling components and variables, as well as providing digital values as a supplement to analogical displays.*

ELEMENTARY GRAPHICAL PERCEPTION TASKS

This section describes findings from research on elementary graphical perception tasks. This research has been conducted primarily in the context of static, statistical graphs. However, some of these ideas can be applied to design of visual forms for dynamic, human-computer interfaces as well.

Quantitative Variables

First, we will deal with designing visual forms that allow operators to accurately extract quantitative information. Qualitative coding will be dealt with in the following subsection.

Position along a common baseline. It has been shown that displaying position along a common baseline allows the most accurate relative judgment of quantitative variables (over position on identical non-aligned scales, length, angle, slope, area, or volume) (Cleveland, 1985).

The variables in the DURESS II EID display are all quantitative (settings, flows, volumes, temperatures), so they are represented, appropriately, by linear scales, which provide the greatest accuracy in visually estimating quantity.

However, the relationships between displays are not optimal. For instance, the feedwater streams have a total of six valves. Each valve has a setting and flow display pair. Each display pair has a different baseline, making it difficult to compare flows. If, for example, VA1 & VA2 have settings whose total is greater than VA, the ratio FA1/VA1 should equal FA2/VA2. It will be more obvious whether this relationship holds if they can be compared side by side along a common baseline. Each individual flow must be read against its own scale, a cognitive task which requires more effort than comparing positions along a common scale, a perceptual task. If one wishes to determine how flow is distributed (to see which valves are in use and to what capacity), it is necessary to scan the screen, reading each flow individually, and then integrating the information.

Fortunately, each display pair has a common baseline, making it easy to compare each flow with its' corresponding setting. Although a lower flow will not necessarily indicate a fault, a higher flow will (valve stuck open). Also, the reservoir inflow display has the same baseline as the outflow display, making it easy to determine net flow.

The output valve displays have a different scale from the feedwater stream displays, which is not obvious, and could lead to misreading.

Figure 1a summarizes a proposed display of the fluid flow information for DURESS II. The flow through the first set of valves is on the left, the second set in the middle, and the third set (output valves) is on the right. The same scale is used throughout, to increase consistency, reducing the need to refer to scales and reducing the chance of misreading.

The 3 flows for FWS A (FA, FA1, FA2) are shown along a common baseline, so that the total flow and its allocation to the 2 reservoirs can be read quickly along one scale. This reduces scan time. The same is done for FWS B.

The feedwater streams are aligned so that the inputs to Reservoir 1 can be added vertically. The sum is shown beneath, so that the 3 flows for R1 (FA1, FB1, MI1) are aligned vertically, to easily assess the relative contributions. This makes it easy to determine which controls can be adjusted to directly control the input to Reservoir 1. The same is done for R2.

The reservoir outputs are shown to the right of the inputs, along a common baseline in close proximity, so that reservoir inputs and outputs can be compared to assess net flow and determine inventory stability.

<u>Framed rectangle</u>. Framed rectangles allow comparison of the length of a bar relative to the length of a rectangle, facilitating judgment of position on identical, non-aligned scales (Cleveland, 1985).

All of the visual elements in the existing EID display for DURESS II use modified framed rectangles (with scales). This provides clear boundaries (minima and maxima, as well as setting the display off from the rest of the interface).

Similarly, most of the solutions proposed in this report use framed rectangles, so that when the rectangle is full, flow is maximum.

<u>Divided bar charts</u>. The reservoir energy input rate is represented by a divided bar chart, which in principle is undesirable because the sections of the bar chart have different baselines and cannot be easily compared (Cleveland, 1985). It is generally preferable to show the individual components along with the total along a common baseline. However, in this case, this is probably not necessary, since there are only two components and knowledge of their relative lengths is not valuable.

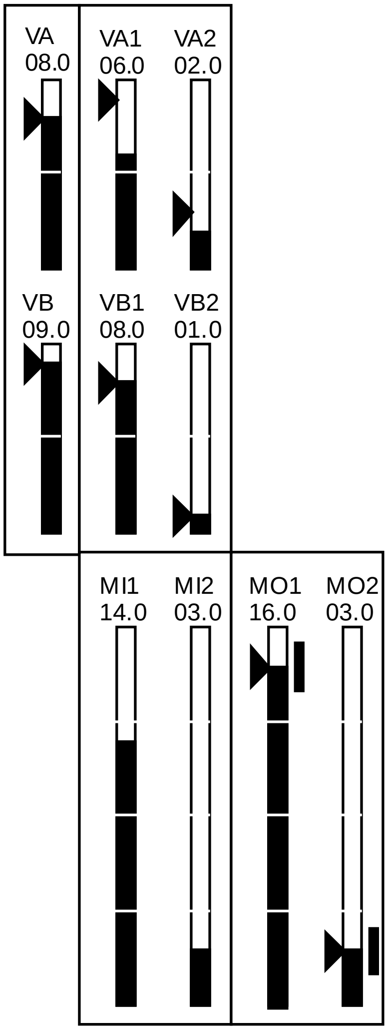


Figure 1a. Valve controls and flows are integrated into single displays, which are functionally grouped.

Each feedwater stream has one baseline for easy reading along one scale.

Flows into each reservoir are added vertically; reservoir inflows and outflows are along a common baseline for easy comparison, and judging if there are net flows.

A white grid is used to reduce non-data ink.

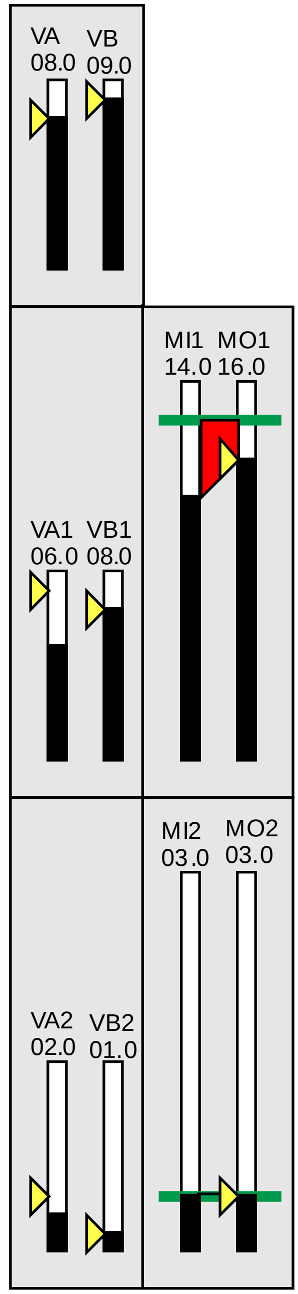


Figure 1b. Valves are grouped so all flows to and from a reservoir are on the same baseline.

Green goal areas are extended, since once the demand is met, a steady volume is desirable.

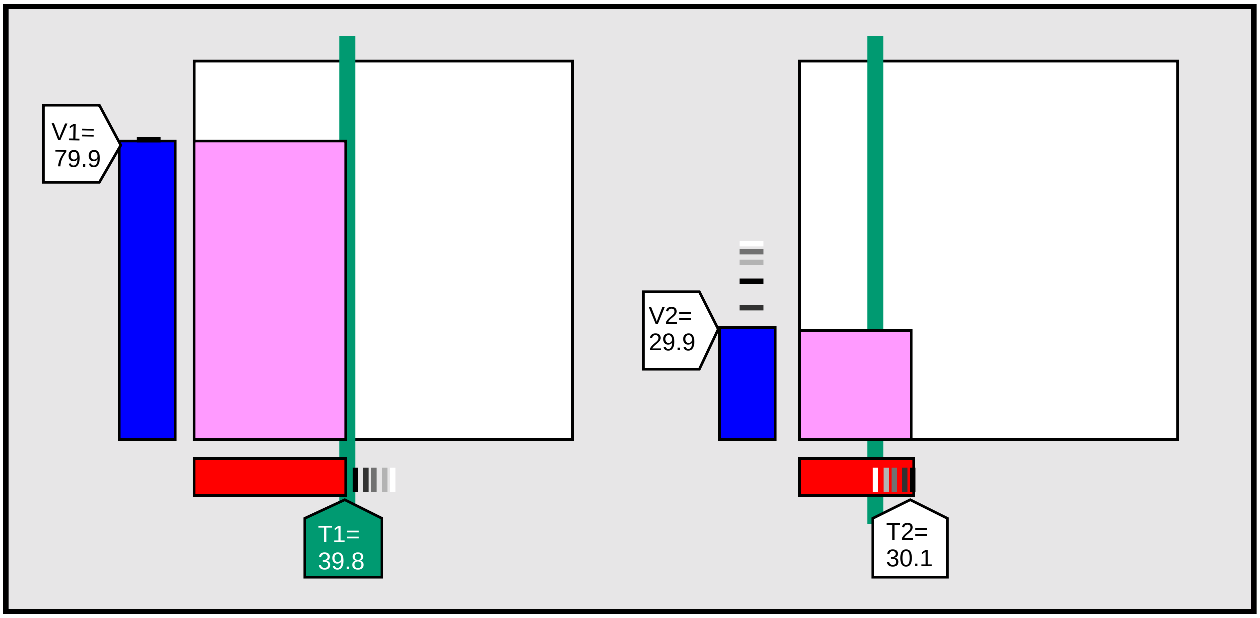
Red areas show deviation of flows from goal.

Effect of angle on slope judgment. The sloped lines on the mass and energy displays provide a perceptually salient and intuitive indication of net flow, but could be deceptive if users try to quantitatively estimate the net flow, since people tend to perceive the angle of a line (in degrees with respect to horizontal, which is the arctangent of the slope of the line), rather than the slope itself (y/x, which is calculated by the net output divided by the span between the input and ouput graphics.) This leads to a bias for sloped lines near vertical. Thus, if the magnitude of the net flow increases, this increase will be underestimated. See Cleveland (1985) for a complete explanation and trigonometric proof of this estimation bias. In addition, proportions of angles are not estimated very accurately, further contributing to error. This may not be of great importance if the operator is using the sloped line only in an ordinal fashion, as a qualitative sign for detection that something is wrong. The scales for input and output allow accurate readings, and can be used to overcome any estimation bias created by the sloped line.

This effect is most likely reduced when there are horizontal and vertical reference lines for judging the slope of a line, since the rise and run (y,x) are explicitly shown, as is the case in Figure 2b.

Distance and detection. Judgment accuracy of relative lengths of elements decreases significantly as the distance between the elements increases (Cleveland, 1985). For example, if two elements are horizontally far apart on a common horizontal baseline, comparison performance is no better than for position on identical, non-aligned scales. Detection of elements is facilitated by meaningful ordering or grouping of data elements so that elements can be easily distinguished, as well as related to other elements.

In the displays proposed in Figures 1b, 4a, 4b, reservoir inflows and outflows are in close proximity for easy comparison. In Figure 1a, flows are grouped in terms of position/function (primary, secondary, input, output) and aligned in terms of feedwater streams. In Figure 1b, flows are grouped in terms of valve pairs and reservoirs, vertically aligned in terms of feedwater streams. In Figure 4a, flows are grouped in terms of feedwater streams and reservoirs, all aligned. All of these groupings help to sort and locate information. Which is the best grouping is something which could be investigated empirically.



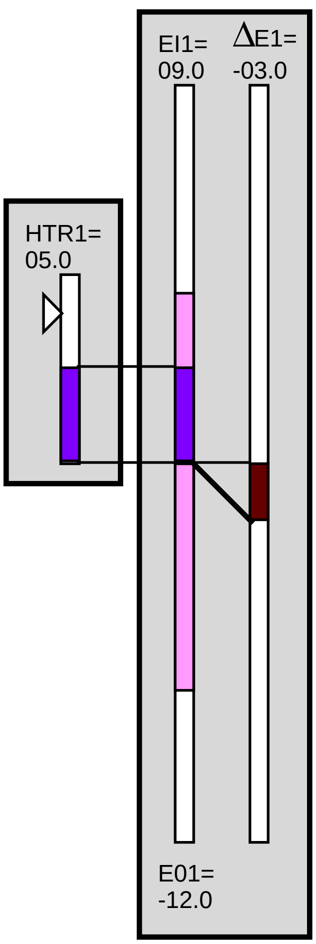


Figure 2a. (above) R1 has V1 (blue) along the y-axis, T1 (red) along the x-axis, E1 (pink) as their product.

When the target temperature is reached, the right energy boundary, temperature bar, and T1 digital display line up with the green goal line, and the digital display turns green. This makes it obvious when the goal is reached, and when it is breached.

5 lines show the recent histories. They fade from black (one minute ago) to white (5 minutes ago). The lines merge when 'steady-state' is reached.

Figure 2b. (left) The link between heat transfer rate and energy inflow is displayed.

The inflow is shown as positive, outflow as negative (making them more distinguishable than bars side by side).

The net energy flow is indicated by a crimson bar (going up for positive, down for negative, again). The slope of the line is positive for net gain, negative for net loss. When there is no net flow, the EI1,EI2 column is symmetrical, and there is no crimson bar or sloped line.

Categorical Variables

A different set of principles govern the design of visual forms for presenting categorical information.

Salience. Bertin (1981) discusses the usefulness of various coding dimensions for distinguishing images on a graphic. Value (gray level) and size of elements are the best characteristics for distinguishing images, but they create a hierarchical order of salience, which may be inappropriate if the images are equally important. (This does not mean that value can be used as a quantitative variable, only that higher values are seen as quantitatively different from lower values). Texture, colour, shape, and orientation are associative characteristics, giving equal salience to all images. It is difficult, though, to distinguish images differentiated by texture or orientation, and very difficult to distinguish images differentiated by the shape of their compositional elements. They also create rather unattractive, overly-detailed displays. Colour is an effective differentiator, but different hues at maximum saturation have intrinsically different values, which create a variation in salience. Note, however, that by varying saturation, one could achieve a display where all colours had equal value.

Colour. In the DURESS II EID interface, different colours are used to represent different categories of information (yellow for fluid flows, blue for volume, etc.). Using yellow (the most salient colour) for fluid flow is logical, since those variables will change faster than any others, so perception of the changes is important. Red is used to display the closely linked variables of heat transfer rate, energy flow, and temperature. Black, white, and gray are used for static information.

The fact that red is used to represent two different variables (temperature and heat) by conceptually different, but visually similar, displays could cause some initial confusion. Differentiation by size, shape, orientation, hue, or texture could help to distinguish them (Bertin, 1981). Yellow is used in a visually similar way to represent two conceptually different quantities as well (volume inflow and energy inflow).

NON-DATA INK

Although exploiting coding dimensions is important in designing visual forms to communicate quantitative or qualitative information, one must also be concerned about overly complex looking displays that can be created by indiscriminantly using many coding dimensions. This problem led Tufte (1983) to develop the concept of data ink vs.

non-data ink. Data ink is that which is required to convey the intended information on a graph. Non-data ink is anything unnecessary. Tufte advocates maximizes the data to ink ratio, with the intent that an informative yet simple display will result.

Scales

In the existing EID display in Figure 0, most of the information given in the interface is useful for interpreting the interface. Boxes define physical devices (reservoirs, heaters) and lines indicate physical links and relationships. However, the feedwater stream valve setting and flow displays use the same format and scale. The repeated information is redundant. Either the setting or flow scales could be erased without losing information. Each pair could, in fact, be integrated into one framed rectangle, saving more non-data ink.

The display in Figure 0 uses standard scales with ticks to divide each scale into ten divisions (with a larger tick at the halfway mark). The minimum and maximum values are labeled. To label more values would be unnecessary for the input valves, but for the output valves, it would clarify the reading, since for consistency, one tick should equal one unit. The ticks and minima and maxima labels provided are sufficient for approximate reading of values, but do not allow exact readings. Subjects complained that they were unable to set controls precisely due to the low resolution of the scale. Precise reading of length indicators is limited by the low resolution of the graphics as well as that of the scale and the discernability of the human eye. This problem would be partly solved by increasing the size of the displays and the resolution of the grids.

The scales are omitted on proposed solutions, for sake of simplicity.

Digital Values

A better solution would be to provide digital displays of the exact values in addition. The number of significant digits displayed should be in accordance with the degree of resolution with which the operator is able to control the system.

Most of the proposed solutions have digital values, to one decimal place. It is unlikely that greater resolution of display would be useful, or that greater resolution of control would be possible.

White Grid

Tufte (1983) proposed a white grid, running through the data bars as reference lines. This makes external tick marks (as are used in the existing EID display for DURESS II) unnecessary, and its proximity to the data makes them easy to compare (while increasing the data-ink ratio). However, a white grid makes the data more difficult to draw (and it looks complex), and the typically low resolution of the white grid makes it difficult to determine the exact value of the data.

The white grid is used only in Figure 1a for illustrative purposes.

Redesign of Box Plots

Simplifications of box plots which reduce non-data ink are discussed by Tufte (1983), including the use of graph axes which show the minimum and maximum data points on a graph (range frame) and sometimes mean and quartiles as well.

> *This concept was adapted for Figure 2a: lines of various gray levels on the temperature and volume plots sample their recent history, one line for each of the past 5 minutes, which gives at a glance an indication of stability (if volume and temperature have been changing, how much, and in what general direction). This feature means that even if displays are infrequently sampled, the range of their behaviour (although not the precise history) is known. If temperature has exceeded the boundaries of the acceptable region at all, it is obvious. Once temperature has remained constant, the history lines will begin to merge. Once 'steady-state' is achieved, the lines will be one.*
>
> *In Figure 2a, volume 1 is stable, while temperature has been decreasing and is now at the desired level. Volume 2 is decreasing, while temperature 2 is rising.*

Commonality

Bertin (1981) states, "Any non-differential element is useless and reduces the visibility of the image; so we should eliminate what is common to all elements" (p.228) (e.g., shifting the baseline value of a bar chart to the shortest bar height, in order to increase resolution and make use of the full scale to display variation).

There is indeed an advantage if the difference among values is most important. However, using the full scale to show differences will artificially magnify them. This is unsuitable for a bar chart, which shows absolute length. The actual values, with respect to a meaningful baseline (usually zero), are lost to perception. They can only be regained by adding the base again. If it is worth printing a graph, it is worth printing it in a large enough form that relative and absolute values can both be readily perceived, assuming both sets of information are useful.

> *Figure 1 uses the same rectangle for the control setting (indicated by the triangle pointer) and the actual flow (indicated by the black column). This increases the data-ink ratio and saves space over the existing EID display, which uses separate rectangles for controls and displays.*

VISUAL SEARCH

Rabbitt (1984) states that visual search is the active interrogation of the visual world to systematically detect patterns and decide where to look. When stimuli are presented in succession at different locations on a screen, adults of all ages can estimate the relative probabilities of stimuli occurring at different locations. However, young adults can use this information to find targets quickly at frequent locations while old adults cannot. People adapt search strategies to optimize for different situations, sometimes retrieving strategies from long-term memory.

Where background items form a pattern (showing "good figure"), subjects recognize targets quickly if they fall outside of the pattern, and more slowly if they fall within the pattern (exhibiting "good continuation").

Searching is most efficient when only one cue is needed for discriminating target items from background items. Discrimination between target and background items usually involves many different features, and generally, the larger the number of target items, the larger the number of features that must be learned and used to optimize target detection. Categorization times increase as a multiplicative function of the number of categories discriminated and the number of items within each of these categories.

People use successive, contingent scanning to improve their search. They usually recognize the category of a symbol (e.g., letter, digit) before recognizing what the symbol is specifically. The optimal sequence of contingencies is dependent upon the number of categories for each dimension, and salience of categories. Serial searching is only possible when stimulus dimensions are "separable" (e.g., shape and colour), but not if they are "integral" (e.g., hue and brightness).

People do not simply learn to perform faster using the same strategies. They actively seek out and try new strategies, continually developing new active searching techniques.

In DURESS II, the goal areas are all green, and are the only displays which are green, making that colour a salient feature for target search.

Consistent use of distinguishing colours and shapes assists visual search. Flows (mass and energy) are represented by narrow framed rectangles in Figures 1a, 1b, 2b, 3a, 3b. These are distinguishable from inventory (e.g., volume, which is represented by a wider unframed rectangle) or intrinsic properties (e.g., temperature, which has intermediate width).

The display in 2a does not have all the advantages of the DURESS II EID interface. Energy is difficult to quantitatively estimate without calculation (if this is desirable). Energy is the most salient feature, although not the most important one. However, the contributions of mass and temperature to the energy inventory are much easier to distinguish. The energy graphic actually provides redundant coding for the quantities mass and temperature.

Although it is not illustrated, the different contributors to the energy and mass balances can be easily differentiated by texture: upward diagonal shading for inflow, horizontal shading for inventory, and downward diagonal shading for outflow. This may be better than differentiating by colour, because a single unifying colour indicates that all three displays relate to the same function (e.g., mass), while the different textures visually illustrate what they represent (rising diagonals suggest rising mass, downward diagonals suggest mass falling, etc.).

The long green goal areas in Figure 2a are very easily detectable.

In Figures 1a, 1b, 3a, 3b, mass flows are grouped to assist searching.

PERCEPTUAL SEGMENTATION

Visual search can be facilitated by perceptual segmentation. This is perhaps one of the single most important principles for the design of visual forms. For an effective interface, it is important to classify elements, making the most important levels the most salient (Woods, 1990). Static elements should be the least salient. The most dynamic and the most critical elements (particularly emergent features) should be the most salient.

There are three basic steps for effective perceptual segmentation:

1. Specify data classes to be coded:
   - Unitizers (frames, windows, borders)
   - Identifiers (labels, scale values, units) and Orienters (landmarks)
   - Dynamic Data Relationships
   - Highlighting Special Interest Anomalies

2. Specify desired relative salience among these classes.
3. Specify physical coding manipulations (size, hue, intensity) that achieve the target relative salience.

The current EID DURESS II display effectively uses perceptual segmentation. The background is gray, and the static identifier displays are black, white and gray. Only the dynamic elements of the interface (pointers, bars, and relationship lines) are coloured. The system goal variables (temperature and outflow) are the only green displays.

EMERGENT FEATURES

In trying to achieve effective perceptual segmentation, the concept of emergent features can play a very important role. Emergent features are high-order relational properties of a display that emerge as a function of how the lower-level display elements are configured together. This concept has received an increasing amount of attention in the literature in recent years.

Direct Perception

Well-designed interfaces provide information and visual forms which allow the use of the efficient processes of perception and pattern recognition, rather than the cognitively intensive processes of memory, integration, and inference (Bennett & Flach, 1992). Pre-attentive processing is the immediate passive perception of information which occurs before conscious attention is given. Use of pre-attentive processing allows fast, effortless assessment of the system state.

An effective interface for a complex system requires direct perception of configural properties that map to high levels in Rasmussen's abstraction hierarchy, and elements that map to low levels (Flach & Vicente, 1989).

Separable, Integral, and Configural Stimuli

The distinction between separable, integratl, and configural stimuli originated in the experimental psychology literature but it has played a central role in visual display design research. Separable features are perceived independently. Integral features interact to yield a unitary perception, making selective attention difficult. In configural stimuli, dimensions remain separable, but their combination produces an emergent property (e.g., closure, symmetry, repetition, colinearity, curvilinearity, parallel curves, vertices) (Flach & Vicente, 1989).

Performance of feature detection for separable, integral, and configural stimuli in a variety of studies were reviewed by Bennett and Flach (1992). They found that the smallest divided attention cost was for configural stimulus dimensions. In graphic display design, separable and integral dimensions may represent idealistic end points along a continuum of configurality.

Figure 3a shows a proposed display for DURESS II with all water flow information along a common baseline. Some of the values are scaled to take advantage of the mathematical relationships between flows. This may be misleading, but the consistent use of the white grid (5 units/division) serves to remind operators of the inconsistent use of scale.

Flow bars are joined by yellow lines. If there are no faults, they form a 4-sided polygon, which uses the emergent features of colinearity. If any of the lines bend, distorting the polygon, there is a pipe leak. The location of the bend indicates the approximate location of the leak.

Expected flows defined by control settings and the mathematical constraints among them are joined by red lines. They always form a 4-sided polygon. If there are no faults, the actual flows match the expected flows, the two polygons coincide, and no red is visible. This makes fault detection easy, since the emergence of red indicates a fault (assuming perfect sensors). If a yellow vertex strays, this indicates a valve fault (leaky or stuck open).

This display allows easy detection and diagnosis of faults. It also assists the operator in setting controls appropriately (lined up). However, the use of two different scales might be confusing.

Figure 3b shows a fault condition. The top yellow line is broken, indicating a leak between VA1 and R1 or between VB1 and R1. The lower right vertex has strayed off the red, indicating a blocked valve (VB2).

Relative Salience

If the emergent features are more salient than the lower-level elements, selective attention may be impaired (Bennett & Flach, 1992). However, a display can be designed to support both divided and focused attention tasks, where an object is a set of hierarchical features (elemental, configural, and global) which vary in their relative salience. Emergent features should correspond to higher-order process constraints, so that faults result in the breaking of geometric constraints. Configural displays provide an opportunity to turn data into information by presenting data in a context that reflects process constraints.

> *Yellow , a salient colour on a dark background is used to display the emergent features in Figures 3a, 3b. Black is used for the labels and outlines, which are static, are not salient, and are not very important for fault detection.*
>
> *In Figures 1b, 2a, large green target areas are visible. The achievement of temperature is made salient by the digital marker turning green. These are critical goals and states which should be very salient.*

Polar Star

The polar star display is an octagon which uses the emergent feature of symmetry to represent the normal operation of a system based on eight state variables (Goodstein, 1981). If symmetry is lost, a fault is indicated.

> *Figure 4a shows a polar star display where the system goals for DURESS II (temperature and outflow) are met. Figure 4b shows the temperature in reservoir 1 has increased beyond the goal region.*
>
> *Figure 4c displays system constraints which hold during normal operation. Each formula is zero, so each point is at zero. If a formula becomes negative, a component is failing low and the point will move inward. If a formula becomes positive, a component is failing high and the point moves outward. Figure 4d displays a Heater 1 failure low, a Reservoir 1 leak, and a valve, VB2, stuck open.*

Constraint Violation Indicators

A fault causes a violation of one or more of the constraints that usually govern a system when it is operating normally. These constraints can be exploited even more fully than they already have been in the existing EID interface for DURESS II. The basic idea is to display both the actual and expected system state in a common, integrated form. If these coincide, then the system is probably functioning normally. If they do not, the divergence of the two display elements provides a salient emergent feature showing that the constraint in question has been violated (thereby supporting fault detection and perhaps fault diagnosis), as well as indicating how far off the actual value is from the expected (thereby supporting fault compensation as well).

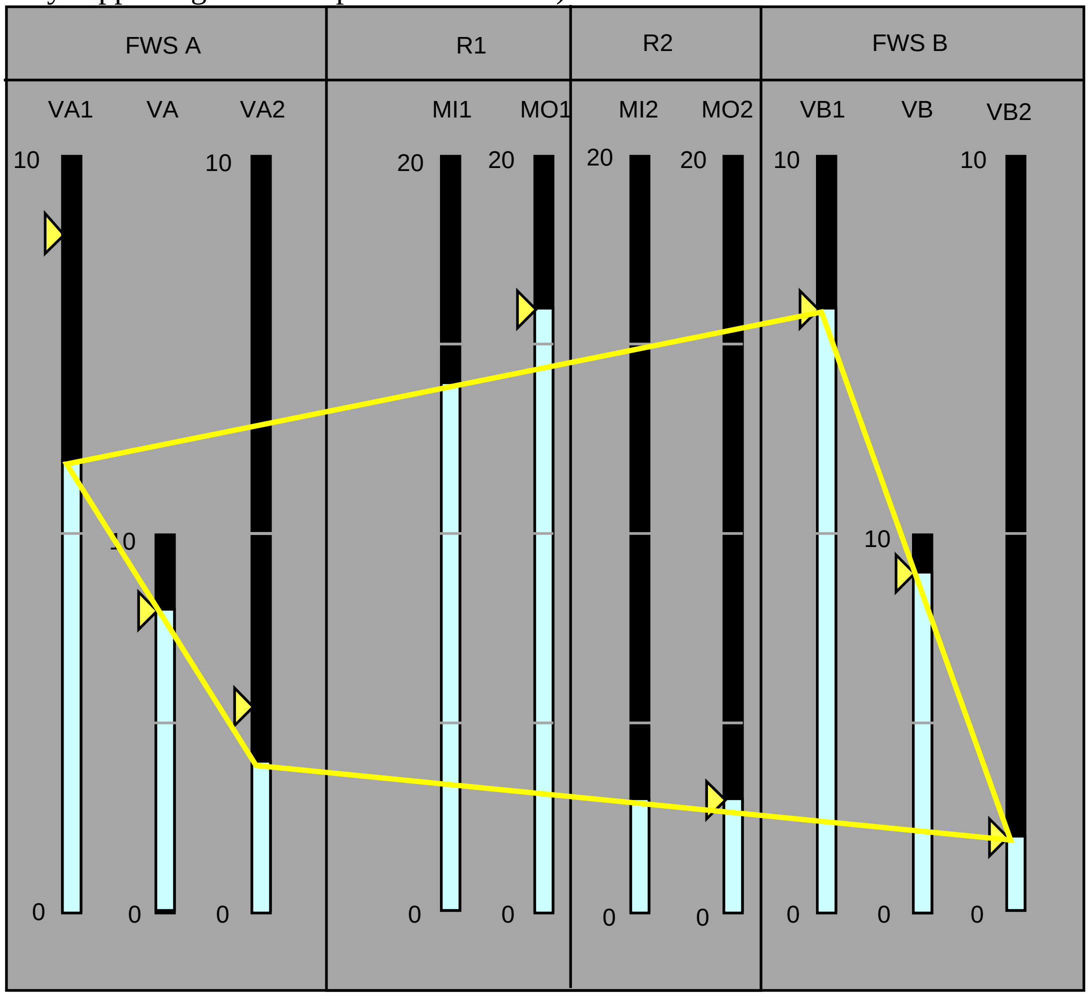


Figure 3a. The 6 inflows through the feedwater stream valves and the 2 reservoir inflows and 2 outflows are shown, arranged and scaled to take advantage of their relationships (VA = VA1 + VA2; MI1 = VA1 + VB1 ...).

These relationships produce an emergent feature, a yellow 4-sided polygon, which joins the water inflow levels.

If a side of the yellow polygon breaks, it means there is a leak after the primary or secondary valves.

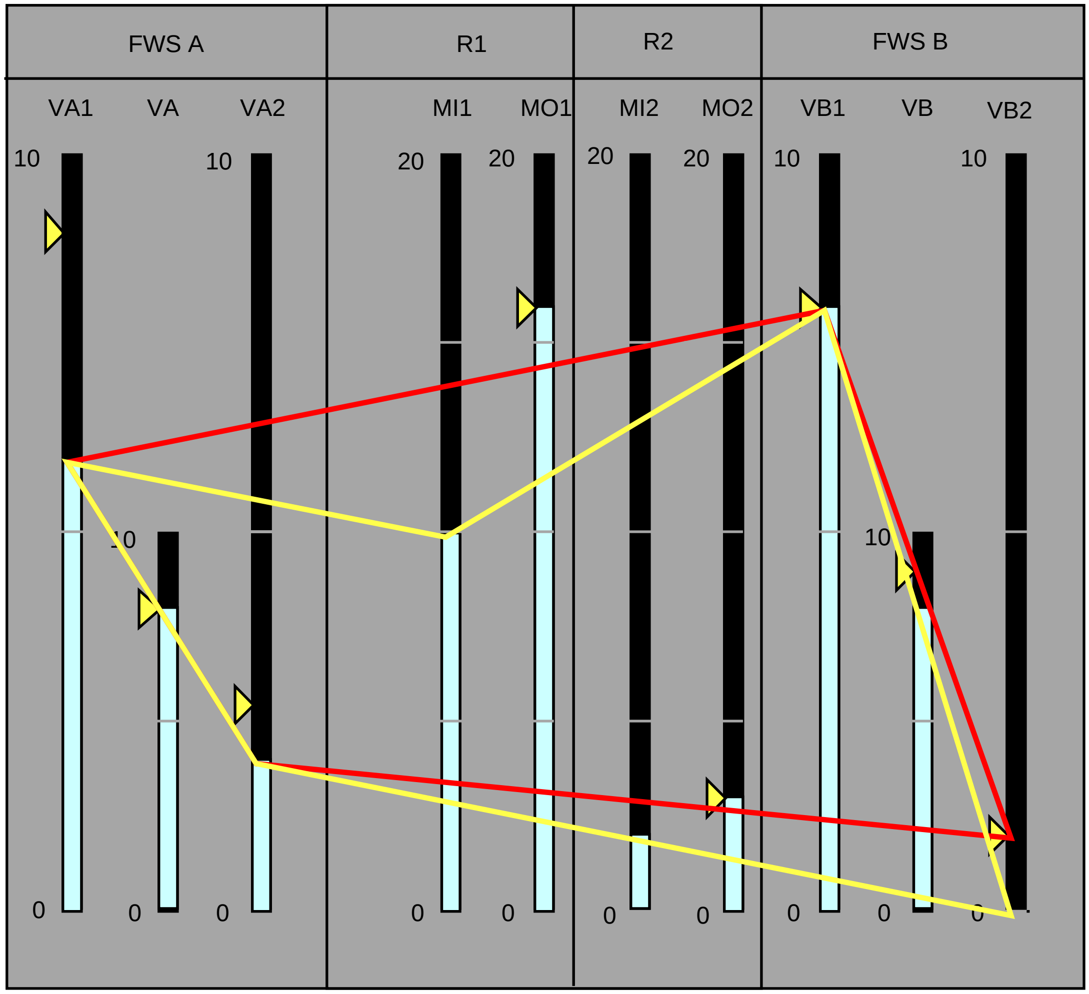


Figure 3b. Two faults have occurred.

A red polygon shows where the inflows SHOULD be, according to the control settings and the system constraints. If system status is OK, the red should be covered by yellow.

However, the yellow polygon does not coincide.

At the top, the yellow line is bent where MI1 has decreased due to a leaky pipe.

The bottom right vertex has strayed from the red, where VB2 is blocked shut.

These faults can be easily diagnosed by the shape of the polygon, and by the appearance of red from beneath.

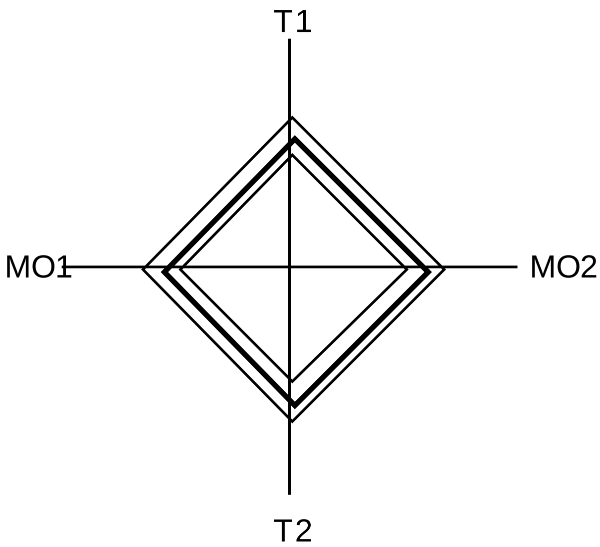


Figure 4a. Polar star display of DURESS' system goals (here satisfied).

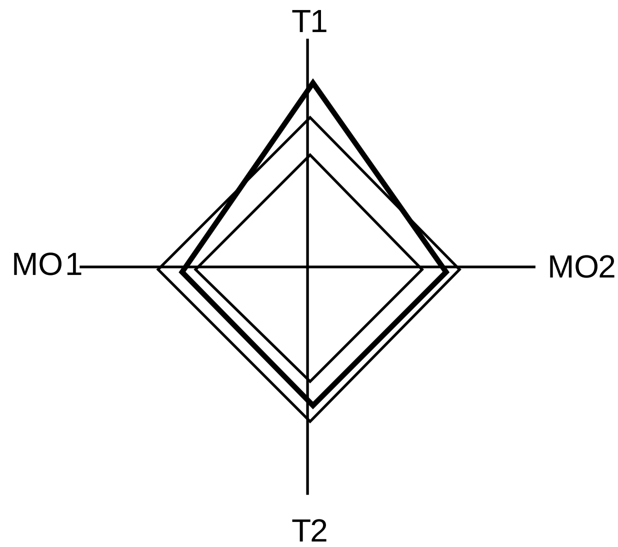


Figure 4b. Temperature goal is violated.

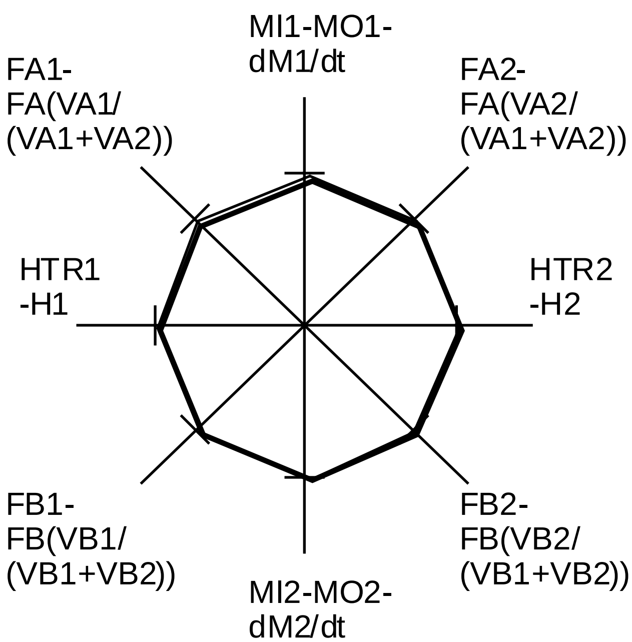


Figure 4c. System constraints. Distortion of the octogon shows Heater failures, reservoir leaks, and valve faults.

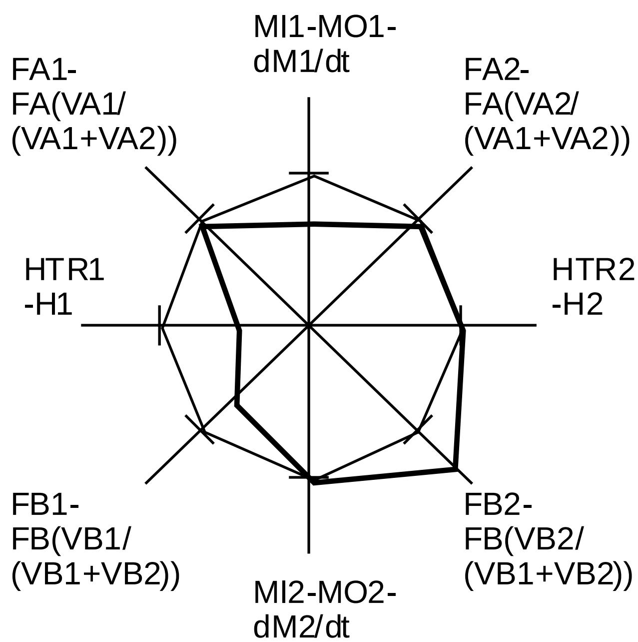


Figure 4d.
Heater 1 failure,
Reservoir 1 leak,
valve VB2 is stuck open.

The general principle is best illustrated through an example. A modified EID display for the mass balance for DURESS II is shown in Figure 5. Unlike the existing EID interface, in this modified version the current volume level is continuously being sampled to determine the actual volume gradient. This value is drawn as a dotted red line connecting the input and output flow indicators, much like the yellow line in the existing display indicating the expected volume gradient. When the system is working normally, the yellow line and red line coincide because the actual and expected system state are the same.

However, only the yellow line is visible under these conditions, since it is drawn over the red line. Thus, under normal operating conditions, this modified display looks exactly the same as the mass balance graphic designed by Vicente and Rasmussen (1990). If the mass balance constraint is violated (either because of a reservoir leak or an unaccounted for influx of fluid), the expected and actual volume gradient will not be the same. In this case, the dotted red line is drawn in such a manner as to reveal the magnitude of the unexpected influx or efflux of liquid. For instance, Figure 5 shows the modified display after a reservoir leak has occurred. Based on the sampled volume gradient and the sensed in and out flows, the display determines that the system is acting as if there is an extra outflow of a specific magnitude. This additional outflow, when added to the sensed outflow, represents the effective mass outflow. Thus, the additional efflux is displayed beside the mass output flowrate (MO1) but drawn in a salient red. This provides a very salient alarm function, indicating that a system constraint has been violated. Moreover, it provides an important aid to fault compensation. Now, all the operator has to do to stabilize the reservoir level is make the dotted red line vertical, rather than the usual procedure of making the solid yellow line vertical.

This modified EID display represents a significant improvement over the existing display. In the current EID interface for DURESS II, violation of conservation of mass must be detected by observing the mass inventory over time and comparing it to the expected gradient defined by the slope of the yellow line. This is a difficult perceptual judgement, if the yellow connecting line is not vertical. Moreover, previous experiments indicate that, in the case of a leak, subjects sometimes became fixated on the perceptual features, and did not realize that they could no longer follow the usual rule of making the yellow expected gradient line vertical, if the mass is to be stabilized (Pawlak & Vicente, 1994). The modified EID display in Figure 5 solves this problem, since there are two connecting lines when a leak (or an abnormal influx) occurs, instead of the usual one. As mentioned above, the new dotted, red line and associated red bar make a fault more salient and support fault compensation. A recent experimental evaluation revealed that this modification to the EID display improves detection times and removes the fixation problems observed with the earlier version of the display (Wang, in press).

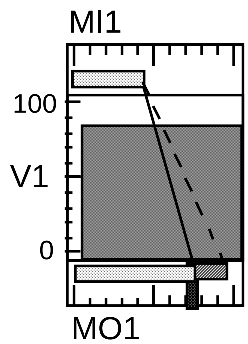


Figure 5. Modified EID Mass Balance Display for DURESS II.

Another example of this technique is shown in Figure 3b. Since the relationships between flows and controls can be somewhat complex, faults are not always obvious. However, the appearance of red (a salient colour) indicates the violation of constraints.

NOMOGRAMS

In many branches of science and engineering, nomography is a recognized means of carrying out calculations in a graphical manner. Nomographs allow complex calculations to be made quickly and accurately by relatively unskilled individuals by off-loading the computation to the nomograph designer, thereby reducing the mental burden on the nomograph user (Brodetsky, 1938).

Some of the many recent applications of nomographs include:

- -prediction of erosional corrosion
- -calculation of spur-gear mesh efficiency
- -improvement of elliptical bearing design
- -calculation of current required for longitudinal magnetization
- -optimum pipe size selection
- -prediction of phase noise under vibration
- -calculating hose pressure drop.

Douglass (1947) has identified several categories of nomographs, each of which is briefly described next.

Stationary Adjacent Scales

This is the simplest type of nomograph. One value is scaled and/or translated by a linear transformation, f(u) = a * u + b. An example is a Celsius-Fahrenheit conversion chart, where two scales share a common stem (see Figure 6a).

Simple Alignment Diagrams

For simple addition, three linear, parallel scales (U, V, W) are laid out in the order (U, W, V), where the central scale is graduated twice as closely as the other (equally graduated) scales and placed midway between them, so that a line drawn between U and V (independent variables) intersects W (dependent variable) at the value W = U + V. Examples of this are used in the display in Figures 3a and 3b, where FA = FA1 + FA2 (the three scales are ordered FA1, FA, FA2, and the central scale is graduated twice as closely) and M1 = FA1 + FB1 (the three scales are ordered FA1, M1, FB1).

Basic Parallel-Line Diagram for the Equation U + V = W

This is similar to the Simple Alignment Diagram, except that the scales for U and V may be different, and the spacings between the three scales may be unequal, to facilitate addition of numbers of different orders of magnitude.

Substitutions

Equations such as $P^2 + Q^2 = R^2$ may be solved by substituting U = P^2, V = Q^2, W = R^2, so that U + V = W. Then, appropriate scaling of the three scales will allow computation through the addition method (drawing a straight line through the three scales) to solve the quadratic equation. This is done in Figure 6b, where a straight line drawn through all three scales will give the three lengths of the sides of a right triangle.

Multiplication by the Type II Diagram

The equation f(P) * g(Q) = h(R) can be converted to the logarithmic equation log f(P) + log g(Q) + log h(R), which can be written f'(P) + g'(Q) = h'(R). Making substitutions may yield the familiar equation U + V + W. Thus, using logarithmic scales will convert a multiplication problem to an addition problem which, again, can be solved by a basic parallel-line diagram. The slide rules uses this principle.

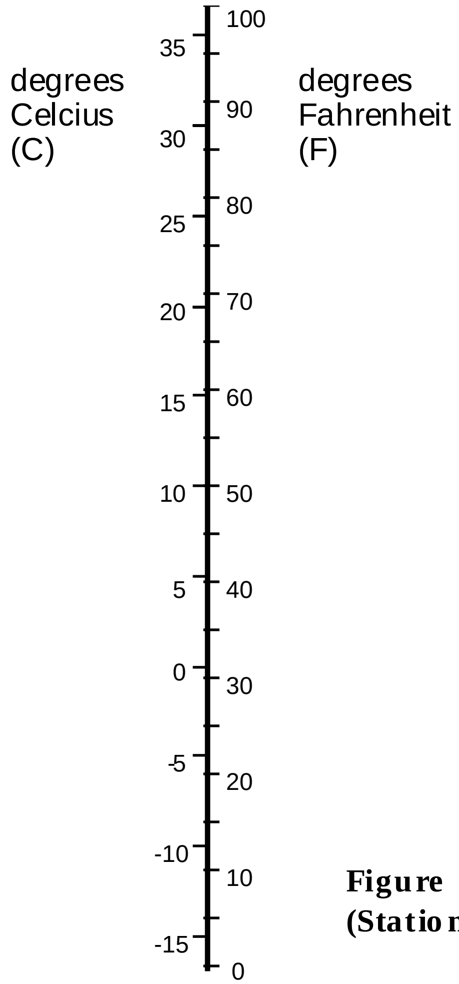


Figure 6a. Temperature Conversion Chart (Stationary Adjacent Scales Nomograph).

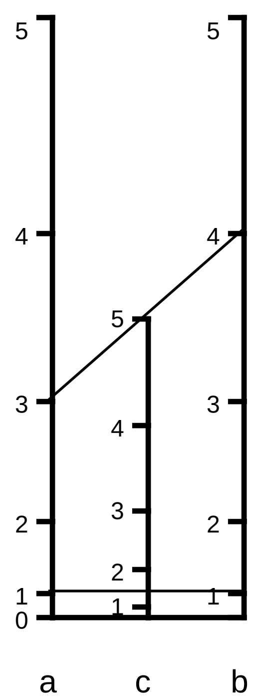


Figure 6b. Nomograph for solution of the Pythagorean theorem, $a^2 + b^2 = c^2$ (Simple Alignment Diagram with Substitutions for a, b, and c).

Nomograms

Nomograms need not always be linear. An example is the Smith chart (see Figure 7 from Smith, 1969), used in electrical engineering for functions such as waveguide phase representation, equivalent circuit representations of impedance and admittance, measurements of standing waves, and network impedance transformations (Smith, 1969.) The 'horizontal' family of curves represents resistance, while the 'vertical' family of curves represents reactance (capacitive below, inductive above). Since each scale runs from zero to infinity, any impedance can be represented. Voltage/current overlay diagrams for the Smith chart allow graphical computation of these variables. To generalize, any point in the complex plane (or in any two-dimensional space) can be represented on a circular nomograph such as the Smith chart. In additional to electromagnetic waves, other types of waves, such as acoustic, can be represented on a modified Smith chart.

Compound Alignment Diagrams

These are complex diagrams using several scales, such as the Molliere diagram used to teach thermodynamics (see Figure 8a from Wood, 1982.) The Molliere diagram is an enthalpy vs. entropy graph, but isobars, isotherms and lines of constant moisture are superimposed, so that state and phase changes in the cycle of a steam generator can be traced (Wood, 1982.) Another example of a compound alignment diagram for DURESS II is illustrated in Figure 8b. This proposed display exploits the relationship between energy, mass, and temperature.

Other types of nomograms, not reviewed here, include “two parallel lines and a slanting line”, and the “hexagonal alignment diagram” (Douglass, 1947).

Dynamic Nomographs

Although nomographs have been traditionally been designed for the static, paper medium, they can also be "brought to life" and made dynamic in the design of computer-based displays. Dynamic algebraic relationships among variables (such as linear and non-linear transformations) can be displayed geometrically via dynamic nomograms on a VDT. Such designs can illustrate how changing one variable will affect related variables, a very important consideration in NPPs.

This can be done by reflection through a diagonal, or through an xy-curve. An example is the graphic in the DURESS II EID interface relating mass inventory, energy inventory, and temperature. Other examples are found in a proposed EID interface for a system other than DURESS II, discussed next .

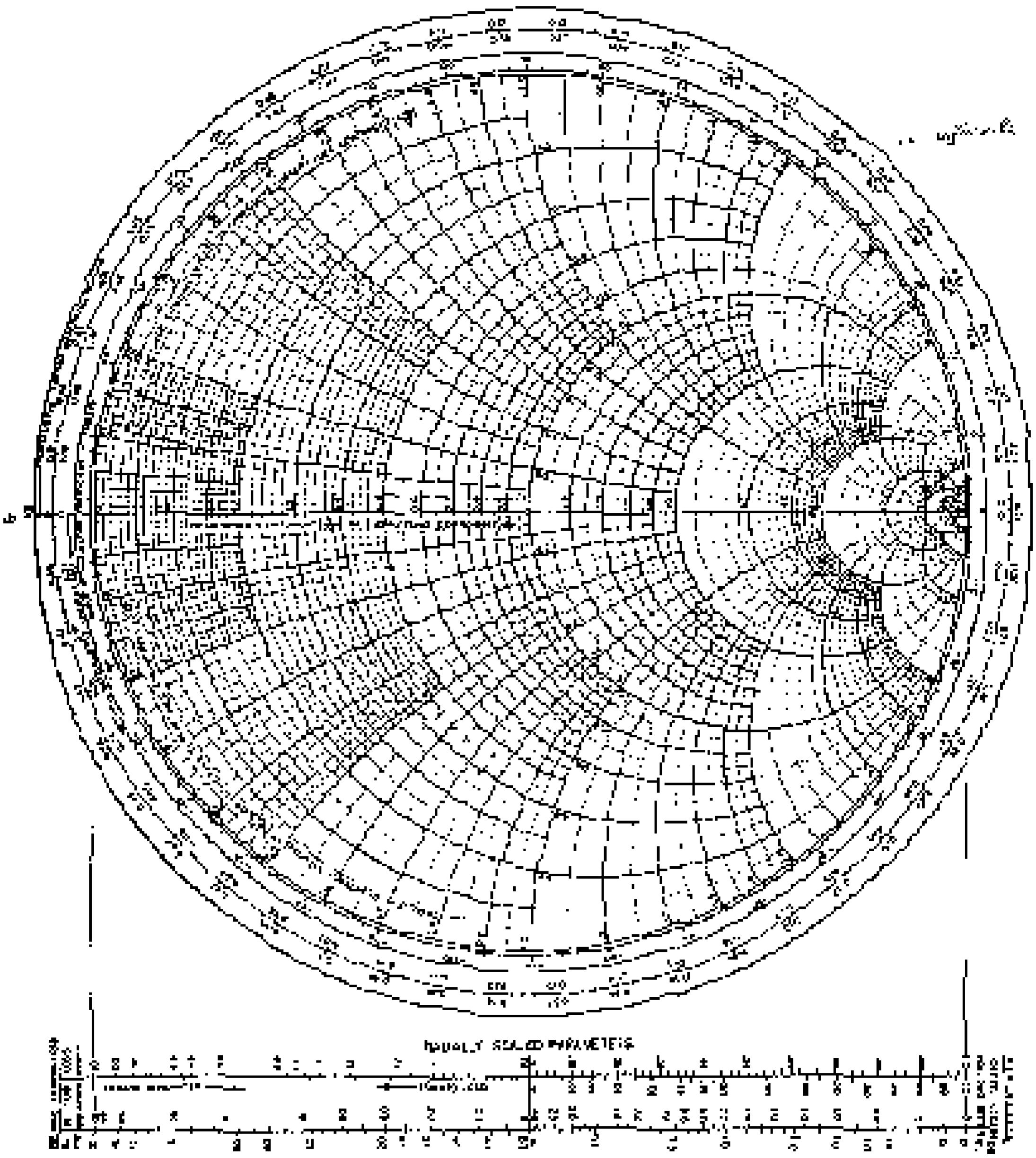


Figure 7. Smith Chart (Smith, 1969).

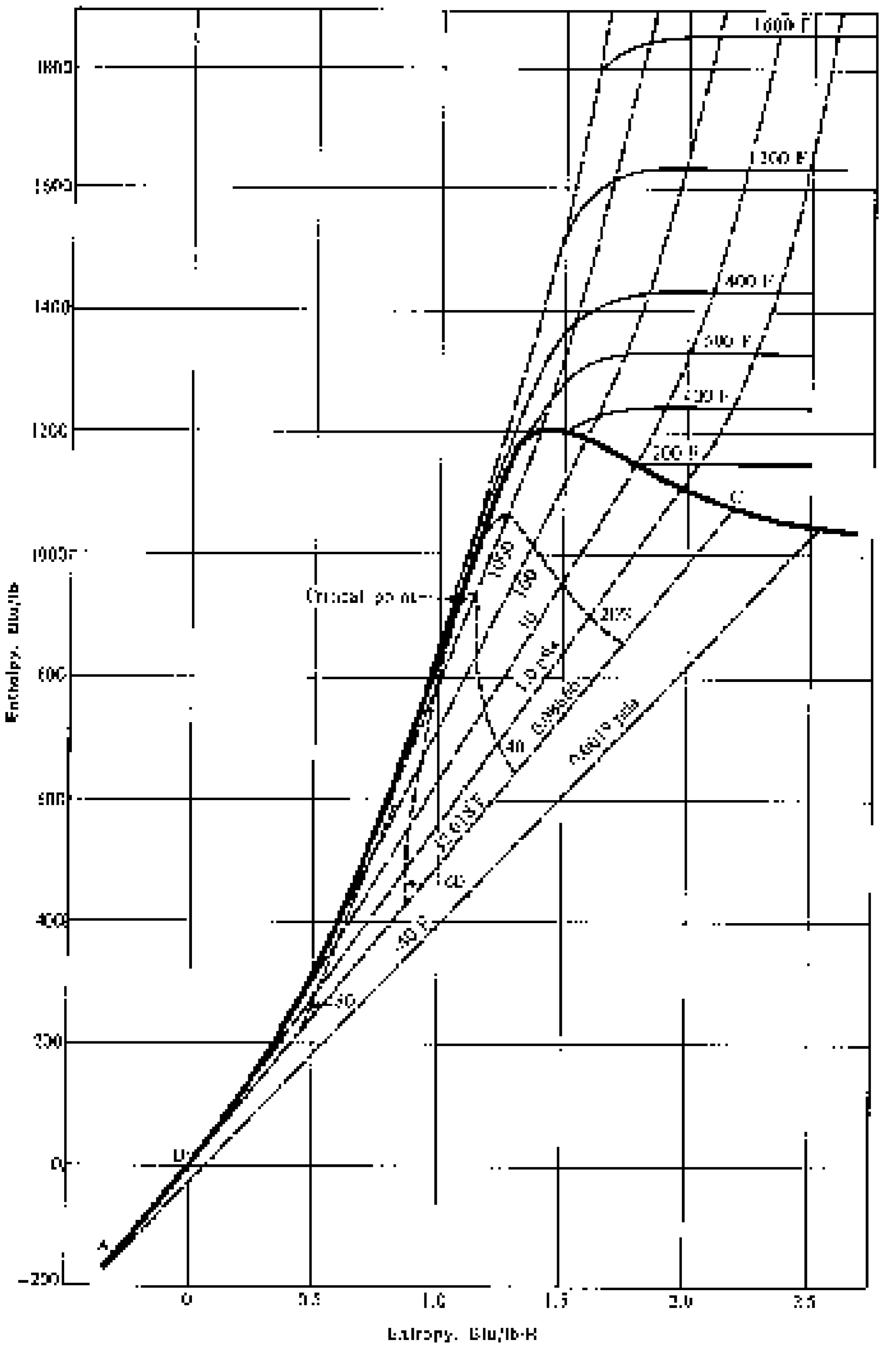


Figure 8a. Molliere Diagram (Wood, 1982).

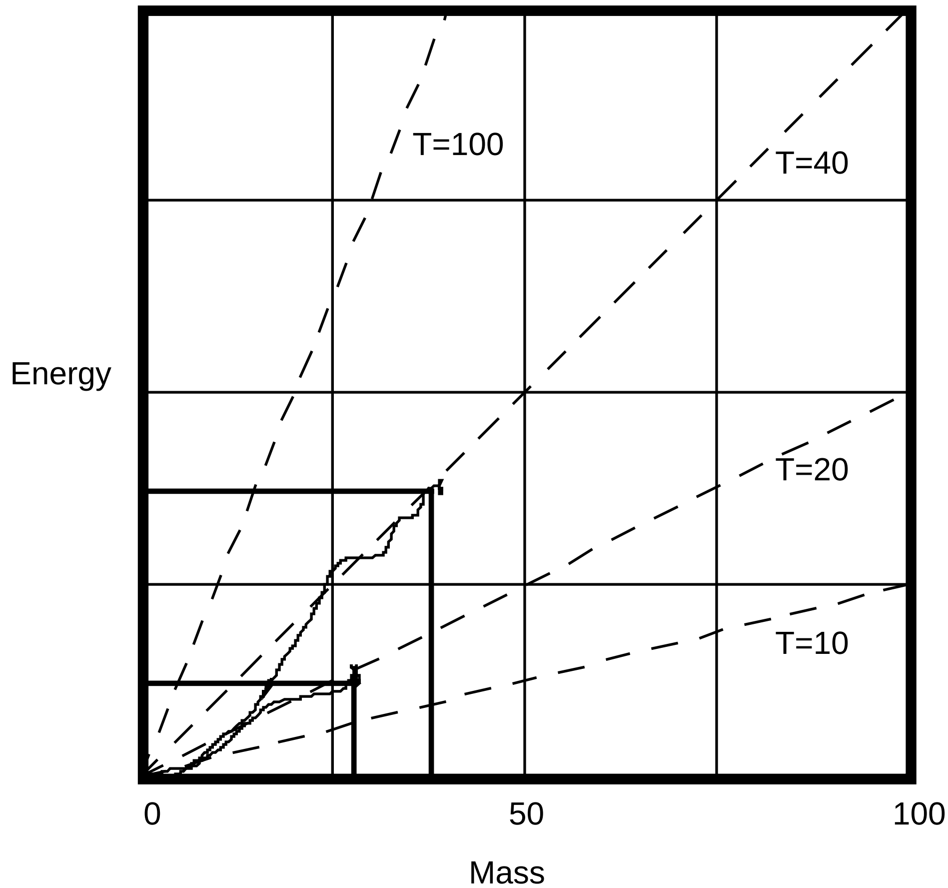


Figure 8b. DURESS Energy vs.Mass display.
This is a Compound Alignment Nomograph. Horizontal lines show constant energy, vertical lines show constant mass, and diagonal lines show constant temperature. The states of the two reservoirs are indicated by points at the intersections of the heavy lines (the 'boxes' would be different colours to differentiate them.) These must form certain shapes (a square for reservoir 1, and a l=2xh rectangle for reservoir 2) in order to reach the goal state. Simply draining a reservoir will bring its point straight back to the origin. Simply adding water (at 10C) will move the point along a path parallel to the T=10 line. Heating will move the point vertically. Since the change of state can be predicted from these actions, the operator can quickly assess which action(s) would be appropriate to yield the desired changes. An emergent feature is also created by the intersection of each 'box' with the diagonal line corresponding to its goal temperature.

MARTS EID Interface

Multivariable Apparatus for Real Time Control Studies (MARTS) (Davison, 1985) is an existing hydraulic system for studying computerized optimal control. The system, shown in Figure 9a, consists of two cylinders, each with a hole in the bottom, where it drains into a large reservoir, from which water is pumped through a valve back into the cylinder. There is also an interacting valve, with a variable setting, connecting the bottoms of the two reservoirs, so that water can flow between them. The goal is to maintain specified levels of water in each cylinder. The interacting valve setting is predetermined for each trial. The interface includes a schematic diagram of the system.

Many of the parameters and relationships in the actual system are not exactly known, so several assumptions have been made for our system, on which the interface is based.

The interface provides controls for the three valves, and shows the mass balances. The mathematical relationships among variables are shown graphically and flows are projected onto the mass balance.

While the high degree of functional interdependence of variables makes the task somewhat difficult, the visual representation of variable dynamics and relationships should facilitate attainment of the goals. A schematic diagram shows the two cylinders, each with a hole, draining water into a reservoir, which is pumped up through a valve back into the cylinder (Figure 9a). The mass balances are shown at the bottom. The maximum possible mass input is 3 kg/s (2 kg/s from the input valve, 1 kg/s from the interacting valve). The maximum possible mass output is 2 kg/s (1 kg/s to the hole, 1 kg/s to the interacting valve).

Inflow. The inflow is determined by the valve setting (VA, VB). This is projected down onto the mass balance graphic.

Outflow. The outflow is determined by the cylinder level, according to the equation:

Q = mu * A * sqrt(2gH)

mu = 0.6

A = 3.76 cm^2

g = 9.81 m/s^2

0 m <= H <= 1 m

The level (H) is reflected through a square root transformation (and scaled) to yield the outflow displayed in the mass balance graphic.

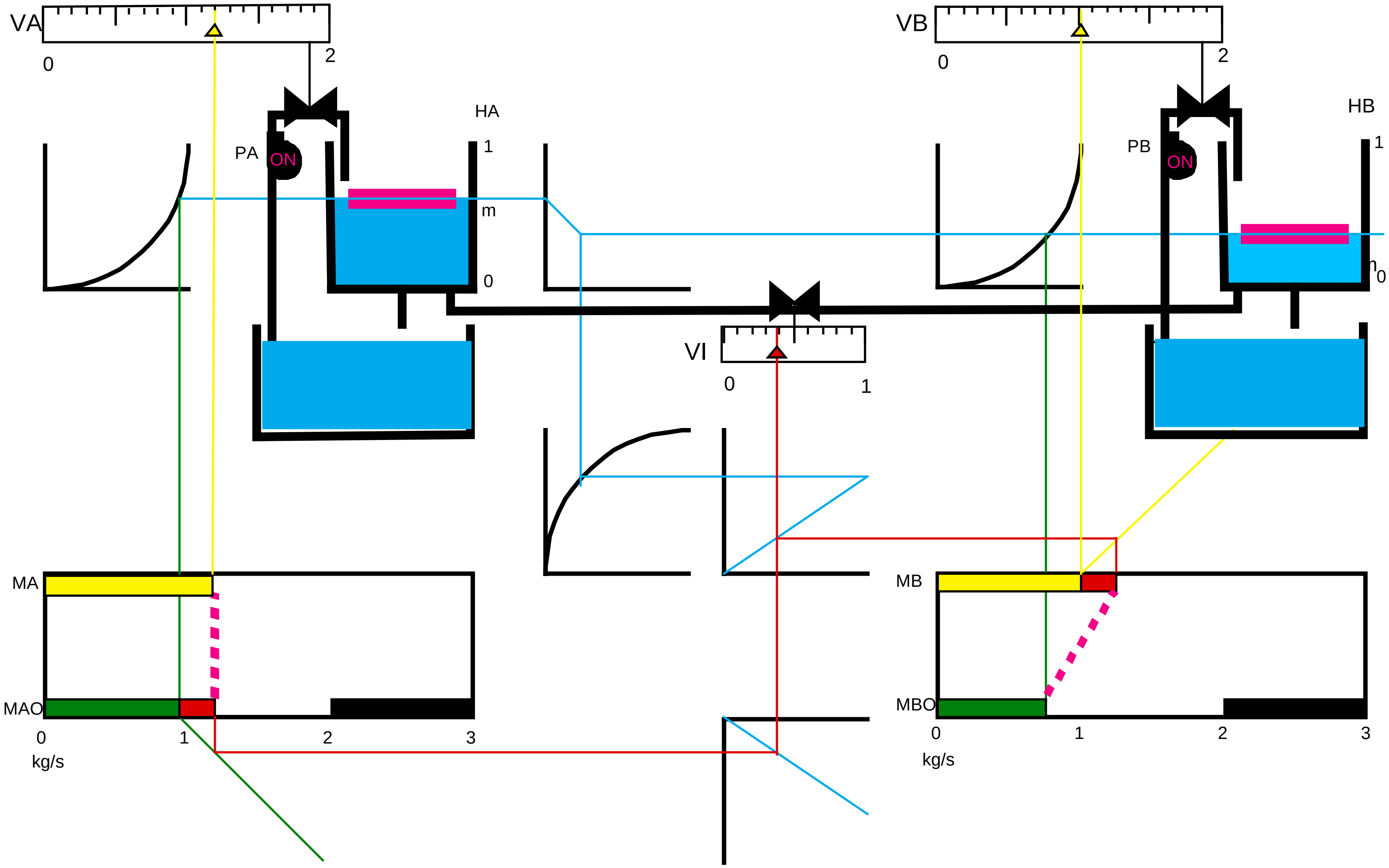


Figure 9a. MARTS Interface

Interflow. The interflow is determined by the difference between the two cylinder levels, according to the equation:

Q = VI * mu * A * sqrt(2g|HA - HB|)

0 <= VI <= 1

mu = 0.6

A = 3.76 cm^2

g = 9.81 m/s^2

0 m <= |HA - HB| <= 1 m

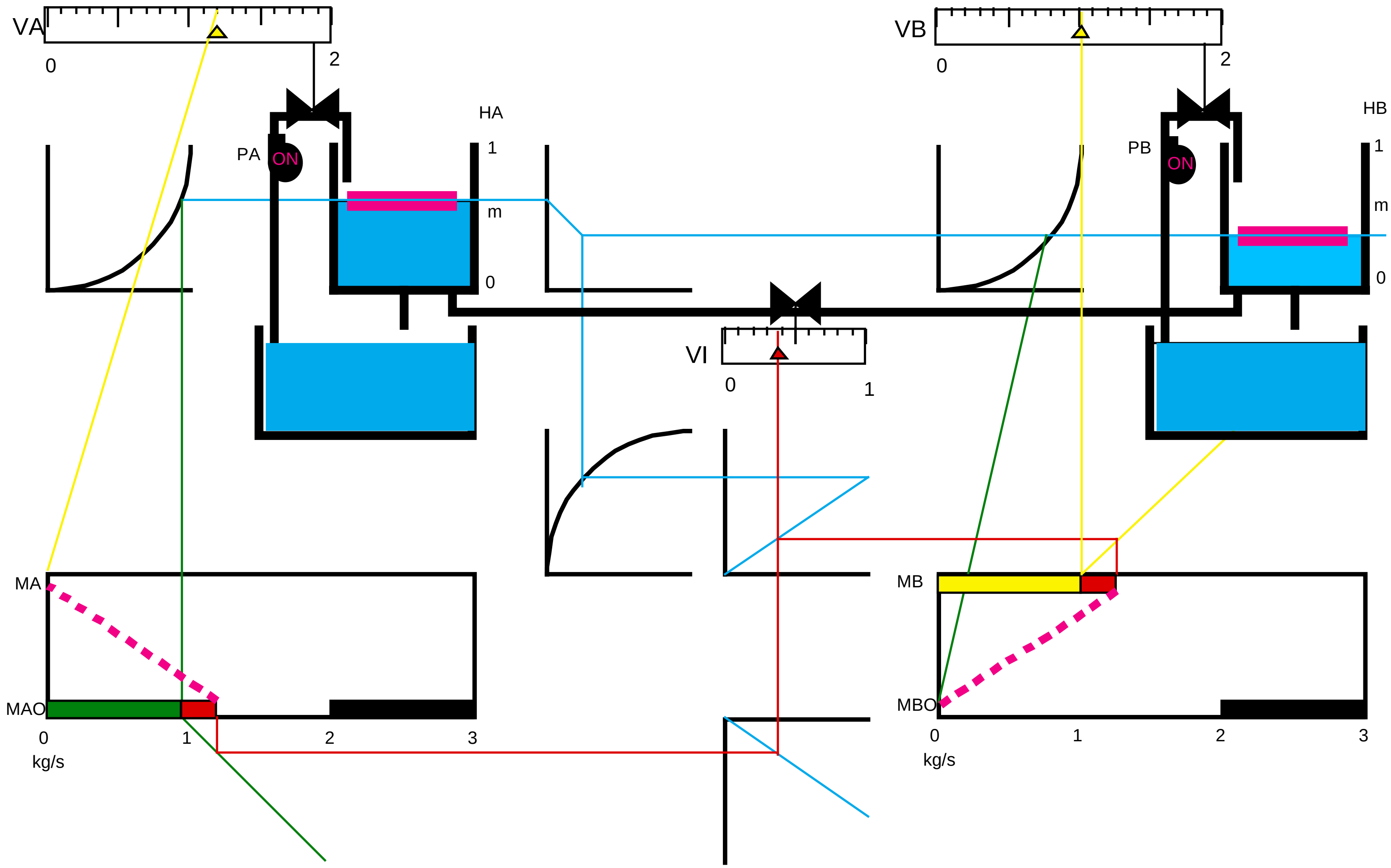
To graphically determine the interflow and project it onto the mass balance graphics in the appropriate places requires several linear and non-linear transformations.

To the right of cylinder CA is a pair of axes. Level HA intersects with the y-axis, from which a 45-degree diagonal line extends downward to intersect with the level HB line (if level HA is higher than level HA, the diagonal line flips upward). The resultant x-axis value yields the absolute value of the difference between the two levels. From there, a vertical line is (scaled and) reflected through a square root transformation (and scaled again), yielding the interflow when the interacting valve is set on maximum.As the extending horizontal line moves, it rotates a diagonal line about its origin (as in the existing EID interface for DURESS II). The interacting valve setting (vertical line) reflects off this diagonal line to yield the interflow (horizontal line). This is reflected off a 45-degree diagonal line emanating from the inflow (FB, not labeled) graphic and projected onto the mass balance MB. It is also reflected in a similar way off a 45-degree diagonal emanating from the outflow (FAO, not labeled), and projected onto the mass balance MAO. When the interflow is in the other direction, the right and left projections are reversed.

The static components of the interface are all black. The dynamic components are all colour-coded to easily distinguish inflow (yellow), outflow (green), and interflow (red). The goal regions are pink, as are the dashed mass balance lines. Water levels are blue.

When there is any kind of valve failure (blocked, stuck open), the vertical flow lines connecting the flow bars with the projected values will become diagonal, indicating the fault. When the dashed lines are vertical, cylinder levels should be stable. Otherwise, conservation of mass is violated, and a fault (reservoir leak) is indicated. Figure 9b shows Valve A blocked, hole B blocked. Since there are no redundancies, faults cannot

Figure 9b. MARTS Interface; Fault Condition.



be compensated for as in DURESS II, but detection and diagnosis are possible, leading to maintenance of the physical system.

The proposed interface is obviously very complex looking, at least initially. However, it is possible that with experience, operators would learn to "ask questions of the display". That is, with experience, operators could perhaps selectively focus in on the information they needed at the present time, and would therefore not have to process all of the visual stimuli in the display at any one time. Only a small subset would be relevant at for a given context. The research on visual attention and perceptual learning reviewed earlier suggests that this is possible. If so, the initial complexity of the display would be greatly reduced over time.

VISUAL MOMENTUM

Woods (1984) defines the concept of visual momentum as follows:
"The amount of visual momentum supported by a display system is inversely proportional to the mental effort required to place a new display into the context of the total data base and the user's information needs. When visual momentum is high, there is an impetus or continuity across successive views which supports the rapid comprehension of data following the transition to a new display." Poor visual momentum results in the "Keyhole" effect (a restricted view of the process; loss of context), and the "Getting Lost" effect (inability to navigate easily within the environment). Previous research has shown that a number of display design techniques (e.g., providing a map or an overview of a workspace) can improve visual momentum (Vicente & Williges, 1988). How can these ideas be applied to NPPs?

Integrated Display Sets

To develop a set of displays for a large-scale process such as a NPP, it is useful to consider the system as a hierarchical collection of subprocesses coupled together in a coordinated fashion (Goodstein, 1982). Any main process requires successful operation of several lower sub-processes, which in turn requires successful operation of sub-sub-processes of the next level down. In order to trace processes through various levels, functional relationships should be revealed through a series of nested display windows:
Window 1 (WHY) - Interface to Process

- Adequacy of delivered function can be judged against higher requirements.
- Effect of deviations on higher processes, alternate possibilities for recovery from disturbances.

Window 2 (WHAT) - Causal Structure

- Subprocess structure and state.
- Condition identification.

Window 3 - Control System

- Web of interrelated constraints which restrict process behaviour to an allowable region compatible with higher level requirements.

Window 4 - (HOW) Configuration Info, Diagram Level

- Physical connections (prescribed, actual, and alternate).
- Actual vs. target states.
- Equipment capability and limitations.
- Procedures and checklists at equipment level.

Windows 5,6 - Procedural Support for Rule-Based Tasks.

Functional array and dynamic flow map. A functional array (Goodstein, Hedegård, Højberg, & Lind, 1984) gives an overview of a system, while a dynamic flow map zooms in on a (sub)process, giving a more detailed display.

The functional array display highlights the position of the process currently displayed (avoiding "getting lost"), as well as functional links with other subprocesses (avoiding the "keyhole" effect).

Alarms. The functional array can also highlight those (sub)processes which are ailing, so that the operator has an overview of all alarming processes and their functional relationships (Goodstein, 1985).

JAERI III: PROPOSED EXPERIMENT

Out of all of the design principles reviewed in this report, visual momentum seems to be the most appropriate to evaluate in the next year of the research program. There are several reasons for this. First, in designing computer-based interfaces for NPPs, hundreds or even thousands of process views must be generated because of the sheer size of the plant. However, these displays can only be displayed on a very small number of viewports, making display navigation a very significant issue. This is in stark contrast to the existing EID interface for DURESS II, which represents the entire system at all levels of abstraction in just one integrated display page. As a result, visual momentum has not been a factor in previous research on DURESS II. Second, despite the importance of the concept, very little empirical research has been done on visual momentum in NPP control rooms. Although several different approaches to the navigation problem have been proposed (Vicente, 1992), empirical evaluations of these design proposals are hard to come by. Third, as will be shown below, the DURESS II simulation can be readily adapted to empirically investigate factors impacting visual momentum. The goal of the proposed study is to provide insights into how information should be organized and divided among process views in a way which facilitates navigation through the database.

One way to achieve this goal would be to develop two interfaces which, based on theoretical reasons, would be expected to lead to differing levels of visual momentum. If the experimental results were consistent with the theoretical predictions, then the practical utility of the visual momentum concept could be said to be supported. However, because of the lack of research in this area, we have decided to adopt a different approach. Rather than comparing an interface with "good" visual momentum against a baseline interface, we have decided instead to investigate the conditions under which operators consult different types of information and how operators transition between different displays. A natural way to do this is to divide the content in the current EID interface for DURESS II into four displays, each representing a level in the abstraction hierarchy. By only allowing operators to view one level at a time, one can determine when and why operators consult specific levels of abstraction, as well as what levels they tend to transition between frequently. Such information would be very valuable since it would provide insight into how interfaces should be constructed to minimize the complexity associated information search behaviour, thereby improving visual momentum. Despite the apparent value of such a study, as far as we know, no experiment of this kind has ever been conducted.

A preliminary design of the multilevel EID interface for DURESS II is presented in Figure 10. There are four different process views, which can only be viewed serially (i.e., one at a time). A control panel with 4 buttons will be provided to allow subjects to select one of the displays. Subjects will be allowed to transition to any display at any point.

<u>Physical Function</u> (Figure 10a)

This level displays reservoir states (volume, temperature) and control settings (for valves and heaters). This is the only process view where there are controls which can be manipulated. This level is also useful for checking violation of physical constraints, i.e., blow-ups (boiling over, reservoir heated empty, etc.)

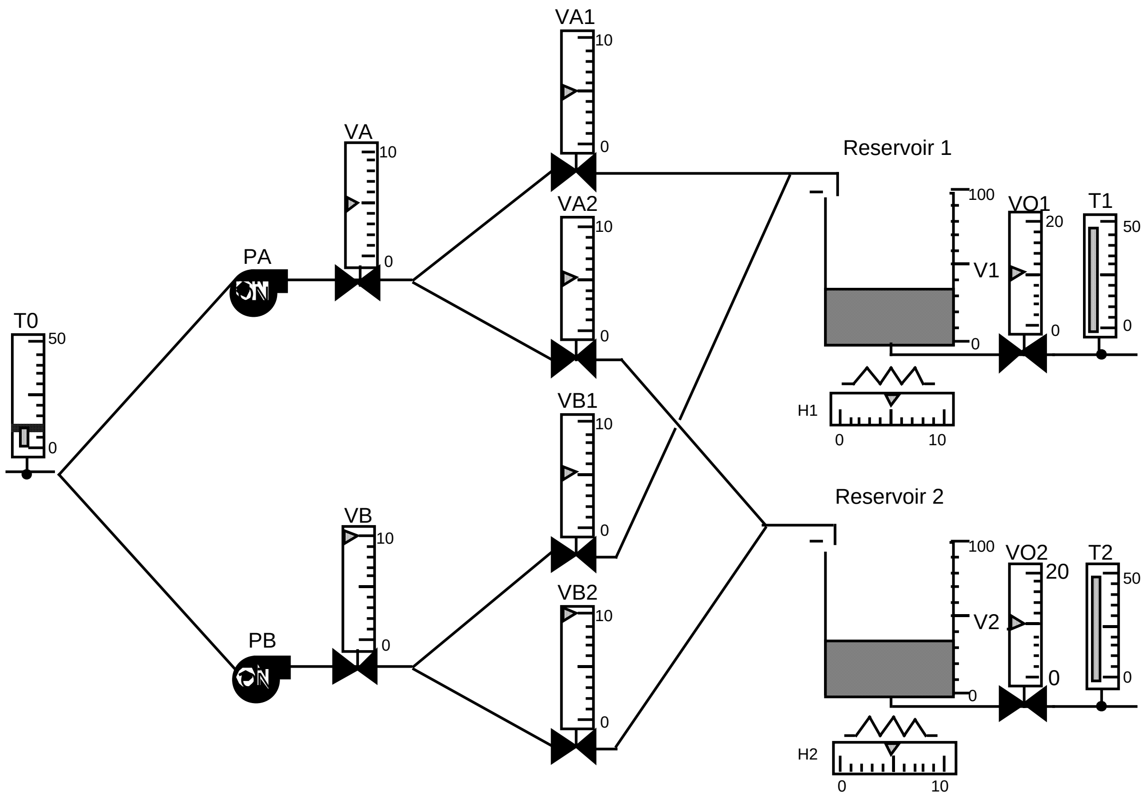


Figure 10a. DURESS Divided EID - Physical Function.

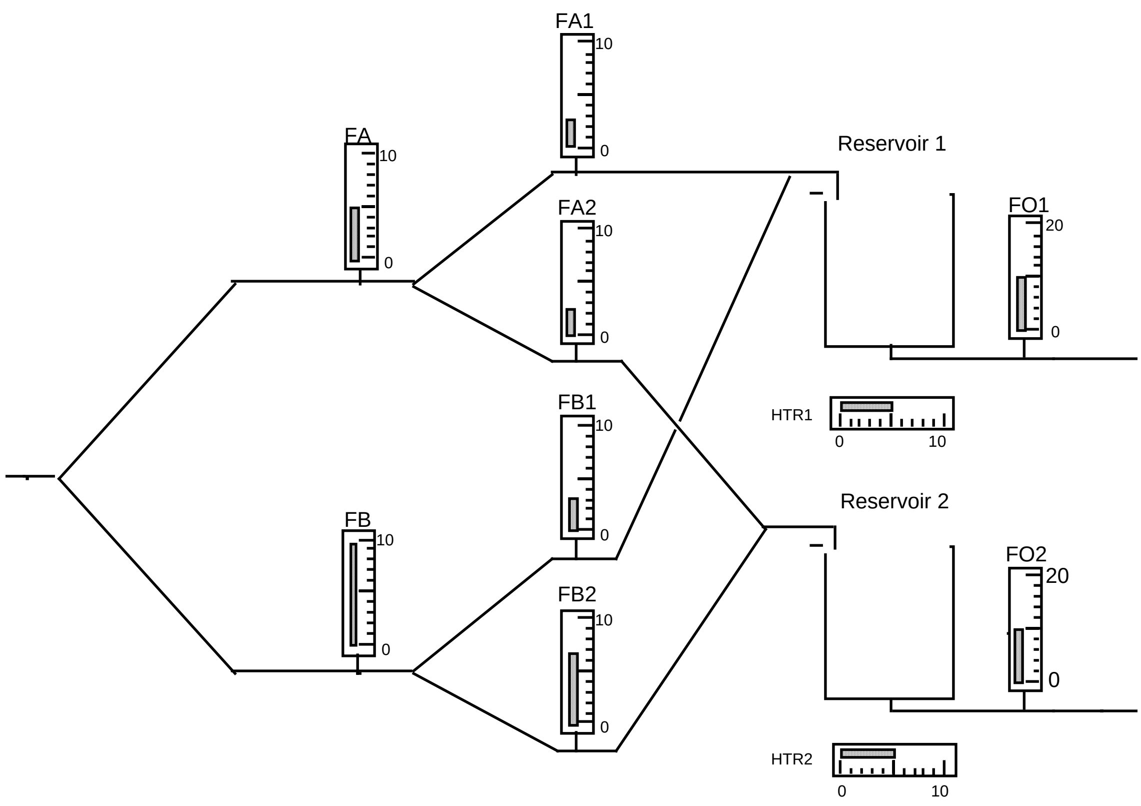
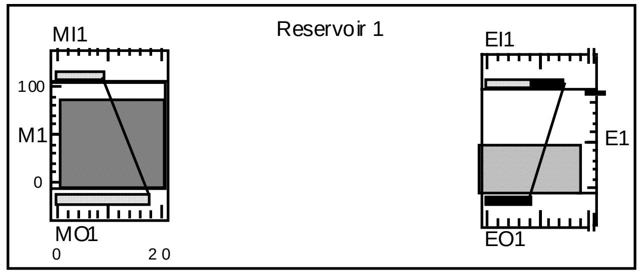


Figure 10b. DURESS Divided EID - Generalized Function.



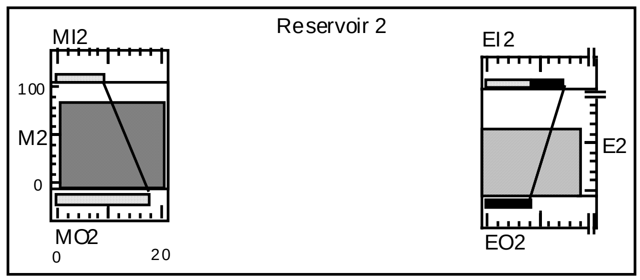


Figure 10c. DURESS Divided EID - Abstract Function.

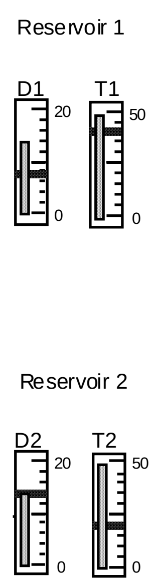


Figure 10d. DURESS Divided EID - Functional Purpose.

Generalized Function (Figure 10b)

This second level displays water flows and heat transfer rates. This information is useful for comparing settings (from Physical Function) with actual flows.

Abstract Function (Figure 10c)

This third level displays mass and energy balances. The level is useful for checking violation of constraints such as the laws of conservation of mass and energy.

Functional Purpose (Figure 10d)

The final level displays demand and temperature goals (along with the current outflows and temperatures). This level is useful for monitoring the current state, compared with the goal state.

Discussion

Performance on the multilevel EID interface will be compared to that on the existing EID interface (Figure 0) under a variety of operating conditions, including both normal and fault scenarios. The experiment will be conducted using methods similar to those used in the experiment conducted in the first two years of the research program (see volume 2 of this report and Christoffersen et al., 1994).

Of major interest is how much time is spent viewing each level. One could expect that at the beginning, the operator would spend most of the time looking at Physical Function, since the controls are there (and several manipulations will be required early on to achieve the goal state), and the state feedback would indicate how near the system is to its goal state (Functional Purposes needs to be checked only briefly, since they will not change during a trial).

Once the goal state is reached and the energy and mass balances are steady, we may predict that the operator will monitor only Functional Purposes, since it provides an uncluttered display with only crucial information, making it easy to detect if the goal state is violated.

If a fault occurs, we would expect the operator to shift down to Abstract Function to see whether the laws of conservation are holding, and then to Generalized Function, to determine which component is responsible for the fault. It will likely be necessary to shift to Physical Function in order to compare settings with flows, and it will always be necessary to shift to Physical Function in order to compensate.

However, it is possible to shift directly from Functional Purposes to Physical Function, and to compensate for the fault, without ever using Abstract Function or

Generalized Function. It is also possible to glance at Functional Purposes, memorize the values, and spend the rest of the trial monitoring Physical Function until steady-state is reached, even if faults occur. Operators may potentially use various strategies, depending on what they consider the most useful information at any point in time.

The amount of time spent observing each level will be studied, as well as when and where transitions between levels occur. These will likely change as the trial proceeds, as the subject gains experience, and when faults occur. As mentioned earlier, no experiment of this type has ever been conducted, so the results are bound to be of practical value.

RECOMMENDATIONS

The recommendations for designing good visual forms that emerged from this literature review are as follows.

1. Effective interface design depends on presentation of relevant information at all levels of abstraction.
2. Non-data ink (providing redundant or useless information) should be minimized, to reduce distraction by meaningless features.
3. Position along a common baseline allows the most accurate comparison of quantified graphical data. Digital values can be added for precise reading.
4. Efficient target search is facilitated when a small set of distinguishing features characterizes target items, displayed on a well-structured background. Variables which are related should have common features to indicate similarities, but also distinguishable features to show their differences. Features include shape and size, colour, texture, location, etc. When possible, features should have a logical semantic link to what they represent (e.g., red means heat or danger). This can assist target search and reduce confusability between some elements while showing relationships among others.
5. Perceptual segmentation requires elements to be categorized and organized according to functional groupings and hierarchical levels of abstraction, through use of unitizers, relative salience, and emergent features. Static features should be the least salient. Emergent features (symmetry, repetition, co-linearity, etc.) should be most salient, and mapped onto higher-order system properties, so that destruction of an emergent feature indicates violation of a system constraint. It should be obvious whether system goals are being satisfied. This information should be the most salient, and make use of emergent features and pre-attentive processing.

6. While past research has concentrated on display syntax (visual form), future research should focus on display semantics (representational form). Various flow information groupings were proposed. All of these groupings may help to sort, locate, and extract information. The arrangements of the displays are different from the actual physical arrangement of the components, which could cause confusion. One could compare operator performance using various groupings to determine the most appropriate one.
7. Nomograms are useful for making graphical calculations in many domains. These ideas can also be used in dynamic interfaces.
8. Where the process view is larger than the viewport, visual momentum can be improved through use of an overview.

Each of these abstract principles was illustrated by one or more concrete design examples. These display examples can serve as a source of inspiration for the design of novel displays for NPP control rooms (cf. Rasmussen et al., 1994). Some of the examples could be used to motivate future experiments whose purpose would be to further the current understanding of what visual forms can lead to more effective operator performance.

The principle of visual momentum was identified as the visual form topic that is most promising for immediate evaluation. An experiment investigating this important design principle was proposed for the third year of this research program.

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