The Manager as a System's Controller: An Application of Management Systems Engineering Concepts

by

João Pedro M. Mendes

Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy
in
Industrial and Systems Engineering

APPROVED:

Harold A. Kurstedt Jr., Chairman

William L. Conger (ChE)

C. Patrick Koelling (ISE)

Steven E. Markham

Steven E. Markham (MGT)

John W. Roach

John W. Roach (CS)

Konstantinos P. Triantis

Konstantinos P. Triantis (ISE)

Hugh F. VanLandingham (EE)

September, 1990
Blacksburg, Virginia

Preface

Going back to school after fifteen years in the ″real-world″ is not easy. But I was lucky for two reasons. The first reason is that I had a chance to work with Management Systems Laboratories. They′re nice people. I regret I cannot refer to all of them. Martin Jones and Kwang Lee stand apart. The Baldwins, Adam and David, helped me assemble my computer. George Ruberg and Andrew Walker taught me a lot about emergency management. Lou Middleman was always eager to help and, *In Short,* did so. From Graduate School, Bernard LaBerge was very helpful without me needing to ask. I′m thankful to all. And to the kindness of Rebecca Wight, who left us too soon. I dedicate this work to her memory.

The other reason I was lucky, and the reason I got to MSL, is that I met Harold Kurstedt. I always received good advice from him and he has helped me personally and academically above and beyond his obligations. I say this not because he was my chairman, God knows he did his best to avoid that. In a way Harold is unique. As an intuitive he can grasp what we hesitantly try to communicate. At the same time, he has the gift to make us *understand* what we think we know. For example, Richard P. Feynman said:

> What is it about nature that lets this happen, that it is possible to guess from one part what the rest is going to do? That is an unscientific question: I do not know how to answer it, and therefore I am going to give an unscientific answer. I think it is because nature has a simplicity and therefore a great beauty.

Harold straightforwardly says "Mother Nature is consistent." I particularly like this simple statement because I always enjoyed putting together apparently unrelated things. Harold encouraged that and supported me in gathering my committee. I was also lucky here. I found the most sympathizing committee I could possibly hope for.

The conceptual foundation for this research is the following:

Question: Can we apply engineering methods to management?

Purpose: To help management evolve from an art to a science.

Objective: To demonstrate the use of standard engineering techniques to solve management problems.

Method:
- Development of a mathematical model of a management system,
- Prediction of performance results using the model, and
- Comparison of predictions with actual data.

This document is organized in six chapters. The first chapter presents the research domain and includes the problem, the objectives, the hypotheses, the delimitations and assumptions, and the importance of this research. The second chapter reviews the literature. The third chapter presents the methodology, including a description of the variables. The fourth chapter presents the data manipulation operations. The fifth chapter presents the mathematical model. And the sixth chapter presents the treatment of the data and the results, along with a critique and recommendations for further research.

Because this document reflects the contributions of my committee members, I like to see it more as a team rather than as an individual effort. The pronoun *we* refers to the researchers, not to the scientific community.

The Manager as a System's Controller: An Application of Management Systems Engineering Concepts

by

João Pedro M. Mendes
Harold A. Kurstedt Jr., Chairman
Industrial and Systems Engineering

(ABSTRACT)

This research is about technology transfer from engineering to management. According to Kerlinger's (1979) terminology, most practical management problems are formulated as engineering problems. So, it is legitimate to adapt general engineering techniques to solve those problems. In *Industrial Dynamics*, Forrester (1961) says "the practice of medicine or of engineering began as an empirical art representing only the exercise of judgment based on experience. The development of the underlying sciences was motivated by the need to understand better the foundation on which the art is rested." Engineering evolved from an art after practitioners applied relationships explained by basic laws of nature. Engineers design[1] and predict the performance of the systems they work with. At most, managers hope for acceptable performance; management is still much an art, whose practitioners study relationships based on data and observation. Therefore, the objective of this research is twofold:

- to establish the groundwork for a discipline of management systems engineering, and
- to provide one example of its application.

A management system is any organizational position, its scope of authority, and its management tools. The Management System Model (MSM) describes a management system as the interaction between the manager, the operation, and the management tools (Kurstedt, Mendes, & Lee, 1988). Management systems engineering involves the specification, design, implementation and mainte-

---

[1] Engineers use the word design in its broadest sense of product design and improvement.

nance of management systems. The specification of a management system identifies the required performance characteristics in response to given events. The design is the prediction, with the aid of mathematical models, of the actual responses (outputs) to those events (inputs). The conceptual part of this research involves the development of mathematical models as fundamental tools to specify and design engineering systems. One significant contribution is the development of the conceptual framework and the demonstration of a quantitative analog for the MSM.

The applied part of this research draws upon an emergency exercise in an industrial plant (the United States Department of Energy's Feed Materials Production Center at Fernald, Ohio). An emergency is any event that threatens the integrity of people, environment, or assets. In the context of this research, emergency response is the set of actions required to neutralize or reduce the effects of the threatening event. An emergency exercise is the live simulation of the response to a dangerous situation in an industrial setting. The management system is composed of the plant management, the industrial plant where a simulated accident occurs, and the management tools used during the emergency. Specifically, the objective of the applied part is to show we can use a mathematical model to describe the dynamics of the emergency management system and make short-term predictions.

The mathematical model is a control theory-based system estimator. The data to compare the model against is time series data generated from information portrayed to the plant management during the unfolding of the exercise. Therefore, this research describes a longitudinal study. The similarity between the data and the model results is apparent in graphical representations and statistically demonstrated through spectral cross-correlation analysis. So, another significant contribution is revitalizing the formal application of control theory to the study of management situations.

Table of Contents

List of Illustrations

List of Tables

The research domain

This is an introductory chapter to put this research in perspective. After explaining the problem and stating the hypothesis, we discuss the type of research, its contribution to the field of management systems engineering, and its significance.

The problem statement

This research is a step toward the development of a discipline of management systems engineering. The ultimate goal of such a discipline is to provide the means to come up with management systems designed to meet specifications. By definition, *the specification of a management system identifies desired performance characteristics when the system responds to external events.* The specification tells what may happen, not how it will happen; we can write performance standards for coping with an emergency, yet ignore how to handle it. Later, at the design stage, we study different alternatives to put together the components of the management system.

A dictionary definition of design is ″to plan the form and structure of.″ Now, how does this apply to a management system? Looking further in the dictionary, we find that plan ″refers to any method of thinking out acts and purposes beforehand," whereas design "suggests art, dexterity, or craft... in the elaboration or execution of a plan, and often tends to emphasize the purpose in view." The purpose of a management system is to provide direction to and maintain control over an operation. So, we may conclude:

Definition: *to design a management system is to think out beforehand the acts required to provide direction to, and maintain control over an operation.*

Control theory gives meaning to the expressions "provide direction" and "maintain control." To provide direction is to regulate, to obtain a desired value for the operation's output; the desired value is the reference input — the external input to the manager. To maintain control is to produce the desired outputs despite environmental variations, to reject disturbances — the external inputs to the operation. Using mathematical control theory as a design tool provides a way to predict, to know beforehand the system's reactions to different kinds of (potential) inputs.

The Management System Model (MSM) has been the conceptual support for several years of research at Management Systems Laboratories (MSL). Nevertheless, despite its extensive theoretical background, simplicity, and intuitive appeal, the MSM has never been (1) formally tested and (2) used to make predictions (Kurstedt, Mendes, & Lee, 1988). This research attempts to find a testing mechanism for the MSM and make it predictable. More precisely, the problem this research proposes to solve is *to provide an algorithm to predict the output of a particular management system, given the description of a task environment traditionally considered unstructured.*

According to the MSM, a management system describes (1) a delimited set of responsibilities assigned to an organizational position with a person in charge (manager), (2) an identifiable scope of authority (operation), and (3) a set of management tools. We will see later what the output of a management system is, but it is different from the output of an operation. An unstructured task environment is a situation where it is difficult to assess the impact of decisions.

Emergency management is an example of an unstructured task environment. Incidentally, the purpose of the emergency management work performed by MSL is to provide some structure to that environment. An emergency calls for accurate decisions and timely actions. After recognizing that an abnormal event cannot be immediately neutralized, the first tasks are to assess and classify the occurrence. A fast and accurate classification is fundamental to notify the right people and mobilize the means to protect the safety and health of the plant employees and off-site population. Next to protecting people comes protecting the environment and the plant processes, property, and inventories. Acting late may lead to harmful consequences, yet acting prematurely may be a waste of resources or cause unnecessary disruption.

This research will focus on predicting the behavior of an emergency management system. Therefore, the research problem is restated as *showing how a control theory analog of the Management System Model can be used to predict the behavior of a management system.*

The subproblems

Useful management tools convey the information needed to determine what decision to make and when to take the corresponding action. When a disturbance affects the operation, the information takes time to reach the manager due to delays caused by the measurements and the management tools.[2] Then, how fast the operation responds to the manager's control action depends on the operation's dynamics.

Solving the research problem helps us understand the relationship between the operation's dynamics and its management. The solution depends on solving the following three subproblems:

---

[2] Management tools include organizational structure, culture, MIS, and other mechanisms converting data into information for the manager.

- The **first subproblem** consists of determining the variable or variables the manager uses to monitor and control the situation; this corresponds to checking the management tools with respect to the information they do or do not convey and determining the influence of the manager over the unfolding of the events.
- The **second subproblem** consists of describing an emergency situation mathematically; this corresponds to developing a mathematical model for the abnormal event and its control. This sub-problem is related to the previous one, because the mathematical model requires the definition of variables.
- The **third subproblem** consists of predicting the time necessary to respond to the emergency (reject the disturbance); this corresponds to gathering data, running the control model, and having its output track the management system's output.

The hypothesis

This research is strongly influenced by Platt (1964). Roughly speaking, his point is that an ideal research project is set up as a decision tree of alternative hypotheses. We 'navigate' this decision tree by "devising a crucial experiment (or several of them), with alternative possible outcomes, each of which will, as nearly as possible, exclude one or more of the hypotheses" (p. 347). By performing the experiment(s) and iterating this process, we are able to move forward faster. See also Mackenzie and House, 1978.

We can state many hypotheses and draw many conclusions from using the MSM; the same is true concerning the application of feedback control to management situations. At this time we are at the vertex of the research tree: the fundamental question we need to answer is whether or not the control theory analog of the MSM is capable of making predictions. This means the model is able to predict (track) the outputs of the operation.

Hypothesis: *The management system for the particular exercise under study and its control theory model have similar dynamic behavior:*

H_0: The system's output and the model's output are not correlated.

H_a: They are correlated.

This formulation only addresses the third subproblem. However, solving the first two subproblems is a necessary condition for tackling the third. Furthermore, verifying the predictions substantiates the control theory model of the management system and helps support the MSM it was derived from.

The type of research

This section classifies this research from a social sciences perspective, rather than from an engineering perspective. The first paragraph, "Research structure," implicitly relates the type of research to research validity. That relationship will be made clearer later. The second paragraph, "Research scope," identifies the methology followed.

Research structure

According to Brinberg and McGrath (1985), research involves three domains called, respectively, *conceptual domain, methodological domain,* and *substantive domain.* Research also proceeds in three stages. The first stage is *preparatory,* involving the generation and evaluation of elements and relations within these domains. The second stage is *exploratory* (the study itself), involving the development of empirical findings. This second stage is composed of three steps: step one concerns choosing the central domain of interest; step two concerns combining elements and relations from the central domain with those from a selected second domain; step three concerns combining this instrumental structure with elements and relations from the third domain. Finally, the third stage is *confirmatory,* involving the replication and generalization of the findings.

Depending on which domain (conceptual, substantive, or methodological) is the central domain of interest, we have *basic research, applied research,* or *technological research,* respectively. This project is **basic research** because the starting point is the conceptual domain. Depending on what second domain forms the instrumental structure, we can have three different research styles or paths: the *experimental path,* the *theoretical path,* and the *empirical path.* This research is **experimental,** because the methodological domain is called for before bringing in the substantive domain.

The conceptual domain: This research project began by recognizing that management decision making is basically a trial-and-error process; managers don't use models to test alternative decisions, because models in the social sciences are basically descriptive, without predictive, testing capabilities. To fix this difficulty requires giving managers modeling and design capabilities similar to those engineers have. Specifically, it requires building symbolic, mathematical models of management systems showing the different ways the system can evolve in response to some input. These dynamic models become predictive by representing behaviors characteristic of the actual system as functions of time.

Blaylock and Rees (1984) call attention to the importance of studying managerial decision-making from a dynamic perspective. But besides Forrester's (1961) work, we know very little about building dynamic models in a management environment. However, we have experience building such models for physical systems. The easiest way to use our experience is to handle this situation in an indirect way: determine the relevant laws and properties in the management system, build a mathematical model describing those properties, and infer the dynamic behavior of the management system from the behavior of this mathematical model.[3]

---

[3] Mallak (1986) makes a first suggestion toward a physical model of the MSM, using a mechanical analogy to convey the image of an interaction between the MSM components. He represents three blocks connected by three springs such that any impact in any of these components disturbs the whole system before it regains equilibrium.

So, the conceptual starting point for this research is the conjecture that we can represent the descriptive MSM as a predictive control loop. This is done by making each component of the MSM equivalent to a component of a control loop (Figure 1 on page 8):

- the manager equivalent to the controller,
- the operation equivalent to the process to be controlled (plant), and
- the tools equivalent to the sensors and displays.

In the upper part of Figure 1, the MSM is "in a vacuum": there are no interactions with the environment. Using the MSM is looking at the "inside world" first, before looking at the "outside world", i.e., figuring out how an organization works within itself before worrying how it interacts best with the outside. However, the control loop shows the interactions between a management system and its environment as inputs (set points), disturbances, and outputs.

The analogy between the MSM and the control loop can be further explored. When something goes wrong and a manager is unable to maintain control over the operation, either the organization changes, the manager is replaced, or both (Meyers, 1986). That corresponds to either replacing the controller or facing an unstable system. Another alternative is to change goals, but that corresponds to changing the reference input, the desired system behavior. Similarly, changing a manager's attitudes is equivalent to tuning the controller, and improving the tools is like calibrating the sensors. Relative to the MSM, the control loop takes into account the decision maker's and the management tool's biases, and connects the management system to the environment (Mendes, Kurstedt & Koelling, 1988). Other benefits are recognizing the situations when the management system is uncontrollable, unobservable, or unstable.

The methodological domain: The MSM brings together the relevant components in a management system, and its control theory analog provides the mathematical tools to study these relationships. At this point, what we are saying is that the management process is an information feedback loop (Figure 2 on page 10). The disturbances in the operation can be looked at as information about

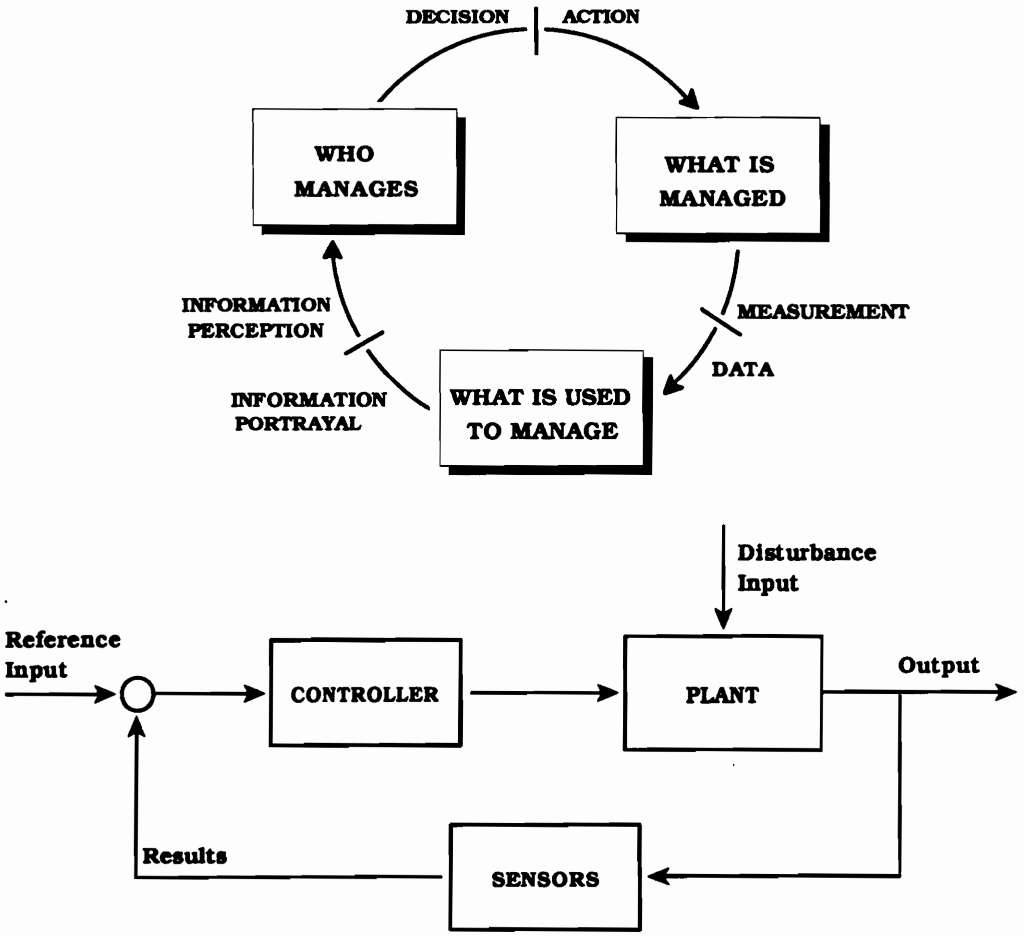


Figure 1. The feedback control loop helps make the MSM predictive.

changes in operational conditions, namely information that an accident has occurred. This research includes interpreting a manager's actions in coping with disturbances in the operation, writing a control theory model for the management system, and showing how to use the model to portray the system's behavior or predict the time required to neutralize (reject) the disturbances.

The subject of this research is to build a state space control theory feedback model. This long list of words is a complete description of our approach. We say feedback to distinguish from feedforward. We say control theory to distinguish from psychological feedback and to emphasize the mathematical treatment. And we say state-space to indicate the form of mathematical treatment. Additional terms also used for convenience here include control loop, feedback model, and other combinations of words from the list. This model consists of two main components: a set of dynamic equations representing the operation alone, and a controller formed by a control law and a state estimator (Figure 3 on page 11).

The substantive domain: The substantive domain is emergency management, but any other substantive domain would be equally well suited, a characteristic of experimental research. Emergency management is a subset of the more general category of crises management (Fink, 1986; Meyers, 1986; Kurstedt & Mendes, 1990). According to the Federal Emergency Management Agency (FEMA), emergency management is a four-phased cycle:

Preparedness:	actions taken to cope with future emergencies,
Response:	actions taken to control and terminate an emergency,
Mitigation:	actions taken to prevent identical emergencies, and
Recovery:	actions taken to regain a normal or a safer state.

This research focuses on emergency response. Consider an accident disturbing an industrial plant that is run by a plant manager with the aid of management tools. When the accident occurs, the plant manager sets up the emergency management system. The management system featured in this

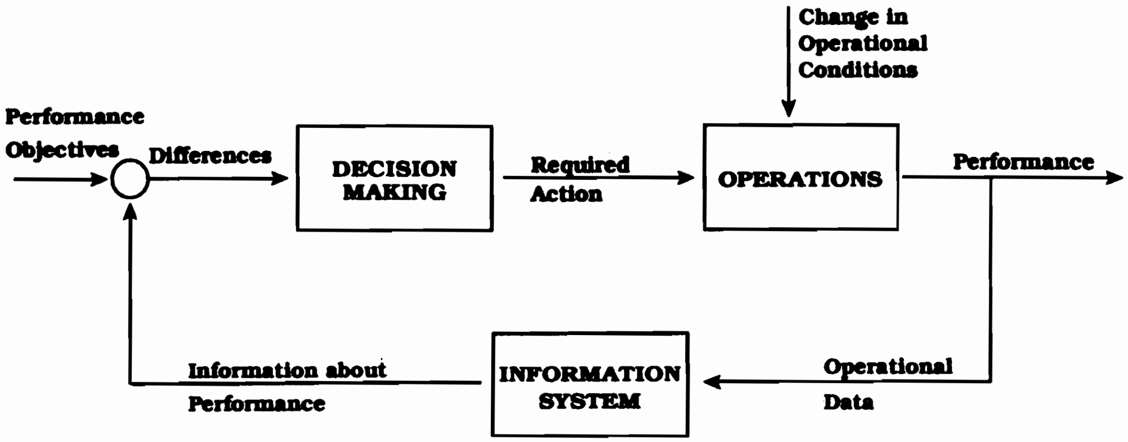


Figure 2. The management process is an information feedback loop.

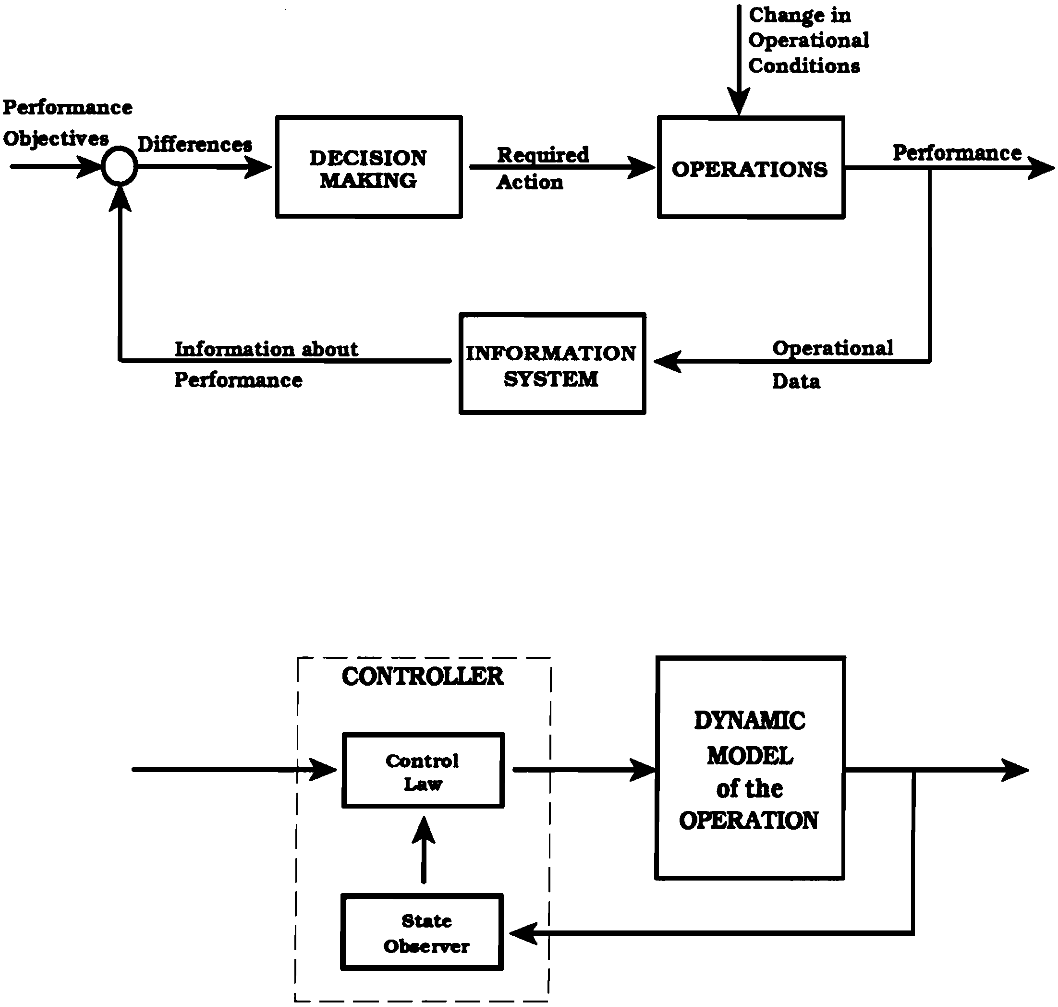


Figure 3. The state space control model represents the management system.

research focuses on a particular disturbance, a simulated accident in an emergency exercise. The accident may result in possibly hazardous consequences if improperly managed.

An emergency exercise is a good candidate for an experiment to test the hypothesis. The emergency exercise provides enough data to verify whether or not a control theory model is capable of accurately representing the management system's behavior. Building a model for the exercise is the experiment; building models for several exercises would be several experiments. "Appendix A. Scenario narrative for "Joint Response 89"" on page 148 presents a detailed description of the "apparatus" for the experiment. Basically, a propane tanker has an accident and catches fire. In turn, the fire impinges on a gas storage causing a release of chlorine. According to Figure 4 on page 13, we have:

1. an emergency management system (the inner control loop), with
   - a manager (the Deputy Emergency Director, DED) who needs to make accurate decisions and take timely actions,
   - a set of management tools (the Emergency Operations Center (EOC) Supervisor, communications, and Status Boards) to provide information about the event,
   - an operation (the plant employees and surrounding population requiring protection), and
   - an environment (the outer control loop, a higher-level operation disturbed by an abnormal event);
2. a feedback control model of the management system, featuring a mathematical description of the event;
3. a set of measurable operational conditions, providing data for the management tools and input for the model; and
4. a set of managerial actions resulting in changes in the operational conditions.

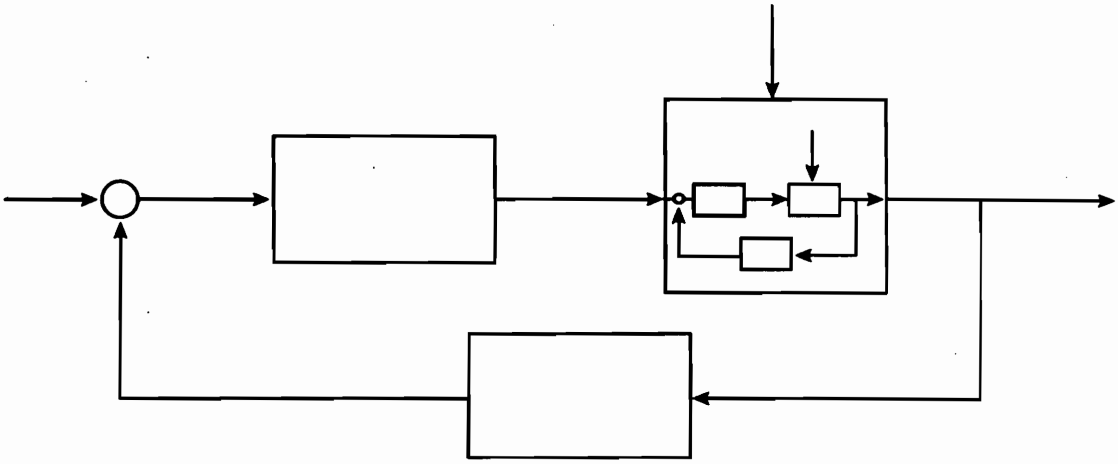


Figure 4. The emergency management system is embedded within a higher-level system.

Research scope

This research does not study a sample from a population of management systems. Rather, it uses a single management system whose time-dependent performance (dynamic behavior) supposedly matches the behavior of a control model. Dealing with a single management system means this research falls in the category of single-case research, despite being difficult to establish a research design.

Barlow and Hersen (1984) develop an extensive discussion of single-case experiments. From the several kinds of experimental designs they present, the one that could possibly fit this research is the **A-B** design (situation **A** before the treatment, then situation **B** after the treatment). In an emergency exercise, we can say **A** is the emergency, the treatment is the management intervention, and **B** is normal operation. However, the emergency management exercise is *not* the experiment this research deals with. This research is not concerned with the experimental design of the intervention of the manager. Furthermore, even if the emergency management system were the subject, this research does not study if or how a change of one variable (treatment) causes a change in observed values.

This research is concerned with building a *control theory analog of the MSM*. We should refrain from force fitting an **A-B** design situation by saying that the analog is the subject, where situation **A** is having an unmodeled management system and situation **B** is having a control theory model for that system. True, the experimental nature of this research is showing a possible approach to go from **A** to **B**, but this is not enough to qualify it as an **A-B** design. Therefore, this work is simply classified as *longitudinal single-case experimental research.*

The contribution of this research

This research does not directly contribute to the body of knowledge of the methodological domain (control theory), and contributes only marginally to the substantive domain (emergency management). Its primary contribution is to the body of knowledge of the conceptual domain, *management systems engineering*. This research brings quantitative methods to the study of management systems. In this, it is different from Operations Research, which brings quantitative methods to the solution of operational problems. And it is different from System Dynamics, because it includes the manager as part of the model and can provide closed-form solutions.

The primary intention of an emergency exercise is to practice operational procedures and decisions. Tactical, higher-level decisions are still made in an intuitive, unstructured way. An example is the decision to shelter or to evacuate. Today, managers are not prepared to face those kinds of decisions, and they don't know *when* they need to make them. The marginal contribution of this research to emergency management is to show what data to collect and how to use those data to structure a decision.

This research is integrative. Its strength is in bringing knowledge from different disciplines to bear on a single problem. It uses principles from mathematics and electrical engineering (control theory), industrial operations (emergency response), and chemical engineering (physical phenomena), together with principles and practice from industrial engineering and management (systems analysis, simulation, performance improvement).

Research boundaries

This research deals only with management systems such as described by the Management System Model. A common definition of a system is a collection of interacting elements functioning together for a given purpose. The interacting elements are only ″who manages,″ ″what is managed,″ and ″what is used to manage.″ The purpose of the management system is defined by the specification. The specification is a description of the system′s desired dynamic behavior for a given mission scenario (coping with a disturbance).

Terms like ″the accounting system,″ ″the reward system,″ and others are common in the management literature. According to the terminology used in this research, these ″systems″ fall into the management tools category (″what is used to manage.″) In addition, the following delimitations apply:

- This research is neither normative, i.e., does not suggest one best way for the manager to accomplish the goal (neutralize the emergency), nor does it address the efficiency or effectiveness of the manager or of the management tools. The objectives of an emergency management exercise are to practice emergency handling procedures at the *operational* level and find areas for improvement. The scenario is written to provide some degree of realism to that practice, not to elicit a detailed analysis of the consequences. It should be viewed as a contribution, rather than a critique, that the modeling techniques used by this research surface issues and questions probably never considered during the exercise.

- This research is not complete, i.e., does not provide a set of relationships between variables. The main objective of this research is to show the applicability of a modeling and predicting technique based on control theory. Later, we can use this modeling technique to prepare future exercises and point out areas for further evaluation. But for now, the objective is only to find out if the control theory-based analog of the MSM is adequate to model management systems. Therefore, this is not research on emergency management, control theory, explosions, heavy gas dispersion, or any other branch of knowledge called for to help attain the objectives.

Boundary conditions: Concerning the particular details of the control theory mathematical model, the experimental part of this research is limited to the specific conditions of the emergency exercise.

This means that to replicate the experimental procedure requires using a similar scenario and similarly trained players. This may not be possible. As a direct consequence, this research will not predict the success of the manager or of the management tools in future or different circumstances. It will simply tell how to set up an algorithm to predict them.

Assumptions

A basic, fundamental assumption behind this research is that managers shift their attention and totally concentrate on emergencies when those occur. That is, the ″operation″ becomes the emergency itself, until the abnormal situation is resolved. Only then is ″normal″ management resumed. We call this the *single concern* assumption. We cannot question this assumption with an emergency management exercise, because we know beforehand the assumption will be true. But we have some support for this single concern assumption from Fink (1985) and Meyers (1986). An interesting consequence of this assumption is that an emergency may have economic, regulatory, or legal effects far beyond its physical effects. For the manager, all these may still be part of the emergency. Anyhow, that is not the case in this research.

This single concern assumption extends beyond emergency management to confer generality to this research. We observe that a manager often has multiple responsibilities like labor, equipment, materials, finance, or whatever. But (Figure 5 on page 18), at a given moment only the decisions referring to a subset of those responsibilities may be important. For example, suppose a manager is concerned with motivating people. Then, the model for that slice of responsibilities could be March and Simon′s (1958) motivation model.[4] In other words, studying a subset of a manager′s responsibilities corresponds to studying a subsystem considered independent.

---

[4] Of course, the difficulty with this approach is that models like these are scarce in the literature. So, we need to develop them. This single concern assumption is the philosophy behind the study of physical systems. For example, in a large chemical plant we may study the control of the entire plant, a section, or only a particular heat exchanger. An interesting corollary is that the same theory is used for different levels of analysis.

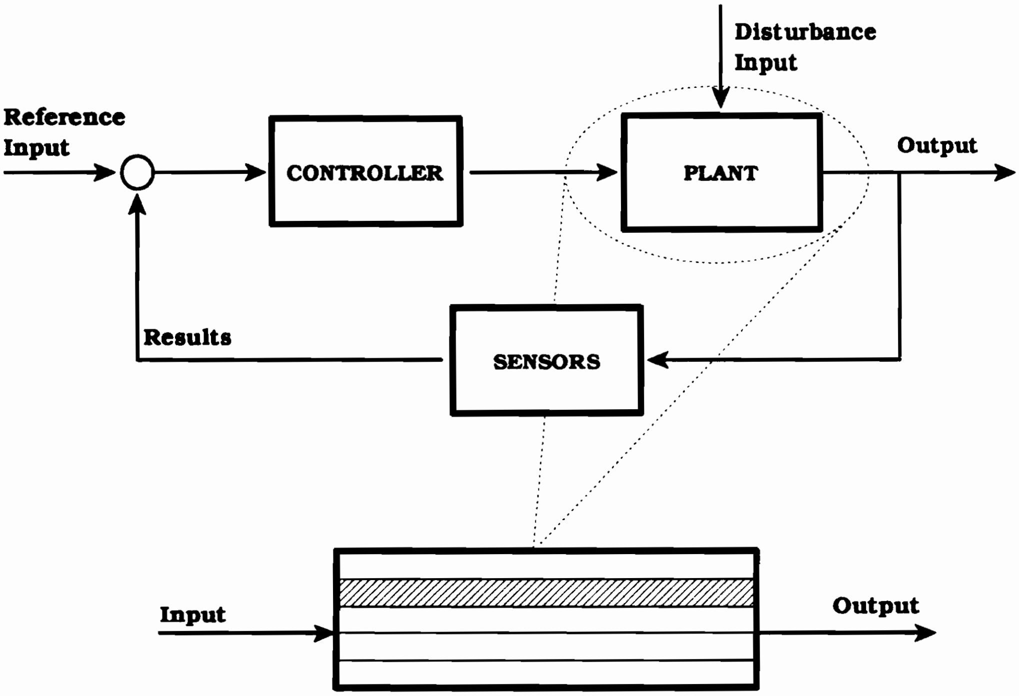


Figure 5. The manager's responsibilities can be sliced in many different ways.

Another assumption related to emergency management is that with experience, managers develop a sense for the rates of change of the various variables in an emergency, and integrate most of them into some "hazard level." This hazard level may either be actual or potential, but the physical emergency is considered finished when this variable goes to zero. (A by-product of this research is capturing this hazard evaluation process in a mathematical model.) According to the MSM, a manager uses information to make decisions, which assumes the manager monitors system output(s) and takes controlling actions accordingly. So we infer the following

Definition: *the output of a management system is the net change in the operation's performance, as a result of a managerial action implementing a sequence of decisions.*

Additional assumptions include:

- The manager and the subordinates are competent and take the appropriate measures to cope with the disturbance. Ultimately, the evaluation of the exercise will determine whether adequate procedures were followed or not. But since the objective of this research is only to provide a modeling technique, this assumption means that the response to the emergency was a result of purposeful action.[5]

- When alerted to emergency conditions, people behave rationally and take the precautions they were trained to take. Although this is the purpose of the exercises, we can only make sure the training was effective when people are actually faced with an emergency. However, Wilson (1984) asks, "how do we get them to stay indoors and miss all the excitement?"

- The physical process under control (the emergency itself) may have been previously studied, and a suitable mathematical model already been published. But no mathematical model has

---

[5] Behind this assumption is another one, the assumption of human rationality. This is perhaps too philosophical a subject, but it has already been invoked in connection with this research.

been published describing the interaction between that physical occurrence and the management of the response.[6]

The significance of the research

A piece of research can be conceptually innovative, methodologically sound, and substantively accurate, yet be of little value because its contribution is not relevant. This section argues about the relevance and worthiness of this work.

Significance of the approach

A **first** source of significance of this research is to lead the way to demonstrate a design process for management systems. Controlling one's operation by design not only promotes better visibility, but also makes it easier to implement improvements. Engineers master their environment because they design for it, whereas managers have been compelled to adapt to it. This research provides a model for the interaction between a physical system (the emergency and its response) and a human system (emergency management). A benefit resulting from using such a model is the possibility of studying how the timeliness of managerial actions influences the dynamic behavior of an operation.

A **second**, related source of significance is the use of predictive instead of only descriptive models of management systems. *Engineers* do design using symbolic models. A symbolic model is described by a state and a set of rules. The state is the description of the system at a given point in time. (See "The state space method" on page 49.) For example, when a manager replaces a management tool, this corresponds to a new state of the management system. A change of state is

---

[6] This assumption turned out to be only partially correct. For all practical purposes, no suitable mathematical model was found in the literature, so everything had to be developed from scratch.

caused by a transaction involving the domain of responsibility. The MSM only depicts relationships, not different states, state changes, or transactions.

The rules show the different ways the system can evolve from one state to another, in response to some input. A dynamic model shows the evolution of states as a function of time. A fairly complete model incorporates a high degree of knowledge about cause-and-effect (input-response) relationships. However, *managers* have not used their knowledge to build models that can predict the dynamic behavior of their organizations. A benefit resulting from this research is the possibility of doing so.

A **third** source of significance of this research is in bringing knowledge from different disciplines to bear on a single research domain — the study of the dynamic behavior of management systems. The resulting benefit is to increase the usefulness of existing management tools, namely in the emergency management information and decision support area. Being the 'controller' of the management system, the manager can combine actual performance data with the model predictions in what might be called a control-based decision support system.

The crux of emergency management is the capability to anticipate the unfolding of the events. A constant update on what is happening may not be enough if critical decisions require preparation to be effective. Without enough time to decide about possible consequences, emergency managers often decide using their emotions when faced with the facts. And this may become too heavy a load. To illustrate this point, consider Stinton's description of an LPG fire disaster in a Spanish campsite. Although this is an extreme example, it falls under the general category of allocation of limited resources (1983, p.400):

> A very controversial issue arose concerning the treatment of the badly burned survivors. The immediate and natural human impulse was to utilize the very limited intensive care facilities to help those who were most badly burned. However, with hindsight it would appear that, had these limited resources been used to help those whose burns were less severe (say less than 75%), more lives may well have been saved. A sobering and very agonising thought.

Significance of the experimental method

One way to carry out the experimental part of this research could be to prepare a business simulation game involving appropriate kinds of decisions. The major draw-back of this solution is that people often don't make realistic decisions during management games. An emergency exercise partially avoids this draw-back: the decisions and the pressures are realistic, despite the time horizon being limited.[7]

There are at least two other advantages of using an emergency management exercise. One advantage has to do with validation. If the predictions of the model don't agree with the observed results, having independent evaluators for the exercise helps determine the origin of the differences. If they do agree, then having independent evaluators helps build confidence in the model.

The other advantage is that this research relates to other MSL activities. MSL is developing expertise in helping managers handling emergencies in their operations. In this area, this research can be significant in two ways. One way is to look at the personal characteristics of the manager acting as a controller, but we are not yet ready to do this. Another way is to look at the management tools from a control viewpoint (although Belardo *et al.,* 1983 have a slightly different perspective). The advantage of using emergency management as a test bed is that the sponsors may foresee a direct connection between their investment in academic research and potential operational applications.

Overview of the research

This research consists of a preparatory part and an exploratory part. The outcomes of the preparatory part are the analogy between the MSM and the control loop, and the management systems

---

[7] A limited time horizon is an advantage rather than a disadvantage from a research viwepoint.

engineering methodology proposed in "Appendix F. Draft of a systems engineering methodology" on page 205. The major steps presented in that Appendix concern the specification of the system and its design. These two steps describe how to build a mathematical model of a management system.

The exploratory part begins with the development of the mathematical model for an emergency exercise. The major steps presented in the next chapters are modeling the management system, arranging the data, and presenting the results. These three steps describe how to predict the behavior of a management system created for an emergency exercise. The life span of the management system is the duration of the exercise. The final outcome of the exploratory part is the prediction of the system's behavior (performance).

Modeling is always a balance between accuracy and precision. The model of the management system we develop here is the simplest possible model we can use to apply the control theory concepts we deal with. As a matter of fact, striving for simplicity is a dominant concern of this research. For Falkenhainer and Forbus (1988), the trade-off between accuracy and precision in modeling physical systems depends on the purpose: people don't use quantum mechanics to understand spilling a cup of coffee. The Artificial Intelligence community uses the term *grain size* to refer to different levels of detail in modeling. This research attempts to provide a coarse model, with the largest grain size.

The management systems engineering methodology is general. This research shows its application to a specific case. This procedure may be (and ideally will be) repeated for more than one exercise. The exercises may be different, and that is simultaneously an advantage and a disadvantage. The advantage is because it helps increase the generalizability of the applications. The disadvantage is because the procedure may require writing different control models.

Terminology

The main sources for this section are DOE 5484.1 (1981), DOE 5500.1A (1987), FMPC (1986), FMPC (1987), and Harris (1982).

Abbreviations and acronyms

ach	air changes per hour
AEDO	Assistant Emergency Duty Officer
ATC	Acute Toxicity Concentration
atm	atmosphere (1 atm = 101,325 $N\ m^{-2}$)
BLEVE	Boiling Liquid Expanding Vapor Explosion
cfm	cubic feet per minute (1 cfm = $0.47195 \times 10^{-3}\ m^3 s^{-1}$)
DED	Deputy Emergency Director
DOE	U.S. Department of Energy
EBS	Emergency Broadcast System
EC	Emergency Chief
ED	Emergency Director
EDO	Emergency Duty Officer
EMA	Emergency Management Advisor
EOC	Emergency Operations Center
ERC	Emergency Response Center
ERT	Emergency Response Team
FEMA	United States Federal Emergency Management Agency
FMPC	Feed Materials Production Center (a uranium processing facility owned by DOE and operated by WMCO)
gpm	gallons per minute (1 gpm = $63.083 \times 10^{-6}\ m^3 s^{-1}$)

HVAC	Heating, Ventilation, and Air Conditioning
IDLH	Immediately Dangerous to Life and Health
INZ	Immediate Notification Zone
JPIC	Joint Public Information Center
LEL	Lower Explosive Limit
LFL	Lower Flammability Limit
LPG	Liquefied Petroleum Gas
OROC	DOE's Oak Ridge Operations Center
PIO	Public Information Officer
prs	persons
ppm	parts per million
PRV	Pressure Relief Valve
psi	pounds per square inch (1 psi = 6894.8 N m^{-2})
TLV	Threshold Limit Value
UVCE	Uncontained Vapor Cloud Explosion
WMCO	Westinghouse Materials Company of Ohio

Definitions

Accident. An unforeseen or abnormal event or event sequence with known undesirable consequences.

Acute Toxicity Concentration. The concentration that for one hour exposure has a probability of causing one fatality out of 20 (5%) (Costanza *et al.*, 1987).

Alert. See incident classification, alert.

Analysis. The process whereby hazards are identified and examined.

Assessment. The process whereby identified hazards are quantified to provide a value for the level of risk.

BLEVE. A catastrophic failure occurring when a pressure vessel is heated so the metal loses its strength and bursts (Kletz, 1977-a). When the vessel contains a flammable liquid, the BLEVE is likely to cause a large fireball.

Cohort. A term first adopted by biostatisticians and now generalized to mean "a group of people alike in a sufficient number of respects that they can be judged equally likely to become victims of a hazard to which they are all exposed" (Urquhart & Heilmann, 1984, p.44).[8]

Controller. An individual who functions as assistant safety officer and evaluator during an exercise and who ensures that safety requirements and rules of engagement are followed.

Deflagration. A flame propagation mechanism caused by heat transfer and diffusion of radicals from the reaction zone to the fresh mixture. The heat transfers from the burned to the unburned gas by conduction and convection (Wiekema, 1980).

DOE Site Manager. DOE's representative at the EOC and management liaison between FMPC and DOE's Oak Ridge Operations Center headquarters.

Deputy Emergency Director (DED). The immediate successor to the Emergency Director, serves as director of the EOC staff to provide leadership and control of emergency response actions.

Detonation. A flame propagation mechanism resulting from a shock wave of such strength that a chemical reaction starts directly behind the discontinuity. The chemical reaction is caused by the almost instantaneous compression and heating of the unburned mixture (Wiekema, 1980).

Domain of responsibility. A connected, identifiable object of authority for which a person is accountable (Kurstedt, 1985).

Emergency. Any significant deviation from planned or expected behavior or course of events that can endanger or adversely affect people, property, or the environment. See also incident classification.

Emergency Brigade (EB). The personnel who execute the response (the response team), supported by the Plant Supervisor.

---

[8] Originally, a cohort was a division in the Roman army.

Emergency Brigade Chief (EBC). The person who directs, at the operational level, the execution of emergency response actions.

Emergency Director (ED). The person who provides strategic-level oversight with the support of the EOC staff.

Emergency Duty Officer (EDO). The person who manages the response at the tactical level, and links all onsite and offsite elements of the FMPC Emergency Management Program. The EDO is supported by the EOC staff.

Emergency Management System. The plans, procedures, and actions aiming at reducing the level of damage after an emergency occurs.

Emergency Operations Center (EOC). A facility from which management and support personnel carry out emergency response activities. The emergency operations center may be a dedicated facility or office, conference room, or other pre-designated location having appropriate communications and information equipment to direct and coordinate the assigned emergency response mission. At FMPC, the EOC is environmentally secure (dedicated HVAC, positive air pressure, air filter system) and equipped with emergency power.

Emergency Plan. A brief, clear and concise description of the overall emergency organization, designation of responsibilities, and descriptions of the procedures, including notifications, involved in coping with any or all aspects of a potential credible emergency.

Emergency Procedure. Detailed instructions and guidance for carrying out emergency response actions.

Engineered Safety Systems. The technical redundancies, alternative processes, and automatic mechanisms to reduce the probability of an hazard to the lowest achievable level.

Exercise. A scheduled and planned event that tests the integrated capability and a major portion of the basic elements of emergency preparedness as specified in emergency plans and procedures.

Fireball. A propagating diffusion flame with a flame geometry varying somewhere between a sphere and a hemisphere (VanAerde, Stewart & Saccommano, 1988).

General Emergency. See incident classification, general emergency.

Hazard. A physical situation with a potential for harm to life or limb.

Hazard Management. The integration of engineered safety systems and the emergency management system.

Hazardous Material. Any solid, liquid, or gaseous material that is toxic, flammable, radioactive, corrosive, chemically reactive, or unstable upon prolonged storage in quantities that could pose a threat to life, property, or the environment.

Hazardous Materials Emergency. A condition or potential condition that can result in the accidental release or loss of control of radioactive or toxic material.

Immediate notification zone (INZ). A two-mile area surrounding the site. For FMPC this includes the populations of Butler and Hamilton counties within the range of the seven offsite siren stations and one onsite siren station as shown in Figure 12 on page 69.

Immediately dangerous to life or health (IDLH). Conditions that pose an immediate threat to life or health or conditions that pose an immediate threat of severe exposure to contaminants, such as toxic materials, which are likely to have adverse cumulative or delayed effects on health.

Incident. An unplanned occurrence that can lead to disruption of operations or to personal injury or property damage.

Incident classification. A method DOE and FMPC use both to categorize an incident's severity and to indicate appropriate response actions. The categories are:

Operational upset. An incident with no potential for reduction of facility safety and with no potential for offsite release.

Unusual event. An incident with potential for reduction of facility safety but with no potential for offsite release.

Alert. An incident with actual or potential substantial reduction of facility safety, offsite release not expected to exceed permissible limits, but where mutual aid is required.

Site Emergency. An event in progress or having occurred with actual or likely substantial reduction of facility safety, potential for offsite releases to exceed permissible limits, and where mutual aid is required.

General Emergency. An event in progress or having occurred which involves actual or imminent substantial failure of facility safety systems needed for the protection of onsite personnel, the public health and safety, and the environment. Offsite releases are expected to exceed permissible limits and mutual aid is required.

Lethal Concentration. The concentration, c, that causes i% mortality for a given exposure time, t, when the degree of injury is proportional to $c^m t^n$.

Lethal Dosage. The concentration-time combination that causes i% mortality when the degree of injury is proportional to $c^m t^n$ and $m = n$.

Lethal Load. The concentration-time combination that causes i% mortality when the degree of injury is proportional to a general function $f(c, t)$, or when the degree of injury is proportional to $c^m t^n$ and $m \neq n$.

Mitigation. The sequence of protective actions aiming at reducing the consequences of an accident.

Occurrence. Any deviation from the planned or expected behavior or course of events in connection with any Department of Energy or Department of Energy-controlled operation if the deviation has environmental protection, safety, or health protection significance.

Planning Basis. A list identifying the hazards that may exist in a facility.

Plume. The hazardous materials profile of a gaseous release as it progresses downwind. For the plume exposure pathway, shelter and/or evacuation would likely be the principal immediate protective actions to be recommended for personnel.

Preparedness. The training of personnel, acquisition of resources and facilities, and testing of emergency plans and procedures to ensure an effective response.

Protective Actions. Actions taken during an emergency for the purpose of preventing or minimizing hazards.

Rally point Location designated for assembly, following evacuation.

Response. The action(s) taken to cope with and minimize the effects of any emergency.

Risk. The probability of a hazard being realized at any specified level in a given span of time; or the probability of an individual suffering a specified level of injury as a result of the realization of a hazard in a given span of time. "Risk involves both the frequency of the undesirable event and the severity of the consequences" (Vesely, 1984).

Shadow Force. A response team held in isolation from the exercise area by a controller.[9]

Shelter. A facility used to protect, house, and supply the essential needs of designated individuals during the period of an emergency. A shelter may or may not be specifically constructed for such use, depending on the type of emergency and the specific programmatic requirements.

Sheltering. An in-place, immediate protective action calling for people to go indoors, close all doors and windows, turn off all sources of outside air, listen to radio or television for emergency information, and remain indoors until official notification that it is safe to go out.

Site Emergency. See incident classification, site emergency.

Substantial. Clearly outside normally accepted or experienced bounds.

Threshold Limit Value — Time Weighted Average (TLV). Concentration of toxic materials for a normal 8-hour work day and a 40-hour work week to which nearly all workers may be exposed day after day without adverse effect.

Toxic Chemicals. Chemicals (other than radioactive chemicals) which at the expected level of exposure, demonstrate the potential to induce cancer, to produce short and long term disease and/or bodily injury, to affect health adversely, to produce acute discomfort, or to endanger life of man or animal resulting from ingestion, inhalation, or absorption through any body surface.

Toxic Front. The distance from the origin of the event of a contour of concentrations above an acceptable limit.

Unicohort. The number of people whose participation in an activity will, on the average, produce one victim during a specified time interval (Urquhart & Heilmann, 1984). "The bigger the unicohort, the smaller is each individual's risk and vice versa" (pp.44).

Unusual Occurrence. An unusual or unplanned event having programmatic significance such that it adversely affects or potentially affects the performance, schedule, reliability, security, or safety of a facility.

---

[9] In the event of an unscheduled alarm, the assigned controller advises the Senior Controller to suspend the exercise to allow the shadow force to respond to the alarm. Exercise activity shall not resume until the shadow force is out of the exercise area and under the direction of its assigned controller.

The review of the literature

This chapter looks at the literature from three different perspectives. The *first* perspective is motivational, showing (a) that other people tried to address the same problems or use the same techniques; (b) reasons for their lack of success; and (c) work in related areas that can bring face validity to this research. The *second* perspective is methodological, building on the usage of engineering methods in management and pointing to some developments in these methods that overcome what might have been impediments to earlier research. The *third* perspective is operational, looking at emergency management from the viewpoint of control and information needs and decision making attitude.

Motivational perspective

The objectives of engineering a feedback controller for a particular ″plant″ are essentially twofold: to make the output of the system reflect any desired changes submitted as input to the controller, and to eliminate the effect of external disturbances. This is basically what is required from a manager in a management system.

Previous work

There is nothing new in the idea of applying control theory to management. Simon (1952) provides an earlier example of analyzing a management problem. But although describing the mathematical aspects of control theory, he ignores the manager's direct involvement with the operation (the problem). On the other hand, Mize, White and Brooks (1971) describe several "feedback and corrective actions" from the manager's perspective, but exclude any mathematical aspects. Also interesting, although still non-mathematical, is the description by VanAken (1982) of control and coordination strategies at Philips Industries in Holland.

Nevertheless, there are some good examples of applying modern control theory (state space approach) to management. Sethi and Thompson (1981) provide a wide coverage of management science, with examples ranging from finance to equipment maintenance. Negoita (1979) relates the state space control approach to system dynamics and provides management examples. (See "System Dynamics" on page 38.) Amey (1986) also recommends the use of modern control theory to solve operational problems, but he doesn't provide any example or application. Again, none of these authors involve the manager's actions.

The two positions presented by the literature are (1) either a mathematical treatment of some aspect of an operation (plant), or (2) an argumentative discussion around feedback control concepts. Apparently, applications of mathematical control theory to managerial actions are non-existent. There are several possible explanations for this. To explain why mathematical control theory is (practically) not used, we look at the sciences supporting management.

Reasons for not using control theory

Reasons from psychology: The body of literature in psychology allegedly involving control theory is quite extensive. But most, if not all, of this work only borrows from control theory the concept of a feedback loop. Carver and Scheier (1981) provide a plausible justification (p.11):[10]

> relatively naive readers (of which we are two) might find tackling a textbook on control systems to be a mind-numbing experience.... Most of the complexity of control theory which will be *ignored* here involves parameters that need to be taken into account in designing systems of control with greater and greater accuracy. If one is trying to produce a better guidance system or computer, this sort of precision is important. And ultimately it may be desirable for psychologists to attend to those subtle issues. For now, however, we believe it is best to stay with the basics. For the same reason, our description ... is also devoid of mathematical equations.

Understanding the mathematical control language is by no means the single difficulty. Perhaps more important is the difficulty of agreeing on cause-effect relationships: control theory was already a well-established field when psychologists were still trying to understand the nature of feedback (e.g., Ashford & Cummings, 1983; Earley, 1986; Erez, 1977; Matsui, Okada, & Inoshita, 1983).

Almost all authors invariably accept a fundamental feedback loop connecting four components: 1) a goal or reference standard, 2) an effector or behavior producing function, 3) a sensor or information gathering function, and 4) a comparator between the goal and the information feedback. But the simple feedback loop representation is often only a vehicle to discuss the relationship between those components (Campion & Lord, 1982; Hollenbeck, 1989; Podsakoff & Farh, 1986; Tracy, 1984). As Negoita (1979) says in his Preface, "borrowing the language of control engineering is one thing and applying its methods to management policies is another."

Industrial and management psychologists feel the same difficulties, augmented by an unfortunate choice of terms. In an extensive literature review, Klein (1989) says that there is a substantial difference between the terms *positive* and *negative feedback* when used by control theory and social psychology:

---

[10] Presenting this and other quotes doesn't necessarily mean subscribing to the justifications. But this author's standpoint is representative of the field.

> The feedback loops discussed above are referred to ... as negative feedback loops because the response to an error is the reduction of that error .... [In control theory,] positive feedback results in an enlargement of the discrepancy, and a positive feedback loop is a system that tries to maximize distance from, rather then match, a standard. The assumption underlying these definitions is that discrepancies in either direction are equally undesirable. Although this is true for many mechanical systems, it usually is not the case with human systems. To avoid confusion, ... *positive feedback* will refer to information denoting one has exceeded a goal, *negative feedback* to information indicating the standard was not attained. (p. 152)

Kurstedt, Mendes and Polk (1988) comment on these discrepancies, but there are more; another source of confusion lies in the usage of the terms *feedback* and *feedforward* (Kreitner, 1982; Brethower, 1982). In short, Green and Welsh (1988) are quite perceptive when they say (p. 287) "we feel the concept of control has not been adequately addressed; we perceive ... a lack of clarity and cohesion in the literature. Sheer abundance of treatment is not an adequate substitute for a clear conception of control." This is what Mendes *et al.* (1991) attempt to provide.

Reasons from research methods: Clearly, the psychological sciences haven't yet generated thorough results supporting the development of applications of mathematical control theory to management. Another, somewhat related explanation for this lack of success concerns the methods used in these studies. On the one hand, the feedback control loop is general. On the other hand, it is limited: control theory only deals with dynamic, time-dependent variables and relationships. The control loop is not adequate to describe those situations requiring one-of-a-kind, non-corrective decisions. Takkenberg (1982) provides further arguments. This time-dependent nature of events calls for longitudinal instead of the more traditional cross-sectional studies.

Reasons from the meaning of control: A third reason for the lack of success of control theory applications to management is that the social sciences provide different perspectives for control. On the one hand, control is identified with bureaucracy (Daft, 1983). On the other hand, control is identified with accounting operations.[11] Possibly due to Lawler and Rhode's (1976, 1982) comments on the dysfunctional effects of control systems, the word "control" presently has a negative

---

[11] Interestingly enough, Maciariello (1984) presents managerial accounting from a feedback control perspective, although without its mathematical support. However, even that may be about to change. In a review of their book *Relevance lost: the rise and fall of managerial accounting*, Johnson and Kaplan (1987) suggest using process control-like time-dependent accounting information. And Ijiri (1988) proposes an accounting system involving first-order differential equations.

connotation for many management authors. Tosi (1983, p.272) defines the control structure as "the set of factors, and the relationships between them, which elicit predictable performance from individuals and groups in organizations." He sees control as influencing people to minimize problems and insure compliance with norms and goals. This is the social scientist's way of stating the quite traditional principle of systems control: to maintain the values of an output variable close to a preset value, and absorb disturbances. Otley (1987) provides additional insight on this topic.

Related work

Organizational learning: Argyris and Schön (1978) don't mention control, but present examples of problems control theory can tackle. They define *organizational learning* as the detection and correction of errors, and this is what feedback control is. These authors deal only with psychological aspects, but the relationship to feedback control is quite apparent and a good indication that control theory is adequate to handle management problems. As an application of the concept of observability, a necessary condition for organizational learning is matching information supply to demand at each level. Managers identify key performance variables in their operations, and design reporting mechanisms to detect errors in those variables.

Human factors: Sanders and McCormick (1987), using original work from Chapanis, show a graphical representation of man-machine interaction. While the machine receives external inputs and provides outputs, environmental and machine variations cause the readings in the machine displays to vary. Changes in the displays become information for the operator who makes a decision to act on some machine control device. The action may be precise enough to cause the desired effect immediately, or may require further adjustments.

Wewerinke and co-workers provide a detailed application of modern control theory in the area of man-machine interaction (Wewerinke, 1987; Wewerinke, Perdok, & van der Tak, 1988). The task is to maintain the trajectory of a ship entering a harbor. Information from the outside environment and instrument panel tells the pilot how to turn the wheel, which in turn acts on the rudder. Given the idealized trajectory, the pilot continuously monitors the position of the ship and applies any required corrections.[12]

Methodological perspective

Many scientific methods are general enough to ignore the boundaries of any specialized domain of application. Sometimes the methods retain the same name across different branches of knowledge, as in the case of statistics. Other times different specialties use different names for basically the same activity, as dissection in biology or destructive testing in engineering. However, some apparently general methods seem to be exclusively used in engineering. And they shouldn't.

Control theory

The term feedback control is relatively recent, but the principles of feedback control were already used to regulate the flow of water many centuries ago. Franklin *et al.* (1986) sketch the history of feedback control referring to both practical and theoretical developments. Presently, control theory is widely used to study, design, and predict the behavior of many kinds of physical dynamic systems (Cochin, 1980; Kecman, 1988). However, although targeting engineering applications, "control theory does not deal with the real world, but only with mathematical models of certain aspects of the real world; therefore the tools as well as results of control theory are mathematical" (Kalman, Falb, & Arbib, 1969, p.27).

Most of the theoretical work during the WW II era focused on systems described by a single, low-order differential equation. This work used the frequency response, or the characteristic

---

[12] After the Exxon Valdez accident, there is some irony in the relationship between this particular example and applications in emergency management.

equation, supported by graphical methods to evaluate stability. The work of Simon (1952) alluded to earlier falls into this category.

The so-called "state space" or "modern" control theory began in the early 20th century with the works of Poincaré and Lyapunov. However, their contributions were only integrated in the control literature with the beginning of the space age in the late 1950s. Relevant researchers at the time were Bellman, Kalman, and Pontryagin, who started using systems of coupled, first-order differential equations instead of transfer functions. The size of such systems was only limited by the availability of digital computers. Applications of the same mathematical principles to non-physical systems related to management include management science and operations research (Sethi & Thompson, 1981; Tzafestas, 1982) and economics (Sengupta, 1987).

Modeling

The control analog of the MSM: The MSM fulfills a global descriptive role because (1) it calls attention to managerial actions influencing operational measurements, (2) to managerial decisions depending on the manager's perceptions of information, and (3) to the information managers use to make decisions originating from operational measurements (Kurstedt, Mendes, & Lee, 1988). This reference contains a good description of the MSM, so we will not do that here. Anyhow, the MSM does not account for the interaction between the management system and the environment. In addition, the MSM is a descriptive model; it is not suitable for quantitative treatments. Using a feedback control analog serves that purpose. Each component in the MSM is equivalent to a component in the control loop: the operation to the process to be controlled, the manager to the controller, and the tools to the sensors and displays (Figure 1 on page 8).

The MSM brings together the relevant components in a management system, and its control theory analog provides the analytical tools to study these relationships. Relative to the MSM, the control loop takes into account the decision maker's and the management tool's biases, and connects the management system to the environment (Mendes, Kurstedt, & Koelling, 1988). Other benefits are recognizing the situations when the management system is uncontrollable, unobservable, or unstable. But there's a limitation: the control theory model is a design tool, not an implementation tool. One difficulty with this limitation is that we don't have criteria to evaluate the design *per se;* we can only evaluate the design after the implementation. And this is confusing.

System Dynamics: Forrester's (1961) *Industrial Dynamics* is the first successful use of control theory principles in the area of management. Forrester argues that management should evolve from an art into a science through the application of principles from other underlying sciences. Engineering and medicine, he says, also evolved from an art to a science after practitioners began applying relationships explained by basic laws of nature. In a set of notes released as a preliminary printing, Forrester (1980) explains how variables originating from different branches of knowledge are consistently grouped as *levels* and *flows.* This consistency lead to the designation of system dynamics models as a generalization of the earlier industrial dynamics.

Forrester provides a very powerful tool to model the dynamics of an operation, but considers the manager at most as an external influence. The tone of his followers is the same (Coyle, 1977; Roberts, 1978). Other authors who use his formulation to deal with management problems take the same approach (Sohn & Surkis, 1985-a,b; Sterman, 1987). Forrester's work is a cornerstone to the development of the MSM. But one of the strengths of the MSM is to include the role of the manager in the behavior of a management system. Forrester doesn't do this.

Engineering versus social science models: Engineers use two kinds of models: mathematical and physical scale models (Figure 6 on page 39). In this research we are only concerned with mathematical dynamic models, as abstract representations of management and physical systems. The body of knowledge of the physical sciences, together with similarities between different specialties, provides endless combinations of components and equations to build a model with. Like engineers, managers solve problems. And according to Kerlinger's (1979) terminology, most practical man-

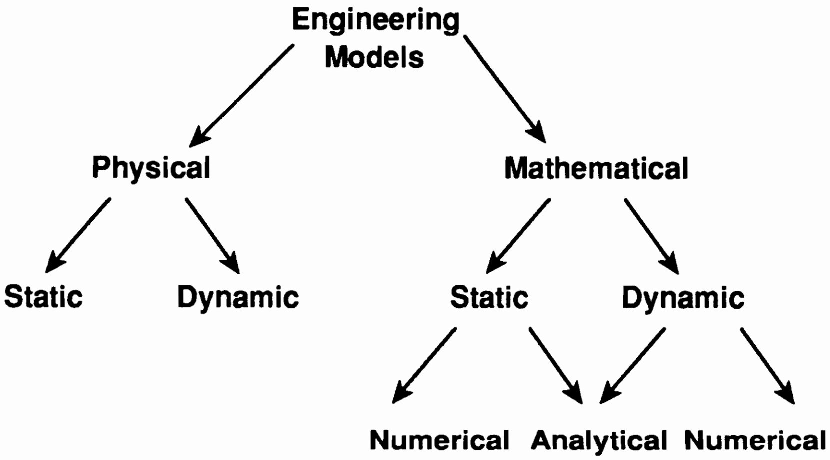


Figure 6. **Classifying a model helps define its usage.** (Gerold Patzak, from Technischen Universität Wien, contributed to this topic with some stimulating discussions.)

agement problems are indeed formulated as engineering problems. So, if managers are social engineers, it would seem natural for managers to use traditional engineering methods.

However, the body of knowledge of the social sciences is not organized to retrieve and combine standard features into larger models. Social sciences' models typically represent single relationships between a small number of variables. They are basically research models; their objective is to expand the body of knowledge (Miller, 1983) rather than serve as decision aids. And "to provide a prediction system that can be manipulated to aid a decision maker is perhaps the most important attribute of models" (Murdick, 1986, p.52). There is a reason for this lack of modeling tools in the social sciences. According to Varela (1978, p.84), "the goal of the social sciences is not to *solve* problems, but to *study* them."

Operational perspective

Smith (1989) defines a *problem* as "an undesirable situation that is significant to and may be solvable by some agent, although probably with difficulty" (p. 965). He decomposes problem formulation into identification, definition, and structuring (see also Mason & Mitroff, 1981). Problem definition is important to avoid Type III errors (solving the wrong problem). Brightman, Elrod, and Ramakrishna (1988) describe different problem formulation aids, arguing the only ones used are those that match a manager's decision style.

Decision attitudes

There are many theories, approaches, or models of decision making. The following definitions form a commonly used taxonomy (Davis, 1988):

Approach	*Description*
Rational:	characterized by a structured view of decision making, where decisions aim at solving problems by reducing them to measurable factors (attributes) that influence the outcome;
Organizational:	characterized by the adherence to policies and guidelines. The choice criteria are the manager's status and security within the organization; and
Political:	characterized by the use of persuasion and power to reach decisions. Since decisions result from bargaining and compromise, they don't necessarily reflect an individual manager's preferences.

All approaches have justification at some decision level or at some point in time, and some people feel more comfortable with some than with others. Furthermore, we may see a predominance of either one of the approaches in different kinds of organizations. But what is most likely to occur is a coexistence of all them: the manager or the government official has to balance the reality of uncertainty and politics against the sudden pressures for rational order and stability that arise during a crisis or an emergency.

Despite defending that "human behavior is intelligent, even when it is not obviously so," March (1978) warns against the inconsistent nature of preferences. He says:

> rational choice involves two kinds of guesses: guesses about future consequences of current actions and guesses about future preferences for those consequences.... Theories of choice under uncertainty emphasize the complications of guessing future consequences. Theories of choice under conflict or ambiguity emphasize the complications of guessing future preferences (p. 589).

When people make decisions based on wrong information (or at least wrong perceptions), their behavior is still rational, although mistaken (Rahmatian, 1985; Rahmatian & Hiatt, 1989). Clearly, rationality implies the viewpoint of the decision-maker. Ultimately, it is preferable to accept the postulate of rationality if we cannot demonstrate otherwise (Cohen, 1981). And in crises and emergency situations managers have to deal with incomplete and often contradictory information.

Crises and emergency management

Broekstra (1984) says that a crisis occurs when some situation is out of control and a pathological condition is reinforced by positive feedback. Supporting this view, Nunamaker *et al.* (1988) focus on organizational capabilities, like learning and quick implementation of decisions, as conditions for successful coping with crises. The trouble, they say, is that ″crises create questions in the minds of those at lower levels in the organization about the competence and perspicacity of their leaders″ (p. 28). Similar to Argyris and Schön′s (1978) work previously alluded to (under "Reasons from the meaning of control" on page 34), learning for crisis management implies organizational information feedback. Of special importance is the capacity to detect, to perceive early warning signals always associated with the emergence of crises (Mitroff, Shrivastava, & Udwadia, 1987; Mitroff, 1988).

Industrial emergency management is a subset of crisis management. Industrial emergencies are associated with physical effects and involve direct or indirect (environmental) life-threatening situations. Managing the four FEMA phases presented in "The substantive domain" on page 9 requires dealing with different levels of uncertainty. A simple framework proposes four pursuits ranging from uncertain to certain (Kurstedt, 1985):

Perplexity:	no start and no end,
Problem:	start but no end,
Program:	start and qualitative end, and
Project:	start and specifications for end.

According to Galbraith (1973), uncertainty is the ratio of the information managers have to the information they need. For each pursuit, people can only cope with uncertainty if they attain a certain level of management maturity. Building on Kurstedt (1985), we further propose four maturity stages that must proceed in sequence:

Awareness:	knowledge and interpretation of key system variables,
Visibility:	complete cognizance of cause and effect relationships,
Control:	achieving steady state by eliminating variations, and
Optimization:	improving performance by adjusting steady state throughput.

Figure 7 on page 44 puts emergency management in the context of these frameworks.

The perception of risk

Building on the extensive work of Kahneman and Tversky, among others, Hink and Woods (1987) conclude that, although people are often inconsistent and suboptimal when dealing with probabilities, they may exercise good sense when evaluating risks. For instance, the hazard assessment of a given occurrence is essentially judgmental in the emergency management procedures followed by FMPC[13] (Figure 8 on page 45). Not all authors discussing the risks associated with technology agree with this position, although some (Longino, 1985; Perrow, 1984; Wenk, 1979) may be more emotional than others (Keeney, 1988).

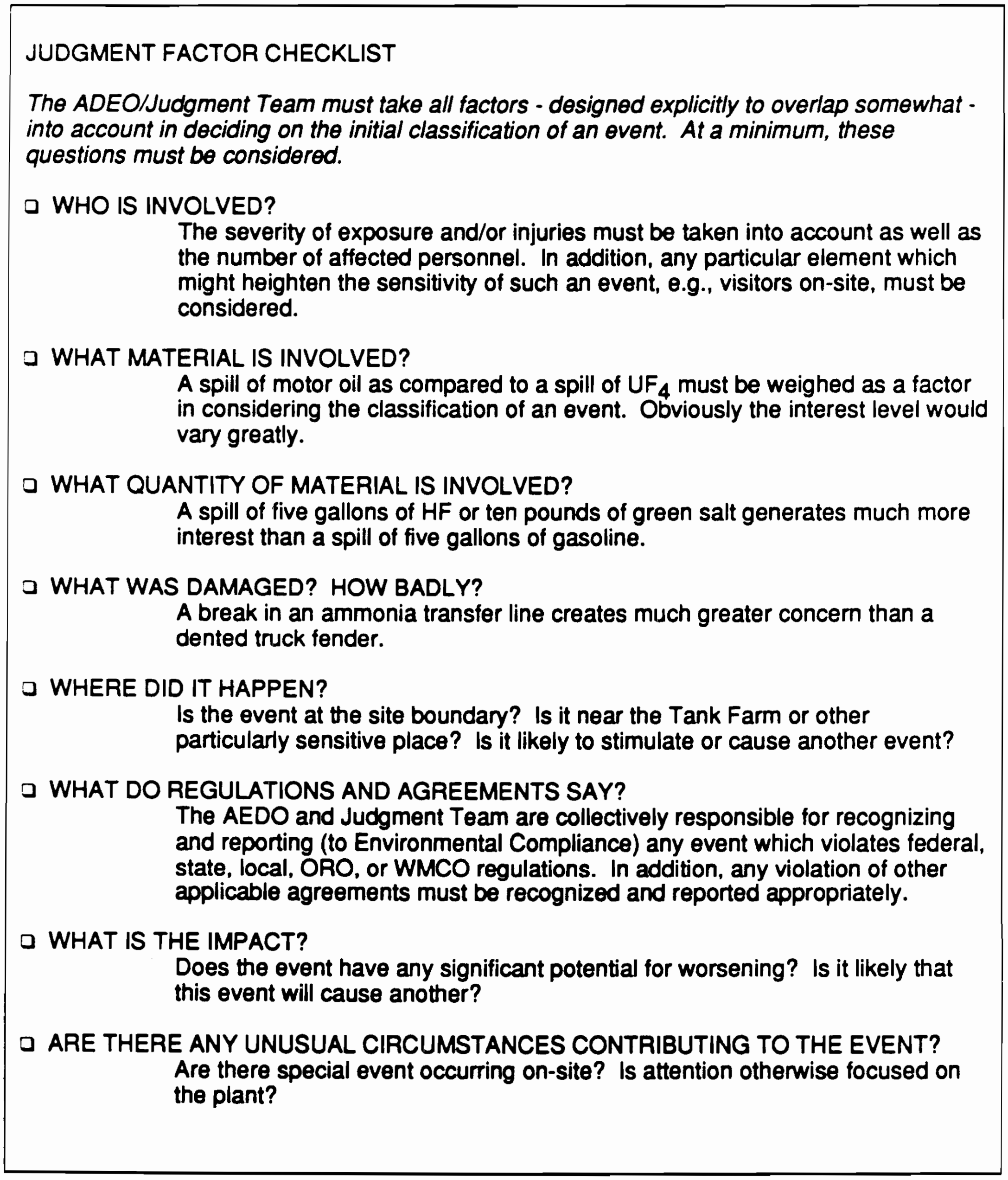
The concept of risk is intimately associated with the concepts of hazard, danger, and peril. Almost invariably, hazards are assessed primarily in terms of people involved (Zeckhauser & Shephard, 1981). However, equipment losses and environmental impact are also important, namely for actuary purposes (Luckritz & Schneider, 1980). As Kletz (1986, p.13) puts it, ″no one has the right to decide what risks are acceptable to other people and no person should ever knowingly fail to act when others′ lives are at risk, but everything cannot be done at once; priorities have to be set.″ And, again, the information supporting those decisions is not clearly organized. Nevertheless, Wilson (1981) provides an extensive list of references concerning emergencies of chemical origin and CMA (1984) presents additional discussion.

---

[13] FMPC stands for Feed Materials Production Center, an uranium processing facility owned by DOE and operated under contract by Westinghouse.

PHASE	UNCERTAINTY	DECISION ATTITUDE	LEVEL OF ENDEAVOR	MATURITY
PREPAREDNESS	PERPLEXITY	POLITICAL	STRATEGIC	AWARENESS
RESPONSE	PROBLEM	ORGANIZATIONAL	TACTICAL	VISIBILITY
MITIGATION	PROGRAM	RATIONAL	OPERATIONAL	CONTROL
RECOVERY	PROJECT	PROCEDURAL	CLERICAL	OPTIMIZATION

Figure 7. Emergency management can be viewed from five interrelated perspectives.



JUDGMENT FACTOR CHECKLIST

The ADEO/Judgment Team must take all factors - designed explicitly to overlap somewhat - into account in deciding on the initial classification of an event. At a minimum, these questions must be considered.

☐ WHO IS INVOLVED?
The severity of exposure and/or injuries must be taken into account as well as the number of affected personnel. In addition, any particular element which might heighten the sensitivity of such an event, e.g., visitors on-site, must be considered.

☐ WHAT MATERIAL IS INVOLVED?
A spill of motor oil as compared to a spill of UF_4 must be weighed as a factor in considering the classification of an event. Obviously the interest level would vary greatly.

☐ WHAT QUANTITY OF MATERIAL IS INVOLVED?
A spill of five gallons of HF or ten pounds of green salt generates much more interest than a spill of five gallons of gasoline.

☐ WHAT WAS DAMAGED? HOW BADLY?
A break in an ammonia transfer line creates much greater concern than a dented truck fender.

☐ WHERE DID IT HAPPEN?
Is the event at the site boundary? Is it near the Tank Farm or other particularly sensitive place? Is it likely to stimulate or cause another event?

☐ WHAT DO REGULATIONS AND AGREEMENTS SAY?
The AEDO and Judgment Team are collectively responsible for recognizing and reporting (to Environmental Compliance) any event which violates federal, state, local, ORO, or WMCO regulations. In addition, any violation of other applicable agreements must be recognized and reported appropriately.

☐ WHAT IS THE IMPACT?
Does the event have any significant potential for worsening? Is it likely that this event will cause another?

☐ ARE THERE ANY UNUSUAL CIRCUMSTANCES CONTRIBUTING TO THE EVENT?
Are there special event occurring on-site? Is attention otherwise focused on the plant?

Figure 8. The evaluation of risks is a judgmental activity. (Courtesy of FMPC.)

Emergency information systems

Information scarcity and overload is a problem often referred to during crisis or emergency situations. To improve the efficiency and effectiveness of the decision making process, several authors recommend using an emergency information system supported by computer technology (Nunamaker *et al.*, 1988; Sage, 1986; Wallace & DeBalogh, 1985). According to the MSM, an emergency information system must fit both the user and the operational situation (Baybutt, 1986; LeMay & Wild, 1988; Smith, 1987; Szewczak & Ramaprasad, 1987). Kurstedt and Mendes (1990) suggest a framework to monitor an organization's vulnerability to crises and use this framework to propose an architecture for a crisis information system.

Another application of technology in the emergency area is in training and simulation (Comfort, 1985; Mendes, Roach, & Kurstedt, 1989; Walker, Ruberg & O'Dell, 1989). However, computer-based simulation and training is but one particular aspect of the overall training needs relevant to crises and emergency response. These needs exist both at the response team (ASTM, 1986) and at the managerial level (Walker *et al.*, 1988). Complete training programs include, among others, field response drills, tabletop scenario exercises, and fully integrated emergency management exercises. Belardo *et al.* (1983) provide a discussion of an exercise based on the perceptions of the players. We will refer to this topic again, in the last chapter.

Overview of the methodology

This chapter provides a management perspective to modern aspects of control theory. Because there is a difference between a manager's view of control theory and exercising managerial control, we first summarize what control theory is about. Then we describe the kinds of variables control theory deals with, in general and in the particular case of this research. And finally we present the data and its treatment within this research.

A summary of control theory

As discussed, control theory has been looked at time and again as a device to model management situations (e.g., Simon, 1952; Forrester, 1961). However, results have fallen below expectations. A possible explanation is that further technological developments were necessary. Now, at the present stage of technological maturity, it is worthwhile to give control theory another chance.

The feedback control philosophy

Control theory deals with change. In Figure 2 on page 10 we show how managers use information feedback to manage change. Change is a system's response to an input. When we design a management system, we place emphasis on the type of input we are mainly designing for. The alternatives are:

1. to design for the ideal way the manager can respond to changing directives;
2. to design for the ideal way the manager can respond to environmental changes; and
3. to design for both.

Alternative 3 is the most realistic. Control engineers design controllers as a means for a plant to track (follow) a reference signal (directive) and respond to disturbances (environmental changes). Roughly speaking, the methodology to design a controller starts with the plant's open-loop response to different input functions. The open-loop response uses no feedback and no controller, only the plant's differential equations. If this response is not acceptable (e.g., if the open-loop system is unstable), we need a controller. We plug the inputs and the desired outputs into the feedback equations, we obtain the control law, and so forth. The feedback equations include the plant equations. The inputs are either a reference signal (set point) or a disturbance. To address alternative 3, we must know how to address alternatives 1 and 2.

Alternative 1 corresponds to "providing direction." This is looking at the manager as an implementer, as someone who wants to move the organization forward by seeking improvement in the operation. The directives are either self-generated or imposed on the manager. In the feedback control model, directives are the set-point or reference input. Depending on the size of the organization and the managerial level we are looking at, we may face a management system with low frequency response dynamics. That is, in large organizations, top-level management needs more time to implement policy changes than lower-level management.[14] Slow reacting systems are more difficult to study in practice, not only because of the total elapsed time required, but also because the complexity of the interactions involved makes it difficult to isolate the effects of specific decisions. Emergency response is (should be) a fast reacting management system and this is why we study it here.

Alternative 2 corresponds to "maintaining control." This is looking at the manager as a controller, as someone who wants to keep the operation stable, under control. In normal circumstances, managers have the operation running smoothly, in steady-state: they're in control. In an emergency, when sudden circumstances affect the operation, managers risk losing control.[15] Maintaining control calls for fast response to eliminate the effect of disturbances. Just as control theory is used to design industrial controllers for rejecting disturbances in physical plants, control theory can also be used to suggest ways to managers for eliminating disturbances in management situations.

While alternative 1 looks at a manager's performance when implementing directives, alternative 2 looks at a manager's performance when handling exceptions. For higher levels of management, intuitively, a study following alternative 2 is likely to require less time to perform. Therefore, this research will deal with modeling a management system for disturbance rejection, keeping in mind that the ideal would be to model also for implementation of directives.

The state space method

This research applies the state space method to model management control systems. The method describes dynamic systems using first-order differential equations with variables called state vari-

---

[14] This might be a topic (hypothesis) for research in management, but it is not the point here. The point is that we may have systems with slow and fast response (slow and fast modes in control theory terminology).

[15] The word emergency, in a broad sense, can mean any disturbance falling outside accepted tolerance limits. From a control theory standpoint, an emergency doesn't necessarily involve life, environment, or asset threatening situations.

ables. The *state variables* for a given system are the minimum set of quantities completely describing the system if (Figure 9 on page 51):

- when we know the values of the state variables $\mathbf{x}(t_0)$ at any initial time t_0, and
- we also know the values of the input sequence $\mathbf{u}_{[t_0, t_1]}$ up to the instant t_1 (with $t_1 > t_0$) then,
- for any time t_1, we can uniquely determine the values of the outputs $\mathbf{y}(t_1)$ and state variables $\mathbf{x}(t_1)$.

The state variables may or may not be directly measurable, but their value at a given instant (a state of the system) is sufficient to completely describe the system. In particular, the *state* of the system at any initial time t_0 is a set $\mathbf{x}(t_0)$ that uniquely associates an output sequence $\mathbf{y}_{[t_0, t]}$ to an input sequence $\mathbf{u}_{[t_0, t]}$ for any $t > t_0$. The solution of the differential equations is time-dependent, and may be described as a trajectory in a state space.[16] The form of the trajectory shows the system's behavior, namely its stability.

The usual practice to develop a state space model is to start with a mathematical description of the plant alone (in the form of a set of first-order differential or difference equations). As described in "Appendix A. Scenario narrative for "Joint Response 89"" on page 148, the emergency management exercise features a fire in a propane tanker that escalates to the release of a toxic gas, chlorine. So, the initial model of the plant contains equations for the heat wave and the dispersion of the gas in the atmosphere ("source" terms). In addition, the model contains equations describing the effects on people ("dose" terms). Describing the effects to the environment and assets is traded-off against keeping the model simple. The variables in all these equations are continuous. However, management interventions are discrete and the information managers receive is also updated in a discrete fashion. Therefore, we need to use a procedure to mathematically convert a continuous to a discrete system (VanLandingham, 1985). The general form of the discrete state space system is (Figure 9):

---

[16] Interesting graphical representations of trajectories appear in Abraham (1982).

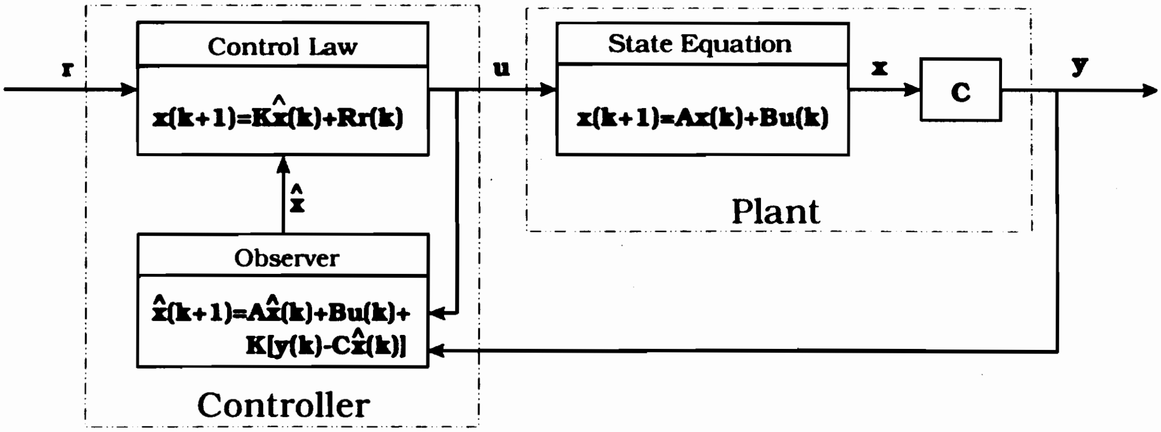


Figure 9. The controller implements the control law and the state estimator.

$$\begin{aligned} \mathbf{x}(k+1) &= A\mathbf{x}(k) + B\mathbf{u}(k) \\ \mathbf{y}(k) &= C\mathbf{x}(k), \end{aligned} \tag{1}$$

where k = time interval counter

$\mathbf{x}$ = $n \times 1$ column vector of state variables,

$\mathbf{u}$ = $p \times 1$ vector of control inputs (emergency response actions)

$\mathbf{y}$ = $q \times 1$ vector of system outputs (results)

A, B, and C = $n \times n$, $n \times p$, and $q \times n$ matrices of known coefficients, respectively.

Equation (1) reads "the next state depends on the previous state through matrix A and on the input through matrix B; the output depends on the current state." The state space method consists of two independent stages, each with several steps.

Before discussing the first stage, we can say upfront that we cannot do the second stage. The second stage is the design of a controller, referred to in the literature as prototype design (Franklin *et al.*, 1986). An explanation of prototype design involves technicalities beyond the scope of this document. Anyhow, we cannot yet tackle prototype design for a management system. To do this would require more knowledge about people than we actually have. But we can perform the first stage.

The first stage begins with a mathematical description of the operation and has three steps. The first step is to design an estimator or observer — a guess of what the system states are as a function of the measured output.

The second step is to determine the *control law* assuming we know the actual values of all state variables. The system's specification defines its desired dynamic behavior, i.e., its state trajectory; any deviations from such trajectory cause the controller to send corrective control inputs to the plant.[17] The control law are the values of the controlling input to the plant, as a function of the measured deviations of its state trajectory from a pre-assigned path.

---

[17] The controlling input to the plant corresponds to managerial action in the MSM.

The third step is to combine both, performing the control law calculations using estimated rather than actual states (Chen, 1984), as shown in Figure 9 on page 51. The figure relates the state space design elements already seen. The controller, the dotted box at the left, includes the state estimator and the control law. Looking at the controller as playing the role of the manager, this conceptualization is also intuitively appealing. The state estimator represents the manager's understanding of what goes on at the operation, and the control law represents the manager's decision on how and when to act.

Figure 9 also shows the reference input, **r**, previously referred to as "directives." The reference input has the same units as, and is compared to the system's output to determine the error to which the controller responds. The system's output, **y**, is converted into an estimate of the states, $\hat{\mathbf{x}}$. The control actions, **u**, are a function of the difference between the estimates of the states, $\hat{\mathbf{x}}$, (through the matrix *K*) and the reference input, **r** (through the matrix *R*).[18] This difference is one way to implement the comparator in Figure 1 on page 8.

In other words, the output of the controller is a function of the error, the difference between the system's output, **y**, and the desired output, **r**. In emergency management, the reference input is the desired status of the operation (zero people in danger, say). Finally, the sensors shown separately in Figure 1 are conceptually included in the matrix *C*; only those state variables provided with sensors can show up in the output. So, this matrix *C* tells how the system states influence the outputs. Omitting sensor dynamics means the information received at the EOC (at the controller) is perceived as accurate and timely.

This research deals only with the determination of the state estimator for a specific test case. But since we must begin with a mathematical model of the operation, the next section describes the possible variables we may include in the model.

---

[18] By hypothesis, after a short transient period, these control actions, **u**, generated by the mathematical control law will be identical to the control actions generated at the EOC ($\tilde{\mathbf{u}}$, say).

The variables

The typical terms independent and dependent variable may be misleading in the context of this research. These terms are also used in engineering, but they have a somewhat different connotation from the social sciences. More precisely, this research *will not attempt to empirically prove any relationship between dependent and independent variables.* (See "The hypothesis" on page 4.)

General groups of variables

As mentioned in the previous section, a state space control model handles three main groups of variables (Figure 10 on page 55): the state variables (**x**), the input and control variables (**u**), and the output variables (**y**). The control variables, **u**, are also known as manipulated or independent variables and the output variables, **y**, are also known as dependent variables; the state variables, **x**, are simply the states. As referred to at the outset, the meaning of the terms independent and dependent may be confusing, and we will not use them. Examples of possible states are the spatial concentration of gas or the spatial distribution of people. The state variables have physical meaning, but may not have managerial meaning. Some of these variables may change their values as the emergency evolves (e.g., the concentration of gas or the spatial distribution of people in the plant), others probably don't (e.g., the surrounding population). The dynamics of the system depends on the rates of change of all variables, although only a few may be of interest to management.

Examples of possible control variables (or controls) are the amount of spray water, the velocity of protection of people, the area warned for sheltering indoors (Wilson, 1986), etc. And possible output variables (or outputs) are the number of people endangered, their location, etc. "Appendix C. EOC Status Boards" on page 160 shows examples of variables actually used for emergency management purposes. Of these few variables — and we can have as many as needed — some may be

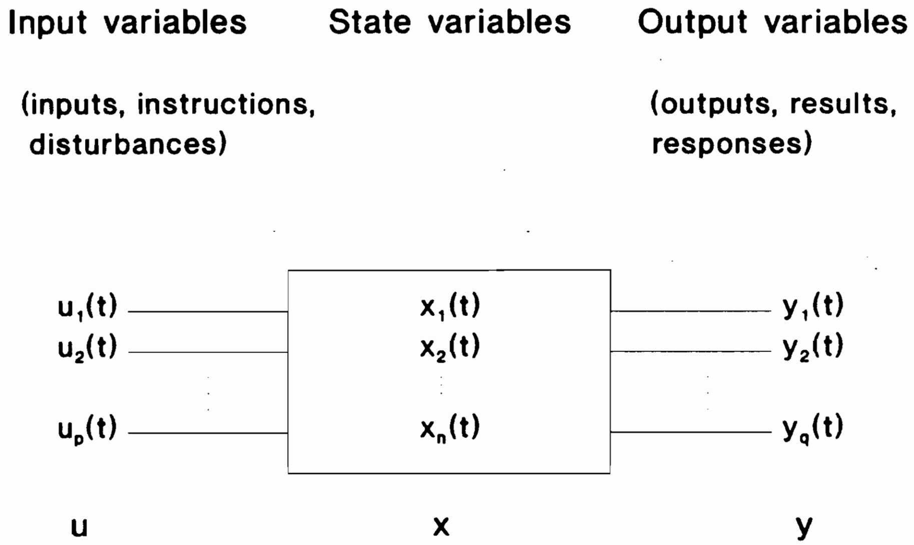


Figure 10. The model of the 'plant' involves three types of variables.

controlled and others not. The velocity and direction of a toxic gas cloud are observable but not controllable: there is little the manager can do to change them. The velocity of protection of populations can be controlled within certain bounds; the control action may be to activate the warning system, send transportation, open one-way roads, etc.

The state variables

The mass of propane: This variable enters in the source term for the heat wave. As described in "Appendix A. Scenario narrative for ″Joint Response 89″" on page 148, the tank is punctured and liquid propane leaks. VanAerde, Stewart and Saccomanno (1988) explain that either flash or pool vaporization may arise. Since the ignition is said to be (almost) immediate — according to Wiekema (1984), this occurs 25% of the time — we assume flash vaporization under continuous release: ″if the material from a continuous release meets with an ignition source immediately, a torch fire will likely develop at the release source location. The heat of this torch will evaporate virtually all liquid released such that no significant liquid pool forms″ (p. 379).

The heat released is a function of the *mass (m) of propane* available at each instant, the state variable x_1. Its initial value is the total amount in the tank. From the shipping papers (data from the exercise), 9002 net gallons of propane (approximately 17 tons[19]) were liquefied under 175 psi (approx. 12 atm) at 46°F. Knowing this initial quantity, we know the value of variable x_1 for time $t = 0$, $x_1(0) = 17.3 \times 10^3$ kg. The history of the system (values of all x_i) for $t < 0$ has no meaning (is not defined.)

The distance to damage: Fire and poison effects on people are usually assessed in terms of dosage received. Dosage is the accumulated effect over time. The contours of equal dosage intensity are called *isopleths*. For simplicity we reduce the isopleths to points on the center-line where we con-

---

[19] The density of propane is 4.235 lb/gal (Perry & Green, 1984, p.9-15). Therefore, 9002 gallons = 9002×4.235 lb/gal $\times 0.454$ kg/lb $\times 10^{-3}$ tons/kg = 17.3 tons.

centrate all the effects. As the event unfolds, we determine successive isopleths and compare them to the hazard thresholds. Hazard thresholds are maximum dosage values a person (or the environment) can support. We shall discuss both thermal and toxic thresholds later.

Field data are usually provided in terms of distance and direction using a polar coordinate system (ℓ, θ). The distance reached (isopleth location, ℓ) is an indicator of the severity of the event. The direction is the angle θ with the horizontal; for example, direction west corresponds to $\theta = 180°$ or $\theta = \pi$. (This is trivial and only stated here for completeness.) We use the same coordinate system, centered at the origin of the incident. Since the direction of the incident "front" is the direction of the wind for both the propane fire and the chlorine spill, we only need to calculate the distance to determine the position of the effect isolines, or isopleths.

In the spill case, the chlorine cloud spreads both by action of gravity and the wind. In the fire case, the flame expands mainly due to gas pressure, although the wind also contributes. The wind and the pressure/gravity effects are independent. Therefore, we account for the *distance to the damage:* through the second state variable x_2, the "cloud" *radius* (R) assuming perfect shape (wind-independent). The initial condition is $x_2(0) = 0$.

Elapsed time: As previously stated, dosage is the accumulated effect over time. For dosage calculation purposes we need to know how much time has passed since the beginning of the event. The *elapsed time* (t_e) is the third state variable x_3, with $x_3(0) = 0$.

Accountability: The two main methods for protecting people are sheltering and evacuation. Coordinating the protection of on-site personnel requires accounting for all people within the range of the emergency.[20] Only then is it possible to determine if anyone is missing who might still be in danger, and where that person is supposed to be. Even in the case of fatalities, it is important to tag unrecognizable bodies according to the place where they were found, to facilitate later identification

---

[20] Accountability is the (possibly specific) emergency management term for counting people.

(Stinton, 1983). At FMPC, accountability guidelines assign "Facility Owners" the responsibility for initiating and maintaining adequate accountability procedures.

For the purpose of this research, the site and the surrounding area are divided into sectors centered around the accident point (145 sectors total). The population counts within each sector, P_j, are the next state variables, x_{j+3}. Handling such a large number of variables is not a conceptual problem from a state space standpoint. But to simplify, without loss of generality, we select only those sectors along the wind direction, and assume the wind does not change direction throughout the exercise. This assumption is almost always wrong. However, it reduces substantially the number of variables and does not interfere with our objective of comparing the open- and closed-loop models. (Both are identically affected.) So, for any given wind direction, the initial values $P_j(0)$ are obtained later under "Accountability data" on page 75.

The concentration of chlorine: This variable enters the source term for the plume dispersion. Chlorine is a dense, toxic gas widely used in chemical operations. It is handled as a liquefied gas and stored and transported in containers of various sizes. FMPC uses 100-lb cylinders, but 150-lb or 1-ton cylinders are also common (Gephart & Moses, 1989). When containment is lost and liquid is spilled, Marshall (1982) estimates that some 25—30% will immediately evaporate and form a gas cloud. In our case, since the loss of containment (in one cylinder) is caused by fire, we can conservatively assume the amount of chlorine in the cloud is the amount stored. The cloud of gas will use a "dispersive mechanism" to get from the point of release to the impact point. The toxic effect is then a function of the local concentration of gas.

Chlorine concentration varies with the distance along the center-line of the plume (cloud), which has the direction of the wind. A two-dimensional coordinate system is sufficient for the purpose of this research, although a more sophisticated three-dimensional representation would be better (Jacobsen & Magnussen, 1987). Instead of a continuous variable, we consider average *chlorine concentration* values (c_j) within each sector as the next state variables, x_j. The initial values are $x_j(0) = 0$.

The output variables

Figure 9 on page 51 shows the relationship between the states and the output variables. In a given system, the states may be unknown because they cannot be measured; only those states that can be measured constitute the outputs **y**. In the control loop provided in Figure 1 on page 8, the sensors only apply to those variables that can be measured.

Hazard assessment: Concerning risks to people, Urquhart and Heilmann (1984) provide a useful and easy way to measure hazards. They relate the number of people at risk to the number of victims as "1 harmful event occurring among so many people at risk, during a sensibly selected period of time" (p. 43). The time interval they use is either one year or an event of usually short duration considered a special hazard. They add:

> the important element... lies in the essential simplicity of the two numbers which are used in [this] method. Everyone knows what the number 'one' means: it means that the event in question happens either to you or to some*one* else. It is also easy to comprehend the meaning of the other number. It is very much like one's class picture — there you are in the middle of a large number of people who all have something in common.... In the 'risk picture,' as in the class picture, everyone shares participation in some particular activity. It is not a picture of every single person who participates in the activity, but only of the number of people whose participation in the activity will, on the average, produce one victim during a defined time interval.

They designate this group by the term *unicohort*. For example, the unicohort at 1% mortality chances in an accident is 100; at 50% mortality chances, the unicohort is 2. The smaller the unicohort, the larger the risk. Here, we are not directly interested in this figure but rather in the actual number of people at risk. That is, we are interested in the number $\zeta = \frac{\textit{population count}}{\textit{unicohort}}$. For simplicity, we still call this ratio unicohort. So, the first output variable is $y_1 = \zeta$, with $y_1(0) = 0$. The objective of the emergency management system (control system) is to maintain $\zeta(t) = 0$ (respectively, $y_1(t) = 0$) for all t. Without emergency response (open loop system), the unicohort depends on the population counts at different places and is obtained as follows:

1. identify curves (equations) of equal probability of injury as a function of the physical intensity (probit equations or probability isolines);

2. for a selected probability, estimate the hazard progression as successive points (curves) of equal intensity of physical effect (isopleths);
3. determine the hazard front for the selected level of severity as the distance from the center of the incident to its isopleth; and
4. evaluate the population counts within the range of the hazard front.

Other output variables: The other variables that can be measured are the *elapsed time* (y_2) and the spatially distributed *chlorine concentrations* ($y_3, y_4, \ldots$). Again, we ignore the dynamics of the sensors that measure these variables; that is, we assume the information received is neither lagged nor distorted.

The control and input variables

Control variables: Control variables are the inputs to the plant produced by the controller. Control variables are also called internal inputs or *endogenous variables,* a term borrowed from the social sciences. These internal inputs aim at modifying the plant's behavior to prevent an increase of, or to cause a decrease of the unicohort. The system focused on in this research is peculiar in the sense that, to some extent, in the absence of "physical" input the plant will still behave as if it had received such input. As a trivial example of this behavior, people run away from a fire without anyone telling them to do so. Actually, in many industrial plants running is forbidden, except when escaping from a fire or flammable vapor (Prugh & Johnson, 1988).

Running is an adequate response to the event we are dealing with because, on average, flash fires produce low flame speeds: "flames progress at 15 feet (5 meters) per second through a large cloud, a rate which is about one-half the speed of a desperate man; running 100 yards (90 meters) in 10 seconds will allow a man to travel 30 feet (10 meters) per second" (Meidl, 1978, p.129). We generalize this concept by defining a control $u_1(t)$ representing the velocity of removing people from affected areas (e.g. during an evacuation.)

Alternatively, in the case of the gas release, people may be warned to take a shelter, to remain in place although protected. Published data on sheltering effectiveness is scarce (e.g. Farmer, 1984; Wilson, 1986). The effectiveness of a shelter depends on its infiltration rate I, expressed in air changes per hour (ach). An average value is $I = 0.5$ ach (Wilson, 1986). The reciprocal of the infiltration rate is the shelter time constant, $\tau = \frac{1}{I}$ hrs. That is, the time constant is the ratio of the air volume in the steady state to the ventilation rate. Besides being a shelter effectiveness indicator, the time constant is also a good indicator of process characteristics for control purposes. Again, we generalize the concept of time constant into a control variable, $u_2(t) = \frac{1}{\tau} P_j(t)$, that accounts for the effectiveness of protecting people (e.g. emergency crews with protective suits). Recall that P_j is the population count in sector j.

External inputs: External inputs are also called *exogenous variables* and are sometimes represented using a different symbol, say v. To keep the model simple, we maintain the symbol u. The only external input we use is the initial concentration of chlorine at the point of release, $c_0(0)$. This input can be modeled in many ways, for instance (1) as an instantaneous release, $u_3(t) = c_0\delta(0)$, (2) as an uniform release of duration k, $u_3(t) = c_0(1 - \mathrm{u}_k(t))$, or (3) as any other arbitrary function.[21] The constant $c_0 = 3.1\ \mathrm{kg\,m^{-3}} \simeq 10^6$ppm is the undiluted amount of gas per unit volume. We obtain this initial value by applying unit conversion factors to the liquid-gas volume relationship — one pound of liquid forms about 5 cu.ft. of gas (The Chlorine Institute).

Wind velocity (w_θ) and *wind direction* (θ) are also possible external inputs, $v_2(t) = w_\theta(t)$, and $v_3(t) = \theta(t)$. These could be candidates for state variables if we were modeling the atmosphere, but that is not the case. Fluctuations in wind direction and velocity can be seen as disturbances to this model of the physical system describing the emergency, whereas the emergency itself is a disturbance to the facility's production. However, for simplicity again, we ignore those variations in this research.

---

[21] The function $\delta(t_0)$ is the Dirac delta function, with properties $\delta(t - t_0) = 0$, for $t \neq t_0$, and $\int_{-\infty}^{\infty} \delta(t - t_0)dt = 1$. The function $\mathrm{u}_k(t)$ is the unit step function, defined for any $k \geq 0$ as $\mathrm{u}_k(t) = \begin{cases} 0, & t < k, \\ 1, & t \geq k. \end{cases}$

Summary

This section related feedback control to management and introduced the particular method, state space, followed in this research. For reasons that will be explained later, some of the variables just defined will be redefined. But for the time being, this is a complete list. The state variables chosen are:

x_1 = mass of propane (m),

x_2 = effect radius (R),

x_3 = elapsed time (t_e).

$x_4, \dots, x_{n+3}$ = population counts (P_j), .

$x_{n+4}, \dots, x_{2n+3}$ = concentrations of chlorine (c_j).

The control and input variables are:

u_1 = velocity of removing people

u_2 = people protection effectiveness

u_3 = initial concentration of chlorine ($c_0\delta(0)$).

The output variables are:

y_1 = unicohort ($\zeta \equiv \sum_j x_j, \quad j = 4, \dots, n+3$),

y_2 = elapsed time ($\equiv x_3$).

y_3 = effect radius ($\equiv x_2$),

$y_4, \dots, y_{n+3}$ = concentrations of chlorine ($\equiv x_{n+4}, \dots, x_{2n+3}$),

The treatment of the data

The objective of this research is to compare the behavior (output) of a control model with the behavior of a management system subject to disturbances (Figure 3 on page 11). The behavior of the management system is obtained directly from the emergency exercise data.

Types of data

This research involves three types of operational data from the emergency management exercise:

- physical data, registering the environmental conditions on- and off-site;
- managerial data, registering the chronology of the actions performed by the players; and
- accountability data, registering the number of people within an area of concern.

The *physical data* describe measurements of wind direction (θ) and velocity (w_θ), and concentration of toxic gas (c). Site data are gathered by automatic instrumentation towers directly connected to the computer in the EOC. Off-site data are collected by monitoring teams and transmitted via portable radio. As seen in "Appendix C. EOC Status Boards" on page 160, most of these data are then registered and portrayed at the EOC.

Managerial data describe the actions taken by the exercise management team (e.g., order sheltering). These data are produced by the exercise players and captured in three media: (1) on videotapes, (2) on *Display Request Forms* at the EOC (ultimately transcribed to the Status Boards), and (3) on evaluator log sheets. Telephone calls and other message exchanges not recorded on any of these three media cannot be retrieved. By hypothesis, these data can be compared to values of the control variables, $\mathbf{u}$.

Accountability data describe population counts (ζ), both within and outside FMPC. Of special concern is injured people whose mobility is restricted. This category includes all data about movements of personnel (in and out of the incident scene) and is captured in the same three media as managerial data.

Organization of the data

The data from the exercise are provided on:

- evaluator log sheets,
- photocopies of "Display Request Forms," and
- a computer log printout.

Gathering all these forms is not enough for the purpose of this research. Organizing the data requires two additional operations of sorting and selection, as described later under "The data-handling procedure" on page 66. Contrary to expectation, no videotapes were made available for this work. The lack of this important data source constrains some of the modeling decisions and affects the sorting and selection operations. The purpose of these two operations is to build a *time series* for each variable. A time series is a collection of data $Z_{t_k}(k = 1,2, \dots , N)$, with a fixed or variable sampling interval $\Delta_k = t_{k+1} - t_k$, where the order in which the observations appear is relevant. These time series are used for hypothesis testing purposes.

Hypothesis testing

The dynamic, time-dependent nature of control theory requires a series of chronologically identified data points: the time series. This research leads to a *longitudinal study* — the study of a system using data in a specified temporal order.[22] This research does not compare different management systems (a population). This research compares a model to a single management system when the change of one variable causes a change in observed values. Symbolically (Leedy, 1985),

$$O_1 \rightarrow O_2 \rightarrow \cdots \rightarrow \cdots O_j \rightarrow X \rightarrow O^*_{j+1} \rightarrow \cdots \rightarrow O^*_{N-1} \rightarrow O^*_N, \qquad (2)$$

---

[22] We refer to a longitudinal study, as opposed to a cross-sectional one. If more than one management system is involved, then we talk about doing multiple longitudinal studies.

where O_i = observations (e.g., values of the unicohort y_1),

X = change in the independent variable (e.g., start of an emergency response action u), and

O_i^* = observations of the same variable of different magnitude or slope (e.g., y_1 close to zero).

There are two main groups of time series, corresponding to the groups of variables supported by the data. As described, one of the groups contains the set of measurements (y) and the other group contains the set of actual managerial actions ($\tilde{\mathbf{u}}$, say). The purpose of this research is to build an algorithm (model) that can predict the last terms of the **y** series, when fed with the initial terms.

The objective of the management system is to obtain particular values of O_N^*. The hypothesis for this research is that we can build a control theory mathematical model that mimics the behavior of the management system, whether the management system accomplishes its objectives or not. We test this hypothesis by comparing time series data from the exercise with the time series generated by the model for the same situation. Although no formal test is available, we can still perform a cross-covariance and spectral analysis of the time series data and the model results.

The data-handling procedure

This chapter is about the data available for this research and its manipulation, a topic already introduced in the previous chapter. Here, we begin with a description of the ″normal″ operating environment or steady state — ultimately, the management goals concerning the response to the particular incident under study. In an information feedback context (Figure 3 on page 11), data on different physical media have different meanings, so we discuss those. But since the data is not directly suitable for this research, we describe the operations necessary to make it so. At the end we show the time series data resulting from the exercise documentation.

The operational environment

The meaning associated with a given piece of data is context dependent. In particular, to interpret data from an emergency exercise, the difference between the emergency and normal operating conditions (steady state) must be clear.

The steady state

The hazard level is the probability of ″something″ happening. Eventually, this probability depends on the specific activity (some activities are more risk prone than others), on the shift (worse for night shifts), or on equipment age (worse for recent or old equipment). To define the steady state, we level off these time-related dependencies to an arbitrary ″zero″ hazard level under regular operation. Before the incident, the hazard level throughout the plant is time-invariant under daily operation. When the incident occurs, the immediate risk for some people becomes higher; it deviates from steady state. So, we infer the following

Performance measure: *Management's primary objective is to maintain individual risk levels at zero, either by neutralizing the sources of danger or by protecting people.*

We evaluate the possibility of a person being killed or injured when modeling the emergency management exercise in this research. (See Farmer (1984) for other viewpoints.) The populations in the FMPC area (Figure 11 on page 68) share different degrees of risk. This is recognized in Figure 12 on page 69, which shows the Immediate Notification Zone (INZ) and the 5-mile emergency planning zone. (Notice the siren locations.) These zones are delimited by the network of roads that are the closest, from the outside, to the nominal distance circles.

The steady state, or static model concerns the study of a system in equilibrium. Control is necessary because we cannot (or do not want to) maintain steady state permanently. As previously described, under "The feedback control philosophy" on page 48, this research deals with modeling a management system whose objective is to regain steady state after a disturbance occurs. The disturbance is the particular incident simulated in the exercise. So, steady state operational data are also the initial conditions for the control model.

Other steady state quantities: For environmental quality, the steady state values are zero levels of concentration of hazardous materials. Ultimately, a zero concentration may not even exist in na-

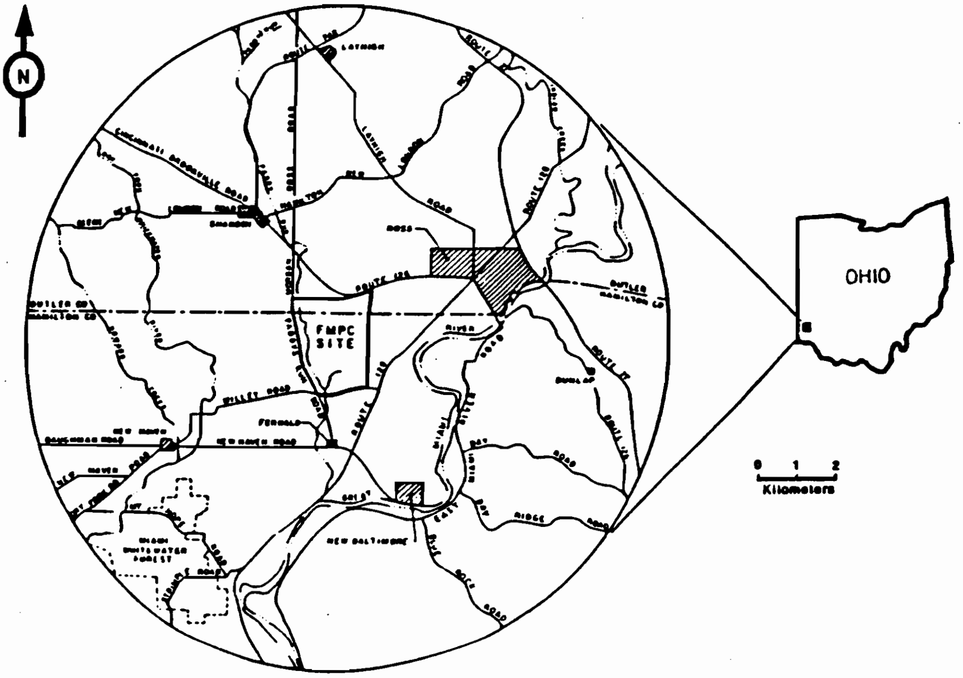
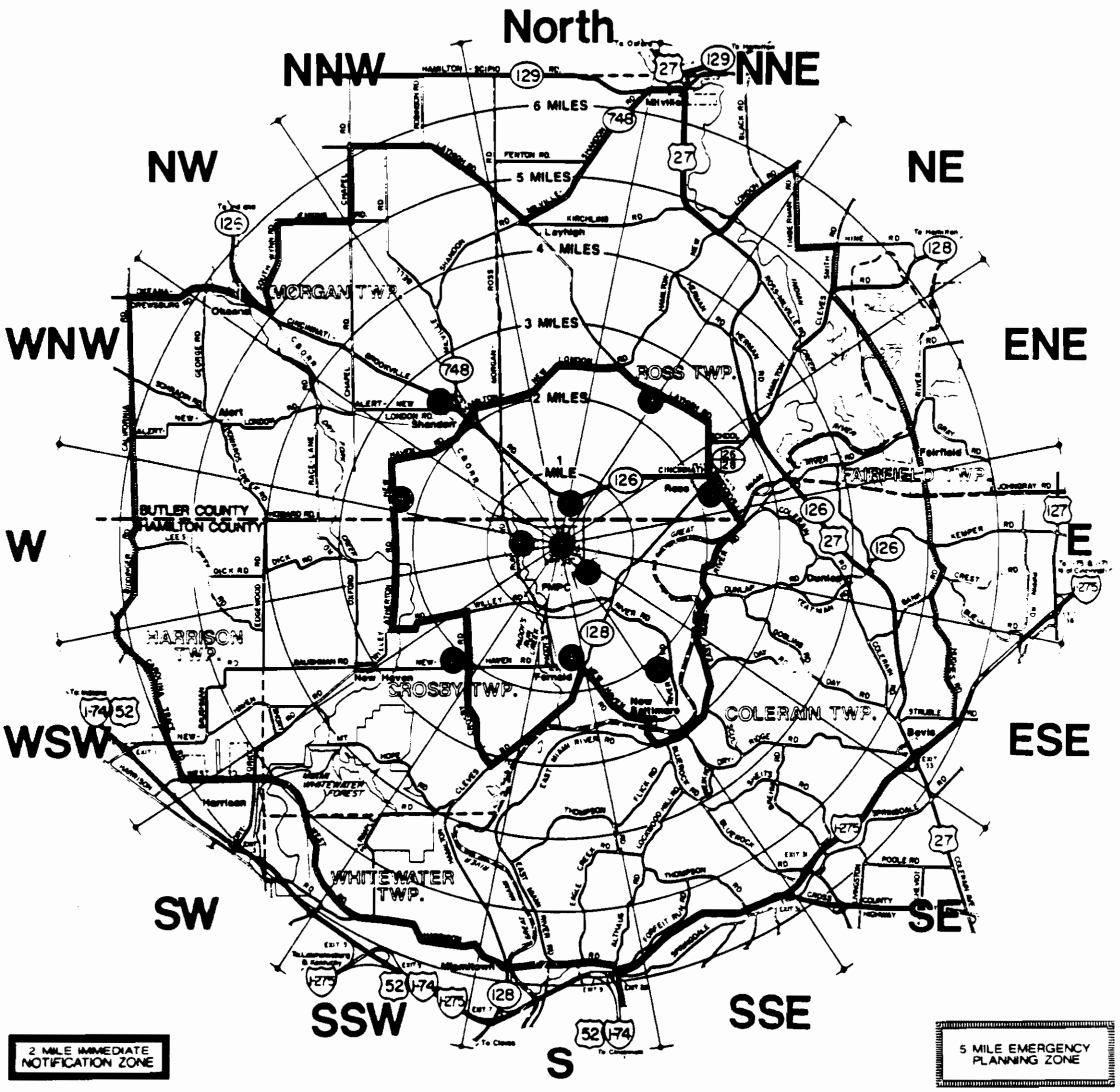


Figure 11. FMPC is located in a scarcely populated zone. (Courtesy of FMPC.)



● SIREN LOCATIONS

HAMILTON COUNTY	BUTLER COUNTY
1. FMPC Central	7. Morgan Township Fire Department
2. Crosby Elementary School	8. New Haven Road
3. New Baltimore	9. Layhigh Road and Windy Knoll Drive
4. Webb's Flea Market	10. FMPC North
5. FMPC Southeast	11. Ross Township Fire Department
6. FMPC West	

Figure 12. Emergency sirens are within the 2 mile immediate notification zone. (Courtesy of FMPC.)

ture. In practice, values within the limits specified by the regulatory agencies or advisory entities are adequate when regaining steady state. The American Industrial Hygiene Association recommends 1 ppm of chlorine as ″the maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to one hour without experiencing other than mild, transient adverse health effects or without perceiving a clearly defined objectionable odor.″

Response

The propane leak: The major risks associated with the tanker accident are the occurrence of an explosion, as discussed in "Extending the emergency model" on page 140. The recommendations to face this possibility include (DePol & Chereminisoff, 1984):

- Letting the gases burn that are already on fire,
- Cooling the tank vapor space using a minimum of 500 gpm,
- Approaching the site only after cooling is established, and
- Evacuating 3000 ft in all directions.

The first two recommendations were followed at the scenario level, although we ignore the amount of cooling water used. We may assume the third recommendation was also followed, and so was the fourth. Although the scenario did not call for an explosion, people in the EOC were aware that an explosion was possible and reacted to that possibility. This is shown later under "Managerial data" on page 86.

The chlorine release: The failure of a rupture disk is the only precaution against the heat-induced catastrophic destruction of a pressurized toxic gas cylinder. In other words, toxic gas containers do not have safety pressure relief valves. The Chlorine Institute provides emergency procedures to handle chlorine releases. These procedures and also mutual-aid are available from the *Chlorine Emergency Plan (CHLOREP),* activated through the 24-hour hotline **1-800-424-9300** (DePol &

Chereminisoff, 1984). Data from the exercise shows evidence that these contacts were considered: one player's log contains a request to the operations tactic group to "identify handling precautions for potentially damaged cylinders."

For specific countermeasures and on-site actions, these same authors quote *The Chlorine Institute* saying "in case of fire, chlorine containers should be removed from the zone immediately.... If no chlorine is escaping, water should be applied" (p.63). These actions are prevented at the scenario level by making the cylinders inaccessible and later causing one to fail. Prugh and Johnson (1988) discuss using water, steam, and air curtains, but exercise data is confusing about these. For instance, one of the evaluators in the field reports that "deluge at NH3 tanks did not work."

The emergency response: Still according to Prugh and Johnson (1988), in addition to or in the absence of measures to control releases at the source, protecting people is the most likely response action. The components of a protection system include:

- warning and communications;
- emergency shutdown routines, where applicable;
- site evacuation and accountability procedures; and
- rescue and mutual-aid.

Performing emergency shutdown procedures was also considered at the EOC through a request to the operations tactic center to "confirm safe shutdown of process facilities." These actions were paid minimal attention because they were marginal to the exercise. The objective of these emergency exercises is to practice response actions for people protection. As mentioned under "Control variables" on page 60, the potential responses are on-site evacuation and sheltering. Conceptually, we can use the term evacuation in the broadest sense to include running away from fires and transportation of injured.

Intermediate rally points help organize site evacuation operations. Figure 13 on page 73 shows intermediate gathering places at FMPC. Using intermediate rally points helps implement accountability procedures. When all people who are supposed to gather at one place are accounted for, that message (or the badge numbers missing) is sent to the Communications Center.

Rally points are not used in the case of a sudden gas release. In that case, people are instructed to take shelter in the nearest building. We assume industrial buildings to have an infiltration rate identical to a regular house, 0.5 air changes per hour. According to Wilson (1984), this means that after two hours, 63% of the original indoor air is replaced by contaminated outdoor air. Anyway, a puff release episode is supposed to last for much less than two hours.

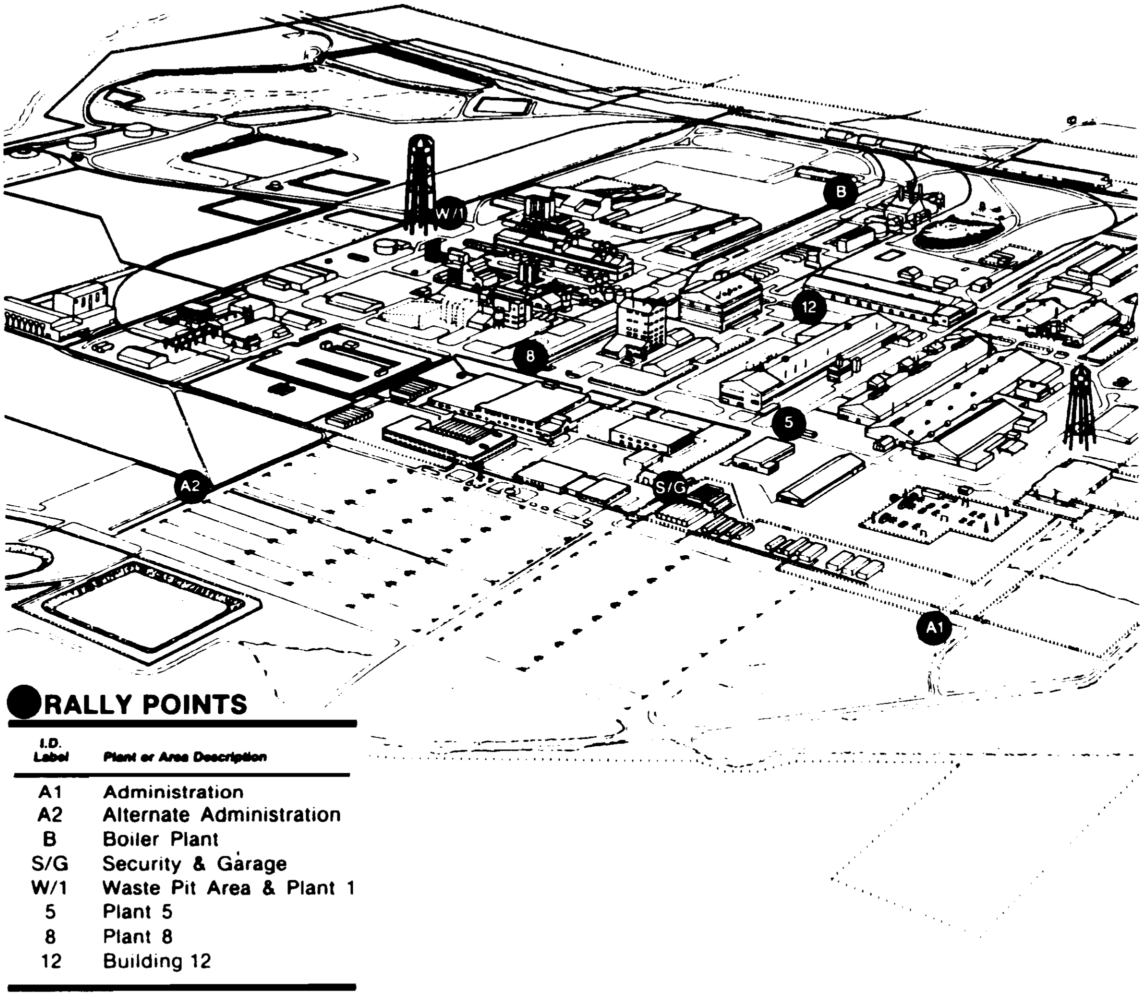
Types of data

Recalling from the "Overview of the methodology" on page 47, this research involves three types of data from the emergency exercise:

- physical data,
- managerial data, and
- accountability data.

Physical data

Wind parameters: Even during normal operation, data about wind velocity (w_θ) and direction (θ) are collected at 10 m height by automatic instrumentation towers directly connected to the computer in the EOC. One of the people staffing the EOC is a meteorologist, who is in charge of running the HARM I computer plume model. This person can provide current readings, either at



●RALLY POINTS

I.D. Label	Plant or Area Description
A1	Administration
A2	Alternate Administration
B	Boiler Plant
S/G	Security & Garage
W/1	Waste Pit Area & Plant 1
5	Plant 5
8	Plant 8
12	Building 12

Figure 13. Rally points help organize site evacuation. (Courtesy of FMPC.)

regular time intervals or upon demand, to update board #1 (in "Appendix C. EOC Status Boards" on page 160).

Field measurements: Data about concentrations of toxic gas (*c*) or presence of explosive gases are gathered by monitoring teams either on-site or off-site. The teams carry portable radios to transmit their readings to the Communications Center, which in turn is in contact with the EOC. Anecdotal knowledge from other meteorologists suggests there is some controversy about whether field data should or should not be input into the models.

How to use field data is often a judgment call. HARM I is a Gaussian model, and these models produce average results. We know field measurements can be in error. So, unless people in the field take special precautions, there is no strong reason to prefer an instantaneous reading from the field over a program-computed value. The most common approach is to use field data to help interpret the results from the model. We don't know for sure what practice is followed at FMPC, what data ends up being posted in board #2. But for this exercise it makes no difference whatsoever, because most (simulated) field data did not reach the EOC.

Event chronology: The data concerning the unfolding of the exercise are an exception to field measurements. These data provide elapsed times for hazard calculations, and concern no other variables. In principle, the sequence of events is set up in the exercise scenario. However, the scenario is more a guide rather than a detailed schedule. The differences start from the very beginning, but the "actual" time stamps are available from the EOC log and other logs. Another use of these data is to assign a time to initial values of other variables. In both the propane fire and the chlorine release, the amounts initially stored in the tank and containers are available from the scenario documentation. The logs provide the points on the time line to place these values.

Managerial data

Data about actual management actions ($\tilde{\mathbf{u}}$) were captured (1) on videotapes, (2) on players' and evaluators' log sheets, and (3) on *Display Request Forms* in the EOC. Before they are transcribed to the Status Boards, these latter forms are also input to a computer and transmitted to DOE's Oak Ridge Operations Center (OROC). Similar to accountability data, the exercise videotapes were not available for this research. But the computer log printout is available (in "Appendix B. EOC computer communications log" on page 152) and copies of the messages sent to OROC are available too. As an extension to this research, these data about managerial actions can be compared to values of the control variables **u** generated by a control model.

Accountability data

The average number of people within and outside FMPC is the steady state value for accountability purposes. Based on Table 1 on page 76, the proportion of the population vulnerable to toxic gas emissions is roughly 25%. These details are not used by FMPC management, at least during exercises. After all, detailed information about the offsite populations is more a concern of the surrounding counties than of FMPC.

On-site population mix: As discussed under "Accountability" on page 57, the site and the surrounding area are divided into sectors centered around the accident point. Figure 14 on page 77 and Figure 15 on page 78 show the number of people (population) at increasing distances from the center of the accident. These are average values only, and the figures trade off accuracy against conciseness by considering uniform population densities within each sector. Clearly, more or fewer people may be in a particular building at a given instant, some may travel between buildings, and some may even work outdoors. For the population living and/or working offsite, the numbers are even more difficult to obtain. "The information required includes the number of people normally

Table 1. The vulnerable population is a subset of the average population. (Source: Withers & Lees, 1985, citing Hewitt.)

Sub-population	No. per 1000 people
Children < 6 months	8
< 12 months	8
12 months - 5 years	75
5 years - 9 years	82
Old people > 70 years	85
People with chronic heart trouble	5
People with respiratory illness	9
People with restricted mobility	4
Blind people	2
Healthy youngsters and adults	722

resident in the area, the numbers who go out of and come into [the] area at different times of the day, the proportion of people particularly vulnerable to the hazard, and the proportion of people outdoors" (Petts, Withers, & Lees, 1987, p.337).

The inner circle in Figure 14 on page 77 is conceptually large enough to contain the accident and the seven people initially involved, yet small enough (say, 10m) to contain no one else. Overlooking the lack of precision introduced by this inner circle, the other four are at 1/8th mile each; the outer circle is 1/2 mile distant from the center. Figure 15 on page 78 shows the surrounding populations using a similar representation. The region is sparsely populated. The innermost sectors account for the number of people between the border of Figure 14 and 1 mile. We assume the hazard does not reach beyond the outer circle, 5 miles away from the accident. So, in this case there are also five sectors per wind direction.

Regardless of the wind direction chosen, we need to consider two additional sectors. One corresponds to the location of the field command post. The other corresponds to the location of the triage center.[23] These are two "floating" locations that may coincide with each other or with any

---

[23] Triage is the operational and dispatching center for health care where wounded people receive immediate treatment, are tagged according to the severity of their state (red, yellow, and green), and are assigned a means of transportation to an hospital, if required.

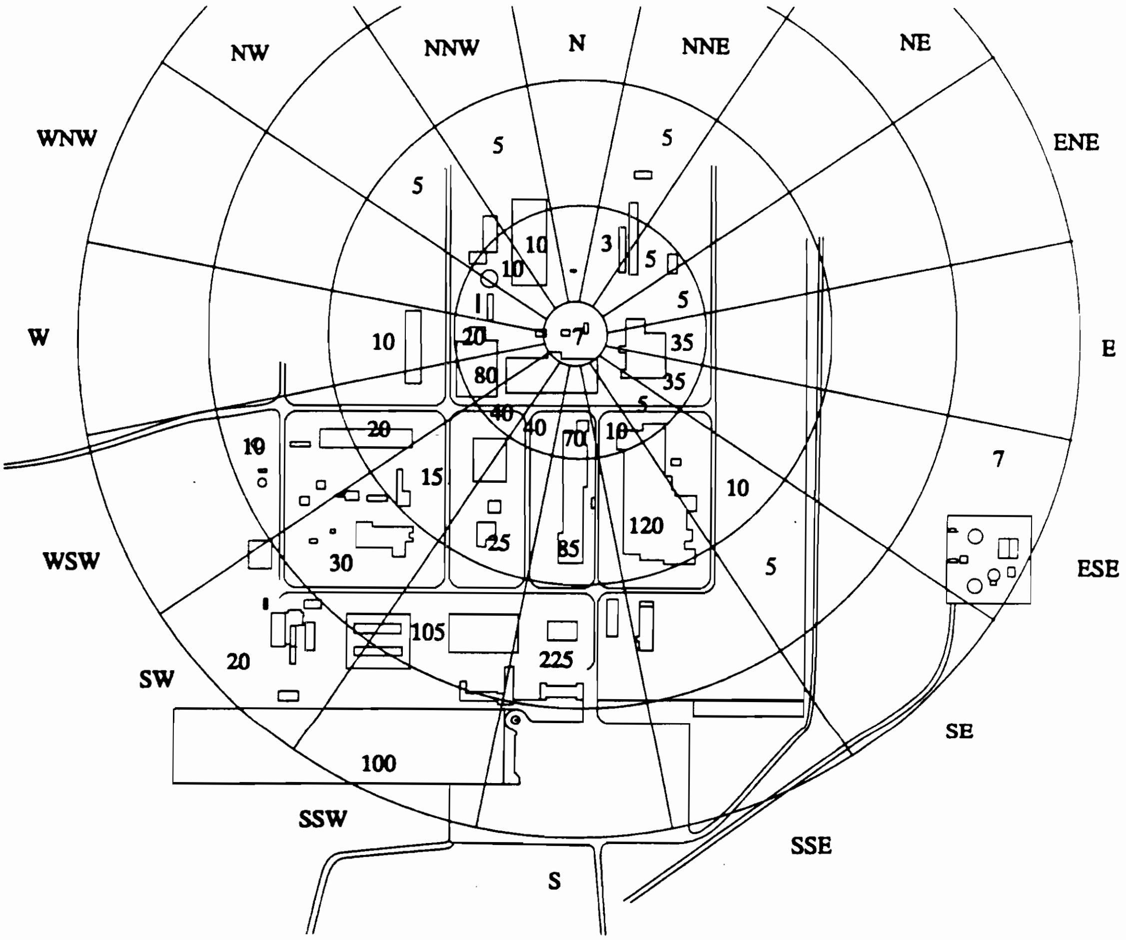


Figure 14. Rosters of building occupants kept by "Facility Owners" provide on-site population counts. (Courtesy of FMPC.)

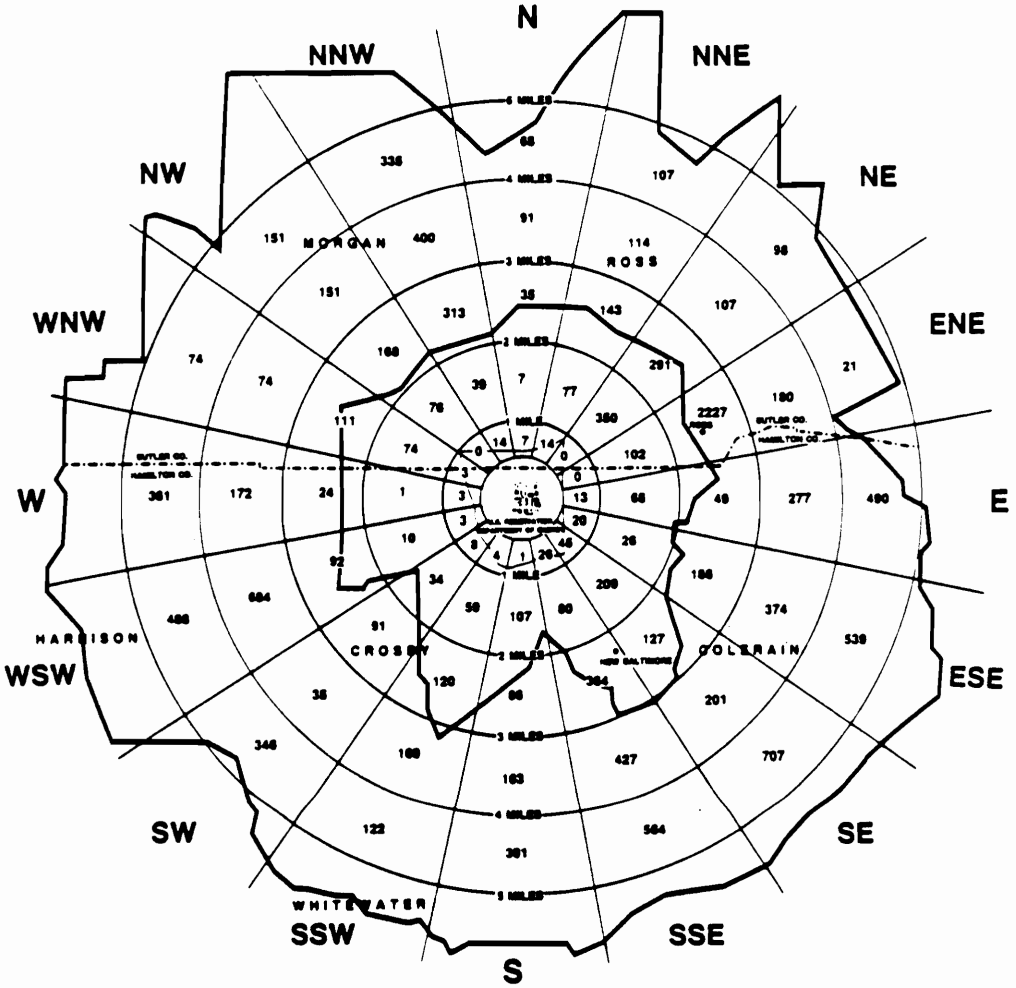


Figure 15. Population densities vary within the site area. (Courtesy of FMPC.)

sector along the wind direction. Regardless of where the sectors are geographically located, we keep a balance count for each of them, starting with zero casualties in each one. The sectors are:

0. Accident center
1-4. Plant sectors along the wind direction
5-9. Surrounding area along the wind direction
10. Command post
11. Triage

Data for initial population counts ($\zeta(0)$) within FMPC are available from Figure 14 on page 77. Those data are not accurate, they are only an educated guess. Since the actual data were not made available for this research, it became necessary to use the knowledge of MSL people familiar with the site. The accuracy of these data should not impact this work, but this assertion is not backed up by sensitivity analyses.

In an industrial setting like FMPC, it is reasonable to assume that most employees belong to the regular population. The exceptions are likely to be the handicapped, if any. After an accident, they and the injured people are those whose mobility is restricted. Handicapped people are usually assisted and trained to evacuate buildings quickly. As protective actions take place, remaining unprotected people become a "highly vulnerable" population. As expected, those people become a focus of attention.

The Accountability Center is integrated with the Communications Center. Its mission is to locate those people missing at some rally point (e.g., because at the time they were in a building assigned to a different rally point). When all people supposed to be in a certain place are accounted for, the EOC is informed. Accountability procedures are a means of shifting attention from the overall population to individuals. Initially, a rough population count is adequate to convey a picture of the situation. But after an incident unfolds, only those "high risk" individuals are considered. Their situation is monitored until they are properly cared for and their families notified. All those data are transmitted to the EOC via Communications Center and normally end up posted in board #3.

Off-site populations: Data for population counts (ζ) outside FMPC are available from Figure 15 on page 78. Those data are official (from FMPC), but they may be outdated. Although these populations are not directly under FMPC's responsibility, they are still a concern. One of the first actions following an accident is to notify county officials. The counties establish hotline numbers everyone can call in case they need assistance. The counties are also in charge of the evacuation procedures, if required. Besides notification, FMPC's role consists of activating the sirens and recommending protective actions, like blocking roads or evacuation. In the materials available for this research, there was no evidence of any data about outside populations being provided to the EOC.

Operations on the data

The data from the exercise is not organized for the purpose of this research. The series of operations described next act on the data to make it usable.

Sorting

Sorting the data is making sure all forms are in proper sequence to form a time series. The evaluator sheets and the display forms are assembled in random order although often (but not always) properly identified with time and source. Since the time stamps for some of the events are not precise, all information from different sources needs to be matched together. (This matching may be considered yet another operation on the data.) The computer log is not in sequence either. In addition, the information it contains may have been delayed when received at the EOC. Therefore, sorting the data requires matching and sequencing the contents of all forms.

Sorting strategy: The data are sorted by time stamp. A datum available from one single source (e.g., an evaluator log) is ranked according to its time stamp. Identical data available from more than one source are collapsed into a single datum and ranked by the earliest available time. There is a reason for this procedure. We have no means to know when the DED (″who manages″) receives a piece of information. Since people are paying attention to different things, some may be slower than others in noticing a particular item, and that may account for different time stamps. But, ideally, the information is available as soon as someone logs-in the data.

Problems encountered: Obtaining data from the evaluators′ log sheets requires making some decisions concerning their inclusion in the final data set:

Problem	***Description and decisions***
Illegible	Discard.
Bad time stamp	Some of the logs are from people who simply capture events without writing on the time column; those logs end up showing as simultaneous events that other people place far apart in time. Therefore, 1. Accept if confirmed elsewhere, or 2. Discard if no other source available. These data are an exception to the ″earliest time″ rule.
No EOC source	Inspection of several documents suggests that people in the field ″generate″ information and that some information they produce never surfaces in the EOC. Of course, most communications are made by radio or telephone and most are never registered either at the source or at the destination. Therefore, 1. Accept if incoming information, or 2. Discard if directive to the field. The decision about whether an item is a directive or operational information is based on content.
Inconsistent	Different sources may report different data with identical time stamps. Therefore,

1. Accept those data points that can be confirmed, otherwise
2. Discard.

Selection

The second operation on the data is to screen the forms to identify references to the variables used by the state-space model (e.g., number of people in a certain location). For example, a message posted on Board #6 saying "0942 — Total medical available: 5 ambulances, 1 air care helicopter" is of no interest because the control model does not deal with resources. Another message on board #6 saying "0915 — Request second ambulance to propane storage. Unit was sent." may be useful to determine action delays, but not to assign values to variables. However, the message on Board #3 "1004 — Badge 798 in route to Mercy Base" tells us to decrease by one the number of people in Triage at that time.

Selection strategy and operations: The only data selected are those that can be converted to a numerical value and are related to people protection or population counts. The data selection operations are:

Operation	*Description*
Uncovering	Consists of making up data from an implicit message. For example, "0843 — Accident ... Multiple Injuries" (DOE Site Mgr's Log, posted at 0850) together with "0857 — Four total injuries identified" (EOC Log) converts to adding four to the number of injured at the accident scene at time $k = 5$. This example is also what we might call triggering data. These data trigger setting up the EOC or requesting mutual aid before knowing exactly how many people might be injured.[24]

---

[24] There are two interesting implications here. First, from a control viewpoint, this suggests an integral rather than a proportional behavior or, at least, that people initially react in an integral mode (they respond to small deltas). There is some support to this perspective in the works of Kahneman and Tversky (e.g.,

Identification Consists of locating injured people on the grid map in Figure 14 on page 77. For example, "nine injured at the command post" requires finding out where the command post is located at that time.

Adjustment Consists of keeping a current balance of the number of people in each sector, by

1. Assignment, if statement of fact
2. Update (±), depending on people entering or leaving the scene.

Problems encountered: We look at source and time stamp for data sorting and we look at content for data selection. The problems encountered are similar, but lack of consistency is more difficult to deal with content wise. This is where having videotapes makes a difference. To give but one example, *all* actors' logs originating from the field refer to a leak in an ammonia tank instead of a chlorine container. They are all consistent concerning the actions people take and when. Incidentally, there is a difference of more than 20 minutes between the "start" of the leak in the field and at the EOC.

An example of a *good* data point is an entry in the Command Post evaluator's log that marks the beginning of the accident: "0838 — Smoke." The reason this is a good data point is because it is well backed up by other entries in the Field Response evaluator's log: "0836 — Exercise began" followed by "0837 — #14 radio wanted to know when to start smoke ...." Conversely, an example of a *not so good* data point is the entry "0853 — Request total evacuation from all areas N. of 1st St. to rally point S. of 1st St." This data point is "worst" because (1) it only appears in the computer log (no other reference available) and (2) it is listed quite out of sequence.

Interestingly enough, and a point for further research, the content of the majority of the logs degrades very rapidly as the emergency unfolds. Apparently, after a while people simply don't have time to write. Some give up writing earlier than others; for instance, one of the logs (unidentified)

1982). Second, from a learning viewpoint, studying different kinds of action triggers may help design better training devices, management exercises included.

starts with four entries close to 0830 and suddenly blanks, only to show the conclusion of the exercise at 1150. There are exceptions, though, both in the field and at the EOC.

The experimental data set

This section presents the final data set after performing the operations just described. By inspection of the data set we assume a sampling period $T = 1$ min.

Physical data

Wind direction: The information about wind directions recorded on the EOC log is:

> 0832 — Need wind speed and direction, from the Southwest at less than 1 mph. ($\theta = \text{SW}$)
> 1001 — Plume is travelling West ($\theta = \text{E}$)
> 1050 — ... Wind direction East Northeast (variable) ... ($\theta = \text{ENE}$)

The first datum is discarded because it provides no contribution to the physical unfolding of the event. The word "need" at the beginning of the message is interesting when looking at the decision to evacuate South: at 0853, when that decision was made, $\theta = \text{SW}$ was the only wind direction posted in board #1. The second entry is probably the cause of the chlorine release. Anyway, the last two entries are responsible for the plume progression. Because the third entry is labelled variable, we conservatively settle for $\theta = \text{E}$.

We say this is a conservative decision after analyzing the Display Request forms initiated by FMPC's meteorologist. Although most of those were not posted on the Status Boards, the forms were available for this research. There we see that in the period 0950 — 1134 the wind directions are, variably, ESE, SE, ENE, E, or NE. Since variable winds facilitate the spreading of the gas cloud, choosing a single direction is more restrictive. Furthermore, the sectors affected are less populated, so this choice will not overemphasize the difference between open- and closed-loop behavior. Incidentally, if the wind is rotating, $\theta = \text{NE}$ starts having a negative effect considering the earlier decision to evacuate South.

Chlorine concentrations: The players sent out for field measurements were supposed to communicate their "readings" to the EOC. For that purpose, they had a printout from the HARM I computer simulation model they were instructed to read at regular time intervals. As discussed in the exercise critique, there were some communication problems between the field and the EOC, and the EOC didn't receive the data points expected. Consequently, the management decisions didn't take chlorine concentrations into account.

Although a couple of Field Monitoring evaluator logs are available for this research, those are highly inconsistent. For example, one of them, reporting on the *Ammonia* (?!) release, shows values twice those from the other evaluator log. Concentration values logged by those two people vary between 100 and 5 ppm. Yet, the highest value in the EOC log is 1 ppm. We are not using these data.

Event chronology: The events recorded sometimes deviated from the original scenario guidelines. In addition, the time stamps associated with actual exercise events are also sometimes different from the times recorded on the EOC log. Using the "earliest time" rule and scenario events whenever possible, we have:

Event	*Time (k) & Record*	
Fire begins	$k = 0$:	0838 — Smoke
Cl_2 release begins	$k = 64$:	0942 — Yellow smoke from Building 12B
Cl_2 release ends	$k = 76$:	0954 — Leak terminated
Fire ends	$k = 88$:	1006 — Propane fire out

Managerial data

There are several entries in the EOC log originating from the DED. Messages like requesting mutual aid or reclassifying the incident are relevant for the overall management of the emergency but not for this research. Only four entries have direct impact on the model variables, the first of which was already referred to:

Time, k	***Record***
15	0853 — Request total evacuation from all areas N. of 1st St. to rally point S. of 1st St.
65	0943 — Order to shelter personnel on site
73	0951 — Offsite sirens were activated (simulated, logged at 1014)
175	1133 — Downgrade to an All Clear

The data for the model are only implicit in these messages. To make it explicit, we convert each message into multiple data points, one data point per message and geographic sector. The data points are (ideally) generated at the instant the message is issued and have magnitude equal to the number of people in the sector at the time. We say ideally because we are not introducing delays in the state variables.

Ordering the accountability procedures at the rally points takes into account the people that may get injured on their way from the workplace. People move at different speeds and may eventually walk (or drive) across other sectors. For simplicity, we assume (1) people leave when the order is issued (message 1), (2) there is a direct link between the departing and the destination point (rally point), (3) all people from a given sector arrive at the same time (when the EOC gets the information), and (4) they move at uniform speed (ramp format). Numerical results for arrival times appear later under accountability.

Accountability data

Accountability data consist of two distinct subsets. One subset refers to the general population distributed by geographical sectors. Since we stipulated a wind direction, we will only refer to the sectors along that direction. The other subset refers to the high risk (injured) population.

General population: Table 2 presents population counts reflecting management (DED) actions as the emergency unfolds. The initial population counts come from Figure 14 on page 77. The numbers in Figure 14 result from somewhat arbitrarily splitting the number of people in the buildings that span more than one sector. Accountability reports are by building. So, the arrival time for each sector is an average between the earliest and latest arrival times weighted by the number of people in each building involved. People in buildings not specifically mentioned are assumed to be counted together with the nearest mentioned building.

According to the available data, it turns out that everybody in every building is accounted for. This means nobody should have been "injured," which we know is not true. But we also know the accountability reports get to the EOC via the Communications Center. The conclusion is that the information provided to the EOC takes into account the badge numbers of those people already reported as injured. Since we have no information about where they come from, they are not included in the initial counts either. This is why we use separate data sets (and separate mathematical

Table 2. The plant responds to the directive at "0853 — Evacuate South."

Sector	Number at time = 0853	Time when number = 0	Slope k (prs s^{-1}) in $f(t) = -kt$,
1	20	0936	0.465
2	10	0930	0.270
3	0	—	—
4	0	—	—

models) for the general and injured populations. In short, the data set for the general population is (practically) nonexistent.

Injured people: The way we defined it, Sector 0 (the origin of the incident) does not belong to the general population sectors. In the general population case we know the departure and arrival times. For the movement of injured people we only know arrival times. So, we assume that values for consecutive time periods remain the same unless explicitly changed (step function instead of ramp format). Equation (3) presents the time series for "high risk" people at sectors 0 (accident), 10 (command post) and 11 (triage):

$$\begin{aligned}
N_0 &= \{3_0 \dots 7_5 \dots 5_{16} \dots 4_{25} \dots 3_{41} \dots 2_{42} \dots 1_{66} \dots 0_{70} \dots\} \\
N_{10} &= \{9_{68} \dots 0_{109} \dots\} \\
N_{11} &= \{2_{16} \dots 3_{25} \dots 4_{41} \dots 5_{42} \dots 6_{66} \dots 7_{70} \dots 5_{78} \dots 3_{80} \dots 12_{109} \dots 11_{114} \dots 6_{132} \dots 0_{147} \dots\}.
\end{aligned} \tag{3}$$

where N_j = time series for the number of people at risk in sector j, with entries

z_k = people count at time k.

The sum of these three time series — the total number of injured people within the FMPC — is depicted in Figure 16 on page 89. This is a graphical summary of the content of status board #3 (in "Appendix C. EOC Status Boards" on page 160) and plays a fundamental role in the rest of this research. This curve is the *overall management system's output in response to external disturbances.* The disturbances correspond to the initial data points in Equation (3), at times $t = 0, 5$, and 68, respectively. The remaining data points are, by assumption, the result of managerial action. Recall, the objective of this research is to build an estimator for the system, and that includes both the disturbance and the managerial response effects.

Equation (3) and Figure 16 are only *one* representation of the data. The reason for representing the data this way is that we need to build a continuous time series for hypothesis testing. We know things happen progressively and not by sudden step changes. But this representation has two ad-

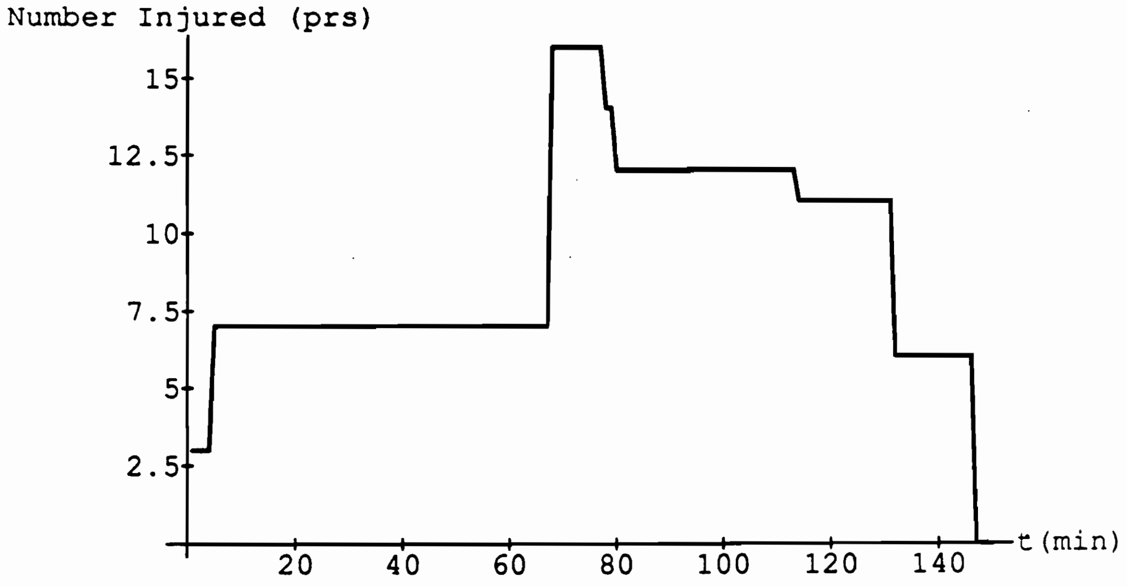


Figure 16. The maximum number of injured people during the exercise is 16. (Data from FMPC.)

vantages: it is the simplest possible and it doesn't "invent" any data points. For instance, fitting the data to a polynomial curve by multiple regression would certainly create a maximum above 16. Anyhow, these are the data available. By hypothesis, we can build a control theory-based mathematical model whose output is similar to (correlated with) the system's output.

The mathematical model

This chapter deals separately with the injured and the general, not injured populations. The chapter begins with an introductory discussion about the overall modeling approach. Next, the modeling sequence starts with the open-loop plant model, the state and output equations for the propane fire, the chlorine release, and the population behavior. This open-loop model describes the evolution of the incident in the absence of any response intervention. Next, we present the closed-loop model, with the same state and output equations augmented with terms for control actions (response). The output trajectories of both open- and closed-loop models are fairly different, the difference being attributed to managerial actions. Next we present the state estimator or state observer. We can build an estimator for both the open- and closed-loop models, but we only show the open-loop estimator for the general population. The last section repeats the whole derivation focusing on the injured population. This time we emphasize the behavior of the closed-loop model estimator.

Emergency response modeling

Figure 7 on page 44 presents a general management view of FEMA's emergency phases. Each phase, and emergency response in particular, can also be looked at from the information feedback perspective of Figure 2 on page 10. External input in the form of "change in operational conditions" suggests we need to characterize the information processing environment. In general,

Problem:	an interrupting input requiring a response;
Response window:	the time available to produce the response;
Demand:	the frequency of interrupting problems.

We can use this template to convert the performance measure on page 67 into a more general

> **Performance criterion:** *The organization is <u>adequately</u> responding to its environment if and only if, for each interrupting problem, the organization produces the required response within the available time window.*

The performance measure on page 67 and this criterion constitute the specification of the emergency response management system.

Hazard thresholds

To determine what is the adequate response and what time window is available, we look at possible consequences. Gephart & Moses (1989) identify three main classes of effects, depending on expected severity:

Class	*Health Impact*
1	Causing only non-serious, transient effects;
2	Causing serious effects; and
3	Causing severe, life-threatening effects.

The incident featured in this research deals with class 3 impacts. For all practical purposes, according to Table 3, a class 2 incident may become class 3 when we deal with the vulnerable sectors of the population. Withers and Lees (1985a) also consider different levels of physical activity, but we will not do this here. "In general," they say, "the injurious effect of the inhalation of a toxic gas is a function both of concentration and of [exposure] time" (p. 232). The concept of injury is associated with the concept of dosage. By definition, heat dosage is $\int_0^{t_e} \dot{q}dt$ where $\dot{q}$ is the instantaneous heat release rate and t_e is the exposure time. Similarly, toxic dosage is $\int_0^{t_e} c(t)dt$, c being the concentration of toxic agent. Both quantities are zero when the incident begins.

Fire hazard: At atmospheric pressure and ambient temperature, propane is a colorless gas with little natural odor.[25] Although propane is not irritating to the eyes or the respiratory system, a concentration greater than 1% will cause dizziness after 10 minutes. High concentrations may be asphyxiating due to oxygen shortage (VanAerde, Stewart, & Saccomanno, 1988). Despite this possibility, the major hazard causes associated with propane and other LPG gases are fire and explosion. We will not deal with explosions.

The variation in space and time of the velocity, temperature, and other characteristics of the flame are unpredictable. But on average, flash fires produce low flame speeds and over-pressures from barely detectable to sufficient to break glass. The torch temperatures for propane range between 1310 – 1450°K. In open space, scorching and soot deposition may extend for thousands of square meters (Crawley, 1982). According to Brasie (1976), the amount of gas necessary to raise the temperature to about 400°K (maximum body tolerance) is less than 2.88 kg/1000 m^3; to raise the temperature to about 700°K (average cellulose flash over point) requires 9.61 kg/1000 m^3. The radiation

Table 3. The risks are higher for the vulnerable population. (Source: Withers & Lees, 1985.)

Effect	Deaths in population (%) General	Vulnerable
Severe effects	0	25
Lethal	3	50
Lethal	50	100

---

[25] Sometimes manufacturers add strong-smelling *Mercaptan* chemicals for leakage detection purposes. This was not the case in this incident, and wouldn't make any difference anyhow.

threshold causing second- and third-degree burns is the minimum level for ignition of cellulose (29.3×10^4 J/m^2).[26] Crawley (1982) states that for a short-term exposure of about 20 seconds to burns, the maximum tolerable heat flux is 6.5 kW/m^2: "this suggests that for a fire with surface heat flux [of] 150 kW/m^2 it should be possible to survive without burns at least 8 fire-pool diameters from the fire-seat for a flame length/diameter of 2 and 7 diameters for a flame length/diameter of 1" (p. 139). Table 4 summarizes these data.

Toxic hazard: Chlorine is a greenish-yellow gas, neither flammable nor combustible, about 2.5 times heavier than air. It is very reactive though, and may lead to fires and explosions upon contact with materials as diverse as domestic gas, some metals, or alcohols (Sax, 1984). Chlorine reacts with moisture to form varying quantities of hydrochloric acid (HCl), hypochlorous acid (HOCl), and nascent oxygen (O_2); all these species are inflammatory upon contact with human (and animal) tissue. For this reason, chlorine is considered a dangerous toxic substance.

In small concentrations, chlorine irritates the eyes and respiratory tract. Increased concentrations cause coughing, suffocation, pain, and ultimately death. Although chlorine damages the whole respiratory system, the cause of immediate death is lung oedema (edema.) Oedema is the accumulation of fluid in the tissue spaces leading to asphyxiation by drowning. Deprivation of oxygen

Table 4. The thermal radiation thresholds correspond to heat dosage levels. (Source: text, Roberts, 1982.)

Effect	Heat flux required (kW/m^2)		
	10s exposure	14.5s exposure	20s exposure
Pain		4.7	
Blistering of bare skin	13.2	9.6	6
Pilot flame ignition of cellulose			34
2nd degree burns	36.1	27.4	
3rd degree burns	64.5	49	
1% lethality	32.9	25	20
50% lethality	58.8	44.7	35

---

[26] These values apply to fires in partially confined spaces as in the case of the simulated incident. (See also Mudan, 1986.)

(anoxemia) causes weakness and lassitude and people fall on the ground where they find the higher concentrations of dense gas. Possible delayed effects are chemical pneumotitis, bronchial spasm, or infection (pneumonia).

Withers and Lees (1985a, b, 1987) provide an extensive review of gas warfare and laboratory results about the lethal toxicity of chlorine for animals and people. Some of these results are also summarized by Gephart and Moses (1989). Concentrations between 1 and 3 ppm will in general cause irritation but no sensible damage.[27] A concentration around 3.5 ppm has a detectable odor and between 15 and 20 ppm may cause immediate irritation, possibly enough to impair the ability to take protective action. Concentrations between 20 and 50 ppm produce almost instantaneous irritation and become increasingly dangerous even for short exposures. Above 100 ppm, even brief exposures may be fatal. The ceiling (maximum acceptable) occupational exposure is 0.5 ppm for 15 min. These results are summarized in Figure 17 on page 96 and in Table 5.

Table 5. The toxic effect thresholds correspond to concentration dosage levels. (Source: Withers & Lees, 1985.)

Effect	Concentration required (ppm) 10 minutes	 30 minutes
Eye and respiratory tract irritation	18	6
Severe pulmonary oedema and delayed effects	120	40
10% lethality	139	80
50% lethality	364	210
90% lethality	805	465

---

[27] 1 ppm = 2.9×10^{-6} kg m^{-3}. These small concentrations are normally used in municipal and swimming pool water treatment.

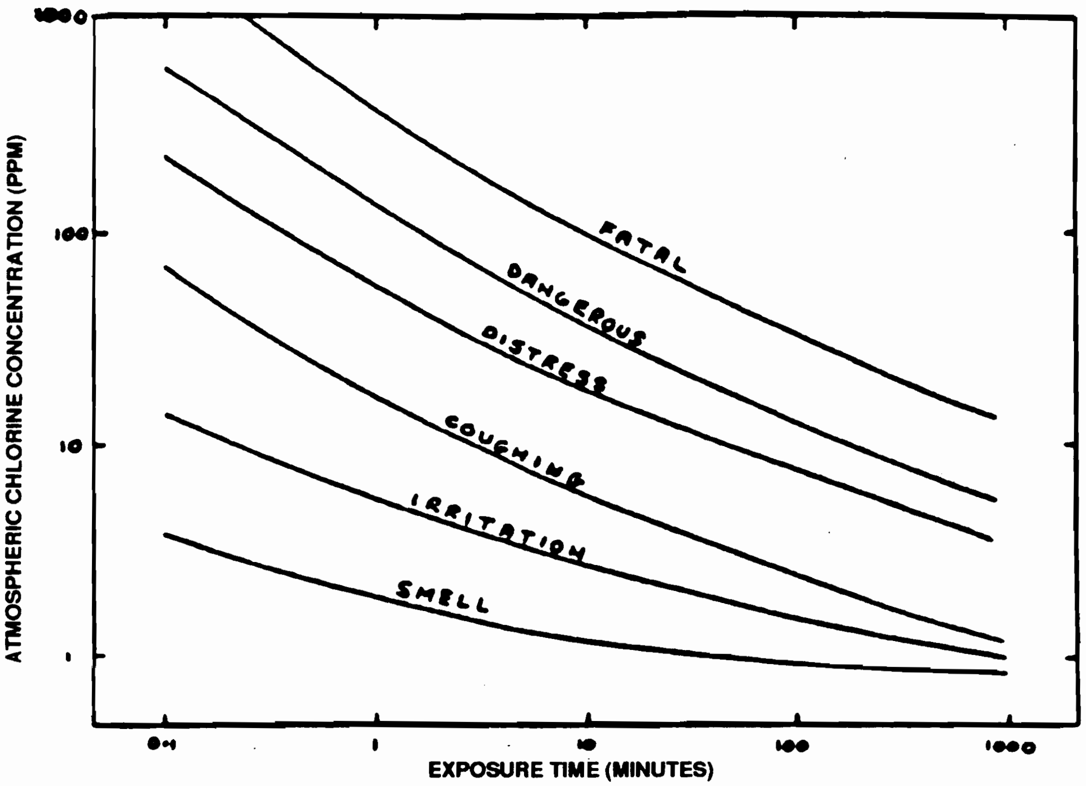


Figure 17. The relationship between concentration and exposure is approximately linear. (Source: Green, 1980.)

The modeling approach

The sequence followed in this work is straightforward:

1. Build the continuous-time open-loop model for the plant (propane fire, chlorine release, and hazardous effects on people):

$$\begin{aligned} \dot{\mathbf{x}} &= F\mathbf{x} + G\mathbf{u} \\ \mathbf{y} &= H\mathbf{x}, \end{aligned} \tag{4}$$

   where $\mathbf{x}$ = $n \times 1$ column vector of state variables,

   $\mathbf{u}$ = $p \times 1$ vector of incident inputs (incident triggering conditions)

   $\mathbf{y}$ = $q \times 1$ vector of system outputs (results)

   F, G, and H = $n \times n$, $n \times p$, and $q \times n$ matrices of known coefficients, respectively.

2. Build the equivalent discrete-time model for the plant, by converting the matrices F, G, and H of Equation (4) into the matrices A, B, and C of Equation (1) on page 52. Since the matrices are different, the states are also different.
3. Obtain the response of this discrete-time open-loop model to the incident conditions. This response consists of a plot of y-values versus time (k). These values increase progressively until they level off at some value of y.
4. Extend the continuous- and discrete-time open-loop model to include expressions for the mitigating actions. These constitute the closed-loop plant models.
5. Obtain the response of the discrete-time closed-loop model to the incident conditions. The response must show y going to zero.
6. Build an estimator for both the open- and the closed-loop plant models.
7. Obtain the estimator response in open- and closed-loop. The response must be similar to the original plant model.

The three subsystems — the fire, the plume, and the population — form a partially coupled system. This means we don′t study how the fire causes the release of chlorine, we simply acknowledge it whenever it occurs. So, we may treat both the fire and the release as independent. In addition, each of those influences the population, but not vice-versa. Even this is only valid for the general sectors of the population, because the injured people are in sectors outside the hazardous zone. The subsystems being almost independent allows us to model them separately. That is, we model the propane fire first, then the chlorine release, and then their joint effect on the population.

This starting point is step 1 in the list at the beginning of this section. The details are in "Appendix D. Development of state equations." on page 163 and the models are summarized next under "The open-loop plant model for the general population". Then we proceed with the other steps in the list, and repeat the process when we model the injured population sectors separately, at the end.

The open-loop plant model for the general population

At this point we start building the ″dynamic model of the operation,″ as described in the lower part of Figure 3 on page 11. This dynamic model features the physical event and its potential consequences, considering no management intervention whatsoever.

The continuous-time plant dynamics

This section presents the plant model in the form of differential equations. Later, we put these differential equations and their variables in state space form.

The propane fire subsystem: The following equations summarize the results presented in "The propane incident" on page 165 with all coefficients converted to minutes (instead of seconds).

Adding a wind velocity term to the distance equation gives the overall front progression. The variables are identified at the end:

1. Propane discharge equation

$$\dot{m} = -\,28.2 \times 10^{-3}\, m, \qquad (5)$$

2. Propane fire effect equation (distance)

$$\dot{R} = K_1\, m + K_2\, t_e, \qquad (6)$$

3. Elapsed time equation

$$\dot{t}_e = 1, \qquad (7)$$

where m = mass of propane available in the system, kg.

R = position of the cloud front (radius), m

t_e = elapsed time, min

K_1, K_2 = constants, from Table 6:

Table 6. The coefficients for Equation (6) are also effect dependent.

Effect	$K_1 \times 10^9$	$K_2 \times 10^9$
Blistering of bare skin	-.864	-3.05
1% lethality	-.468	-1.65
50% lethality	-.360	-1.27

The release subsystem: The following equations summarize the results presented in "The chlorine incident" on page 180. We can also add a wind velocity term to the spreading equation (number 2) to obtain the front progression. Again, the constants are expressed in minutes and the variables identified at the end:

1. Chlorine transport equations

$$\begin{aligned}
\dot{c}_1 &= -755.4c_1 - 481.2c_2 + c_0\delta(t) \\
\dot{c}_j &= 1236.0c_{j-1} - 755.4c_j - 481.2c_{j+1}, \quad j = 2, \dots, 8 \\
\dot{c}_n &= 1236.0c_8 - 755.4c_9.
\end{aligned} \tag{8}$$

2. Chlorine gravity spreading equation

$$\dot{R} = -109.2 \times 10^{-3} R, \tag{9}$$

3. Elapsed time equation

$$\dot{t}_e = 1, \tag{10}$$

where R = position of the cloud front (radius), m

c_j = concentration of chlorine in point (sector) j, kg m^{-3}

c_0 = concentration of chlorine at the release point, $c_0 = 10^6$ ppm (an input or external variable)

$\delta(t)$ = unit impulse (Dirac delta)

t_e = elapsed time, min

(*Note:* to maintain a uniform structure for the system, Equation (9) should be written under the form $\dot{R} = K_c c_n + K_t t_e$. This equation and Equation (6) are included here for completeness only.)

The population subsystem: The following equations summarize the results presented in "The population behavior" on page 187 for the general population model. And, once again, the coefficients are in minutes and the variables are identified at the end:

$$\dot{P}_j = -\frac{190.8}{L_j} P_j + 1.918 \times 10^{-3} P_j^o m + 1.983 c_j P_j^o + 0.122 P_j^o 1_x, \quad j = 1, \dots, 9. \tag{11}$$

where P_j = number of injured people in point j, prs

L_j = distance from the origin of the incident to point j, m

P_j^o = initial number of people in point j, prs

m = mass of propane available in the system, kg.

c_j = concentration of chlorine in point j, ppm

1_x = state variable made equal to 1

t_e = elapsed time, min

The output equation: The next equation provides the unicohort value. This is the only output we are using.

$$\zeta = \sum_{j=1}^{n} P_j, \qquad (12)$$

where ζ = unicohort

P_j = population count in sector j.

Summary: the open-loop plant model

State variables: At this point we want to put all equations in the standard format

$$\begin{cases} \mathbf{x}(k+1) = A\mathbf{x}(k) + B\mathbf{u}(k) \\ \mathbf{y}(k) = C\mathbf{x}(k). \end{cases}$$

To do that, we redefine the state variables as follows:

x_1 = mass of propane (m)

$x_2, \dots, x_{10}$ = concentration of chlorine in sector j (c_j, $j = 1, \dots, n$, $n = 9$)

x_{11}, x_{12} = elapsed time (t_e), subject to $\begin{cases} \dot{x}_3 = x_4 \\ \dot{x}_4 = 0. \end{cases}$

$x_{13}, \dots, x_{21}$ = population count in sector j, (P_j, $j = 1, \dots, n$, $n = 12$); the first 9 sectors cover the general population and the other 3 sectors the points where injured people gather.

As explained, we don't need the state variables representing the effect radius (R).

Initial conditions: To obtain the initial number of people in each sector (P_j^o) we retrieve the values along the $\theta = \text{E}$ wind direction at $n = 9$ different points in Figure 14 and Figure 15 on page 78. The initial number of injured people in those sectors is zero, leading to:

$x_1(0) = 17.3\times10^3$
$x_2(0) = 0$
$x_3(0) = 0$
$x_4(0) = 0$
$x_5(0) = 0$
$x_6(0) = 0$
$x_7(0) = 0$
$x_8(0) = 0$
$x_9(0) = 0$
$x_{10}(0) = 0$
$x_{11}(0) = 0$
$x_{12}(0) = 1$
$x_{13}(0) = 0$
$x_{14}(0) = 0$
$x_{15}(0) = 0$
$x_{16}(0) = 0$
$x_{17}(0) = 0$
$x_{18}(0) = 0$
$x_{19}(0) = 0$
$x_{20}(0) = 0$
$x_{21}(0) = 0$

Input variables: For simplicity we use an average value instead of an input variable for the wind velocity. In turn, this average value is is used when calculating the model coefficients. As discussed under "External inputs" on page 61, the only exogenous input we use is the chlorine concentration at the point of release, which we assume to be instantaneous. We also anticipate using two controls later, for evacuation and sheltering. To maintain the same model structure throughout this exercise, we aggregate all inputs in the same vector:

$u_1 = 0$
$u_2 = 0$
$u_3 = 10^6\delta(0)$.

Output variables:

y_1 = unicohort (ζ), to be obtained.

State space model: The continuous version of Equation (1) on page 52, shows the open-loop plant model as a partially coupled system:

$$\begin{aligned} \dot{\mathbf{x}} &= \begin{bmatrix} \mathbf{F}_{11} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{F}_{22} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{F}_{33} & \mathbf{0} \\ \mathbf{F}_{41} & \mathbf{F}_{42} & \mathbf{F}_{43} & \mathbf{F}_{44} \end{bmatrix} \mathbf{x} + \begin{bmatrix} \mathbf{0} \\ \mathbf{G}_2 \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} \mathbf{u} \\ y_1 &= [\, \mathbf{0} \quad \mathbf{0} \quad \mathbf{0} \quad \mathbf{1} \,]\, \mathbf{x}, \end{aligned} \tag{13}$$

where $\mathbf{F}_{11} = [-28.2 \times 10^{-3}]$

$$\mathbf{F}_{22} = \begin{bmatrix} -755.4 & -481.2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1236.0 & -755.4 & -481.2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1236.0 & -755.4 & -481.2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1236.0 & -755.4 & -481.2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1236.0 & -755.4 & -481.2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1236.0 & -755.4 & -481.2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1236.0 & -755.4 & -481.2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1236.0 & -755.4 & -481.2 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1236.0 & -755.4 \end{bmatrix}$$

$$\mathbf{F}_{33} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$$

$$\mathbf{F}_{41} = [0.0384 \quad 0.0192 \quad 0 \quad 0 \quad 0.0058 \quad 0.0019 \quad 0.0460 \quad 0.3299 \quad 0.6924]^T$$

$$\mathbf{F}_{42} = \begin{bmatrix} 39.66 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 19.83 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 5.949 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.983 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 47.592 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 341.076 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 715.863 \end{bmatrix}$$

$$\mathbf{F}_{43} = \begin{bmatrix} 2.44 & 1.22 & 0 & 0 & 0.366 & 0.122 & 2.928 & 20.984 & 44.042 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

$$\mathbf{F}_{44} = \begin{bmatrix} -0.9485 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.4742 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.3162 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.2371 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.1186 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -0.0593 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -0.0395 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.0296 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.0237 \end{bmatrix}$$

$$\mathbf{G}_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

and the superscript T means transpose.

The equivalent discrete-time system

The discrete-time version of the system relates to the continuous-time version through:

$$\begin{aligned} \mathbf{x}(kT+T) &= \{e^{FT}\}\mathbf{x}(kT) + \left\{\int_0^T e^{Ft}G\,dt\right\}\mathbf{u}(kT) \\ \mathbf{y} &= H\mathbf{x}, \end{aligned} \tag{14}$$

where T = sampling period, $T = .0001\text{s}$ to capture the dynamics of the fire and gas release

$\mathbf{A} = \Phi(T) = e^{FT} =$ state transition matrix

$\mathbf{B} = \Gamma(T) = \int_0^T e^{Ft}G\,dt =$ input matrix

$\mathbf{C} = \mathbf{H} =$ output matrix

Omitting the sampling period T from Equation (14) and making these substitutions we obtain the discrete-time system described by Equation (1) on page 52. The details of the transformation and the resulting matrices are in "Appendix E. Machine calculations" on page 198.

The open-loop system response

We obtain the system response by recursion. Using the inputs $u_3(0) = 10^6$ and $u_3(1) = u_3(2) = \cdots = 0$ together with the initial values of the state variables we make:

$\mathbf{x}(1) = A\mathbf{x}(0) + B\mathbf{u}(0)$

$\mathbf{x}(2) = A\mathbf{x}(1) + B\mathbf{u}(1)$

etc.

This is step 3 in the list under "The modeling approach" on page 97. The results are depicted in Figure 18 on page 105 in the next page. They represent the model's outputs assuming the system (the emergency) is free to evolve by itself. Notice that the total number of people within the affected sectors is 391. Next, we perform step 4: we build the control model by adding inputs to the system where appropriate.

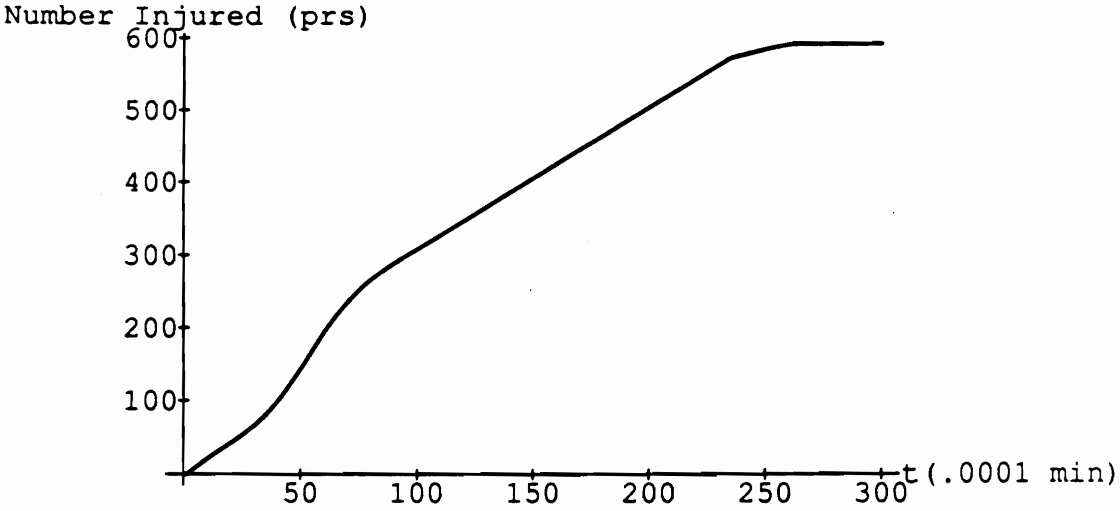


Figure 18. The open-loop system response for the general population shows the potential danger.

The closed-loop plant model for the general population

Now we extend the "dynamic model of the operation" of Figure 3 on page 11 with inputs that supposedly represent management interventions.

The control inputs

Inputs to the propane fire subsystem: There are no control inputs in this case, because neither a BLEVE nor an UVCE are considered and the fire is allowed to burn.

Inputs to the chlorine release subsystem: Similarly, there are no control inputs because no physical countermeasures were used against the spreading of the toxic cloud.

Inputs to the population subsystem: Equation (64-a) on page 191 proposes the dynamic behavior of the population at risk in the open-air or inside fully ventilated buildings. Now we need to add the input terms for sheltering and escaping. Concerning escaping, a simple formulation for leaving sector j with velocity μ_j corresponds to decreasing the risk rate at j by that velocity:

$$\dot{P}_j = -\frac{v}{L_j} P_j + u_j^1, \quad j = 1, \dots, n \tag{15}$$

where $u_j^1 = \mu_j$ = migration rate, prs min^{-1}, negative if people leave the scene (sector) and positive otherwise. (See also the comments on Equation (63) on page 189.)

Sheltering involves replacing people's environment, by putting them in an environment with a larger time constant. The time constant for the shelter is the reciprocal of the air change (infiltration) rate. To model this situation we use a control input that, when applied, may replace the right-hand side of Equation (64-a) by a term reflecting the infiltration rate of the new environment. For each sector j,

$$\dot{P}_j = -\frac{v}{L_j} P_j + \left(1 - \frac{1}{\tau}\right) \frac{v}{L_j} u_j^2, \quad j = 1, \dots, n \tag{16}$$

where τ = shelter infiltration rate, ach (air changes per hour); on average, $\tau = 0.5$ ach and $1/\tau = 120$ min

u_j^2 = number of people protected, prs; when $u_j^2 = P_j^0$, the right-hand side of Equation (64-a) is replaced by $\frac{1}{\tau} P_j^0$; when $u_j^2 = 0$, the right-hand side of Equation (64-a) holds.

Although both these formulations fit the situation, they do not quite reflect the management system for the exercise. A more elegant solution is to make $u_1 = t$ and $u_2 = 1$ when the directives to evacuate South or shelter in place are sent. At the same time, change the entries of the matrix **G** to reflect the actual protective actions.

Concerning evacuation, the directive was issued only to the plant. We stipulate an average evacuation velocity $\mu = -0.5$ and change two entries in the first column of the matrix **G** to $\mathbf{G}[1] = -\mu$; with hindsight, the velocity values for sectors 1 and 2 are $\mu = -0.465$ and $\mu = -0.27$. The second column, for sheltering, the entries are $\mathbf{G}[2] = -119 P_j^0$.

Summary: the closed-loop plant model

All variables, initial conditions, and relationships not explicitly mentioned remain the same relative to the previous summary on page 101.

Endogenous input variables

u^1 = evacuation speed, $u^1 = 1$ when control is applied, $u^1 = 0$ otherwise

u^2 = protection rate, $u^1 = 1$ when control is applied, $u^1 = 0$ otherwise

Continuous-time state space model

$$\dot{\mathbf{x}} = \begin{bmatrix} \mathbf{F}_{11} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{F}_{22} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{F}_{33} & \mathbf{0} \\ \mathbf{F}_{41} & \mathbf{F}_{42} & \mathbf{F}_{43} & \mathbf{F}_{44} \end{bmatrix} \mathbf{x} + \begin{bmatrix} \mathbf{0} \\ \mathbf{G}_2 \\ \mathbf{0} \\ \mathbf{G}_4 \end{bmatrix} \mathbf{u} \qquad (17)$$

$$y_1 = [\,\mathbf{0} \quad \mathbf{0} \quad \mathbf{0} \quad \mathbf{1}\,]\,\mathbf{x},$$

where $\mathbf{G}_4 = \begin{bmatrix} -0.5 & -0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -2380 & -1190 & 0 & 0 & -357 & -119 & -2856 & -20468 & -42959 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$

The closed-loop system response

The difference between the open- and the closed-loop versions of this system shows up in the input matrix, **B**. We can use the closed-loop formulation in both cases by simply changing the input controls: $u_1 = u_2 = 0$ in open-loop and $u_1 = t$, $u_2 = 0$ in closed-loop. This makes it easier to obtain the system response.

The closed-loop system response is close to zero and not shown. For practical purposes we can consider it to be zero. At this point, the intermediate conclusion we can make is that *we can build a simple control theory mathematical model that behaves like the actual management system.* Most likely, if we refine the model we may obtain an identically zero response. But that is not necessary now.

The state estimator

Relative to Figure 3 on page 11, this research concentrates exclusively on the estimator, as shown in Figure 19 on page 109. The state estimator for the system in Equation (1) on page 52 is a new dynamic system of the form:

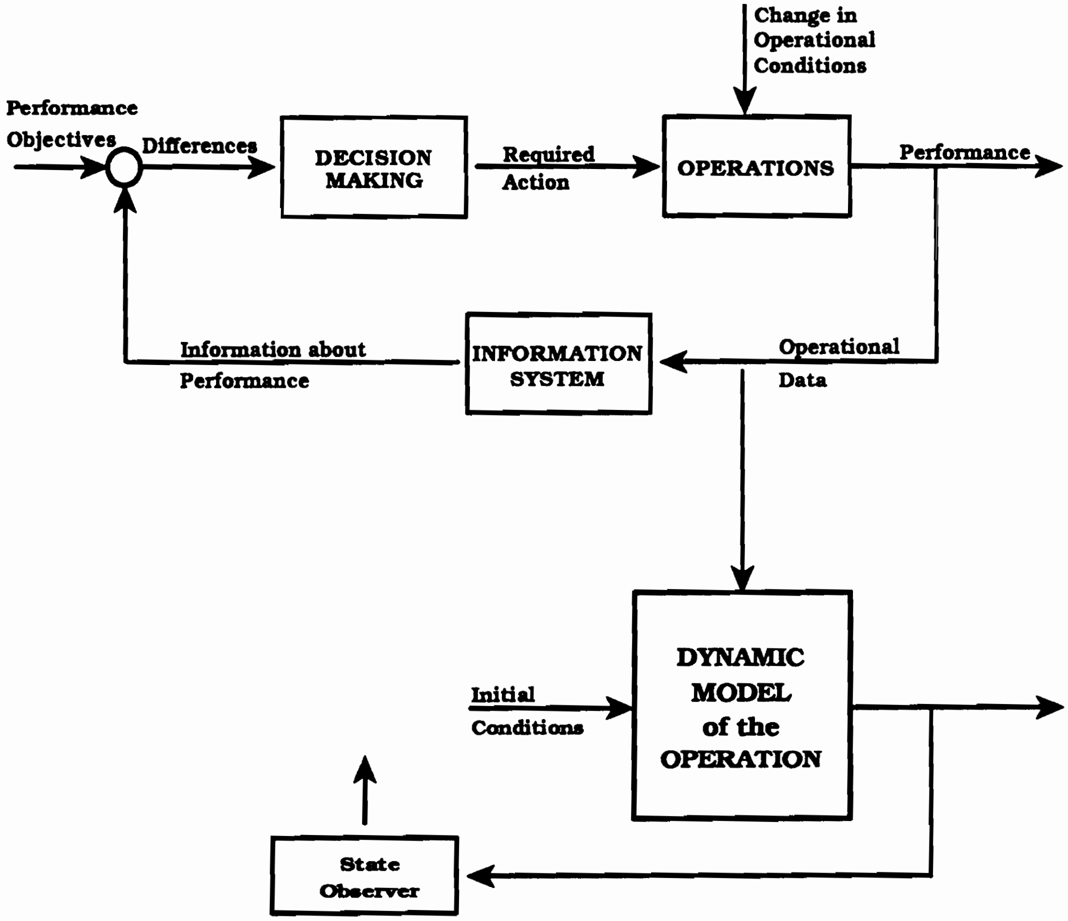


Figure 19. The input to the state estimator is the system's output.

$$\begin{aligned}\hat{\mathbf{x}}_o(k+1) &= \hat{A}_o\hat{\mathbf{x}}_o(k) + B_o\mathbf{u}(k) + K_o\mathbf{y}(k)\\ \mathbf{y}_o(k) &= C_o\hat{\mathbf{x}}_o(k),\end{aligned} \tag{18}$$

where $\hat{\mathbf{x}}_o$ = $n \times 1$ column vector of state estimates, approximating the original plant state vector $\mathbf{x}$

$\mathbf{u}$ = $p \times 1$ vector of incident inputs

$\mathbf{y}$ = $q \times 1$ vector of outputs from the original system, now serving as inputs

$\mathbf{y}_o$ = $q \times 1$ vector of outputs from the estimator

K_o = $n \times p$ estimator or Kalman gain matrix

$\hat{A}_o$ = $A_o - K_oC_o$ = $n \times n$ state estimator transition matrix

B_o, C_o = $n \times p$, $q \times n$ observer canonical forms of matrices B and C

Basically, a system is observable when all state variables are either measured directly or fed back to other state variables that are measured. To build an estimator is to obtain the matrix K_o to plug in Equation (18), such that $\hat{\mathbf{x}}_o$ approximates $\mathbf{x}$ causing $\mathbf{y}_o$ to approximate $\mathbf{y}$. To check whether we can build an estimator or not, we calculate the rank of the *observability matrix*

$$O \triangleq \begin{bmatrix} C \\ CA \\ CA^2 \\ \cdots \\ CA^{n-1} \end{bmatrix}.$$

This system passes the test because the matrix has full rank ($n = 21$). This is also shown in "Appendix E. Machine calculations" on page 198.

Estimator design

Building the estimator consists of two major steps: transformation to observable canonical form and building the estimator gain matrix (VanLandingham, 1985):

Transformation to observable canonical form: To rewrite the emergency management model in *observable canonical form,* we perform a series of matrix manipulation operations whose details and corresponding results are also in Appendix E. The operations consist of:

1. Calculating the eigenvalues of matrix **A**,
2. Calculating the characteristic polynomial of **A** using the eigenvalues,
3. Building the observable canonical form of **A** using the coefficients of the characteristic polynomial,
4. Building the observable canonical form of **C**,
5. Recalculating the observability matrix using the observable forms of **A** and **C**, and
6. Calculating the observable canonical form of **B** using both forms of the observability matrix.

After performing these operations the model consists of matrices $\mathbf{A}_o$, $\mathbf{B}_o$ and $\mathbf{C}_o$, the subscript **o** standing for ″observable form.″ But it is still the same system. The objective of these operations is to make the design of the estimator simpler.

Building the estimator gain matrix: This second step assumes the system is in observable form. The next operations are:

1. Selecting the desired eigenvalues for the estimator,
2. Calculating the characteristic polynomial using these eigenvalues,
3. Calculating the estimator state transition matrix using the coefficients of the characteristic polynomial, and
4. Calculating the estimator gain matrix.

The first operation is critical from a performance standpoint. Franklin, *et al.* (1986) present some methods to tackle this problem but we didn′t follow those here. Knowing that for stability the eigenvalues must be within the unit circle centered at the origin ($0 \leq z_o \leq 1$), we make all eigenvalues equal to 0.5. Then, the characteristic polynomial is $p_o(z) = (z - 0.5)^n$, which is then expanded to obtain the coefficients. The details for all these operations and the corresponding results are also described under “Appendix E. Machine calculations” on page 198.

Estimator response

We obtain new response curves by recursively solving Equation (18) on page 110. The curve for the open-loop case is in Figure 20. (The curves for the closed-loop case are not relevant.) We obtain the estimator response by assuming the open-loop model output is the management system output. In other words, in the absence of general population data from the exercise, we check the state estimator behavior as if we had those data. There are a few points worth noticing:

State uncertainty: The initial output estimates are quite different due to the uncertainty of the states. The effect is magnified in Figure 21 on page 114. The same problem occurs again when there is a change of inflection in the system response. This is not surprising.

Performance: Figure 21 also shows a certain distance between the final portions of the system and estimator response curves. This lack of performance is caused by the arbitrary way we assigned the estimator eigenvalues. We will talk about other causes later, when dealing with the injured population sectors.

The emergency management model for the injured population

As mentioned at the beginning of the chapter, the development of a model for the injured population follows the same steps we just went through. Now we build a totally abstract model of a management situation. In the previous case we had to model the interaction between a human system and a physical system. Now we don't consider any details about the rescue operations. We only model the system's behavior. And this makes the model simpler.

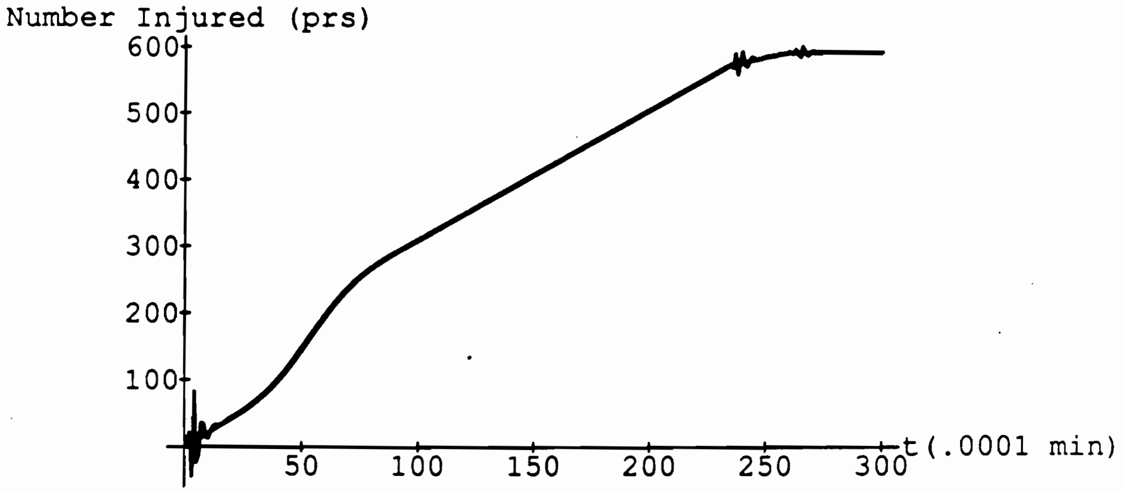


Figure 20. Superimposing the system and the estimator curves shows acceptable agreement.

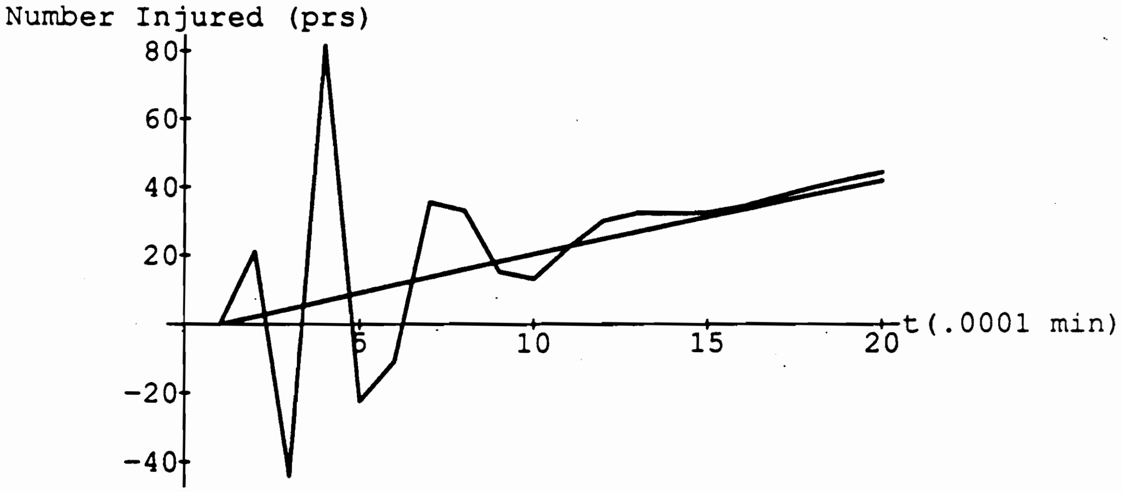


Figure 21. Initial state uncertainty causes erratic output estimates.

The continuous-time model

As seen in the previous case, the open-loop model is a particular instance of the closed-loop model when we don't activate the controls. Let the incident scene be sector 1, the command post sector 2, and the triage center sector 3. Understanding we are dealing with injured people, Equation (63) on page 189 applies under the following conditions:

- People only enter the system through sectors 1 and 2;
- People go from sectors 1 and 2 to sector 3;
- People only leave the system through sector 3;
- The total number of people in the system is the sum of sectors 1, 2, and 3;

Model building: Without looking at the data, we don't know the rates for people entering and leaving the sectors. In a more elaborate model we can choose exponential entering rates and Poisson leaving rates. Here, the simplest alternative is to set an arbitrary uniform rate, $\mu = \pm\, 0.5$, say. Adding these controls to Equation (76) on page 197 leads to the state space model:

$$\begin{aligned} \dot{\mathbf{x}} &= \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \mathbf{x} + \begin{bmatrix} -.5 & 0 & 0 & 1 & 0 \\ 0 & -.5 & 0 & 0 & 1 \\ .5 & .5 & -.5 & 0 & 0 \end{bmatrix} \mathbf{u} \\ y &= \begin{bmatrix} 1 & 1 & 1 \end{bmatrix} \mathbf{x}, \end{aligned} \qquad (19)$$

where the diagonal terms -1 in matrix **F** correspond to $\frac{1}{\tau}$,

the diagonal terms -.5 in matrix **G** correspond to evacuation rates,

the terms .5 in **G** are admission rates to the triage center, and

the terms 1 in **G** are multipliers for the number of people entering the system.

The input vector is $u[1] = u[2] = u[3] = t$ (not applied in open-loop), and $u[4] = u[5] = P_j^i$, where P_j^i is the number of people entering sector j at time i. The inputs $u[1]$ to $u[3]$ are endogenous inputs or controls. The inputs $u[4]$ and $u[5]$ are exogenous or external inputs. This input vector remains the same when we convert the model from continuous- to discrete-time.

Equivalent discrete-time system

As discussed in "The experimental data set" on page 84, the sampling period for this case is $T = 1$ min. Referring to Equation (14) on page 104, obtaining $A = \Phi(T) = e^{FT}$ is simplified because $\exp\{AT\} = \exp\{\mathrm{diag}[\lambda_i T]\} = \mathrm{diag}\{\exp[\lambda_i T]\}$. Furthermore, $B = \Gamma(T) = \left\{\int_0^T e^{Ft} G dt\right\} = -e^{-t}G\,|_0^1$. The resulting discrete-time system becomes:

$$\mathbf{x}(k+1) = \begin{bmatrix} 0.3679 & 0 & 0 \\ 0 & 0.3679 & 0 \\ 0 & 0 & 0.3679 \end{bmatrix} \mathbf{x} + \begin{bmatrix} -0.0632 & 0 & 0 & 0.0632 & 0 \\ 0 & -0.0632 & 0 & 0 & 0.0632 \\ 0.0632 & 0.0632 & -0.0632 & 0 & 0 \end{bmatrix} \mathbf{u}$$

$$y = [1 \quad 1 \quad 1]\,\mathbf{x}, \tag{20}$$

The discrete-time system response

To obtain the system response (by recursion) we apply the inputs $u[4] = 7$ at $k = 0$ and $u[5] = 9$ at $k = 68$, according to Equation (3) on page 88. Figure 22 on page 117 shows the open-loop behavior when the model is given the same inputs as the system. The agreement between the model and the uncontrolled part of the system is acceptable.

For the closed-loop model we maintain the same external inputs. In addition, we set controls 1 and 2 together with the inputs ($t = 0$ and $t = 68$, respectively). The third control, activating the exit rate from triage, is arbitrarily set at $t = 100$. The model performance is quite poor now (Figure 23 on page 118). This is not surprising. The controls we are using do not "affect" any system variables. In other words, we are not looking at how people are taken care of at each location. Anyhow, the

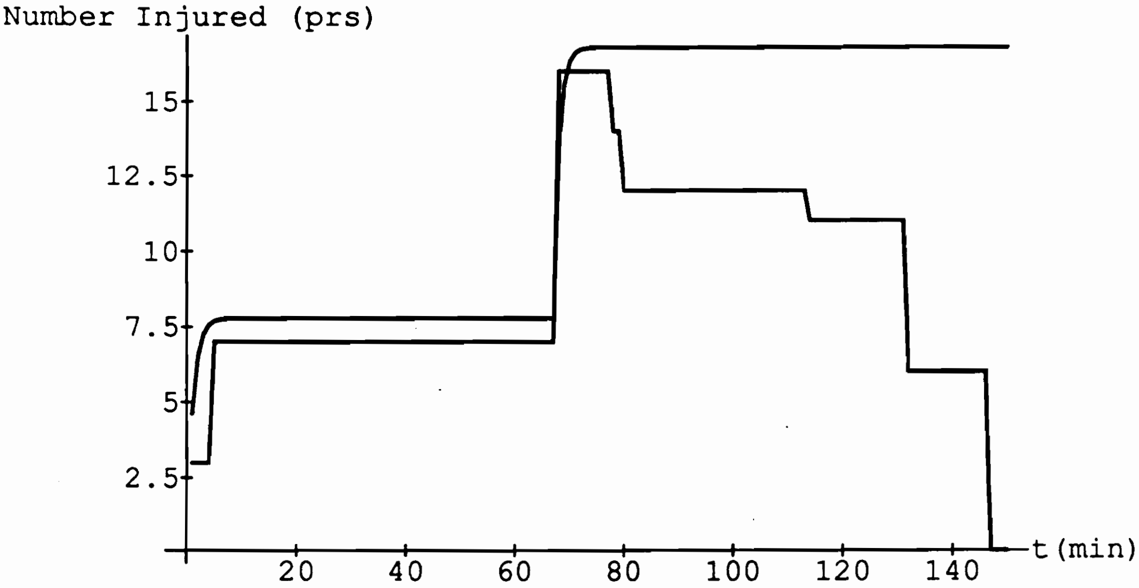


Figure 22. The open-loop model output levels off at the total number of people injured.

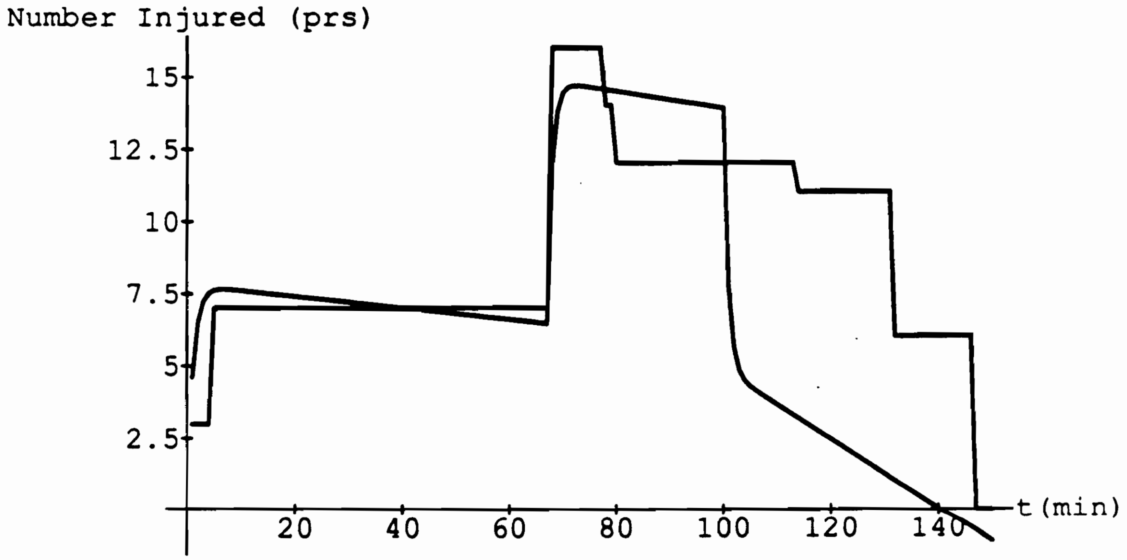


Figure 23. The closed-loop model estimates the duration of the rescue operations.

objective of this research is not to build the perfect model. The objective of this research is to show we can track the exercise output.

The estimator output

The observability test: With the values of τ in Equation (76) on page 197 all equal to 1, the system fails the observability test. When we change $1/\tau$ to 0.9, 1, and 1.1, respectively, the observability matrix becomes

$$\begin{bmatrix} 1 & 1 & 1 \\ 0.4066 & 0.3679 & 0.3329 \\ 0.1653 & 0.1353 & 0.1108 \end{bmatrix}$$

which has rank $n = 3$. Of course, this changes the system in Equation (20). But this is a minor arbitrariness compared to arbitrarily setting the values of τ.

Transformation to observable form: The series of steps to put the (modified) system of Equation (20) in observable form are (VanLandingham, 1985):

1. Calculate the characteristic polynomial,

   $p(z) = -0.0498 + 0.4074z - 1.1073z^2 + z^3$

2. Calculate the observable state and output matrices,

   $$A_o = \begin{bmatrix} 0 & 0 & 0.0498 \\ 1 & 0 & -0.4074 \\ 0 & 1 & 1.1073 \end{bmatrix}, \quad C_o = [0 \;\; 0 \;\; 1]$$

3. Calculate the two observability matrices,

   $$O = \begin{bmatrix} 1 & 1 & 1 \\ 0.4066 & 0.3679 & 0.3329 \\ 0.1653 & 0.1353 & 0.1108 \end{bmatrix}, \quad O_o = \begin{bmatrix} 42.946 & -245.76 & 350.70 \\ -99.917 & 542.92 & -738.29 \\ 57.971 & -300.17 & 387.59 \end{bmatrix}$$

4. Calculate the observable input matrix,

   $$B_o = 10^{-3}\begin{bmatrix} 0.997 & 0.516 & -9.07 & 80.7 & 85.5 \\ -0.764 & -0.227 & 46.9 & -462 & -467 \\ -5.29 & -2.56 & -60.6 & 659 & 632 \end{bmatrix}$$

The estimator gain matrix: Similar to the general population case, we place the eigenvalues of the estimator at $z = 0.5$. Then, the characteristic polynomial becomes

$p(z) = -0.125 + 0.75z - 1.5z^2 + z^3$,

yielding the estimator gain matrix

$$K_o = \begin{bmatrix} 0.0752 \\ -0.3426 \\ 0.3927 \end{bmatrix}.$$

The state estimator: The structure of the data includes the step functions representing inputs u_4 and u_5. It doesn't make sense to break apart matrix B to use the other controls. Therefore, we remove matrix B from the estimator, under the assumption that the only available input is the exercise data we need to track down. So, the state space model for the estimator or observer is

$$\begin{aligned} \hat{\mathbf{x}}_o(k+1) &= \begin{bmatrix} 0 & 0 & 0.125 \\ 1 & 0 & -0.75 \\ 0 & 1 & 1.5 \end{bmatrix} \hat{\mathbf{x}}_o + \begin{bmatrix} 0.0752 \\ -0.3426 \\ 0.3927 \end{bmatrix} y_d \\ y_o &= [0 \;\; 0 \;\; 1]\,\mathbf{x}, \end{aligned} \tag{21}$$

where $\hat{\mathbf{x}}_o$ = estimate of the observable state vector, $\hat{\mathbf{x}}_o(0) = 0$,

y_d = exercise time series data, and

y_o = estimator output.

The results are in Figure 24 on page 121. The first half of the curve (increasing part) reflects the behavior of the system subject to a "change in operational conditions" (Figure 2 on page 10). After that, the response team starts appropriate actions that end up neutralizing the emergency (having zero injured people in the site).

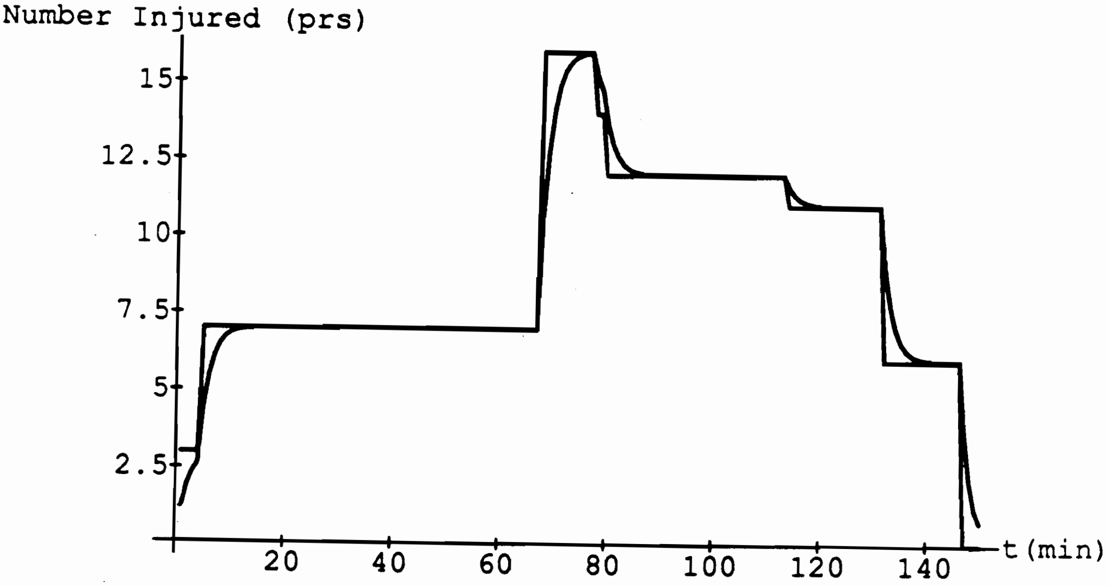


Figure 24. The state estimator tracks the emergency exercise data.

The results

This is the last chapter of this document. The chapter begins with a summary of preliminary results and their relevance to emergency response. The results are relevant, but that is not enough to substantiate the hypothesis. To do that, we use data about the injured sector of the population. Specifically, we show how the output from a state estimator describes the same phenomena as the time series data about (simulated) injuries during the emergency exercise. Since we don't have a formal test for the hypothesis, we provide a critique we make extensive to the entire research effort. We finish this work with a few suggestions for further research.

The emergency response management system

The performance criterion on page 92 implicitly defines emergency response as an interrupt handling activity. An interrupt is any asynchronous event indicating that something needs attention. Some events are more serious than others as show by the different "incident classifications" in "Definitions" on page 25. The adequate procedure associated with each incident class states whether to activate the emergency team, call for mutual aid, and so forth (Figure 25 on page

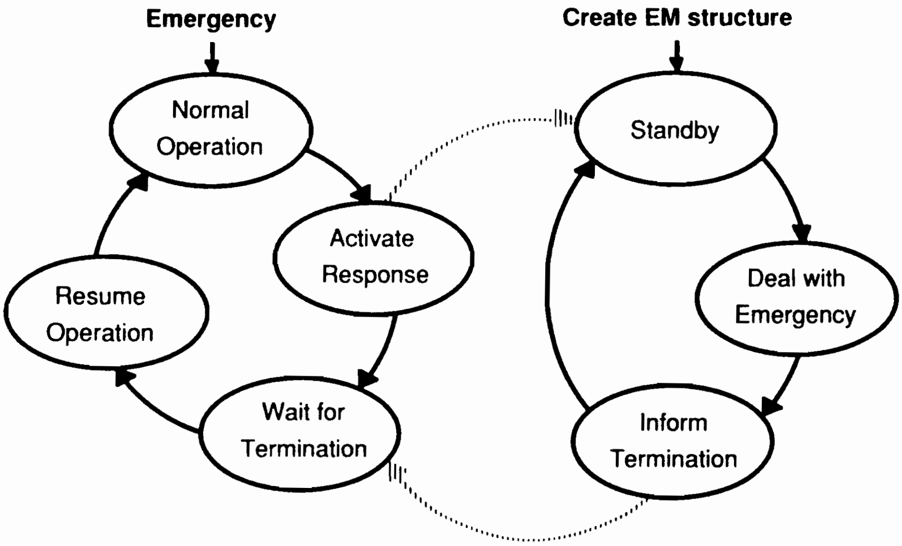


Figure 25. Emergency response is an interrupt handling activity.

123). There are two main possibilities when activating an emergency response team: either the whole organization stops operating until the emergency ends, or the work continues while a dedicated task force is put in charge of the occurrence. Industrial emergencies, like the one featured in the exercise, tend to fall in the first case.

Each oval in Figure 25 is a state of the organization and the arrows are transactions that switch the organization from one state to another. When *all* input transactions to a given state are satisfied, that ″simultaneously″ activates the output transactions and moves the organization to the next state. Consider the state ″Normal Operation.″ The organization stays in this state until an interrupting event occurs. After the event is classified and shown to be an emergency, the organization switches to the ″activate response″ state. This state requires no further input transactions; the output transactions can be immediately activated and that corresponds to activating the emergency response team (upper dotted line) and halting current operation. At that point, the emergency response team in standby can start working, while the rest of the organization waits for the end of the event. And so forth.

Referring to Figure 7 on page 44, we assume emergency responders know most cause and effect relationships. Therefore, the uncertainty associated with emergency response relates to knowing what resources (quantity) will be required to cope with the emergency, how long will the emergency last, and what values of key variables will hold at the end. To keep the model simple, we excluded all aspects associated with resource management. But the other two questions are addressed here.

Summary of preliminary results

As discussed at the end of the paragraph "On-site population mix" on page 75, emergency managers switch their attention between global protective actions and the situation of injured people. In MSM terminology, this means they split the ″what is managed″ component of the emergency management system. This doesn′t necessarily violate the ″single concern″ of the "Assumptions" on page 17. We can always say emergency managers alternate between one focus of concern and the other, but only pay attention to one of them at a time.

This research provides two simple mathematical models to represent this management environment. The models are mutually independent. Describing the management system as a control loop, both models are run in two modes. In open-loop mode, they show what happens when the events are left to evolve uncontrolled. In closed-loop mode, the models show the effect of management action when responding to disturbances. Formulating the management system as a control theory analog helps increase the descriptive power of the MSM.

The general population model: This is a global protection model, featuring simple relationships that describe evacuation and sheltering. A global protection model looks at the interaction between physical hazard factors and overall protective measures. The model shows mathematically the essence of emergency management: in the absence of response actions, the unicohort grows to the size of the population (Figure 18 on page 105); otherwise it maintains its steady-state level.

The injured population model: This is a rescue analysis model, showing where and how long injured people stay at the site before they are evacuated. A rescue model looks at the efficiency and effectiveness of rescue operations. The model mathematically shows the requests to handle injured people (Figure 22 on page 117) and the movement of people into and out of the triage center (Figure 23 on page 118).

The predictive nature of control theory

The terms *prediction* and *forecasting* are often used as synonyms. The forecasting problem consists of guessing (extrapolating) the value $\hat{y}_{t_{N+m}}(m = 1,2, \dots)$ given a time series of data $y(t) = y_{t_k}(k = 1,2, \dots, N)$. (See "Organization of the data" on page 64.) The problem of finding the weights c_k in $\hat{y}_{t_{N+m}} = \sum c_j y_{t_{k-j}}$ is called pure linear forecasting, but there are many other forecasting techniques. Forecasting is a statistical, data-manipulation technique.

Control theory is a process-based technique. That is, control theory can only make predictions when a mathematical model of the process (plant) is available. This research provides a good example: feeding a single input data point (the amount of chlorine released) to the global emergency model is enough to produce Figure 18. But, by definition, a model can only approximate a system's behavior. An observer or estimator is a mathematical device that uses actual system measurements to adjust the model predictions. When only a rough model is available, the estimator can still track the system's arbitrary behavior. This research shows two instances of that capability (Figure 20 on page 113 and Figure 24 on page 121).

The key point to remember is that in a control theory model the output behavior is *always* related to the input. Predictions are only allowed if they fall within a time horizon (window) where the present input is still valid. Otherwise, predicting beyond that time horizon requires guessing the inputs, which control theory doesn't do. But statistical forecasting does.

The test of the hypothesis

According to Chatfield (1980), there are two perspectives to study the relationship between two time series. One perspective relates to determining the properties of a linear system that produces one of the time series as output when using the other time series as the input. In control literature this is known as *system identification.* The other perspective relates to determining the correlation between the two time series. Unfortunately, there is no test statistic we can use to determine whether two time series are likely to represent the same or different phenomena.

Nevertheless we can still test the hypothesis by running both time series through the following procedure:

1. Calculate the autocovariance functions for each time series.
2. Calculate the cross-covariance function.
3. Calculate the amplitude and phase angle of the spectral density function (spectrum) for each time series..
4. Calculate the cross-amplitude and phase angle spectra for the bivariate process.
5. Calculate the squared coherency.

For each frequency, the coherency is analogous to the square of the traditional correlation coefficient. We use the square root of the average coherency as an estimator of the correlation between the two processes. This analysis borrows mainly from Chatfield (1980). The details appear under "Appendix E. Machine calculations" on page 198.

Application of the method

Analysis in the time domain: Given a time series of data $y(t) = y_{t_j}(j = 1,2, \ldots ,N)$, the interval k between two data points (observations) y_{t_j} and $y_{t_{j+k}}$ is the *lag*. (From now on we use y_j instead of y_{t_j}.) An estimator for the *autocovariance coefficient* for lag k is:

$$v_y(k) = \frac{1}{N} \sum_{j=1}^{N-k} (y_j - \bar{y})(y_{j+k} - \bar{y}). \qquad (22)$$

For all k, we have the autocovariance function. The values of $\bar{y}$ for both time series are shown in Table 7:

Table 7. Sample autocovariance estimates use N = 150.

	Data	Model
Mean	8.913	8.925
Variance	11.813	10.886

For the bivariate process, an estimator for the *cross-covariance coefficient* for lag k is:

$$v_{y_d y_o}(k) = \begin{cases} \frac{1}{N} \sum_{j=1}^{N-k} (y_{d_j} - \bar{y}_d)(y_{o_{j+k}} - \bar{y}_o), & (k = 0,1, \dots , N-1) \\ \frac{1}{N} \sum_{j=1-k}^{N} (y_{d_j} - \bar{y}_d)(y_{o_{j+k}} - \bar{y}_o), & (k = -1, -2, \dots , -(N-1)), \end{cases} \tag{23}$$

where the subscripts d and o refer to the data and the observer, respectively.

Analysis in the frequency domain: This method assumes the variation in a time series is a linear function of the variations at different frequencies,

$$y_k = \sum_j R_j \cos(\omega_j k + \theta_j) + Z_k, \tag{24}$$

where ω_j = frequency of the variation (rad min^{-1}), the particular $\omega_k = 2\pi k/N$ is the kth harmonic;

R_j = amplitude of the variation at frequency ω_j (prs);

θ_j = phase (rad); and

Z_j = stationary random time series.

The function $f(\omega)$, such that $\int_0^{\pi} f(\omega) d\omega = \sigma^2$, is the spectral density function or *spectrum*. In other words, the contribution to the variance of the frequencies in the range $[\omega, \omega + d\omega]$ is $f(\omega)d\omega$. To obtain the spectrum, we take the Fourier transform of the autocovariance function. For the bivariate process, to obtain the cross-spectrum we take the Fourier transform of the cross-covariance function. The spectra are complex functions, with a real and an imaginary part: $f(\omega) = \mathrm{Re}(\omega) - i\mathrm{Im}(\omega)$. In particular, for each spectrum,

$$\mathscr{R}(\omega) = \sqrt{\mathrm{Re}^2(\omega) + \mathrm{Im}^2(\omega)} \;=\; \text{amplitude spectrum}$$

$$\vartheta(\omega) = \tan^{-1}(-\mathrm{Im}(\omega)/\mathrm{Re}(\omega)) \;=\; \text{phase spectrum}$$

$$C(\omega) = \frac{\mathscr{R}^2_{do}(\omega)}{\mathscr{R}_d(\omega)\mathscr{R}_o(\omega)} \;=\; \text{(squared) } \textit{coherency}$$

Synthesis of the results: The analysis through the Fourier transform splits the variability of the time series into harmonics at frequency multiples of $\frac{2\pi}{N}$. This is equivalent to splitting the sum of squares $\sum_{k=1}^{N}(y_k - \bar{y})^2$ into (1) the residual sum of squares and (2) the contributions to the variance of the spectra at harmonics ω_k. According to Chatfield (1980, p.177), the coherency at frequency ω_k "measures the linear correlation between the two components of the bivariate process." A higher coherency for a given ω_k means ω_k "explains" more variance than another frequency with a lower coherency. The square root of the coherency, which is a larger number, is comparable to the correlation coefficient. Figure 26 on page 130 shows a plot of $C(\omega)$. The statistics for $C(\omega)$ are:

Sample range = 0.2422

Mean = 0.6510

Mean deviation = 0.0369

Median = 0.6396

Median deviation = 0.0244

Quartiles = 0.6204, 0.6859

Inter-quartile range = 0.0655

Quartile deviation = 0.0328

Variance = 0.0022

Standard deviation = 0.0471

Conclusions

Figure 26 supports the alternative hypothesis: the output of the management system and the output of the control theory state estimator are correlated. In other words, these results show that *the time series data from the exercise and the output from the state estimator describe the same phenomena.* On the one hand this is surprising, for two reasons. The first reason is because the plant models are too rough, sometimes with totally arbitrary parameters. The second reason is because

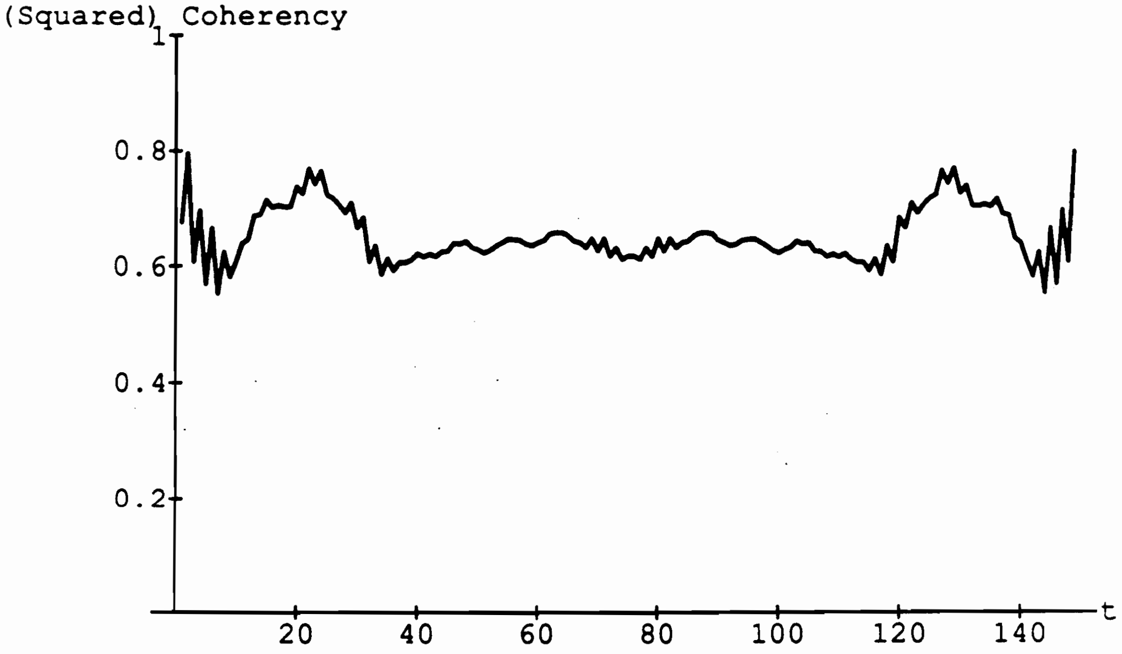


Figure 26. The data and the observer output are correlated.

the data are highly inaccurate, and have to be interpreted to suit the model needs. Interpreting the data to generate stepwise time series may not be the best decision.

On the other hand, statistical agreement is not surprising, also for two reasons. The first reason is because we are applying a well-proven technique. If instead of a simple observer we had developed an optimum observer (Kalman filter), the results would be even more impressive. The second reason, somewhat related to the first, is because the technique is quite insensitive to model errors. This allows us to obtain good results with mediocre models.

As promised, this research shows an application of control theory to a management problem. Certainly, this is only one example. But a long time has passed since control theory was abandoned by managament researchers (e.g., Simon, 1952), and a lot of work has been done meanwhile. The technique is now mature, and available for use in the social sciences and management.

Critique

Longitudinal single-case experimental research imposes several methodological restrictions. This section looks at the strengths and weaknesses of the methodology.

Evaluation of the results

Inspired by Kazdin (1984), we use two criteria to evaluate the results. These criteria are what we might call the "necessary and sufficient" conditions for good research. The *experimental criterion* tells whether or not the way we analyze the results can show the research has accomplished its objectives. The research may accomplish its objectives but only before the trained eye of an experienced researcher; or it may show the results even to the naked eye of the non-specialist. The *significance criterion* tells whether or not the accomplishments of the research can stand for themselves. The results may be interesting, but it must be evident they are the intended outcome of the research.

This research proposes visual inspection and statistical analysis to evaluate each criterion. Visual inspection consists of looking at (examining) a graphic display of results and determining whether the plots reject the hypothesis or not. Statistical analysis provides quantitative means to determine the reliability of the results. These two methods are mutually supportive, although the results may come as no surprise.

Effectiveness of the methodology

Data gathering: A procedure for gathering exercise data is nonexistent. Last minute changes prompted by the sensitive nature of the exercise prevented collecting much of the data initially promised. The data available were provided directly by FMPC, but they were gathered for other purposes. Often the number of data points was insufficient and forced the artificial construction of the time series (ramp and step functions). There is no point in discussing this any further.

Besides exercise data, this research also uses model output data. A possible question concerning model data is whether or not they should have been gathered (the model built) *before* collecting exercise data. The implication is that it may be impossible to build a control theory model for a management system whose behavior is not known beforehand.

The refutation is twofold: (1) it is still possible to make arbitrary changes in the exercise data and check whether the model output reacts properly or not; and (2) the output of the model depends only on the input and initial conditions (by construction and definition of state), not on the format of the intended output.

Model building: If any model were available in the literature fitting this research, it would have been used. The key decision in all modeling is balancing simplicity against completeness. Where the balance lies depends on the model objectives. Whenever possible, this research tries to keep the models simple and the models featured here are far from complete (e.g., do not include resource management). As previously referred, they are quite inaccurate, too. Most of the parameters were either inferred from the theory or arbitrarily set.

The estimator is not the best possible estimator either. The optimum estimator was developed by R.E. Kalman in the early sixties: it is called the Kalman filter estimator, or Kalman filter for short (Goodwin & Payne, 1977; Hannan & Deistler, 1988). A Kalman filter explicitly separates the variability in the process from the variability in the measurements. According to Grimble (1987, p.131),

> the most important role for the Kalman filter in control systems is as a state estimator. That is, the filter is used to provide estimates of the states of a system where only the noisy outputs can be measured. These estimates are then used as if they were the actual plant states in a feedback control scheme.... Experience has shown that the filter is relatively insensitive to modelling errors and uncertainties.

Hypothesis testing: According to Kazdin (1984), the statistical methods usual in between-group research are not applicable in time series-based, single-case research. So, he proposes several methods whose main objective is to determine whether performance differences between and after treatment were significant or not. This is not the case with this research. The objective of any model suitable for this research is to determine whether two subjects exhibit the same response to identical treatments or not. The subjects here are the system and its model. The treatments are the response to hazardous episodes.

Since statistical tests were only an additional support to graphic methods, they were not subject to the scrutiny other operations were in this research. There may be some recent developments best suited for this research. But the methodology used serves the purpose.

Validity and generalizability

As discussed in "The type of research" on page 5, this research is structured along the work of Brinberg and McGrath (1985). They define validity as value from the perspective of the worthiness of the concepts. This concept of validity is closely related to the concept of generalizability. A piece of research is valuable if it is generalizable and can be used time and again by future researchers under different circumstances. To demonstrate this research's validity we must show this work is generalizable. The rest of this section draws upon Chapanis (1988).

Generalization through similarity: The argument for emergency management as a research environment in "Significance of the experimental method" on page 22 is particularly relevant here:

> The closer the research situation matches some real one, the more justified we are in generalizing from the empirical findings to what would happen in a real environment. Even though we cannot measure precisely... the similarity between two situations, we have here some empirical support for generalization. (p.259)

Generalization through replication: The rationale for generalizing about control theory is that control theory explains a wide variety of experiments ranging from the biological and psychological sciences to engineering and management. It is true that most applications outside engineering don't use its mathematical structure, but that mathematical structure doesn't require empirical support. The reason to confer generality on control theory is that it has been applied "formally and informally in a wide range of settings and with a large number of machines and systems" (p.260).

Generalization through precautions taken: Still building on decisions made earlier, the choice of emergency management as the experimental environment is robust against external validity, and therefore against threats to generalizability. The most often cited threats are:

- Using unrepresentative subjects — This is management systems engineering research involving actual managers.

- Inadequate subject preparation — Exercise preparation involves tabletop sessions and field drills.
- Inadequate sampling of situations — The exercise scenario is based on real-life work, according to company officials and MSL consultants.
- Improper choice of dependent variables — The number of injured is the most important criterion in the emergency management world.
- Intrusiveness of measurement devices (Hawthorne effect) — The exercise actors are under the same (or at most less) scrutiny as real-emergency actors.

Interpretation of the results

We discussed the similarity between the output of the management system and the output of the estimator (Figure 19 on page 109). Recall, the output of the management system is the exercise data. From a substantive viewpoint (emergency management), that similarity has several implications:

1. The output of the management system reflects the overall performance of the organization; that is, Figure 16 on page 89 reflects the performance measure on page 67.
2. The output of the management system shows how external disturbances affect performance and how effective is managerial action; that is, Figure 16 on page 89 reflects the performance criterion on page 92.
3. The emergency response management system is an information feedback loop; that is, continually updating the lower part of Figure 19 on page 109 corresponds to closing the loop in the lower part of Figure 3 on page 11.
4. The output of the estimator shows exponentials are a surrogate dynamic behavior of rescue operations; that is, the mathematical form of the estimator in Figure 9 on page 51 depends on the form of the dynamic model of the operation.

Figure 18 on page 105 can also be interpreted from the emergency manager's perspective. The curve represents the potential consequences of the emergency, showing how the situation becomes worse as time passes. For reasons discussed in "The propane incident" on page 165, the time scale may be totally inaccurate. But the curve still gives a sense of urgency for the response. Similarly, Figure 23 on page 118 provides a first-cut estimate for the duration of the rescue operations when the number of "injuries" is known.

Topics for further research

The research question we asked at the vertex of the research tree was whether or not we could build a predictive model of a management system. Now that we have a positive answer, we can proceed along the tree and select the next node according to individual research preferences. There are many ways we can extend this work, leading either to short- or long-term research projects. This section presents a topical view of a possible research plan.

Focusing on the substantive domain

This branch of the research tree has two main alternatives. One alternative consists of further studying emergency management. Another alternative consists of studying a different management area.

Refining the emergency management application: By looking at the global output of the management system, we overlooked all aspects related to the effect of information on individual decisions, the effect of decisions on performance, or the effect of the communications pattern on performance. As discussed in "The data-handling procedure" on page 66, some of the players were too busy to remember logging relevant events. The question is what were they doing, or why were they too busy.

1. *The lack of information syndrome*. We still don't know what information emergency managers use and what information they require. But we can ask. An appropriate data collection procedure may help characterize uncertainty for different players at different levels. Then, the control model can focus on perhaps more relevant variables.

2. *The information overload syndrome*. Similarly, we can also improve the control model by knowing what decisions people make based on what information. In particular, the format and content of the status boards may be relevant to different people with different degrees. For instance, if we find that different people prefer to use different boards, that may be a clue to improving the layout of the EOC.

3. *The information portrayal syndrome*. The output of the observer can be used as a decision aid during the emergency (Figure 27 on page 138). We may assume individual characteristics (e.g., personality) influence preferences for a particular information portrayal format (Figure 1 on page 8). But we don't know what characteristics contribute to better performance during emergencies and what information portrayal format is best suited for them.

Extending the application range: A large percentage of new businesses die in the first years of existence. In part, this high failure rate may be due to lack of design, but that is not the point here. Rather, the point is that more general problems are symptoms of unstable dynamic behavior. These problems may occur even in surviving organizations, manufacturing or service, public or private, old or new. They can, and do occur in any part of the organization, reflecting changes in management in the same or in other parts.

1. *The reorganization syndrome*. In many private and public-sector organizations, what managers call a "reorganization" is only a periodic trial-and-error experiment in shuffling people. Those

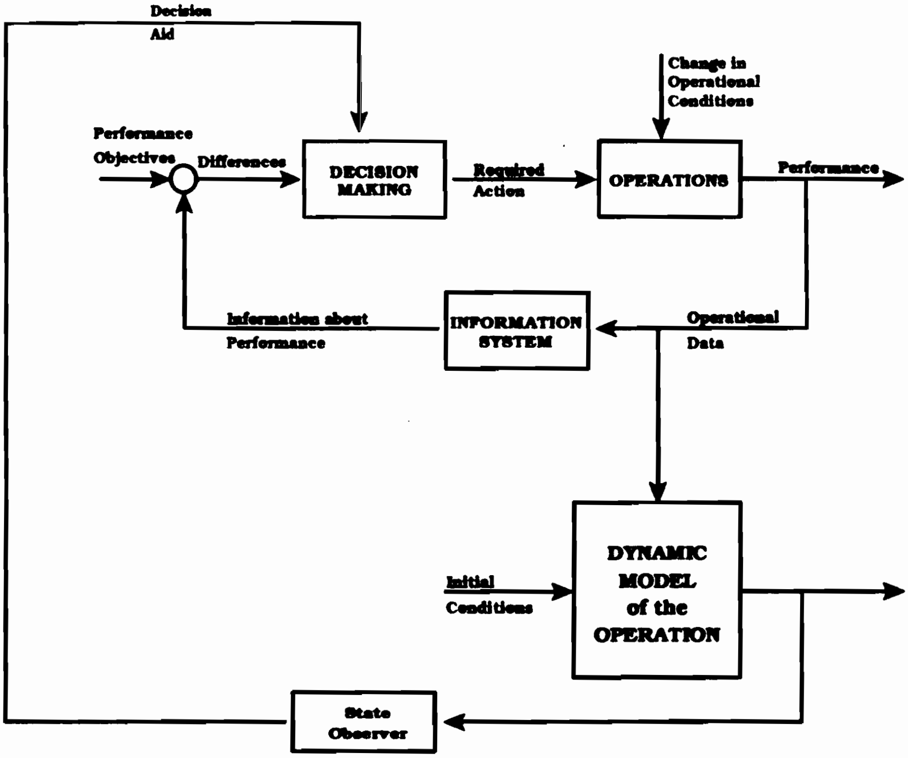


Figure 27. The state estimator shows the unfolding of the emergency.

reorganizations are inspired by the feeling the organization can perform better if a few people or the names of some departments are changed. But the stability of the organization may be sensitive to organizational structure changes, not to the structure itself. It would be nice to provide managers with methods they could use to figure out beforehand the effect of different alternatives. The managers would save effort and time, and their people would save the frustration and anxiety associated with being shuffled.

2. *The succession syndrome.* A disruptive event for any operation occurs when a person leaves the organization and another person, with different personal characteristics, is hired to fill the vacant position (Gabarro, 1987). Changing a manager corresponds to changing the controller in the control loop. Organizations often look only for someone who has the professional background to match the job description, but this may not be enough. A possible end result is known as the "Peter Principle." It would be nice to provide higher-level managers with modeling tools they might use to predict the behavior resulting from changes within their management systems. The managers would improve their hiring and reward procedures.

3. *The turbulence syndrome.* In management literature we see terms like "turbulent environment" to classify situations where changes are frequent. However, as shown by Forrester (1961), the environment also reacts to and amplifies the fluctuations in an organization's output, often giving a false sensation of turbulence. This false sensation leads to more fluctuations, up to a point where real turbulence causes someone to leave or management to feel the need to "reorganize." It would be nice to provide managers with (feed-forward) modeling tools to anticipate and attenuate the effects of environmental changes impacting on an existing management system. The managers would be capable of proactively stabilizing their operations.

Focusing on the methodological domain

The methodological domain consists not only of control theory, but also of all activities leading to the dynamic model of the operation.

Extending the emergency model: In addition to modeling other kinds of emergencies, one way to enlarge this mathematical model is to consider what happens when the scenario assumptions are not met. Extending the model is outside the scope of this research, and will not be done in detail. But it may be interesting to show here how we would proceed for a few cases.

1. *Fireball formation.* A first extension may be the situation where ignition does not occur immediately, leading to the development of a liquid pool of propane that evaporates to form a gas cloud. This cloud may drift and meet a source of ignition later (Heinrich, Gerold & Wietfelt, 1988; Wierzba, Karim, & Cheng, 1988). According to Kletz (1977-b, p.2), "if flammable gases or vapours are mixed with air in flammable concentrations, then experience shows that sources of ignition are likely to turn up. They are one of the few things in life we get free." The ignition of a cloud of gas in the open air produces an Unconfined Vapor Cloud Explosion, or UVCE.

   Another deviation from the scenario occurs when weather and local conditions are such that the flame is allowed to impinge on the tank, causing the inside temperature to rise. In general, pressure relief valves (PRV's) open at 60°C and release enough vapor to maintain this temperature. But the vapor may in turn ignite: "the discharge from burning relief valves can create a giant torch seriously endangering not only exposures but also the tank itself" (Meidl, 1978:129). There's also the possibility of overheating the PRV (Moodie, Billinge & Cutler, 1985). Then, if the PRV fails, the pressure builds up to a point where it exceeds the built-in stress limits for the tank, which fails catastrophically with an explosion (BLEVE). In such cases we assume all will die beneath the fireball (Stinton, 1983). Beyond the fireball, houses collapse and flying tank fragments (called missiles) may injure about 10% of the population within reach of a 0.2 atm overpressure.

We have models describing the temperature and pressure build-up within the tank (Hunt & Ramskill, 1985[28]). We can also calculate the dimensions and duration of the fireball, the temperature rise, and the overpressure from the shock-wave for an UVCE or a BLEVE. Then we obtain hazard assessment contours for different heat radiation and shock wave threshold values. To obtain the dimensions of the fireball and estimate the thermal hazard we can use the guidelines provided by Williamson and Mann (1981). Referring to "Hazard thresholds" on page 92, in the case of a propane explosion, we first calculate the TNT equivalent yield from the amount of gas and from its standard heat of combustion; then, we obtain a characteristic explosion length and other quantities. Nevertheless, although we have differential equations to describe an explosion (Wiekema, 1980), they are not used here because the scenario doesn't call for them.

2. *Fire hazard response*. If the potential BLEVE resulting from a pressure build-up inside the tank is to be considered, then the response action consists of reducing the pressure to a safe level. According to Meidl (1978:107), there are three possibilities:

   a. Increase the volume of the container. Since the only way a steel container can increase its volume is by bursting, this is the least desirable way to reduce pressure.
   b. Lower the temperature and pressure of an exposed cylinder by applying a cooling water spray....
   c. Reduce the amount of gas within a cylinder by pressure relief devices.

   Still according to Meidl (1978:129), "although dry chemical will extinguish a very small LP gas fire, *there is no known method or material that will extinguish a large one*. However, the proper use of water will be of assistance. Water is absolutely indispensable." Although extinguishment is not planned in the scenario (the propane tank is allowed to burn), cooling down the fire is. Therefore, accounting for this form of response involves calculating water spray duration and quantity.

---

[28] The companion paper by Moodie, Billinge & Cutler previously cited contains experimental data confirming these models.

3. *Environmental and economic effects.* One of the main problems of the chemical and nuclear industries today is a problem of image. Industrial safety is a key part of this image. Emergency exercises serve the double purpose of improving the site's accident response capacity and improving the image before the public's eyes. Yet many companies seem to relegate these activities to low priority. For one reason, exercises are expensive. For another reason, the consequences of an accident are difficult to foresee and the return on the investment is unclear. In turn, the main reason why this is so is because the public reaction and environmental dynamics are not well understood by many decision makers.

   Anecdotal observation shows that once security and environmental issues are taken care of, public-related problems are minimized. One way to face those issues with low investment is through modeling. Writing a model in state space form allows it to be expressed either as a time series forecasting problem, a linear programming problem, or an optimal control problem. For instance, the relationships between operations research and optimal control are easier to understand using the state space notation. Guariso and Werthner (1989) present environmental simulation, forecast, planning, and management models along these lines.

Improving the control model: From the methodological standpoint, this direction is probably the closest to this research.

1. *System identification.* To identify a system is to obtain its mathematical description (the values of matrices A, B, and C) from direct measurements of its inputs and outputs. At the output side, measurement data $y(t)$ is composed of a process signal $s(t)$ and noise $n(t)$, $y(t) = s(t) + n(t)$. The same thing happens at the input side. The prediction of signal values (elimination of noise) is called *filtering*.

   System identification uses the transfer function. The transfer function is the mathematical description of the system as a black box: any input multiplied by the transfer function produces the output. Every feedback control system has two major transfer functions. There is a transfer function from the reference input to the output, and another from the disturbance input to the output.[29] The key factor in this project is good data collection. (See Goodwin & Payne, 1977 for details.)

2. *Optimum estimator.* With better data, it's worthwhile to build a Kalman filter. Although theoretically more sound than general regression, Kalman filtering requires a good model of the system; therefore, there are no general-purpose computer packages available (Andersen, 1981). These drawbacks are naturally overcome because control theory also requires a model of the system. Indeed, the major advantage of Kalman filtering, from the perspective of this research, is that it is integrated with control theory (Catlin, 1989; Miller & Leskiw, 1987; Stark & Woods, 1986; VanLandingham, 1985).

The state estimator generates $\hat{\mathbf{x}}$ in Figure 9 on page 51. The application of the Kalman filter to the system described by the general control model formulation of Equation (1) on page 52 is as follows:

$$\begin{aligned} \mathbf{x}(k+1) &= A\mathbf{x}(k) + B_1\mathbf{u}(k) + B_2\mathbf{w}_1(k) \\ \mathbf{y}(k) &= C\mathbf{x}(k) + \mathbf{w}_2(k), \end{aligned} \tag{25}$$

where $\mathbf{w}_1$ is an error term accounting for the variability in the system and $\mathbf{w}_2$ is an error term accounting for the variability in the measurements. These error terms have mean matrix

$$E[\mathbf{w}(k)] = E\begin{bmatrix} \mathbf{w}_1(k) \\ \mathbf{w}_2(k) \end{bmatrix} = 0 \tag{26}$$

and covariance matrix

---

[29] The transfer function is represented by a polynomial fraction; the roots of the numerator are called the zeros, and the roots of the denominator are called the poles. Prototype design, referred to under "The state space method" on page 49, is the selection of the zeros and poles. The exact value (location) of these zeros and poles affects the system's performance, stability, etc.

$$E[\mathbf{w}(k)\mathbf{w}^T(k)] = E\begin{bmatrix} Q_1 & Q_{12} \\ Q_{12}^T & Q_2 \end{bmatrix}, \qquad (27)$$

where E = expectation operator

superscript T denotes the transpose[30]

$Q_2 > 0$.

This formulation leads to the Kalman gain matrix $K(k) = [AP(k)C^T + B_2Q_{12}][CP(k)C^T + Q_2]^{-1}$, where $P(k)$ is obtained through a recurrence relation involving previous values. So, the optimal estimators, in a least-squares sense, for the system's states are:

$$\hat{\mathbf{x}}(k+1) = A\hat{\mathbf{x}}(k) + B_1\mathbf{u}(k) + K(k)[\mathbf{y}(k) - C\hat{\mathbf{x}}(k)]. \qquad (28)$$

3. *Controller design.* Alternatively, or in parallel with the work done here for the estimator, we can design a controller to predict the manager's control actions. The algorithm will generate a time series of **u**-values (controlling inputs), which can then be compared to previously collected managerial directives $\tilde{\mathbf{u}}$. This task is in many aspects similar to what we did here, so there's no need to describe it any further.

   Next, as described under "The state space method" on page 49, compensator design consists of putting together an estimator and a controller. The injured population model used in this research is too rough for this purpose. But the idea is to move toward the full simulation of a management system (Mendes, Roach, and Kurstedt, 1989).

4. *Sensor and actuator modeling.* The sensors are the mechanisms that convert data from measurements at the site into information for management decisions. The actuators are the mechanisms that convert the manager's action (instructions and recommendations) into actual

---

[30] The transpose of the 2 × 1 column vector **w** is a 1 × 2 line vector; their product is a 2 × 2 square matrix whose elements Q obey the particular configuration of Equation (27). This formulation is general, in the sense that both components $\mathbf{w}_1$ and $\mathbf{w}_2$ of **w** are themselves vectors.

action at the site or off-site. We know information losses and distortions occur in real life (Mintzberg, 1975). These can be modeled as constants (*gain* in control terminology) and delays (*dead time, transport lag* or *transportation lag).* The dead time occurs either in the transmission of a directive or reception of information. In the first case, the dead time is a period during which the operation is unaware of a requested change; in the second case the manager is unaware of what has happened.

5. *Optimal control.* As discussed in "Research boundaries" on page 15, this research is not normative. In the future, however, it can evolve into a decision aid by applying an optimal control law to the model of the system in Equation (1) on page 52. The optimal control law is the one that results from minimizing the linear quadratic functional:

$$J = \frac{1}{2} \sum_{k=0}^{\infty} [\mathbf{x}^T Q \mathbf{x} + \mathbf{u}^T R \mathbf{u}] dt, \tag{29}$$

where Q and R are called the weighting matrices. Their choice depends on the trade-off between penalizing deviations from the zero reference state ($\mathbf{x}^T Q \mathbf{x}$) and the need to assign a penalty (cost, resource availability) to limit the control action ($\mathbf{u}^T R \mathbf{u}$). "With Q large relative to R, nonzero $\mathbf{x}$ values are penalized more than $\mathbf{u}$ values so that the system response will be fast.... Similarly, with R large relative to Q the system will tend to be sluggish, but the input amplitudes will be small" (VanLandingham, 1985).

Focusing on the conceptual domain

In this research we showed how to build a control theory analog for the Management System Model. By further showing how its output was correlated to the output of a real management system, we solved the research problem we proposed at the outset. Now, what?

With so much work to do in the substantive and methodological domains, exploring the conceptual domain may be too far down the road. But we can set general directions. One general direction is to research alternative designs like feedforward control, adaptive control, or fuzzy control. Another general direction is to use the state space approach as an engineering tool, in a prescriptive mode. And, of course combine both. The objective can either be to improve the performance of management systems, to produce training packages, to design information systems, or to refine consulting methods (Figure 28 on page 147).

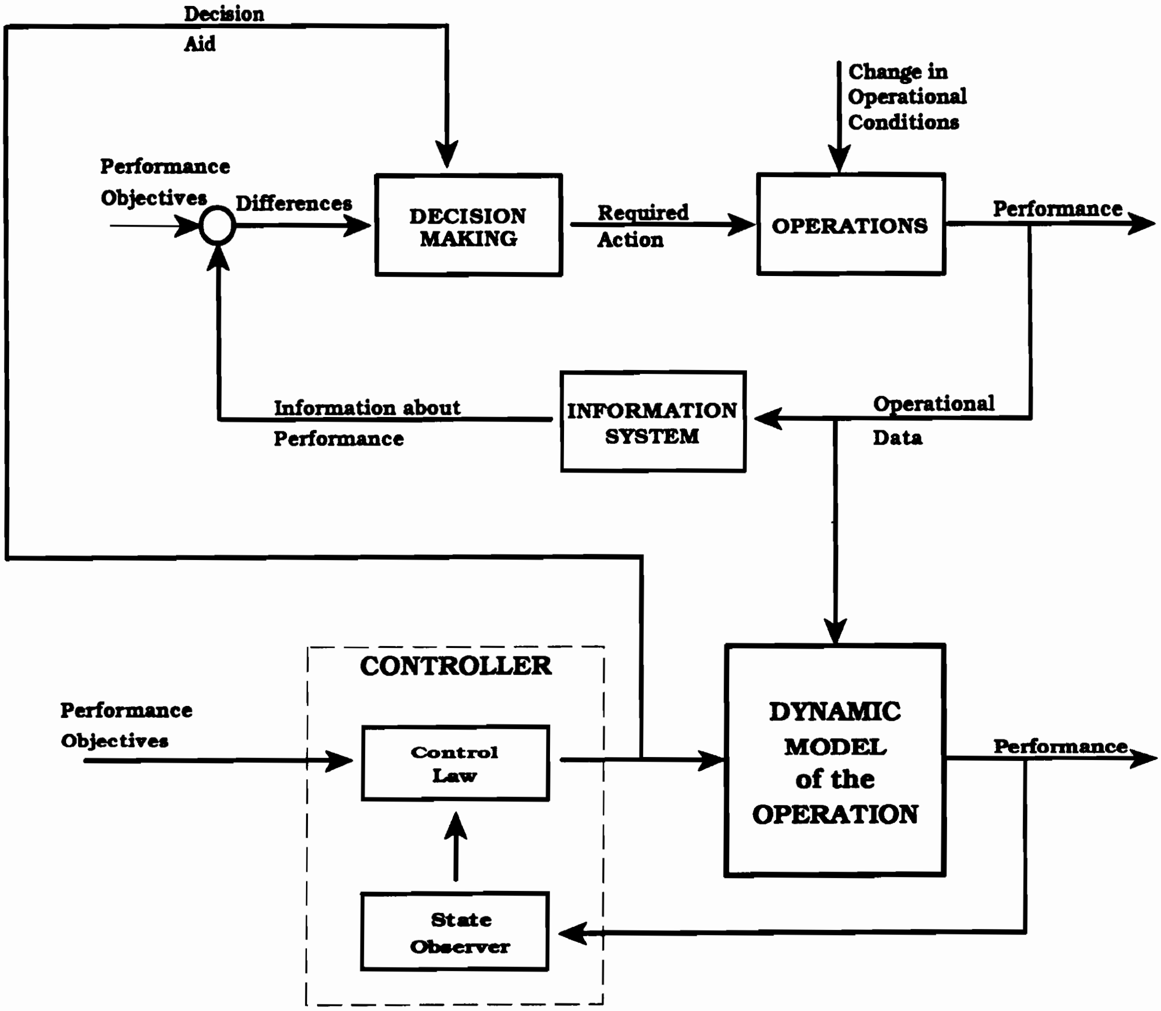


Figure 28. The state space approach is a flexible tool to engineer management systems.

Appendix A. Scenario narrative for "Joint Response 89"

The following description is quoted from FMPC (1989, p.30-33), courtesy of the Feed Materials Production Center. Figure 29 on page 150points out the incident area in the FMPC site layout, and Figure 30 on page 151 shows the incident scene.

> At 0815 on June 24, 1989 (simulating a Friday) an AAA Gas Company tractor trailer arrives at the FMPC main vehicle gate to make a scheduled delivery of propane.
>
> At 0830 the truck proceeds from the main gate to the propane area travelling north on D Street to Gamma Street. The propane tanker makes an exceptionally wide turn to get onto Gamma. As the driver attempts to recover from the turn, the trailer strikes a cylinder storage rack causing the angle iron frame to penetrate the tanker shell (see Figure 29 on page 150 and Figure 30 on page 151). A small leak of liquid propane results and ignites. The flame is almost impinging on the east side of the loading dock of the cylinder storage building. The fire and heat make the cylinder area inaccessible. The sudden stop causes the driver of the propane tanker to strike his head on the door frame knocking him unconscious. Two employees working on the cylinder storage building dock receive minor burns and jump from the dock; one falls and is injured.
>
> At the same time, an FMPC van containing four people is travelling south on Gamma Street. The driver swerves to avoid the oncoming propane tanker and strikes the overhead stanchions on the north side of building 24B, Railroad Engine House. The vehicle is severely damaged, doors are jammed, and all four people are injured.
>
> Employees in Building 12 hear the crash and go to investigate. When they see the accident, one employee reports the accident to the Communications Center.
>
> The Communications Center receives the call just after 0830 and notifies the AEDO and shift Safety & Fire Inspector (Emergency Chief). The 2-2 Plant Alarm Signal is issued activating the ERT for emergency response.
>
> After an initial survey the AEDO classifies the emergency (as either an Alert or Site Emergency) and calls for mutual aid. The Communications Officer activates the A,B,C, and D Group Pagers and activates the EOC.

The AEDO establishes a Command Post. The ERT begins extricating the injuries and controlling the fire. The number and seriousness of injuries warrants the request for Air Care for triage and medical support.

The AEDO orders onsite protective actions.

Butler and Hamilton counties activate their EOCs and Ross township activates a Command Post. Ross and Crosby Township activate their Emergency Locations (only if Site Emergency). The counties plan/implement offsite protective actions.

By 0845 the FMPC EOC is operational and the emergency has been reported to DOE Oak Ridge. All required notifications have been made. DOE Oak Ridge notifies the OHIO EOC, which is activated (Crisis Stage 2 or 3). Liaisons from various state agencies are dispatched to County EOCs to provide advice and support. The Ohio EPA dispatches a representative to the Ross Township Command Post.

The JPIC is activated and Butler and Hamilton county, Ohio EMA, and FMPC PIOs and staff begin reporting to the JPIC on Route 4 in Fairfield.

By 0900 injuries are being moved from the incident scene to a medical facility and are being treated, offsite medical support is arriving and providing assistance, the Air Care Helicopter is onscene.

Also by 0900 both county EOCs are operational as well as the JPIC.

At approximately 0915 one of the people evacuated from Building 12 (or a person in Building 12 if no evacuation is ordered) complains of nausea, exhaustion, and feeling faint. Emergency medical personnel are dispatched.

By 0940 all of the 8 injuries are receiving initial treatment and stabilization, are at the FMPC medical facility, the field triage unit, or enroute to local hospitals.

At the scene of the propane fire, the fire continues to burn with flame impinging on the cylinder storage building. Although cooling efforts are expected the fire will not be extinguished.

At 0945 heat from the fire causes the rupture disk on one or several 100 lb. cylinders of chlorine to fail. A toxic chlorine gas release occurs. (note: Exercise Controllers will prevent responders from moving any cylinders out of the building although these planned actions will be noted by evaluators if attempted.

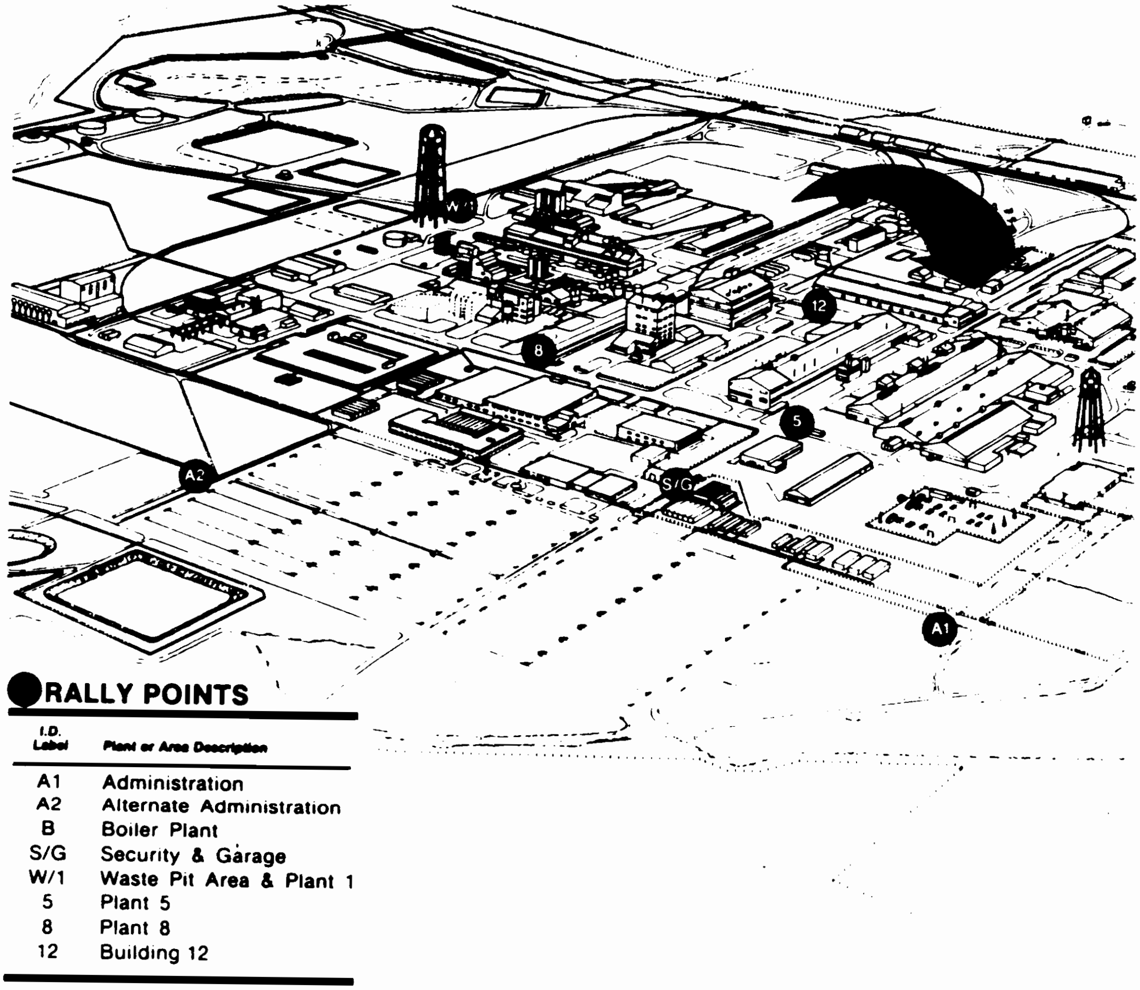
When the release of chlorine is observed and assessed the event should be upgraded to a General Emergency causing the activation of the FMPC Offsite Emergency Warning System Sirens, the issuance of an EBS message by Buttler County, and the initiation of onsite and offsite protective actions.

Shortly after the release a van carrying 9 people inadvertently travels through the plume. Realizing their mistake and experiencing exposure symptoms (coughing, eye burning & hitching), they seek medical assistance. Due to excitement and fear, one person experiences severe chest pains.

Also by 1000 offsite concentrations of chlorine will be detected by monitoring teams at or above the TLV up to 1.5 miles from the FMPC site. By 1100 no concentrations will be detectable.

Between 0945 and 1145 monitoring teams should be dispatched, modeling estimates performed, and offsite protective actions developed and implemented by all EOCs. When the plume disperses (after 1100) the EOCs should transition to recovery planning and when appropriate, plans for downgrading the event discussed. The propane tank will continue to burn throughout the exercise--extinguishment is not planned.

The exercise will be terminated at 11:45 a.m.



RALLY POINTS

I.D. Label	Plant or Area Description
A1	Administration
A2	Alternate Administration
B	Boiler Plant
S/G	Security & Garage
W/1	Waste Pit Area & Plant 1
5	Plant 5
8	Plant 8
12	Building 12

Figure 29. The accident is not close to highly occupied buildings. (Courtesy of FMPC.)

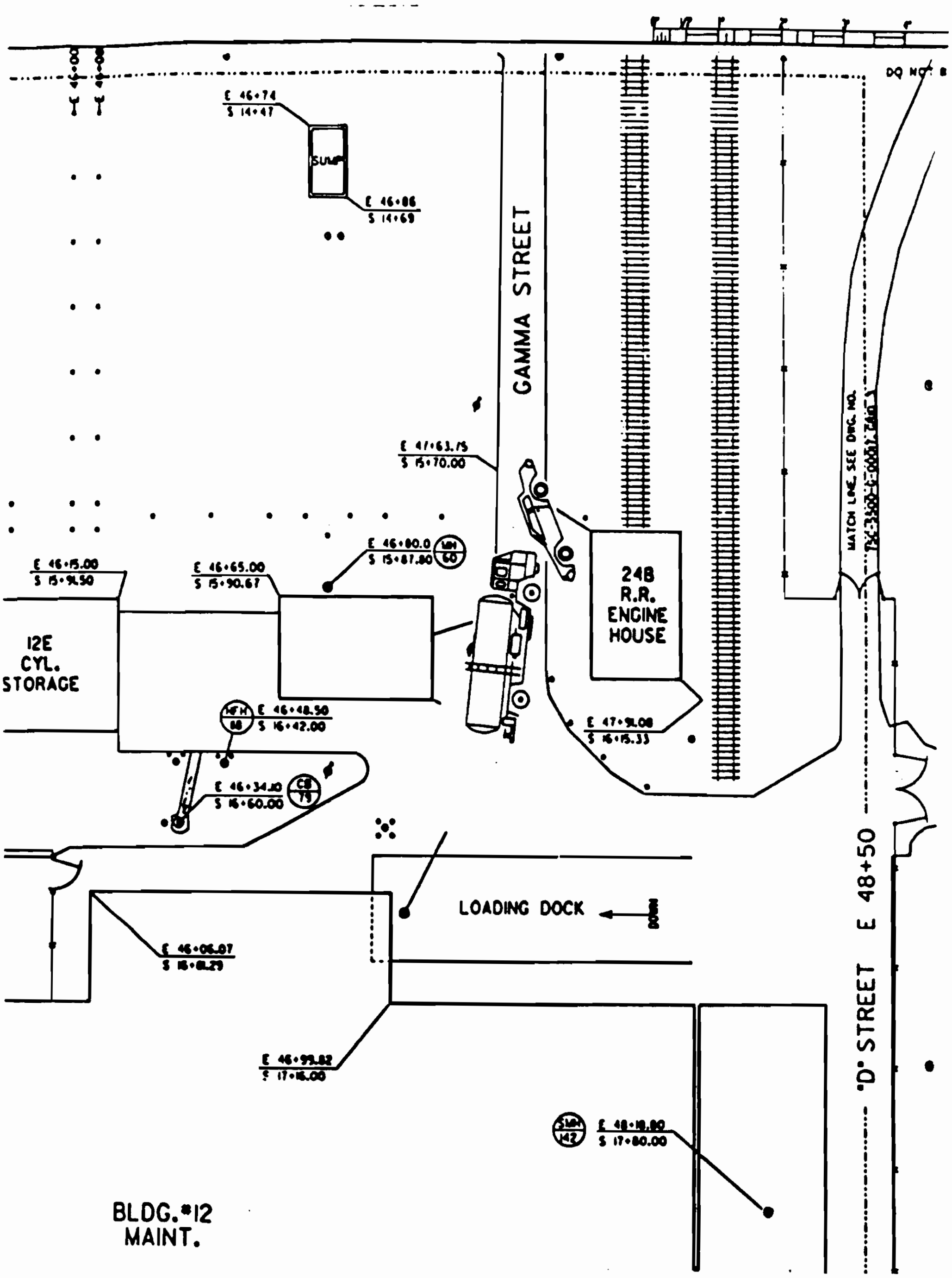


Figure 30. A detail of the incident scene shows the position of the vehicles involved. (Courtesy of FMPC.)

Appendix B. EOC computer communications log

The log on the next seven pages is a hardcopy from the actual computer file at FMPC. The file is sequential, the sequence being the order by which the messages are input. That is, an earlier message may appear later in the log if it is typed in later. The organization of the file is the following:

Column	*Description*
Time	The time stamp in the *Display Request Forms* (DRP), if available, or operator input otherwise.
Event	A two-column, two-line-per-column message text. Messages occupy a maximum of two lines, and read vertically within the left column before continuing in the second column. The text of the message is provided in the DRP.
B	The Status Board that message is posted on ("Appendix C. EOC Status Boards"), as mentioned in the DRP. In the cases where this datum is missing in the form, it may still be verbally provided to the operator. Other entries marked "E" or "P" show messages between computers, like the Communications Center computer.
Date	The date of the exercise.

```
Page No.     1
07/11/89
                                      FMPC
                        Emergency Operations Center Log

TIME                               EVENT                                    B DATE


0004 TEST MESSAGE FROM COMM. CENTER TO                                      E 06/24/89
     EOC.
0110 TEST MESSAGE FROM COMM. CENTER TO                                      E 06/24/89
     EOC.
0201 TEST MESSAGE FROM COMM. CENTER TO                                      E 06/24/89
     EOC.
0310 TEST MESSAGE FROM COMM. CENTER TO                                      E 06/24/89
     EOC.
0451 TEST MESSAGE FROM COMM. CENTER TO                                      E 06/24/89
     EOC.
0548 TEST MESSAGE FROM COMM. CENTER TO                                      E 06/24/89
     EOC.
0652 TEST MESSAGE FROM COMM. CENTER TO                                      E 06/24/89
     EOC.
0752 TEST MESSAGE TO EOC FROM COMM                                          E 06/24/89
     DENTER.
0806 3-3 TO ADVISE THAT AN EMERGANCY    EXERCISE WILL BE CONDUCTED          E 06/24/89
     RESPONSE                           BETWEEN 8 &1200
0830 THIS IS AN EXERCISE ,PROPANE FIRE  PROPANE STORAGE, PERSONNEL          4 06/24/89
     AT                                 INJURED.
0830 I.S. ENROUTE TO PROPANE STORAGE.                                       6 06/24/89
0832 NEED WIND SPEED AND DIRECTION, FROM THWEST AT LESS THEN 1 MPH.         1 06/24/89
     THE SOU
0840 MESSAGE NUMBER 1, THIS IS A DRILL, CALL 6295 IF THIS MESSAGE IS        E 06/24/89
     PLEASE                             RECEIVED
0841 I.S. REAR OF MEDICAL, NEED                                             E 06/24/89
     DIRECTION
0832 RPI TO PROPANE STORAGE WIND FROM SW THAN 1 MPH                         E 06/24/89
     A LESS
0843 COMMAND POST SET UP SOUTH OF .     STORAGE.                            6 06/24/89
     PROPANE
0844 LOCATION AT COMMAND POST FOR       TRAFFIC                             P 06/24/89
     SECURITY
0846 OROC NOTIFIED                                                          5 06/24/89
0848 AIR CARE HELICOPTER REQUESTED                                          6 06/24/89
0850 VEHICLE ACCIDENT, MULTIPLE         CLASSIFIED ALERT                    5 06/24/89
     INJURIES, CP CORNER OF 2ND AND D
```

```
     STREET
0847 INJURIES: MUTUAL AID REQUESTED                                                6 06/24/89
0843 HAVE MUTUAL AID FROM HAMILTON AND   (2 AMBULANCES AND 2 PUMPERS)              E 06/24/89
     BUTLER
0851 1.  INJURIES - TAKE CARE OF ALL                                               4 06/24/89
     2.  FIGHT FIRE
0854 TWO AMBULANCES ARE ON SCENE.  FOUR  TWO ENGINE COMPANIES REQUESTED            6 06/24/89
     MORE NEEDED (MUTUAL AID REQUESTED)
0845 JPIC ACTIVATED  MEDIA ADVISORY                                                5 06/24/89
     ISSUED.
0850 BUTLER AND HAMILTON COUNTIES                                                  5 06/24/89
     NOTIFIED
0855 NEED TOTAL OF FOUR (4) AMBULANCES   (2) TANKERS, TV RESPONSE.                 E 06/24/89
     AND TWO



Page No.     2
07/11/89
                                        FMPC
                            Emergency Operations Center Log

TIME                                   EVENT                                       B DATE


0857 FOUR TOTAL INJURIES IDENTIFIED.                                               3 06/24/89
0857 TRIAGE AREA BEING ESTABLISHED,                                                6 06/24/89
     SOUTHEAST PLANT 6 BUILDING 82
0858 UPGRADE TO SITE EMERGENCY                                                     4 06/24/89
0854 PROPANE TANK - 22,070 GALLONS.      1,443 GALLONS IN THE AREA                 2 06/24/89
     DIESEL FUEL 5,066 GALLONS, KEROSENE
0849 REQUEST AIR-CARE TO SOUTH EAST      HAMILTON LANDING                          E 06/24/89
     CORNER,
0853 BUILDING 12 CONTENTS: PROPANE 350   TANKS INSIDE ALSO CHLORINE,               2 06/24/89
     GALLONS. GASOLINE TANK 500 GALLONS  HELIUM, ACETYLENE.
0902 FLAME FROM FIRE PREVENTS MOVEMENT                                             5 06/24/89
     OF CYLINDERS IN STORAGE
0900 TWO INJURED NOW AT TRIAGE                                                     3 06/24/89
0859 TOXIC MATERIAL LAB BUILDING,        POSSIBLY TOO HOT TO REMOVE.               5 06/24/89
     POTENTIAL TOXIC, POTENTIAL
     EXPLOSION.
0905 INPLACE ACCOUNTABILITY AT RALLY                                               3 06/24/89
     POINTS
0905 VICTIM #1, BADGE 79. VICTIM #2,                                               3 06/24/89
     BADGE 450
0906 WASTE OPERATIONS ACCOUNTED FOR.                                               3 06/24/89
0904 COLERAIN FIRE PUMPER ON SCENE                                                 6 06/24/89
0909 PLANT 8 ACCOUNTED FOR                                                         3 06/24/89
0909 TRIAGE AT RIMIA                                                               6 06/24/89
0909 THIRD INJURED AT TRIAGE.                                                      3 06/24/89
0853 REQUEST TOTAL EVACUATION FROM ALL   N. OF 1ST ST. TO RALLY POINT              5 06/24/89
     AREAS                               S. OF 1ST ST.
0910 CROSBY PUMPER AND CROSBY LIFE SQUAD                                           6 06/24/89
     ON SITE
0912 AIR-CARE HAVE LANDED SOUTH EAST     LANDING PAD #1.                           6 06/24/89
     CORNER
0907 WAREHOUSING AND                     HAVE BEEN ACCOUNTED FOR.                  3 06/24/89
     RECEIVING/ADMINISTRATION
0915 COLERAIN AMBULANCE ON SCENE                                                   6 06/24/89
0915 REQUEST SECOND AMBULANCE TO PROPANE STORAGE.  UNIT WAS SENT.                  6 06/24/89
0916 REQUESTED OPERATIONS TACTIC CENTER  FACILITIES                                5 06/24/89
     TO CONFIRM SAFE SHUTDOWN OF PROCESS
```

```
0916 PLANT 8, PLANT 4, PLANT 6 AND      MAINTENANCE (BUILDING 12) ARE  E 06/24/89
                                        ACCOUNTED FOR
0915 3.  THREE CYLINDERS OF CHLORINE,                                  4 06/24/89
     POSSIBLE RELEASE
0918 EMERGENCY PREPAREDNESS ALL                                        3 06/24/89
     ACCOUNTED FOR.
0919 BADGE NUMBER CORRECTION:  #450 IS                                 3 06/24/89
     ACTUALLY 4580
0916 SECOND COLERAIN PUMPER IS ON SCENE                                6 06/24/89
0921 PLANT 5, ALL PERSONNEL ACCOUNTED                                  3 06/24/89
     FOR.
0925 DRIVER RESCUED (FOURTH INJURED)                                   3 06/24/89
0924 IN PLACE SITE ACCOUNTABILITY                                      5 06/24/89
     REQUESTED




Page No.     3
07/11/89
                                        FMPC
                          Emergency Operations Center Log

TIME                               EVENT                               B DATE


0924 BUTLER AND HAMILTON COUNTY         ARRIVED AT FMPC.               6 06/24/89
     SHERIFF'S
0924 THIS IS AN EXERCISE. THERE IS A    BUILDING 12 FROM A RUPTURED    5 06/24/89
     FIRE NEAR                          PROPANE TANK
0925 (CONT) TANKER. THE EMERGENCY TEAM  ACTIVATED. PLEASE STAND BY FOR E 06/24/89
     HAS BEEN                           FURTHER
0926 (CONT) INSTRUCTIONS. CONDUCT       ACCOUNTABILITY IN PLACE.       E 06/24/89
     SITEWIDE                           REPORT RESULTS TO
0927 (CONT) THE COMMUNICATIONS CENTER                                  E 06/24/89
     EXT. 6202.
0928 HARRISON SQUAD ARRIVING AT SCENES  ROSS SQUAD.                    6 06/24/89
     WITH
0928 PUBLIC AFFAIRS - ALL PERSONNEL     FOR.                           3 06/24/89
     ACCOUNTED
0929 HARRISON LIFE SQUAD AT RALLY POINT                                6 06/24/89
0925 EMERGENCY RESPONSE TEAM ACTIVATED                                 6 06/24/89
0930 PLANT 1 AND DECONTAM PERSONNEL     FOR.                           3 06/24/89
     ACCOUNTED
0930 CROSBY TOWNSHIP PUMPER ARRIVED AT  AREA.                          6 06/24/89
     STAGING
0931 AIR-CARE IS BACK ON GROUND.                                       E 06/24/89
0928 BUTLER COUNTY EOC ACTIVATED                                       5 06/24/89
0932 GARAGE PERSONNEL ACCOUNTED FOR.                                   3 06/24/89
0933 PLANT 6 - MACHINING, PERSONNEL     FOR.                           3 06/24/89
     ACCOUNTED
0933 PLANT 6 - INSPECTION, PERSONNEL    FOR.                           3 06/24/89
     ACCOUNTED
0925 BADGE #79 AND 4580: FAMILIES HAVE                                 5 06/24/89
     BEEN NOTIFIED.
0926 TRUCK ID IS AAA TRUCKING COMPANY                                  5 06/24/89
0929 PUBLIC AFFAIRS AND COMMUNICATION                                  3 06/24/89
     PERSONNEL ACCOUNTED FOR
0935 PILOT PLANT PERSONNEL ACCOUNTED                                   3 06/24/89
     FOR.
0935                                                                     06/24/89
0936 PLANT 8 AND PLANT 4 PERSONNEL      FOR.                           3 06/24/89
     ACCOUNTED
```

```
0936 LAUNDRY PERSONNEL ACCOUNTED FOR.                                   3 06/24/89
0936 RESTORATION PERSONNEL ACCOUNTED                                    3 06/24/89
     FOR.
0937 REQUEST UPDATE ON SQUADS AT RALLY   HARRISON STANDING BY.          E 06/24/89
     POINTS,
0950 QUALITY AND SAFETY PERSONNEL                                       3 06/24/89
     ACCOUNTED FOR.
0936 INJURY #3 IS BADGE 479.                                            3 06/24/89
0953 EMPLOYEE BADGE NO. 954 HAS BEEN                                    3 06/24/89
     LOCATED
0940 PLANT 6 INSPECTION HAVE BEEN                                       3 06/24/89
     ACCOUNTED FOR.
0942 TOTAL MEDICAL AVAILABLE: 5                                         6 06/24/89
     AMBULANCES, 1 AIR CARE HELICOPTER




Page No.      4
07/11/89
                                      FMPC
                        Emergency Operations Center Log

TIME                                   EVENT                            B DATE


0942 YELLOW SMOKE FROM BUILDING 12B.                                    4 06/24/89
     GENERAL EMERGENCY.
0943 ORDER TO SHELTER PERSONNEL ON SITE                                 5 06/24/89
0942 NOTIFIED FAMILY OF BADGE #479                                      3 06/24/89
0946 THIS IS AN EXERCISE. AS A           MEASURE, ALL PERSONNEL SHOULD  E 06/24/89
     PRECAUTIONARY                       REPORT TO
0946 SERVICE BUILDING CAFETERIA. ALSO    OUTSIDE BUILDING VENTILATION   E 06/24/89
     ALL                                 SHOULD SECURED
0947 OFFICE OF COUNCIL PERSONNEL                                        3 06/24/89
     ACCOUNTED FOR.
0948 OPERATIONS AND ENGINEER SERV.       ACCOUNTED FOR.                 3 06/24/89
     PERSONNEL
0949 GENERAL OPERATIONS PERSONNEL                                       3 06/24/89
     ACCOUNTED FOR.
0950 INJURIES bADGE 87: CHEST WOUND,     ACCIDENT, HEAD INJURY/RIGHT    3 06/24/89
     STILL ON SITE.  BADGE 798, AUTO     WRIST INJURY, STILL ON SITE
0950 UNKNOWN FIRE PERSONNEL EXPOSED TO   TRIAGE                         3 06/24/89
     CHLORINE GAS, BEING TRANSPORTED TO
0949 SAFEGUARDS AND SECURITY PERSONNEL   FOR.                           3 06/24/89
     ACCOUNTED
0958 ALL SITE PERSONNEL MUST REMAIN      SECURE VENILATION.             E 06/24/89
     INDOORS AND
1002 BADGE 481, HEAD INJURY.  IN ROUTE                                  3 06/24/89
     TO MERCY SOUTH
1002 BADGE 479, REMAINS ON SITE                                         3 06/24/89
1002 REQUEST TWO AMBULANCES TO STAGING                                  E 06/24/89
     AREA.
1004 BADGE 4580 ON ROUTE TO PROVIDENCE                                  3 06/24/89
     BASE
1004 BADGE 798 IN ROUTE TO MERCY BASE                                   3 06/24/89
1004 ALL SITE PERSONNEL ACCOUNTED FOR                                   3 06/24/89
1004 HAMILTON COUNTY NOTIFIED TWO (2)    AMBULANCES NEEDED AT THE       5 06/24/89
     ADDITIONAL                          STAGING AREA.
1005 SITEWIDE PERSONNEL HAS BEEN                                        E 06/24/89
     ACCOUNTED FOR.
1001 PLUME IS TRAVELING WEST                                            5 06/24/89
1005 MOVING COMMAND POST TO SECOND AND D                                 5 06/24/89
```

```
     STREET BY RIMIA
1006 COMMAND POST HAS BEEN NOTIFIED THAT SITEWIDE PERSONNEL HAS BEEN    E 06/24/89
                                         ACCOUNTED FOR.
1005 9 PERSONS NOW AT COMMAND POST DROVE RESPIRATORY DISTRESS           5 06/24/89
     THROUGH PLUME.  POSSIBLE
1009 PROPANE FIRE OUT.  CHLORINE LEAK                                   5 06/24/89
     STOPPED
1009 ALL RALLY POINTS HAVE REPORTED TO   CAFETERIA AT THIS TIME.        5 06/24/89
     THE
1012 ACTIVATED OFFSITE WARNING SYSTEM IN EMERGENCY (SIMULATED).         E 06/24/89
     GENERAL
1014 OFFSITE SIRENS WERE ACTIVATED AT                                   5 06/24/89
     0951 (SIMULATED)




Page No.     5
07/11/89
                                      FMPC
                        Emergency Operations Center Log

TIME                               EVENT                                B DATE


1013 THE FOLLOWING TWO MESSAGES IS TO    ACCOUNTABILITY OF OFFSITE      E 06/24/89
     UPDATE                              PERSONNEL.
1014 SIX (6) LIFE SQUADS CAME IN WITH    (14) PERSONNEL.                E 06/24/89
     FOURTEEN
1015 FOUR (4) PUMPERS ON SITE STILL IN   PRODUCTION WITH TWELVE (12)    6 06/24/89
                                         PERSONNEL.
1011 STRATEGY NOW CHLORINE EXPOSURES.                                   4 06/24/89
     ACTION: TREATMENT/MONITORING
1014 MONITOR PH IN STORM WATER RETENTION                                4 06/24/89
     BASIN
1021 INJURY #7, BADGE 7343, EYE INJURY   WAS HYSTERICAL, NOW STABLE.    3 06/24/89
     AT TRIAGE. INJURY #8, BADGE 5450,   INJ.#9, BADGE 31, OVERHEATED,
                                         SHORT/BREATH
1016 REQUESTED OPERATIONS TACTIC GROUP   POTENTIALLY DAMAGED CYLINDERS  5 06/24/89
     TO IDENTIFY HANDLING PRECAUTIONS
     FOR
1016 CHEMICAL/PH MONITORING OF STORM                                    5 06/24/89
     WATER BEGUN.
1025 PRESENTLY NO DETECTABLE CHLORINE                                   5 06/24/89
     READINGS.
1028 P: CHLORINE EXPOSURE A: DECON AND   HOSPITAL  P:WATER RUN OFF  A:  4 06/24/89
     TREAT  P: INJURIES  A: TRANSPORT TO MONITOR PH
1025 SIMULATED OFF SITE WARNING SYSTEM                                  E 06/24/89
     ACTIVATED
1031 REQUEST IF TWO (2) COLERAIN         WERE ONSITE. STAGING ADVISED   E 06/24/89
     TOWNSHIP PUMPER                     AFFIRMATIVE.
1032 CHLORINE CYLINDER CONTAINS 100 LBS.                                2 06/24/89
     EACH
1038 THIS IS AN EXERCISE. ALL SITE       SHOULD REMAIN INDOORS AND      E 06/24/89
     PERSONNEL                           SECURE VENILATION
1040 MONITORING TEAM HAS DETECTED 1 PPM  MILE AWAY FROM PLANT.          5 06/24/89
     CHLORINE AT BOUNDARY STATION 7, 1
1038 (INJURIES) #10, #739, RESPIRATORY   #11, #7283, SHORTNESS OF       3 06/24/89
     ARREST, AIR CARE TRANSPORTED.       BREATH, EYE IRRITATION
1038 (INJURIES) #12, B#353, #13, B#7245, INHALATION PROBLEMS            3 06/24/89
     #14, B#7206, AND #15, B#250
1038 (INJURIES) #16, B#7096, COLERAIN    #17, B#4046, RESPIRATORY       3 06/24/89
```

```
     AMBULANCE TRANSPORTED TO UC         PROBLEMS, TO UC.
1038 #18, B#7411, RESPIRATORY PROBLEMS,                                 3 06/24/89
     REMAINS ON SITE.
1041 WIND SPEED 1.5 MPH (10 M).          CEILING: UNKNOWN. 24 HOUR      1 06/24/89
     TEMPERATURE 81 F.  CURRENT WEATHER: FORECASE, SAME
     HAZY.
1049 ONSITE MONITORING: EAST 2ND STREET, MONITORED AND CLEAR            5 06/24/89
     EAST B STREET.  ALL BUILDINGS
1051 DOWNGRADE FROM SITE EMERGENCY TO                                   4 06/24/89
     ALERT
1050 WIND SPEED: 2.7 MPH (10M). WIND     TEMPERATURE: 82.5 f.  CURRENT  1 06/24/89
     DIRECTION, EAST NORTHEAST           WEATHER: CLEAR. CEILING:
     (VARIABLE)                          UNKOWN




Page No.     6
07/11/89
                                   FMPC
                       Emergency Operations Center Log

TIME                               EVENT                                B DATE


1052 REMY BUILDING, F ST. NEW COMMAND    DOWN TO ALERT STATUS           E 06/24/89
     POST. ALSO
1050 24 HOUR WEATHER FORECAST SAME                                      1 06/24/89
1053 THIS IS AN EXERCISE. ALL SITE       SHOULD REMAIN INDOORS AND      E 06/24/89
     PERSONNEL                           SECURE VENILATION
1053 COMMAND POST RELOCATED TO RIMIA                                    6 06/24/89
1053 ERT MOVING TO HEAVY EQUIPMENT                                      6 06/24/89
     BUILDING
1053 MONITORING RESULTS: EXPLOSION -     NEGATIVE                       5 06/24/89
     NEGATIVE. PH - NORMAL.  CHLORINE -
1056 INJURIES #19 - V500, FUMES, THROAT  #21, V499, FUMES, EYE, THROAT  3 06/24/89
     IRRITATION.  #20, V487, FUMES, EYE. IRRITATION
1056 INJURIES: #22, B#2809, EYE AND                                     3 06/24/89
     THROAT.  #23, B#1479, EYE AND
     THROAT
1103 PH OF WATER RUNOFF TO STORMWATER,                                  5 06/24/89
     CONFIRMED NORMAL (7.9)
1053 ON SCENE MONITORING: EXPLOSIVE      PH 7.9                         5 06/24/89
     GASES 0% LEL. CHLORINE
     NONDETECTABLE
1056 INJURIES #10, B#739 AIR CARE. #11,  #12, B#353, #13, B#7245, #14,  3 06/24/89
     B#7283 PROVIDENCE EMERGENCY CARE.   B#7206, #15, B#215 - PROV.
                                         EMERG. CARE
1050 DOE/ORO HAS NOTIFIED PORTSMOUTH AND ALERTED AND WILL BE ABLE TO    5 06/24/89
     PADUCAH PLANTS.  MOUND HAS BEEN     SEND HELP BY 1100
1110 ALL INJURED PERSONS REMOVED FROM                                   5 06/24/89
     TRIAGE AREA.
1112 FAMILIES OF VICTIMS #1-#18 HAVE                                    3 06/24/89
     BEEN NOTIFIED.
1113 SIMULATE RECEIVED CALL REFERENCE    DRUG SCREEN ANALYSIS FOR       E 06/24/89
     REQUEST OF                          PROPANE TRUCK DRIVER
1117 FIRE SCENE SECURED, FIVE (5)        IN TRIAGE AREA.                5 06/24/89
     PERSONS STILL
1113 RECEIVED CALL REQUESTING DRUG                                      5 06/24/89
     SCREEN ANALYSIS FOR PROPANE TRUCK
     DRIVER
1118 WIND SPEED 4.2 MPH (10M) WIND       CURRENT WEATHER CLEAR.         1 06/24/89
```

```
     DIRECTION NORTHEAST.  TEMPERATURE   CEILING UNKNOWN. FORECAST SAME
     84.2 F                              AS PREVIOUS
1126 FOLLOWING INJURED TRANSPORTED TO    22, 23)                         3 06/24/89
     PROVIDENCE BASE (INJURY #19, 20,
     21,
1121 THIS IS AN EXERCISE. ALL SITE       SHOULD REMAIN INDOORS AND       E 06/24/89
     PERSONNEL                           SECURE VENILATION
1130 THIS IS AN EXERCISE. THE EMERGENCY  CONTROL. RESUME NORMAL          E 06/24/89
     IS UNDER                            OPERATIONS.
1133 FIRE CHIEF CONFIRMED ON SCENE IS    DOWNGRADE TO AN ALL CLEAR       4 06/24/89
     SECURE.  SECONDARY INSPECTION
     COMPLETE
1131 (CONT)THE INCIDENT AREA NORTH OF    SOUTH PROPANE STORAGE HAS BEEN E 06/24/89
     BLDG 12 &                           SECURED.....




Page No.     7
07/11/89
                                      FMPC
                        Emergency Operations Center Log

TIME                               EVENT                                 B DATE


1133 (CONT)...STAY CLEAR FROM THIS AREA  FURTHER NOTICE.                 E 06/24/89
     UNTIL
1137 ALL FAMILIES NOTIFIED EXCEPT 19,                                    5 06/24/89
     20, 21
1131 SCENE HAS BEEN SECURED.  ACCIDENT                                   5 06/24/89
     INVESTIGATOR SEND TO SCENE.
1148 EXERCISE TERMINATED                                                 5 06/24/89
1149 COUNTIES HAVE BEEN NOTIFIED THAT                                    5 06/24/89
     THE EXERCISE HAS BEEN TERMINATED.
1152 THE 33'S THAT JUST SOUNDED IS TO    THAT JOINT RESPONSE 89 IS NOW   E 06/24/89
     INFORM                              TERMINATED.
1504 EOC TEST OF COMM. CT.                                               E 07/05/89
1828 EOC TEST OF COMM. CT.                                               E 07/05/89
0650 TEST MESSAGE TO EOC FROM                                            E 07/07/89
     COMM/CENTER.
0941 TEST MESSAGE TO EOC FROM                                            E 07/07/89
     COMM/CENTER.
1143 TEST MESSAGE TO EOC FROM                                            E 07/07/89
     COMM/CENTER.
0615 EOC TEST OF COMM. CT.                                               E 07/08/89
0712 EOC TEST OF COMM. CT.                                               E 07/08/89
0806 O/S PP  POST 8                                                      E 07/08/89
0806 EOC TEST OF COMM. CT.                                               E 07/08/89
0938 EOC TEST OF COMM. CT.                                               E 07/08/89
1103 EOC TEST OF COMM. CT.                                               E 07/08/89
1113 EOC TEST OF COMM. CT.                                               E 07/08/89
ING                                                                      R 07/08/89
ONNE                                                                     C 07/09/89
0700 EOC TEST OF COMM. CT.                                               E 07/11/89
0805 EOC TEST OF COMM. CT.                                               E 07/11/89
1114 EOC TEST OF COMM. CT.                                               E 07/11/89
```

Appendix C. EOC Status Boards

The following pages present examples of the status boards in an emergency operations center (EOC). The boards are continually updated and their content is frequently checked by the emergency management team.

These boards provide a first cut of the variables emergency managers use to control an emergency.

1	SITE METEOROLOGICAL DATA

TIME:

WIND SPEED:

WIND DIRECTION FROM:

TEMPERATURE:

CURRENT WEATHER:

CEILING:

PLUME MODEL DATA SENT:

24 HOUR DATA CAST:

2	ENVIRONMENTAL SAFETY AND HEALTH		
TIME	MATERIAL	LOCATION, DATA, AND CONSEQUENCES	HAZARD CONTROL ACTION

3	PERSONNEL STATUS	
TIME	IDENTITY	STATUS

4 INITIAL EVENT INFORMATION

DATE:	DESCRIPTION:
TIME:	CRISIS MANAGER:
INSTALLATION:	AGENCY-IN-CHARGE:
LOCATION:	
CLASSIFICATION:	TIME:

STRATEGY

TIME	OPERATIONAL CONCERN	ACTION

5 NEGOTIATIONS AND DEMANDS

TIME	DEMANDS AND DEADLINES	STRATEGY

6 RESPONSE FORCES

TIME	RESOURCES	STATUS

Appendix D. Development of state equations.

Fundamental conservation laws

The dynamic equations describing the leak of propane and the spreading of chlorine are based on identical principles. This analysis draws upon Coulson & Richardson (1977), Kecman (1988), and Luyben (1973), but other engineering textbooks are equally adequate.

Mass balance

The principle of conservation of mass says that the

$$\begin{pmatrix} \textit{Time rate of change} \\ \textit{of mass inside system} \end{pmatrix} = \begin{pmatrix} \textit{mass flow} \\ \textit{into system} \end{pmatrix} - \begin{pmatrix} \textit{mass flow} \\ \textit{out of system} \end{pmatrix}. \tag{30}$$

Equation (30) is called the *continuity equation.* It has units of mass per unit time, with the left-hand side written as a derivative, d/dt (or $\partial/\partial t$.) Using the dynamic system represented by the control volume dV of Figure 31, we apply Equation (30) by computing the mass entering the system through the boundary at x and leaving the system through the boundary at $x + dx$. These boundaries have area dA. The time rate of change of mass inside the system is equal to the difference between these two quantities. After simplification, we end up with:

$$\frac{\partial \rho}{\partial t} dV = -\frac{\partial \rho v}{\partial x} dx dA, \qquad (31)$$

where ρ = density of the fluid, kg m^{-3}, and

v = fluid velocity along the x-direction, m s^{-1} (considered constant).

Force balance

Since we've already restricted the direction of flow, the principle of conservation of momentum says that the

$$\begin{pmatrix} \textit{Time rate of change} \\ \textit{of momentum} \\ \textit{in the x direction} \end{pmatrix} = \begin{pmatrix} \textit{sum of forces} \\ \textit{pushing along} \\ \textit{the x direction} \end{pmatrix} - \begin{pmatrix} \textit{sum of forces} \\ \textit{pushing against} \\ \textit{the x direction} \end{pmatrix}. \qquad (32)$$

Momentum is the product of mass and velocity. Equation (32) is nothing more than Newton's second law of motion, $\sum F = ma$. The forces acting on the control volume dV of Figure 31 are the pressure force (P), the gravitational force ($g\rho \cos \alpha$), and the shear force (resistance to flow caused by adjacent fluid or tank walls). As in the preceding case, we evaluate these forces at the boundaries x and $x + dx$, and make their difference equal to the rate of change of momentum. The final result is equivalent to a differential form of the Navier-Stokes equation for one-dimensional flow:

$$\frac{\partial \rho v}{\partial t} dV = -\frac{\partial P}{\partial x} dx dA - g\rho \frac{\partial z}{\partial x} dV - f dV, \qquad (33)$$

where P = pressure inside the tank, Pa,

g = acceleration of gravity, 9.81 m s^{-2} at the sea level,

$\frac{\partial z}{\partial x}$ = term accounting for the cos α gravity effect, and

f = friction resistance coefficient, Pa m^{-1}.

Energy balance

The principle of conservation of energy says that the

$$\begin{pmatrix}\textit{Time rate of change of}\\ \textit{energy inside system}\end{pmatrix} = \begin{pmatrix}\textit{flow of energy}\\ \textit{into system by}\\ \textit{convection or diffusion}\end{pmatrix} + \begin{pmatrix}\textit{heat added to}\\ \textit{system by conduction,}\\ \textit{radiation, or reaction}\end{pmatrix}$$
$$- \begin{pmatrix}\textit{flow of energy}\\ \textit{out of system by}\\ \textit{convection or diffusion}\end{pmatrix} - \begin{pmatrix}\textit{work done}\\ \textit{by system}\\ \textit{on surroundings}\end{pmatrix}. \tag{34}$$

Equation (34) is based on the first law of thermodynamics and has units of energy (work, quantity of heat) per unit time. Neglecting friction losses, the flow of energy due to bulk flow through the boundaries at x and $x + dx$ includes the flow of (1) internal thermal energy (enthalpy, h), (2) kinetic energy ($\frac{1}{2}v^2$), and (3) mechanical potential energy (gz). The work term is the power (Pv) required to move the fluid through the control volume dV:

$$\frac{\partial}{\partial t}[\rho(h + \tfrac{1}{2}v^2 + gz)]dV = -\frac{\partial[\rho v(h + \tfrac{1}{2}v^2 + gz)]}{\partial x}dxdA - \frac{\partial Pv}{\partial x}dxdA + \dot{q}, \tag{35}$$

where h = enthalpy (C_pT for liquids), J kg^{-1},

C_p = average specific heat at constant pressure, J kg^{-1} °K^{-1},

T = absolute temperature of the fluid, °K, and

$\dot{q}$ = heat flow rate added to system, J s^{-1}.

The propane incident

Altough the first (simulated) injuries result from a traffic accident, the subsequent release of propane has a high hazardous potential.

Table 8. Most physical properties of propane are temperature dependent. (Source: Meidl, 1978; Perry & Green, 1984.)

PROPANE (C_3H_8)

Density of gas[1]	1.858 kg/m^3
Vapor Pressure (273°K)	372×10^3 N m^{-2}
Critical Pressure	4.26×10^6 N m^{-2}
Critical Temperature	370°K
Heat of Formation[2]	-2.357×10^6 J kg^{-1}
Free Energy of Formation[2]	-0.533×10^6 J kg^{-1}
Heat of Combustion[3]	-46.39×10^6 J kg^{-1}
Ignition Temperature	739°K
Adiabatic Flame Temperature[4]	2250 °K
Flammable Limits[5]	2.2% to 9.5%

[1] At 298°K and atmospheric pressure.

[2] At 298°K and constant pressure.

[3] At 298°K and constant pressure, to form H_2O (gas) and CO_2 (gas).

[4] From Marshall, 1987.

[5] Percentage by volume in air. Below lower f.l. there is not enough gas to burn; above upper f.l. there is not enough oxygen. See also Wierzba, Karim, & Cheng (1988).

The propane discharge

Background: Figure 31 represents a small control volume dV(m^3). For convenience, we only assume flow along the x-direction; this corresponds to travelling the very small distance dx(m) inside the control volume dV. In the case of the hole in the propane tank wall, the interface of area dA(m^2) separates the sub-volume dV_1 inside the tank, from the sub-volume dV_2 outside. (The total area of the hole is $A_0 = \int dA$.) We stipulate that propane only burns outside the tank. According to the data from Table 8 on page 166, it cannot burn inside the tank because there's not enough air to form a flammable mixture. So, we separate the events inside the tank from the events outside. In particular, we study the discharge from inside the tank.

Before the accident, the liquid and the vapor in the tank are in equilibrium. One of the basic accomplishments of thermodynamics was to establish the equilibrium relationship between the con-

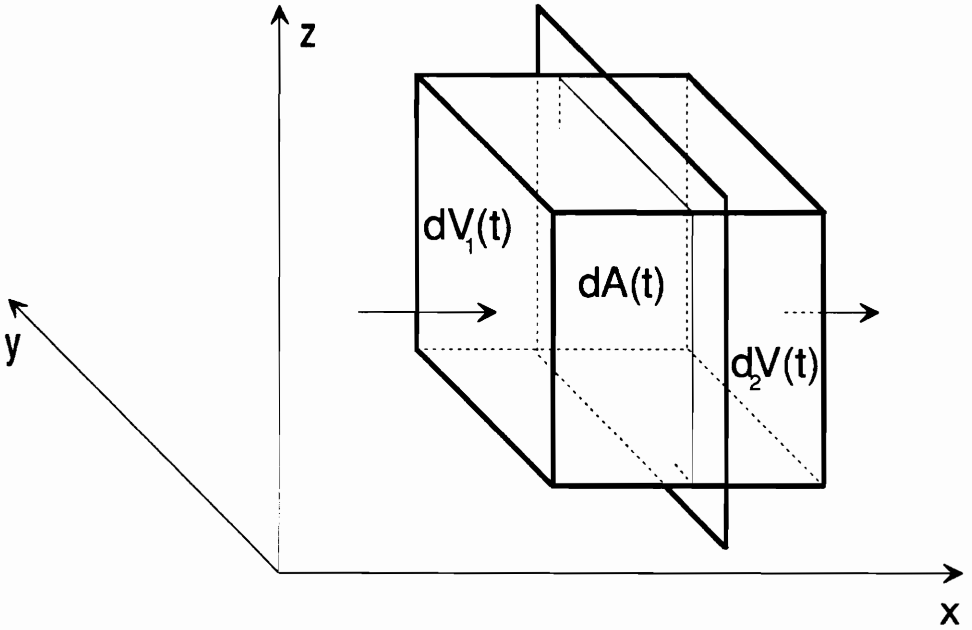


Figure 31. The control element shows the fluid flow through defined boundaries.

ditions of pressure, volume, temperature, and composition for any homogeneous system. This relationship is called the *equation of state*. The simplest equation of state is the ideal gas law:[31]

$$\rho = \frac{P}{\mathcal{R}T}, \tag{36}$$

where $\mathcal{R} = 188.6 \text{ J kg}^{-1} \,^{\circ}\text{K}^{-1}$ is a universal constant adjusted for the molecular weight of propane (Chopey & Hicks, 1984). (Combining the molecular weight of propane in the constant $\mathcal{R}$ is a mechanical engineering practice that helps keep the equations more compact, at the expense of making the constant $\mathcal{R}$ non-universal.)

If V is the total tank volume, we have the system *physical constraint:*

$$V = V_l + V_v, \tag{37}$$

where V_l and V_v (m^3) are the volumes occupied by the liquid and the vapor, respectively.

The propane flow rate: Figure 32 schematically shows the tank conditions during the propane discharge. For convenience, we represent the tank as a cylinder of radius R and length L. The notation in the figure has the following meaning: for a very small time interval of duration dt, the liquid level z decreases by a very small height dz and the volume of liquid in the tank decreases by $dV = A(z) \times dz$.[32] As z varies, the area $A(z)$ also varies. The fluid element of volume dV contains a mass dm. The overall propane discharge rate through the hole is $\dot{m} = dm/dt$ (kg s^{-1}). The hole in the side wall has area A_0.

We don't know A_0. From the conditions of the accident, we may infer that A_0 (1) cannot be too small (because then the consequences would be minimal), and (2) cannot be too large (because then

---

[31] This is different from the state-variable equations, or state-equations, previously referred to in "The state space method" on page 49. Although there is no such thing as an ideal gas, this law is a good approximation for most practical purposes.

[32] Figure 31 on page 167 and Figure 32 represent conceptually distinct, although related, volume elements: $dV_{hole} = A_0 \times dx \not\equiv dV_{tank} = 2\sqrt{2Rz - z^2} \times L \times dz$.

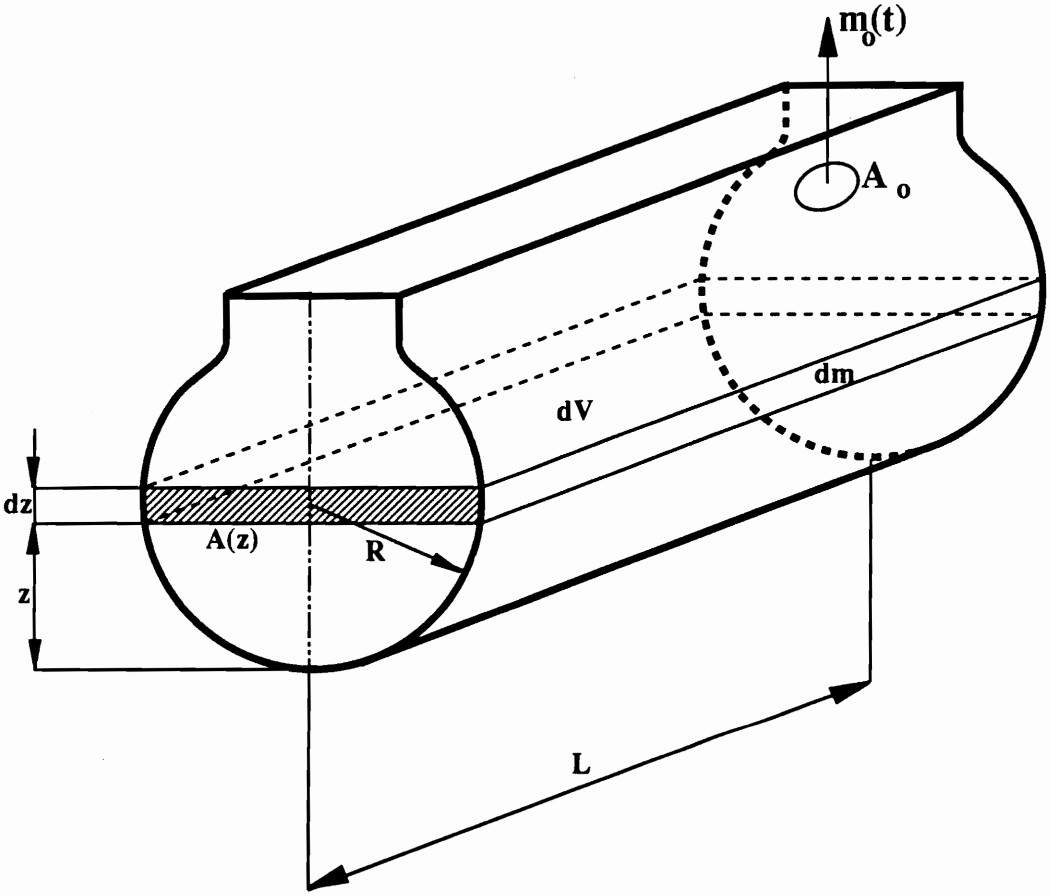


Figure 32. The horizontal cylindrical tank contains propane liquefied under pressure.

we would have a catastrophic, explosive vessel failure). But, although A_0 may be measured after the fire is over, there is no way to find it out in "real time." Usually, in engineering design situations, A_0 is a design parameter; here, it either has to be guessed or to be estimated in some way.

The equilibrium conditions in the tank change as the leak proceeds. From the scenario description, the puncture point is likely to be on the center-line side of the tank, at $z = R$. If so, it is relatively straightforward to consider an initial regime of 100% liquid flow. Due to the high pressure, the superheated propane[33] does not flash before leaving the tank. Inside the tank, the pressure drops gradually, because propane gas is generated (by boiling) at a slower rate than the leak rate. As the boiling rate increases, the escaping liquid soon starts entraining gas bubbles, forming a two-phase flow (liquid and gas). The two-phase flow varies progressively from liquid-rich to gas-rich (gas entraining liquid droplets or aerosol) up to a point where only gas flows. Meanwhile, the pressure inside the tank keeps dropping. When it finally equals the atmospheric pressure, the leak stops.

This description is not valid if the hole is near the top of the tank. In that case, although two-phase flow may occur at the beginning, the majority is gas flow; the same occurs when the PRV opens. Modeling only for the particular case of gas flow may lead to conservative estimates because (1) the release may take longer and (2) the initial jet may also be oversized. Nevertheless, dealing with initial liquid flow involves using non-linear differential equations that are difficult to manipulate. The approximations required to linearize those equations partially offset the gain of precision from using a more accurate model.

Again, this is a matter of granularity, or level of detail. In our case, where the purpose is simply to show the feedback loop behavior of a management system, high model accuracy is not fundamental. So, for simplicity, we consider only the *particular case* of gas flow regime. Another, perhaps more drastic simplification consists of ignoring the volume changes due to vaporization inside

---

[33] A fluid is superheated when it is stored under pressure at a temperature above its boiling point at atmospheric pressure (Fletcher, 1982).

the tank. As a result, Equation (37) on page 168 reduces to $V = V_v$. For a constant volume system with no input, the mass balance of Equation (31) on page 164 becomes:

$$\dot{m} = -V\frac{d\rho}{dt}, \tag{38}$$

where $\dot{m}$ = mass flow rate out of system, kg s^{-1}

V = volume of tank, m^3

ρ = density of gas, kg m^{-3}.

As shown by Equation (36) on page 168, what makes gas flow distinct from liquid flow is the functional dependency of gas density on pressure and temperature, $\rho = \rho(P,T)$. To simplify the calculations, and because the fire does not impinge on the tank, we may consider the entire contents of the tank as being released under constant temperature. This eliminates the dependency on T, leading to:

$$\dot{m} = -\frac{V}{\mathscr{R}T}\frac{dP}{dt}. \tag{39}$$

The outflow of gas is driven by the differential between the pressure P inside the tank and the atmospheric pressure P_{atm}. We obtain the discharge rate $\dot{m}$ from the energy balance by applying the following simplifications to Equation (35) on page 165:

- the flames don't impinge on the tank and the gas undergoes slow change — the heat transfer rate, $\dot{q}$, is negligible;
- the flow is highly turbulent and the distance travelled is short — the friction losses through the orifice are negligible; and
- the flow is horizontal — the potential energy term dz is negligible.

In spite of considering only gas flow, we still have a two-stage leaking process. Initially, when P is high compared to P_{atm}, the flow attains the velocity of sound and becomes independent of P_{atm}. Under the assumption of ideal gas behavior, this occurs when:

$$P > P_{cr} = P \times c_r, \qquad (40)$$

where P_{cr} = critical pressure (from Table 8 on page 166)

c_r = critical pressure ratio for discharge through an orifice, $c_r = [2/(\gamma + 1)]^{\gamma/(\gamma - 1)}$

γ = specific heat ratio, $\gamma = C_p/C_v = 1.127$ for propane at ambient temperature

C_p, C_v = average specific heat at constant pressure and volume, J kg^{-1} °K^{-1}.

a) Sonic flow: Combining the enthalpy, kinetic energy, and work terms of Equation (35) on page 165 together with the relationship from thermodynamics $C_p - C_v = \mathcal{R}$, leads to:

$$\dot{m} = C_D A_0 \sqrt{(\gamma P \rho)\left[\frac{2}{\gamma + 1}\right]^{(\gamma + 1)/(\gamma - 1)}}, \qquad (41)$$

where C_D = numerical coefficient[34], $C_D = 0.5$

A_0 = cross-sectional area of the hole, m^2

$$\sqrt{\gamma\left[\frac{2}{\gamma + 1}\right]^{(\gamma + 1)/(\gamma - 1)}} \simeq 0.634.$$

At constant temperature, $\rho = (\rho_{atm}/P_{atm})P$ from Equation (36) on page 168. Let $\sqrt{\rho_{atm}/P_{atm}}$ = 4.4×10^{-3} s m^{-1} for $P_{atm} = 101.325$ kPa and $\rho_{atm} = 1.858$ kg m^{-3} (from Table 8 on page 166). Then, defining a constant $K_a = 0.634 \times 0.5 \times A_0 \times 4.4 \times 10^{-3} = 1.4 \times 10^{-3} A_0$ m s, for some value of A_0, Equation (41) results in:

$$\dot{m} = K_a P. \qquad (41 - a)$$

Equation (41-a) shows the linear dependency of mass flow rate $\dot{m}$ on pressure P, when $P > P_{cr}$. The mass balance from Equation (39) on page 171 becomes:

$$\frac{V}{\mathcal{R}T}\frac{dP}{dt} + K_a P = 0, \qquad (42)$$

---

[34] The industry accepted value for circular sharp edged orifices is $C_D = 0.61$. Kim-E and Reid (1983) explain they found a good correlation to $C_D = 0.26$ because of deviations from a perfect shape. Although trying to be close to the industry standard, the value used here reflects irregularities, metal bent inwards, etc.

which is a linear differential equation in P with constant coefficients. However, we are not interested in pressure variations, we are interested in mass variations. Noting that $\rho = \frac{m}{V}$, we use again Equation (36) on page 168 to obtain:

$$\dot{m} = -\frac{\mathscr{R}T}{V} K_a\, m. \tag{43}$$

Integrating Equation (43) with the initial condition $m(0) = m_0$ (from "The mass of propane" on page 56) leads to $m = m_0 \exp(- \frac{\mathscr{R}T}{V} K_a)t$. The information we get from this relationship is twofold. First, the discharge will come to an end by itself, but this is just common sense put in mathematical form. What this means in control theory terms is that this process is naturally stable. Second, doubling the discharge area is equivalent to squaring the exponential. In turn, this means that whatever value we guess for A_0 will have a large influence on the final result.

b) Subsonic flow: When the pressure inside the tank drops below the critical value, the mass flow rate resulting from the energy balance takes the form:

$$\begin{aligned} \dot{m} &= C_D A_0 \rho_{atm} \sqrt{2P\rho \frac{\gamma}{\gamma - 1}\left[1 - \left(\frac{P_{atm}}{P}\right)^{(\gamma-1)/\gamma}\right]} \\ &= C_D A_0 \frac{P_{atm}}{\mathscr{R}T}\left(\frac{2}{\mathscr{R}T}\frac{\gamma}{\gamma - 1}\right)^{½} P\sqrt{1 - (P_{atm})^{(\gamma-1)/\gamma}(P)^{-(\gamma-1)/\gamma}} \\ &= K_b P\sqrt{1 - (P_{atm})^{(\gamma-1)/\gamma}(P)^{-(\gamma-1)/\gamma}}\ . \end{aligned} \tag{44}$$

The square root makes these equations non-linear. Figure 33 shows the rate of discharge as a function of the relative pressure inside the tank $(P - P_{atm})$. The nonlinear subsonic flow, magnified in the detail, accounts for a small amount of the total flow. The constant K_b contains the contributions of the gas characteristics $(\gamma, \mathscr{R})$ and discharge characteristics (C_D, A_0, P_{atm}, T). Some of these contributions are variable quantities. By using constants, we assume their variability does not affect the results substantially. In practical applications, Equation (44) is usually approximated by $\dot{m} = K_b\sqrt{P_{atm}(P - P_{atm})}$.

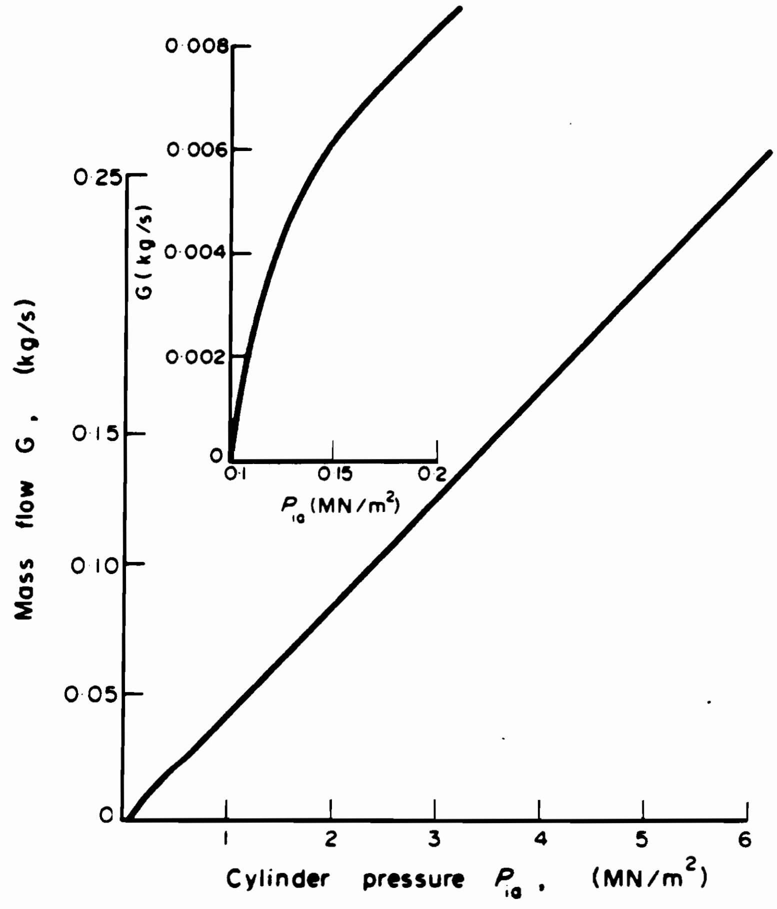


Figure 33. For low pressures the free discharge is nonlinear. (Source: Coulson & Richardson, 1977.)

Both Equation (43) on page 173 for supersonic flow and Equation (44) for subsonic flow depend on A_0 through the constants K_a and K_b. Considering the arguments in the preceding paragraphs, we realize that the gain in precision by including subsonic flow is largely offset by the uncertainty in A_0. This justifies using the supersonic equation alone (Equation (43) on page 173.)

Discharge duration: The overall duration of the propane discharge depends on how long it takes for the tank pressure to drop to atmospheric pressure. Assuming the tank is at ambient temperature, we compute the elapsed time at any instant under supersonic discharge by integrating Equation (42) on page 172:

$$\begin{aligned} dt &= -\frac{V}{K_a \mathscr{R} T}\frac{dP}{P} \\ t_e &= -\frac{V}{K_a \mathscr{R} T}\int_{P_0}^{P}\frac{1}{P}\,dP \\ &= -\frac{V}{K_a \mathscr{R} T}\ln\frac{P}{P_0}, \end{aligned} \tag{45}$$

where t_e = elapsed time during supersonic (and subsonic) flow

V = tank volume, V = 34 m^3.

$\mathscr{R}$ = 188.6 J kg^{-1}°K^{-1}

T = discharge temperature (taken from Table 8 on page 166), $T = 2250$°K

P = tank pressure, $P = P_{atm} = 0.101325 \times 10^6$ N m^{-2} for $t_e = t_f$ when the discharge ends

P_0 = initial tank pressure, $P_0 = 1.21 \times 10^6$ N m^{-2}

The discharge time is inversely proportional to the area of the orifice A_0 (through the coefficient K_a). Equation (45) shows we can determine A_0 as soon as we have one pressure measurement. Because we are dealing with a fictitious situation, we shouldn't expect that to happen. But even in a real-life situation, this is not likely to happen either. We would need an operator, truck driver, or someone else willing to read a tank manometer under life-threatening conditions while simultaneously keeping track of exact time.[35]

---

[35] We may have other solutions. At the tanker, we can have telemetry measurements, airplane-like recording

From "Event chronology" on page 85 we estimate an elapsed time of $t_e = 5280$ s. Then, substituting this value back into Equation (45), we end up with a hole of approximately 6 mm diameter. This may be too small a hole to cause the accident to escalate the way it did. So, either we simply guess A_0, or we use 6 mm in spite of knowing it may be unrealistic. Choosing the second alternative, Equation (45) leads to $K_a = 37.6 \times 10^{-9}$ m s. Then, Equation (43) on page 173 becomes:

$$\dot{m} = -.47 \times 10^{-3}\, m. \qquad (46)$$

The propane fire

Background: At atmospheric pressure, the combustion of propane corresponds to the overall chemical reaction:

$$C_3H_8(g) + 5O_2 \xrightarrow[298^\circ K]{} 3CO_2(g) + 4H_2O(g), \qquad \Delta H^\circ_c = -46.4 \times 10^6\ \mathrm{J\,kg^{-1}}, \qquad (47)$$

where ΔH°_c is the heat generated[36] (from Table 8 on page 166). This is only an overall, theoretical reaction. In actual circumstances, the combustion proceeds through combinations of reversible, chained, and/or parallel intermediate reactions, leading to intermediate combustion products. These include carbon monoxide (CO), formaldehyde (HCOH), ozone (O_3), and many other species in variable quantities. Intermediate species combine or dissociate at different temperatures, with some reactions absorbing heat (endothermic reactions) or vice-versa (exothermic reactions). The complexity of determining the heat generated depends on the different reaction products chosen (Glassman, 1987).

"black boxes," or other monitoring instrumentation; these are not installed in today's trucks and may never become part of future regulations. At the site, we can have photographic equipment; comparing the size of the hole to the height of the truck in a picture may be enough for the degree of precision we need.

[36] By convention, a positive sign corresponds to heat absorbed and a negative sign to heat generated.

Assuming all propane burns according to Equation (47), the starting point to calculate the heat released is the determination of the burning rate. As mentioned under "The mass of propane" on page 56, we also assume combustion at the release point. This means we don't need to calculate a burning rate, the burning rate being the mass flow rate.

Fire calculations are different from gas flow calculations. The gas flow process is well understood and predictable; the major sources of uncertainty are relegated to numerical coefficients such as the discharge coefficient C_D. On the contrary, as also mentioned in "The propane fire" on page 176, flame characteristics are unpredictable. As a consequence, most of the results available consist of numerical correlations. Within the spirit of the preceding section, we look at the simplest possible relationships to build a model of the incident.

Damage evaluation: Heat transfers from a fire to its surroundings by thermal radiation (or by conduction in the case of direct contact). Crocker and Napier (1986, 1988) review several mathematical formulations for the thermal radiation effects from a jet fire. The simplest of those formulations reduces the flame geometry to a point, resulting in the so called "point-source model." We use this formulation with a procedure partially laid out by VanAerde, Stewart and Saccomanno (1988):

a) Calculate the heat release rate

$$\dot{q} = \eta \, \dot{m} \, \Delta H_c^\circ, \tag{48}$$

where $\dot{q}$ = total heat release rate, W

η = fraction of combustion heat radiated, $\eta = 0.3$.

b) Calculate the heat flux for a given damage level

$$\dot{\mathrm{q}} = c_1 t_e^{-c_2}, \tag{49}$$

where $\dot{\mathrm{q}}$ = heat flux causing the damage, W m^{-2}

t_e = elapsed time, s.

c_1, c_2 = damage level coefficients, given by Table 9

Table 9. Constants for Equation (49) are effect dependent. (Source: VanAerde, Stewart & Saccomanno, 1988.)

Effect	c_1	c_2
Blistering of bare skin	56.36	.7481
1% lethality	184.50	.7418
50% lethality	331.13	.7498

c) Calculate the distance to damage

$$\ell = \left(\frac{\dot{q}}{\dot{\mathrm{q}}} \right)^{1/2}, \qquad (50)$$

where ℓ = distance to the selected damage level, m.

Substituting the results from steps **a)** and **b)** together with Equation (46) on page 176 leads to:

$$\ell = \sqrt{-\frac{\eta\, \Delta H_{\mathrm{c}}^{\mathrm{o}}\, K_a\, \mathcal{R}T}{c_1\, V}}\; \sqrt{m}\; t_e^{\frac{1}{2}c_2}. \qquad (51)$$

To obtain the velocity of the incident front, we apply the chain rule to Equation (51) and use the definition of t_e provided in “Discharge duration” on page 175:

$$\dot{\ell} = -\frac{1}{2}\left(\frac{\mathcal{R}T}{V} K_a + \frac{V}{\mathcal{R}TK_a} \frac{c_2}{t_e} \frac{1}{m} \right)\ell. \qquad (52)$$

Equation (52) is non-linear. It can be "linearized" by taking the first terms of the Taylor series expansion around a steady-state or average value $\bar{\ell}$. This method corresponds to replacing a curve (or n-dimensional hypersurface) by a tangent straight line (tangent hyperplane).[37] To apply this method to Equation (52), we start by differentiating it:

---

[37] For a generic function $F_{(a)} = K\sqrt{a}$, this linearization technique leads to $F_{(a)} \simeq K\sqrt{\bar{a}} + (K/2\sqrt{\bar{a}})(a - \bar{a})$. If we use $\Delta a = a - \bar{a}$ instead of a, that reduces $F_{(a)}$ to $F_{(a)} \simeq K'\Delta a$. This is also valid for a product of variables and other non-linear functions.

$$d\dot{\ell} = \left(\frac{\partial \bar{\dot{\ell}}}{\partial m} \right) dm + \left(\frac{\partial \bar{\dot{\ell}}}{\partial t_e} \right) dt_e, \qquad (52-a)$$

where $\left(\frac{\partial \bar{\dot{\ell}}}{\partial m} \right) = -\frac{1}{2\bar{m}} \left[\bar{\dot{\ell}} + \frac{\mathscr{R}TK_a}{V} \bar{\ell} \right]$

$$\left(\frac{\partial \bar{\dot{\ell}}}{\partial t_e} \right) = -\frac{1}{2\bar{t}_e} \left[(2-c_2)\bar{\dot{\ell}} + \frac{\mathscr{R}TK_a}{V} \bar{\ell} \right].$$

For convenience, we choose the following average values (the subscript 0 mans initial and the subscript f means final):

$\bar{t}_e = ½ t_f = 2640$ s (from “Discharge duration” on page 175),

$\bar{m} = ½ m_0 = 8650$ kg (easier to use than the possibly more accurate $½(P_0 - P_{atm})V/\mathscr{R}T$),

$\bar{\ell} = ½\ell_f = \frac{1}{2}\sqrt{-\frac{\eta\, \Delta H_c^\circ\, K_a\, P_{atm}}{c_1\, t_f^{\,c_2}}}$ (instead of $\bar{\ell} = \ell|_{\bar{m}, \bar{t}_e}$), and

$\bar{\dot{\ell}} = \ell_f / t_f$ (also instead of $\bar{\dot{\ell}} = \dot{\ell}|_{\bar{m}, \bar{t}_e}$).

Now we replace the differentials by finite differences:

$$\Delta\dot{\ell} = -\frac{1}{2\bar{m}} \left[\bar{\dot{\ell}} + \mathscr{R}T\frac{K_a}{V}\bar{\ell} \right] \Delta m - \frac{1}{2\bar{t}_e} \left[(2-c_2)\bar{\dot{\ell}} + \mathscr{R}T\frac{K_a}{V}\bar{\ell} \right] \Delta t_e. \qquad (52-b)$$

Although Equation (52-b) is linear, it uses different variables. To make all variables compatible, the alternatives are either to rewrite all equations using Δ-variables, or to rewrite Equation (52-b) using regular variables. The easiest way out is to simply remove the Δ's from Equation (52-b); while understanding this is formally incorrect, we hope the error is not large compared to others we were earlier compelled to introduce. So, substituting the definition of the average values leads to Equation (52-c), whose coefficients are listed in Table 10. The fictitious nature of the simulation exercise forced us to guess many parameters. As a result, the coefficients may be quite unrealistic; but at least we show we can calculate them:

$$\dot{\ell} = K_1\, m + K_2\, t_e \qquad (52-c)$$

Table 10. The coefficients for Equation (52-c) are effect dependent.

Effect	$K_1 \times 10^6$	$K_2 \times 10^6$
Blistering of bare skin	-14.4	-50.9
1% lethality	-7.8	-27.5
50% lethality	-6.0	-21.2

(*Note*: For the average front velocity we use $\bar{\ell} = \ell_f / t_f$ For a 50% lethality level, $\bar{\ell} = 0.11(\mathrm{m\ s^{-1}})$.)

The chlorine incident

As a consequence of a propane tank fire, the release of chlorine escalates the accident to an emergency.

The chlorine dispersion

Background: Table 11 shows some physical properties of chlorine. A common assumption to model limited releases under pressure is to consider the instantaneous formation of a cylindrical cloud at the point of release. In the case of chlorine, the greenish dense cloud simultaneously disperses and moves due to diffusion and bulk flow (by action of the gravity and wind). Under the assumption of spatial homogeneity and ignoring other driving forces (e.g., wind), diffusion is simply described by Fick's law:[38]

$$\frac{\partial c}{\partial t} = D\,\nabla^2 c, \qquad (53)$$

---

[38] Spatial homogeneity means $\nabla D = 0$, 'D' being the same in all directions x, y, and z.
Notation: $\nabla(\bullet)$ is a vector field called the *gradient* of $(\bullet)$ and defined as $\nabla(\bullet) = \frac{\partial(\bullet)}{\partial x}\mathbf{i} + \frac{\partial(\bullet)}{\partial y}\mathbf{j} + \frac{\partial(\bullet)}{\partial z}\mathbf{k}$
Similarly $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$ is called the *Laplacian*.

Table 11. **Few properties of chlorine are used by dispersion equations. (Source: Int. Critical Tables; The Chlorine Institute.)**

CHLORINE (Cl_2)

Boiling Point	239 °K
Critical Pressure	7.71×10^6 N m^{-2}
Critical Temperature	417 °K
Critical Density	573 kg m^{-3}
Volume of gas per lb liquid	5 ft^3 (.141585 m^3)
Vapor Density[1]	12.8 kg m^{-3}
Vapor Pressure (0°C)	$.366 \times 10^6$ N m^{-2}

[1] Saturated, at 273°K(0°C)

---

where c = concentration, kg m^{-3} and

D = diffusion coefficient, D = 777×10^{-4} m^2 s^{-1} at ambient temperature (298°K) and atmospheric pressure for a binary mixture of chlorine and air (estimated from Perry & Green, 1984, p.3-285).

The existing models for heavy gas dispersion basically fall into three major categories (Havens, 1982, 1985; Jagger, 1983):

1. Similarity or wind-tunnel models, providing physical simulations of spatial and temporal variations of heavy gas clouds by applying scale factors to dimensionless arrangements of variables (Langhaar, 1983);
2. Box (slab, top-hat) profile mathematical models, using empirical correlations to describe the shape, position, and properties of the cloud represented as an uniformly mixed volume; and
3. Diffusivity (K-theory) hydrodynamic mathematical models, representing mass, momentum, and energy balances for the cloud as partial differential equations (e.g., Navier-Stokes equations).

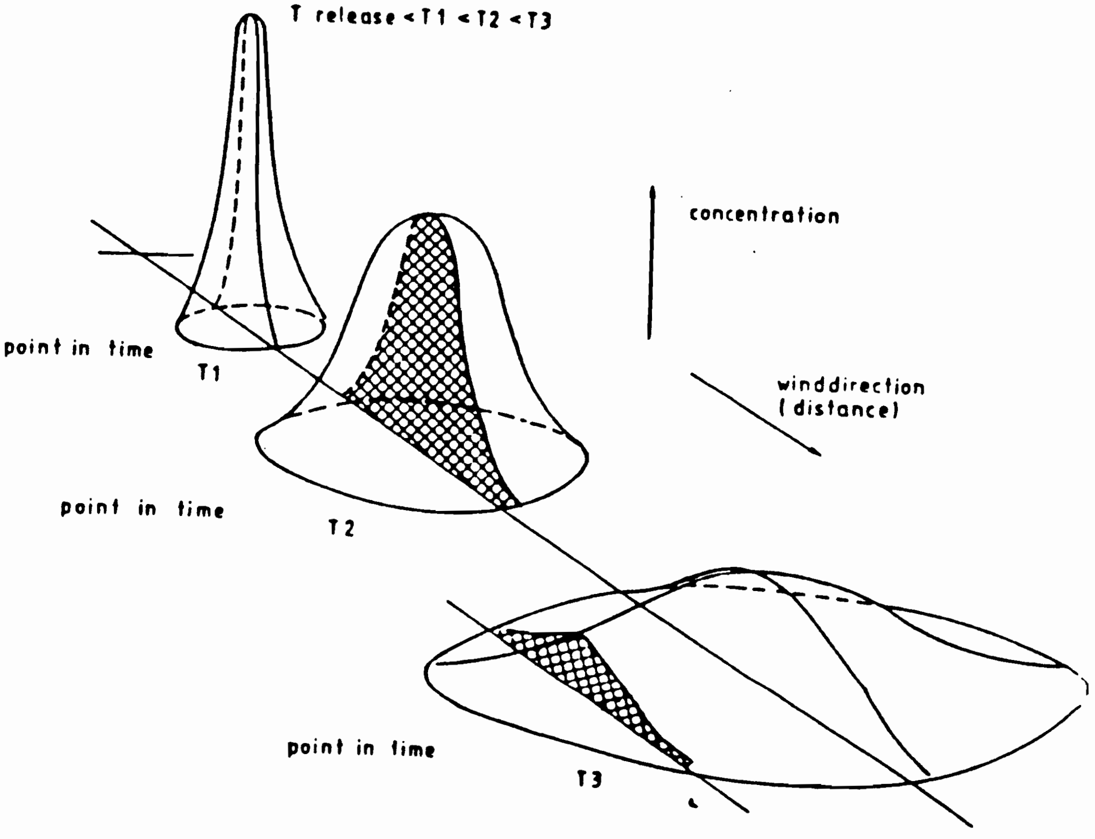


Figure 34. Gaussian models provide a first approximation to cloud shapes. (Source: Pietersen, 1984.)

The third group, ranging from elementary Gaussian models to fully three-dimensional mass, momentum, and energy conservation models, is the best suited for the purpose of this research. Equation (53) is the fundamental equation of the *gradient transport theory* or K-theory for short.[39] The integration of Equation (53) over a finite line normal to the wind and located at a given distance upwind of the source leads to an expression representing the *Gaussian distribution* with variance $\sigma = 2Dt$ (Figure 34 on page 182). That is, Equation (53) is the differential equation whose integrated form is at the origin of the Gaussian plume models for gas dispersion. Unfortunately, published models generally present the integrated form of the balance equations, and this is not what we are interested in for this research. Our objective is to write the equations in the general form of Equation (1) on page 52, as we have been doing so far. In addition, basic Gaussian plume models, like the *HARM I* computer program installed at FMPC at the time of the exercise, don't account for gas density effects (Blackmore, Herman, & Woodward, 1982; Till & Meyer, 1983).

The dispersion model: The dispersion of the cloud ultimately dilutes the gas with air to concentrations within tolerable toxicity limits. To model the cloud dynamics we need to make a few assumptions (McQuaid, 1985). According to Blackmore, Herman, and Woodward (1982), most models rely on assumptions like:

- the terrain is flat, with constant roughness (Deaves, 1984; Fannelop & Zumsteg, 1986);
- the cloud progression faces no obstacles (Deaves, 1984; Davies & Singh, 1985; Rottman *et al.*, 1985); and
- the dense gas is not reactive (Geiger, 1984; Sax, 1984; Wiekema, 1984).

We can do without an energy balance by further assuming the ground has constant thermal properties and that the viscous dissipation and heating terms can be neglected compared to other terms

---

[39] The reason for this name is that Fick's law proposes a mechanism for molecular diffusion similar to the mechanism for heat conduction. In heat conduction, the variation of temperature with distance is proportional to the thermal conductivity K. Many texts on atmospheric diffusion also use the symbol K instead of D for the diffusion coefficient. An alternative to K-theory is the *statistical theory*, Lagrangian, while gradient transport is Eulerian. Both theories lead to similar results for large diffusion times.

(Jagger, 1982). To develop the force (momentum) and mass balances, we consider that the wind blows in the x (or θ) direction with velocity w_x. The wind velocity is a time-varying exogenous input variable. The modeling strategy to avoid dealing with a time varying system consists of simplifying the momentum balance to a front velocity equation (by assuming constant density) while using a constant velocity coefficient in the mass balance equation.

a) Cloud spreading: According to Woodward *et al.* (1982), the amount of air entrained in the cloud does not affect its gravity-spreading velocity. Assuming constant gas density, gravity spreading depends on the cloud radius alone, according to a complex relationship presented by Schnatz, Kirsch, and Heurdorfer (1983). Lees (1980) presents a less rigorous but much simpler relationship:

$$\dot{R} = \frac{c_e}{R}\sqrt{\frac{gV_0(\rho - \rho_{atm})}{\pi\rho}} = \frac{5.934}{R}\ \mathrm{m\ s^{-1}}, \tag{54}$$

where $\dot{R}$ = progression rate due to gravity, m s^{-1}

c_e = constant, c_e = 1.16 (Spicer & Havens, 1984); other authors use different constants or slightly different relationships (e.g., Gunn, 1982)

R = cloud radius, m

g = acceleration due to gravity, g = 9.81 m s^{-2}

V_0 = volume corresponding to the quantity of chlorine spilled under atmospheric conditions, V_0 = 14 m^3 (from Table 11 on page 181)

ρ = gas density, $\rho = 3.2204$ kg m^{-3} (at 298°K and 1 atm, Perry & Green, 1984)

ρ_{atm} = ambient air density, $\rho_{atm} = 1.2928$ kg m^{-3} (at 298°K and 1 atm, Perry & Green, 1984).

Equation (54), which is equivalent to $\dot{R}R = 5.934$, is non-linear. Let F be the distance from the release point to the farthest monitoring teams, $F = 2400$ m. We make Equation (54) linear by writing:

$$\bar{\dot{R}}\bar{R} + \bar{R}(\dot{R} - \bar{\dot{R}}) + \bar{\dot{R}}(R - \bar{R}) = 5.934, \tag{55}$$

where $\overline{R}$ = average cloud radius, $\overline{R} = \frac{F}{2} = 1200\,\text{m}$ by assuming an unconfined release; this arbitrary point is simply the one around which we linearize the equation

$\bar{\dot{R}}$ = average spreading velocity, $\bar{\dot{R}} = \frac{1}{2}\dot{R}_0 = 2.18\,\text{m s}^{-1}$ by using in Equation (54) the value $R_0 = \frac{1}{\sqrt{\pi}} V_0^{1/3} = 1.36\,\text{m}$, based on a discussion by Puttock, Blackmore and Colenbrander (1982). As discussed by Schnatz, Kirsch, and Heurdorfer (1983), this relationship assumes a maximum velocity at the instant of the release, which is not correct; nevertheless, it is a simple and useful approximation.

Performing the operations leads to

$$\dot{R} = -\,1.82 \times 10^{-3} R + 2.19. \tag{56}$$

So, offsetting the wind velocity, w_x, by 2.19 and replacing this result in Equation (56) leads to an equation for the velocity of the cloud front:

$$\dot{\ell} = -\,1.82 \times 10^{-3} R + \underline{w}_x, \tag{57}$$

where $\underline{w}_x$ = adjusted wind velocity, m s^{-1}.

b) Component continuity: To establish the mass balance, we assume that the diffusion along the y and z directions is negligible compared to the transport of material with gravity and the wind (Pasquill & Smith, 1983). We neglect the effects in the y and z directions by considering all the effects concentrated along the center line of the cloud and at ground level. Actually, the concentration of chlorine in the cloud changes in all three directions (x, y, and z). We account for the effects along the y direction by grouping the endangered population into sectors and then assuming the cloud occupies an entire sector. Concerning the effects along the z direction, because chlorine is a dense gas, the cloud 'flattens' quickly, and the x terms soon become more significant than the z terms. So,

$$\frac{\partial c}{\partial t} = \mathrm{D}\frac{\partial^2 c}{\partial x^2} - v\frac{\partial c}{\partial x}, \tag{58}$$

where c = concentration of chlorine, kg m^{-3}

v = average cloud velocity (in the x direction), $v = \bar{R} + \bar{w}_x = 2.18 + 1 = 3.18$ m s^{-1}; actually, this is a time varying coefficient made constant only for simplicity

D = diffusion coefficient, D = 777×10^{-4} m^2 s^{-1}.

Equation (58) represents a linear homogeneous parabolic partial differential equation (PDE). Physical systems described by PDEs are common in science and engineering. In particular, Equation (58) applies to other problems besides gas dispersion (Henry, Sadikou, & Yvon, 1989). However, control problems based on PDEs are difficult to solve in closed form, among other reasons because of their strong dependency on boundary and initial conditions.

Concentration is a function of both distance and time, $c = c(\ell,t)$, ℓ being the distance from the release point measured along the x direction. So, Equation (58) describes a distributed parameter system: the state c is indexed by the parameter x that takes infinitely many values "distributed" between 0 and F (Russel, 1979). There are many alternatives for dealing with this distributed system. One of them is to discretize the system in Equation (58) by *central finite differences:*

$$\begin{aligned} x_j &= \frac{j}{n}, \quad j = 1, 2, \dots, n \\ \frac{dc}{dx} &\simeq \frac{n}{2}(-c_{j-1} + c_{j+1}) \\ \frac{d^2c}{dx^2} &\simeq n^2(c_{j-1} - 2c_j + c_{j+1}). \end{aligned} \tag{59}$$

where n = number of "stations" in the uniform mesh $0 = x_0 < x_1 < \cdots < x_n = 1$ (Hall & Porsching, 1990) and

$c_j \simeq c(x_j)$ = concentration at station j.

To make matters simpler, we convert the problem originally posed in the interval $0 \leq \ell \leq F$ into a problem posed in the interval $0 \leq x \leq 1$ by applying the change of variable $x = \ell/F$. Then, the state equation for Equation (58) becomes:

$$\begin{aligned}\dot{c}_j &= Dn^2(c_{j-1} - 2c_j + c_{j+1}) - \frac{vn}{2}(-c_{j-1} + c_{j+1}) \\ &= \left(Dn^2 + \frac{vn}{2}\right)c_{j-1} - 2Dn^2c_j + \left(Dn^2 - \frac{vn}{2}\right)c_{j+1}, \quad j = 2, \dots, n-1,\end{aligned}$$

or, using c_0 as an input,

$$\begin{aligned}\dot{c}_1 &= -2Dn^2c_1 + \left(Dn^2 - \frac{vn}{2}\right)c_2 + c_0 \\ \dot{c}_j &= \left(Dn^2 + \frac{vn}{2}\right)c_{j-1} - 2Dn^2c_j + \left(Dn^2 - \frac{vn}{2}\right)c_{j+1}, \quad j = 2, \dots, n-1 \\ \dot{c}_n &= \left(Dn^2 + \frac{vn}{2}\right)c_{n-1} - 2Dn^2c_n.\end{aligned} \tag{60}$$

According to the discussion under "Accountability data" on page 87, we use two data sets to track people. One data set covers nine contiguous sectors (general population). The other data set covers three non-contiguous sectors (injured). With $n = 9$, Equations (60) yield:

$$\begin{aligned}\dot{c}_1 &= -12.59c_1 - 8.02c_2 + c_0 \\ \dot{c}_j &= 20.60c_{j-1} - 12.59c_j - 8.02c_{j+1}, \quad j = 2, \dots, 8 \\ \dot{c}_n &= 20.60c_{n-1} - 12.59c_n.\end{aligned} \tag{61}$$

The population behavior

We separated the injured people from the rest of the population because hazard has a different meaning for each group. For the general population, hazard relates to the probability of people being injured to some degree. For the already injured group of people, hazard relates to the urgency and degree of medical care required to avoid casualties or permanent injuries. We handle these two groups differently.

Injury factors: Previously, under "The distance to damage" on page 56 and "Elapsed time" on page 57, we referred to *dosage* as the accumulated effect over time. Dosage is an empirical concept with no recognizable physical dimensions (Marshall, 1987). Let z be a generic physical cause; then dosage is $\int z^n dt$, where the exponent n accounts for the severity of the effect. The integral can be replaced by a summation in those cases where the effect is interrupted yet cumulative. The empirical literature normally provides "integrated" forms for dosage. And, almost invariably, the results in the literature relate the probability of injury to a physical cause or injury factor.

a) Fire hazard: The injury factor proposed by both Marshall (1987) and Poblete, Lees, and Simpson (1984), based on identical source, is $x = \dot{q}^n t_e$, where

$\dot{q}$ = radiation intensity or heat flux (W m^{-2})

n = exponent, $n = 4/3$

t_e = elapsed time (s).

Marshall uses the term dosage to refer to the product $\dot{q}^{4/3} t_e$. Both references provide the following set of values:

Table 12. The probability of fatal burns depends on heat dosage. (Source: Marshall, 1987.)

Probability	$\dot{q}^{4/3} t_e \times 10^{-3}$
1%	1.0
50%	2.3
99%	6.5

b) Toxic hazard: Withers and Lees (1985a, b, 1987) provide extensive information on chlorine toxicity for various types of populations and degrees of physical activity. For a gas like chlorine, they say high peak concentrations are more harmful than overall dosage. Therefore, $x = c$ for simple injury (leading to hospitalization) or $x = c^2 t_e$ for mortality, where

c = concentration (ppm)

t_e = elapsed time (min)

Table 13. The probability of deaths depends on toxic dosage. (Source: Withers and Lees, 1985b.)

Probability	$ct_e^{0.5} \times 10^{-3}$
10%	0.685
50%	1.369
90%	2.739

A static model: We need to establish the degree and probability of injury as a function of physical intensity for both the fire and the toxic release. Poblete, Lees, and Simpson (1984) present a hazard impact model that serves this purpose. Their model assumes an inverse square law for the variation of effect with distance and a uniformly distributed population around the incident point:

$$I = \int_0^{\infty} 2\pi d_p \mathrm{P}(r) r dr, \qquad (62)$$

where I = total number of people injured (prs)

d_p = population density (prs m^{-2})

$\mathrm{P}(r)$ = probability of injury, assumed to follow a lognormal distribution

r = radius (distance, m) at which the probability of injury is $\mathrm{P}(r)$.

This is a static model because it does not depend on time. As discussed by Mendes and Kurstedt (1990), static models are useful design tools but provide little run-time guidance. For the particular case of emergency management, static models are useful to design overall protection plans but are of little help during the unfolding of an emergency. Nevertheless, to develop a dynamic model we start with a static one.

A dynamic model: To develop a dynamic model, we perform a *people balance* applied to an arbitrary sector j. This is what we might call the *people continuity equation:*

$$\begin{pmatrix} \textit{Time rate of change} \\ \textit{of people inside sector} \end{pmatrix} = \begin{pmatrix} \textit{people flow} \\ \textit{into sector} \end{pmatrix} - \begin{pmatrix} \textit{people flow} \\ \textit{out of sector} \end{pmatrix} - \begin{pmatrix} \textit{people injury rate} \\ \textit{inside sector} \end{pmatrix}. \qquad (63)$$

The dimensions of this equation are persons per unit time (prs min^{-1}). The left hand side is again written as a derivative d/dt (or $\partial/\partial t$). At a basic level of detail, when we ignore the movement of people between sectors, we can still use Equation (63) without loss of generality. In this case the model dynamics only reflect the injury term.

In the hazard impact model of Equation (62) on page 189, the distance r reflects the incident "size." It also plays a double role. On the one hand, r accounts for the number of people affected (through the population density.) On the other hand, r accounts for the probability of injury. In a dynamic model, these two roles correspond to effect and cause (source) terms, respectively.

a) Effect term: At this time we ignore the movements of people represented by the flow terms in Equation (63). That is, we consider a sufficiently brief snapshot during which people remain quiet within their sectors. We deal with the number of people per sector instead of dealing with a population density. Conceptually, a given sector j concentrates all its P_j people in a point L_j miles away from the source of the hazard. The hazard front approaches that point at the average velocity v. Using these elements, we propose the following *risk equation* to describe hazard effects on an unprotected, non-moving population:

$$\dot{P}_j = -\frac{v}{L_j} P_j, \qquad (64)$$

where P_j = population affected in sector j, (prs)

v = average front velocity, $v = 0.11\ \text{m s}^{-1}$ for the fire subsystem (from Note on page 180) and $v = 3.18\ \text{m s}^{-1}$ for the release subsystem (from Equation (58) on page 185)

L_j = distance circle delimiting sector j (miles, converted to meters later); this term weights the contribution of distance to the overall risk.

Equation (64) represents the injury rate effect as an exponential decay. That is, as time goes on, P_j "decays" from its value at time t to zero. How fast that happens depends on the system's *time constant*. The time constant is the inverse of the coefficient of P_j in Equation (64), $\tau = \frac{1}{v/L_j}$ (min). Equation (64) can also be written in homogeneous form as

$$\dot{P}_j + \frac{1}{\tau} P_j = 0. \qquad (64-a)$$

With the right hand side equal to zero Equation (64-a) has no input. And in the absence of some input function no risk should exist. So, we write $\dot{P}_j + \frac{1}{\tau} P_j = f(t)$. The function $f(t)$ is called the *forcing function* and represents the source of injury or source term. Figure 35 on page 192 shows the behavior of $P_j/P_j(0)$ when $f(t)$ is a unit step. $P_j/P_j(0)$ is the normalized variation of personal risk for people in sector j relative to the number of people originally in sector j. After $f(t)$ is applied, the risk grows exponentially toward 100%. The growth rate depends on the time constant τ. When $\tau < 1$, the 100% value is never reached; when $\tau = 1$, the curve approaches 100% asymptotically; and when $\tau > 1$, the curve (theoretically) overshoots 100%.

b) Source term: According to Equation (62) on page 189, the number of people injured depends on the probability of injury, P. To provide a forcing function $f(t)$ we first consider that people are close to the physical hazard. We propose the following *injury function* to describe the impact of physical causes on an unprotected, non-moving population:

$$f_j(t) = \frac{d\mathrm{P}}{dt} P_j^o. \qquad (65)$$

where $\frac{d\mathrm{P}}{dt}$ = rate of change of probability of injury, (min^{-1})

P_j^o = initial number of people in sector j, $P_j(0)$ (prs).

We want to calculate $\frac{d\mathrm{P}}{dt}$. Presenting the probability of injury as a function of distance (radius) in Equation (62) on page 189 is simply a matter of convenience. Injury depends on some physical factor, which happens to vary with distance. Usually, the literature presents probability-injury relationships as probit equations. A probit equation takes the form

$$Y = a + b \ln x, \qquad (66)$$

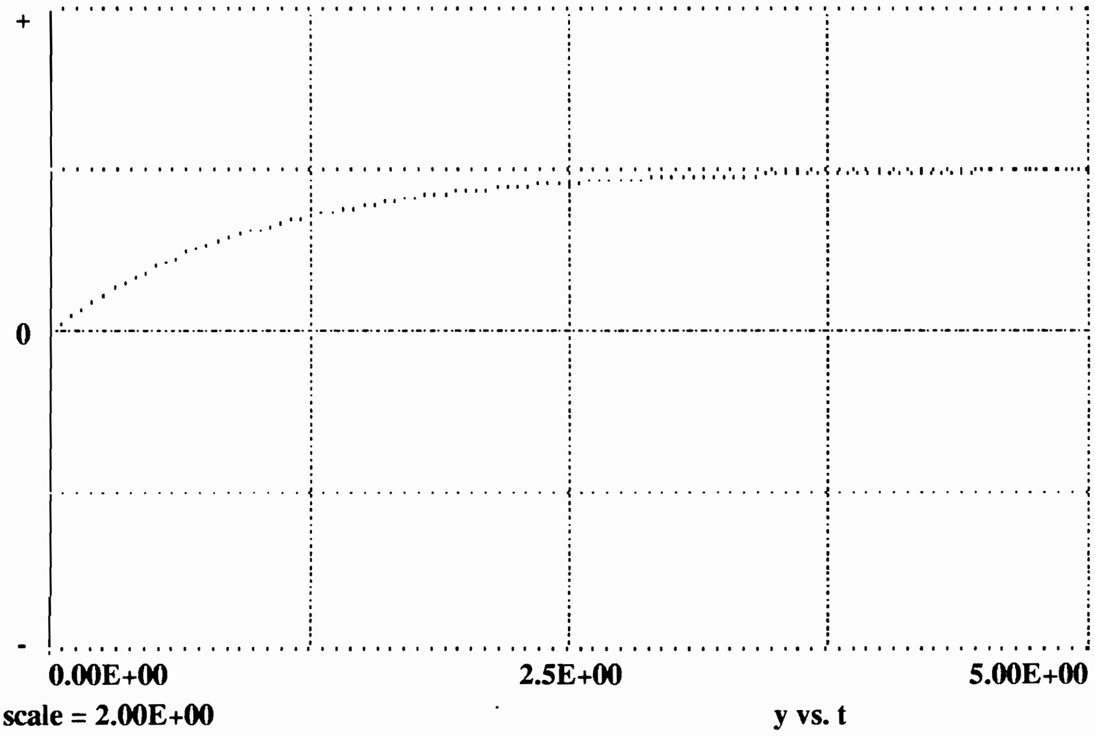


Figure 35. The response of the risk equation to a step input reaches 100% exponentially.

where Y = probit, a statistical artifact consisting of a Gaussian distributed random variable with a mean of 5 and a variance of 1; for example, a probit of 5 corresponds to a probability of 50%

a, b = constants

x = dosage, the physical injury factor.

Poblete, Lees, and Simpson (1984) say a probit Y verifies the relation $\mathrm{P} = F(Y-5) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} e^{-\frac{1}{2}u^2} du$. Alternatively, let X be a random variable representing the degree of injury. Poblete *et al.* (1984) also say X follows a lognormal distribution. Probits and probabilities are therefore related, because the constants of the probit equation depend on the parameters of the lognormal distribution: $a = 5 - \mu/\sigma$ and $b = 1/\sigma$.

The probability of limiting an accident's injuries to some level ξ is $\mathrm{P}(X < \xi) = F(\xi) = \int_{-\infty}^{\xi} f(x)dx$. (Contrary to the usual practice in probability and statistics, this notation distinguishes between the random variable X and the variable of integration x.) From Equation (66), $\xi = Y - 5 = a + b \ln x - 5$. The variable x is the injury factor, described under "Injury factors" on page 188. Then, either $\xi = \xi(\dot{q}, t_e)$ or $\xi = \xi(c, t_e)$, depending on the subsystem we're dealing with. Considering, for instance, the release case, we have:

$$\frac{d\mathrm{P}}{dt} = \frac{\partial \mathrm{P}}{\partial c}\frac{dc}{dt} + \frac{\partial \mathrm{P}}{\partial t_e}\frac{dt_e}{dt}. \tag{67}$$

Each term on the right hand side of Equation (67) is handled identically. Let z be a generic variable standing for either $\dot{q}$, c, or t_e. From the fundamental theorem of integral calculus,

$$\begin{aligned} \frac{\partial \mathrm{P}}{\partial z} &= \frac{\partial}{\partial z} \int_{-\infty}^{\xi(z)} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}u^2} du \\ &= f(\xi)\frac{d\xi}{dz}, \end{aligned} \tag{68}$$

where P = probability of injury

$\xi = a - 5 + b \ln x = \left(\frac{\ln x - \mu}{\sigma} \right)$

$f(\xi) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}\xi^2}$

$\frac{d\xi}{dz} = \frac{n}{\sigma z}$, n being the exponent of the variable z in the hazard factor x.

The right hand side of Equation (68) is nonlinear and has to be linearized around some point $\bar{\xi}$. Let $\bar{\xi} = 0$, corresponding to a 50% probability of injury. Then, $f(\bar{\xi}) = \frac{1}{\sqrt{2\pi}}$ and $f_\xi(\bar{\xi}) = 0$:

$$
\begin{aligned}
f(\xi)\frac{d\xi}{dz} &\simeq f(\bar{\xi})\frac{d\xi}{dz}\Big|_{\bar{\xi}} + f_\xi(\bar{\xi})\frac{d\xi}{dz}\Big|_{\bar{\xi}}(\xi - \bar{\xi}) + f(\bar{\xi})\frac{d^2\xi}{dz^2}\Big|_{\bar{\xi}}(\xi - \bar{\xi}) \\
&\simeq f(\bar{\xi})\left[\frac{d\xi}{dz}\Big|_{\bar{\xi}} + \frac{d^2\xi}{dz^2}\Big|_{\bar{\xi}}\xi\right] \\
&\simeq \frac{n}{\sqrt{2\pi}\,\sigma\bar{z}}\left[1 - \frac{\xi(z)}{\bar{z}}\right] \\
&\simeq \frac{n}{\sqrt{2\pi}\,\sigma\bar{z}}\,.
\end{aligned}
\tag{69}
$$

The units of $\bar{z}$ are those used by the probit equations, namely time in minutes. This is convenient for the rest of this work, but we need to convert to minutes all other terms involving time. We still need to multiply this result by dz/dt to complete each term of Equation (67) on page 193. To substitute $z = \dot{q}$ by $z = \dot{m}$ we make $\bar{\dot{q}} = \eta\overline{m}\Delta H_c^o$ and therefore cancel the coefficient $\eta\Delta H_c^o$. So, the equations for both the fire and plume subsystems are:

$$
\begin{cases}
\dfrac{dP}{dt} = \dfrac{4/3}{\sqrt{2\pi}\,\sigma\overline{m}}\dot{m} + \dfrac{1}{\sqrt{2\pi}\,\sigma\bar{t}_e}\dot{t}_e \\
\dfrac{dP}{dt} = \dfrac{2}{\sqrt{2\pi}\,\sigma\bar{c}}\dot{c} + \dfrac{1}{\sqrt{2\pi}\,\sigma\bar{t}_e}\dot{t}_e .
\end{cases}
\tag{70}
$$

The values of σ and $\bar{t}_e$ are not the same for both equations. To obtain these and the other constants we use (1) $\mu^{(f)} = 7.77$, $\sigma^{(f)} = 0.391$ from Marshall (1987) and $\mu^{(g)} = 14.446$, $\sigma^{(g)} = 0.543$, from Poblete, Lees and Simpson (1984); (2) $\bar{t}_e = \frac{1}{2} t_f$ (min) estimated, for each incident, from the data in "Event chronology" on page 85; and (3) $\overline{m} = \left(\frac{2e^\mu}{t_f}\right)^{3/4}$, $\bar{c}_j = \sqrt{2e^\mu/t_f}$ corresponding to $\bar{\xi}$:

$$
\begin{cases}
\dfrac{dP}{dt} = 0.068\dot{m} + 0.023\dot{t}_e \\
\dfrac{dP}{dt} = 2.626 \times 10^{-3}\dot{c} + .122\dot{t}_e .
\end{cases}
\tag{71}
$$

Our objective is to come up with a source term $f(t)$ to plug in Equation (63) on page 189, $\dot{P}_j = -\frac{1}{\tau} P_j + f(t)$. So, we multiply Equations (71) by P_j^o and substitute other, previously developed state equations (linear functions of state variables). Then, the state equation for the population subsystem becomes:[40]

$$\begin{cases} \text{Fire:} \quad \dot{P}_j = -\dfrac{6.6}{L_j} P_j + 1.918 \times 10^{-3} P_j^o m + 0.023 P_j^o 1_x \\ \text{Gas:} \quad \dot{P}_j = -\dfrac{190.8}{L_j} P_j + (3.246 c_{j-1} - 1.983 c_j - 1.263 c_{j+1}) P_j^o + 0.122 P_j^o 1_x . \end{cases} \tag{72}$$

Model refinement: An intent of this research is to obtain the cumulative effect of the whole incident on the population. If we develop a separate model for each incident, then we cannot obtain the cumulative effect as a direct output. So, we need to combine both subsystems into a single model. The simplest way to do that is to add both Equations (72).

With the exception of t_e, the forcing functions in Equations (72) have different variables. And even the t_e's are "different," because both subsystems have different starting points. If we use separate "clocks," then we can add together the forcing functions and still preserve the subsystem's independence. The only trouble with doing this is that we want to use a single time line.

Time translation: According to "Event chronology" on page 85, the chlorine release starts $\tau = 64$ seconds after the propane fire. Let $r(t)$ be any of the state variables associated with the chlorine release ($c_j(t)$ or $t_e(t)$.) To use a single time line we define $y = s(t) = \begin{cases} 0, & t < \tau, \\ r(t-\tau), & t \geq \tau, \end{cases}$ which shifts r a distance τ in the positive t direction. A convenient way to represent this translation of time is to use a step function $u_\tau(t)$, leading to $s(t) = u_\tau(t) r(t-\tau)$.

The concept of time translation is also relevant when we deal with average front velocities. On the one hand, the chlorine cloud velocity is only applicable after the event starts; on the other hand,

---

[40] The notation 1_x means a state variable made permanently equal to 1.

neither one is valid after their respective events end. Let the subscripts $\tau = 76$ and $\tau = 88$ represent the end of the release and fire events, respectively. For the gas release, for instance, $v_{(gas)} \triangleq u_{64}(t)v(1 - u_{76}(t))$, where $v = 190.8\ \mathrm{m\ min^{-1}}$ ($v = 6.6$ for the fire). So, the combination of Equations (72) yields:

$$\begin{aligned}\dot{P}_j = &-\frac{1}{L_j}[6.6(1 - u_{88}(t)) + 190.8u_{64}(t)(1 - u_{76}(t))]P_j - 1.918 \times 10^{-3} P_j^o m \\ &+ u_{64}(t)(3.246c_{j-1} - 1.983c_j - 1.263c_{j+1})P_j^o \\ &+ (0.023 + 0.122u_{64}(t))P_j^o 1_x, \quad j = 1, \ldots ,9.\end{aligned} \tag{73}$$

Further simplification: Equation (73) has time-varying coefficients and that is a major disadvantage if we want to keep the model simple. To avoid using separate models, the simplest way out is to assume both events are simultaneous. We do that by ignoring the effects of the fire until the release starts, and then assuming that (1) the front velocity is the cloud velocity and (2) the elapsed time effect is the cumulative effect of both hazards.

A second source of simplification is to drop the concentration terms related to the sectors adjacent to sector j. Keeping in mind all terms constituting the forcing function are positive, we end up with:

$$\dot{P}_j = -\frac{190.8}{L_j} P_j + 1.918 \times 10^{-3} P_j^o m + 1.983 P_j^o c_j + 0.145 P_j^o 1_x, \quad j = 1, \ldots ,9. \tag{74}$$

The injured people

Equation (74) is only valid for the general population, but the approach followed so far is still good. That is, we still have a continuity equation where injury rate is composed of an effect and a source term. The effect term has also a similar structure:

$$\dot{P}_j = -\frac{1}{\tau} P_j. \tag{75}$$

The value of τ depends on how serious the injuries are. In the footnote on page 76 we referred to people being differently color tagged according to their injuries, but we cannot convert that information into a value for τ. So, for simplicity, we assume $\tau = 1$ at this time.

For the source term we consider that casualties or permanent injuries are certain after some period without adequate care. The simplest model fitting this description is the source term P_j^i, and the population model for injured people becomes:

$$\dot{P}_j = -\frac{1}{\tau} P_j + P_j^i, \quad j = 10, \ldots, 12, \tag{76}$$

where P_j^i is the number of injured people input into sector j.

We decided to use only nine sectors for gas dispersion when we set up Equation (61) on page 187. We used that result in Equation (74). Now, we can justify that decision by noticing that Equation (76) doesn't involve propane mass or chlorine concentrations. In short, sectors 0, 11, and 12 can be thought of as having neither physical location nor dimensions. Sector 0 is simply a means to provide an initial number of injured people and an initial concentration of chlorine. Sectors 11 and 12 simulate the "content" of the command and triage posts, which are supposed to be outside the range of the physical hazard.

Appendix E. Machine calculations

Simulation software

The model building process consists of three steps:

- Developing the theoretical formulation
- Simulating by numerical integration
- Correcting and iterating whenever necessary

The final products, the state space model for each subsystem, are transparent to this process. But performing the process for each individual equation helps build confidence in the overall, aggregated model. The simulation software used here is a reduced version of *DESIRE* (Korn, 1989). Figure 35 on page 192 is a simulation result.

The general population model

The bulk computations are done under *Mathematica*™ (Wolfram, 1988). The programming statements follow.

System matrices

```
n=21;

p0 = {20, 10, 0, 0, 3, 1, 24, 172, 361}; (* People/sector *)

1 = {201.16750, 402.3350, 603.50250. 804.670, 1609.340, 3218.680,
  4828.020, 6437.360, 8046.70}; (* Distance to sector (m) *)

(* Build F *)
  f=Table[0,{n},{n}];
  f[[1,1]]=-.02820;        (* m *)
  For[i=1, i<10, i++, For[j=1, j<10, j++,
     f[[i+1,j+1]]=Switch[i-j, -1,-481, 0,-755, 1,1236, _,0] ] ] (* c *)
  f[[11,12]]=1;        (* t*)
  For[k=1, k<10, k++, f[[k+12,1]]=1.9180 10¬-3 p0[[k]] ]
  For[k=1, k<10, k++, f[[k+12,k+1]]=1.9830 p0[[k]] ]
  For[k=1, k<10, k++, f[[k+12,11]]=.1220 p0[[k]] ]
  For[k=1, k<10, k++, f[[k+12,k+12]]= - 190.80 / l[[k]] ]   (* p *)

(* Build G *)
  g=Table[0,{n},{3}];
  g[[13,1]]=-.1;    (* Evacuate at ...*)
  g[[14,1]]=-.1;    (* ... std v=-.1t *)
  For[k=1, k<10, k++, g[[k+12,2]]=-119 p0[[k]] ] (* Shelter *)
  g[[2,3]]=1;    (* Cl2(0) *)

(* Build H *)
  h={{0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1}};

(* Initialize x *)
  x = {{17300.}, {0}, {0}, {0}, {0}, {0}, {0}, {0}, {0}, {0}, {0}, {1},
    {0}, {0}, {0}, {0}, {0}, {0}, {0}, {0}, {0}}
```

State space model

```
t=.0001    (* Sampling period *)

(* Equivalent discrete-time system *)
  q=f t¬2/2; e=IdentityMatrix[n] t + q;
```

```
    For[k=in, k<n, k+ +, q=q.f t/k; e=e+q];
    a=IdentityMatrix[n]+f.e; b=e.g; c=h;

 (*  System response by recursion  *)
    w=Table[0,{n},{1}]; y=Table[0,{300}];
    For[p=1, p<301, p+ +,
       If[p>1, u[[3,1]]=0];
       For[k=1, k<10, k+ +,
          w[[k+12,1]]=Min[p0[[k]], Max[w[[k+12,1]], x[[k+12,1]] ] ] ];
       x=a.x+b.u;
       y[[p]]=(c.w)[[1,1]] ];


 (***   Observer   ***)

 (* Step 1: Calculate the coefficients of the characteristic polynomial *)
      pz=Det[ Chop[z IdentityMatrix[n] - a] ];
      cpz=CoefficientList[pz,z];

 (* Step 2: Construct the matrices Ao and Co *)
      ao=Table[Switch[i-j, -1,0, 0,0, 1,1, _,0], {i,n},{j,n}];
        For[k=1, k<n+1, k+ +, ao[[k,n]]=-cpz[[k]] ]
      co=Table[0,{1},{n}]; co[[1,n]]=1;

 (* Step 3: Construct the observability matrices O and Oo *)
       o=Table[0,{n},{n}]; o[[1]]=c[[1]]; w=c;
        For[k=1, k<n, k+ +, w=w.a; o[[k+1]]=w[[1]] ]
      oo=Table[0,{n},{n}]; oo[[1]]=co[[1]]; w=co;
        For[k=1, k<n, k+ +, w=w.ao; oo[[k+1]]=w[[1]] ]

 (* Step 4: Calculate the (inverse of the) transformation matrix *)
      q=Table[0,{n},{n}]; q[[n]]=c[[1]];
       For[k=n-1, k>0, k--, q[[k]]=q[[k+1]].a  +  cpz[[k+1]] q[[n]] ]

 (* Step 5: Complete the observable form model *)
      bo=q.b;

 (* Step 6: Select the desired characteristic polynomial for the estimator *)
      ev=Table[.5,{n}];
      ez=CoefficientList[ Expand[ Product[z-ev[[i]],{i,1,n}] ], z]

 (* Step 7: Calculate the observer gain matrix L and feedback matrix F *)
      l=Table[0,{n},{1}];
       For[k=1, k<n+1, k+ +, l[[k,1]]=ez[[k]]-cpz[[k]] ]

 (* Step 8: Obtain the estimated system response *)
  f=Table[Switch[i-j, -1,0, 0,0, 1,1, _,0], {i,n},{j,n}];
    For[k=1, k<n+1, k+ +, f[[k,n]]=-ez[[k]] ]
  x=Table[0,{n},{1}]; w=x; yo=Table[0,{300}];
  For[p=1, p<301, p+ +,
     If[p>1, u[[3,1]]=0];
     x=f.x+y[[p]] l;
     yo[[p]]=(co.x)[[1,1]] ];

 (*  Time Function Plots  *)
  g1=ListPlot[y, PlotJoined->True,
               PlotLabel->"Cumulative Injuries",
               AxesLabel->{"t", None}]
  g2=MultipleListPlot[{y,yo},
          PlotJoined->True,
               PlotLabel->"System and Observer Response",
               AxesLabel->{"t", None}]
```

```
y1 = Drop[y, -280]
y2 = Drop[yo, -280]
g3 = MultipleListPlot[{y1,y2},
     PlotJoined- > True,
          PlotLabel- > "Magnified Joint Initial Response",
          AxesLabel- > {"t", None}]
```

Input vector in open-loop: u = {{0},{0},{1000000}}

Input vector in closed-loop: u = {{p},{1},{1000000}}, where p is the iterator variable implementing time.

The injured population model

Exercise data

```
(* Origin *)
n10 = Table[0,{150}];
en = 1;
in = en; en = 5;  v = 3; For[k = in, k < en, k + +, n10[[k]] = v]
in = en; en = 16; v = 7; For[k = in, k < en, k + +, n10[[k]] = v]
in = en; en = 25; v = 5; For[k = in, k < en, k + +, n10[[k]] = v]
in = en; en = 41; v = 4; For[k = in, k < en, k + +, n10[[k]] = v]
in = en; en = 42; v = 3; For[k = in, k < en, k + +, n10[[k]] = v]
in = en; en = 66; v = 2; For[k = in, k < en, k + +, n10[[k]] = v]
in = en; en = 70; v = 1; For[k = in, k < en, k + +, n10[[k]] = v]

(* Command Post *)
n11 = Table[0,{150}];
in = 68; en = 109; v = 9; For[k = in, k < en, k + +, n11[[k]] = v]

(* Triage Center *)
n12 = Table[0,{150}];
en = 16;
in = en; en = 25;  v = 2;  For[k = in, k < en, k + +, n12[[k]] = v]
in = en; en = 41;  v = 3;  For[k = in, k < en, k + +, n12[[k]] = v]
in = en; en = 42;  v = 4;  For[k = in, k < en, k + +, n12[[k]] = v]
in = en; en = 66;  v = 5;  For[k = in, k < en, k + +, n12[[k]] = v]
in = en; en = 70;  v = 6;  For[k = in, k < en, k + +, n12[[k]] = v]
in = en; en = 78;  v = 7;  For[k = in, k < en, k + +, n12[[k]] = v]
in = en; en = 80;  v = 5;  For[k = in, k < en, k + +, n12[[k]] = v]
in = en; en = 109; v = 3;  For[k = in, k < en, k + +, n12[[k]] = v]
in = en; en = 114; v = 12; For[k = in, k < en, k + +, n12[[k]] = v]
in = en; en = 132; v = 11; For[k = in, k < en, k + +, n12[[k]] = v]
in = en; en = 147; v = 6;  For[k = in, k < en, k + +, n12[[k]] = v]
in = en; en = 151; v = 0;  For[k = in, k < en, k + +, n12[[k]] = v]
```

```
(* Overall response *)
 y = Table[0,{150}];
   For[k = 1,k < 151,k + +, y[[k]] = n10[[k]] + n11[[k]] + n12[[k]]]

(* Plots *) (* g1 = ListPlot[n10, PlotJoined- > True]
 g2 = ListPlot[n11, PlotJoined- > True]
 g3 = ListPlot[n12, PlotJoined- > True] *)
 g4 = ListPlot[y,  PlotJoined- > True,
                  PlotLabel- > "Actual Response Curve"]
```

System matrices

```
n = 3;

a = DiagonalMatrix[{Exp[-.9t],Exp[-t],Exp[-1.1t]}]; (* PHI = e¬At *)

b = Table[0,{n},{5}];   b[[1,1]] = -.1;   b[[2,2]] = -.1;   b[[3,3]] = -.1;      (*   Evacuation   rates   *)
b[[1,4]] = b[[2,5]] = 1;      (* Injured people in *) b[[3,1]] = .1; b[[3,2]] = .1;     (* Triage admission rates
*)

b = N[Integrate[a.b, {t,0,1}]]; a = N[a/.t- > 1];

c = {{1,1,1}};     (* Sum over all stations *)

x = {{0},{0},{0}};    (* Initial values *) u = {{0},{0},{0},{0},{0}};
```

State space model

Open-loop response: The inputs are fed to the model according to the scenario.

```
(* Model response by recursion *)
 w = Table[0,{n},{1}]; y = Table[0,{150}];
 For[p = 1, p < 151, p + +,
    If[p > 0,  u[[4,1]] = 7];  (* Input *)
    If[p > 67, u[[5,1]] = 9];
    x = a.x + b.u;   (* Differential equation *)
    ym[[p]] = (c.x)[[1,1]] ];  (* Output equation *)

(* Plot the results *)
 f4 = ListPlot[ym,  PlotJoined- > True,
   PlotLabel- > "Overall Open-Loop System Response"]
 Show[g4,f4, PlotLabel- > "Open-Loop vs Actual System Response"]
```

Closed-loop response: The input vector includes evacuation.

```
(* Model response by recursion *)
 w = Table[0,{n},{1}]; ym = Table[0,{150}];
```

```
 For[p = 1, p < 151, p + +,
    If[p > 0,  u[[1,1]] = p;u[[4,1]] = 7]; (* Input *)
    If[p > 67, u[[2,1]] = p;u[[5,1]] = 9];
    If[p > 100,u[[3,1]] = p];
    x = a.x + b.u;    (* Differential equation *)
    ym[[p]] = (c.x)[[1,1]] ];  (* Output equation *)

(*  Plot the model results  *)
 f4 = ListPlot[ym, PlotJoined- > True,
   PlotLabel- > "Overall Closed-Loop System Response"]
 Show[g4,f4, PlotLabel- > "Closed-Loop vs Actual System Response"]
```

Observer: The input to the observer is the exercise time series data.

```
(* Step 1: Calculate the coefficients of the characteristic polynomial *)
    pz = Det[ Chop[z IdentityMatrix[n] - a] ];
    cpz = CoefficientList[pz,z];

(* Step 2: Construct the matrices Ao and Co *)
    ao = Table[Switch[i-j, -1,0, 0,0, 1,1, _,0], {i,n},{j,n}];
      For[k = 1, k < n + 1, k + +, ao[[k,n]] = -cpz[[k]] ]
    co = Table[0,{1},{n}]; co[[1,n]] = 1;

(* Step 3: Construct the observability matrices O and Oo *)
     o = Table[0,{n},{n}]; o[[1]] = c[[1]]; w = c;
      For[k = 1, k < n, k + +, w = w.a; o[[k + 1]] = w[[1]] ]
    oo = Table[0,{n},{n}]; oo[[1]] = co[[1]]; w = co;
      For[k = 1, k < n, k + +, w = w.ao; oo[[k + 1]] = w[[1]] ]

(* Step 4: Calculate the (inverse of the) transformation matrix *)
    q = Table[0,{n},{n}]; q[[n]] = c[[1]];
     For[k = n-1, k > 0, k--, q[[k]] = q[[k + 1]].a  +  cpz[[k + 1]] q[[n]] ]

(* Step 5: Complete the observable form model *)
    bo = q.b;

(* Step 6: Select the desired characteristic polynomial for the estimator *)
    ev = Table[.5,{n}];
    ez = CoefficientList[ Expand[ Product[z-ev[[i]],{i,1,n}] ], z]

(* Step 7: Calculate the observer gain matrix L and feedback matrix F *)
    l = Table[0,{n},{1}];
     For[k = 1, k < n + 1, k + +, l[[k,1]] = cpz[[k]]-ez[[k]] ]
    f = Table[Switch[i-j, -1,0, 0,0, 1,1, _,0], {i,n},{j,n}];
     For[k = 1, k < n + 1, k + +, f[[k,n]] = -ez[[k]] ]

(* Step 8: Obtain the observer response *)
 xo = Table[0,{n},{1}]; yo = Table[0,{150}];
 For[p = 1, p < 151, p + +,
    xo = f.xo + y[[p]] l;   (* Output feedback to state *)
    yo[[p]] = (co.xo)[[1,1]] ];  (* Observer output *)

(*  Plot results  *)
 g2 = ListPlot[yo, PlotJoined- > True,
             PlotLabel- > "Observer Response"]
 z1 = Show[f4,g2,
  PlotLabel- > "Superimposed System and Observer Response"]
```

Hypothesis testing

```
n = 150;

(***   BASIC DATA ANALYSIS   ***)
 m1 = Mean[y]; m2 = Mean[yo];
 s1 = Variance[y]; s2 = Variance[yo];

  (*  Autocovariance  *)
 d1 = d2 = Table[0,{n-1}];
 For[k = 1, k < n, k + + ,
    d1[[k]] = N[Sum[ (y[[t]]-m1) (y[[t + k]]-m1),  {t,n-k}]/(n-k) ];
    d2[[k]] = N[Sum[(yo[[t]]-m2) (yo[[t + k]]-m2), {t,n-k}]/(n-k) ] ];

  (*  (Power) Spectral density function (spectrum); amplitude & phase  *)
 f1 = Fourier[d1];  f2 = Fourier[d2];
 r1 = Re[f1];  r2 = Re[f2];
 i1 = Im[f1];  i2 = Im[f2];
 a1 = Sqrt[r1 ¬ 2 + i1 ¬ 2]; a2 = Sqrt[r2 ¬ 2 + i2 ¬ 2];
 p1 = ArcTan[-i1/r1]; p2 = ArcTan[-i2/r2];

  (*  Cross-covariance function for Y with Yo  *)
 c = Table[0,{n-1}];
 For[k = 1, k < n, k + + ,
  c[[k]] = Sum[(y[[t]]-m1)*(yo[[t + k]]-m2), {t,n-k}]/(n-k)];
 r = c/Sqrt[s1*s2];

(***   CROSS-SPECTRAL ANALYSIS   ****)
  (*  Amplitude and Phase Angle spectra  *)
 f = Fourier[c]; re = Re[f]; im = Im[f];
 a = Sqrt[re ¬ 2 + im ¬ 2];  p = ArcTan[-im/re];
 cw = a ¬ 2/(a1*a2);   pw = p/Sqrt[p1*p2];
 gw = a/r1;   hw = Sqrt[p]/p1

  (*  Plots  *)
 q4 = ListPlot[cw, PlotJoined- > True,PlotRange- > {0,1},
         PlotLabel- > "(Squared) Coherency between the Data and the Observer"];

l1 = LocationReport[cw]     l2 = DispersionReport[cw]     l3 = ShapeReport[cw]     l4 = Quartiles[cw]
l5 = InterquartileRange[cw]
```

Appendix F. Draft of a systems engineering methodology

To engineer a management system, we must start with its mathematical model, in turn based on some verbal or graphic description. We have experience building mathematical models for physical systems, and we can use our experience to deal with management systems. A small number of relationships, involving consistent patterns of variables, describe general properties common to many different physical systems. So, we study each domain of responsibility to identify variables falling into the same patterns, and describe relationships similar to those found in physical systems (Mendes and Kurstedt, 1989). Then, we build a mathematical model representing those variables and relationships, and infer the dynamic behavior of the management system from the behavior of this mathematical model.

Borrowing from Blanchard & Fabrycky (1981), the next paragraphs describe the three stages of what we might call the management systems engineering process. The process iterates through system specification, system design, and prototype implementation.

System specification

After defining the need for the new (or improved) management system — for which we have a procedure or a manager's job description — this first stage of the systems engineering process concerns studying the needs analysis, operational requirements, and maintenance concept. At the specification stage we describe the MSM components and their interaction (believing the Management System Model represents any management situation). This stage corresponds to using the MSM to describe a domain of responsibility through the following steps:

1. Characterizing the domain of responsibility: This step is in turn composed of a series of tasks,

- Determine the "who manages" goals, purpose, and objectives, or, in engineering terminology, the mission scenario.
- Describe the management context, showing broad classes of inputs and outputs in a context diagram.
- Identify the particular aspects of the Pursuit, Endeavor, Decision, and Maturity framework that apply to the domain. (The capitalized terms are the names of a set of frameworks introduced by Kurstedt (1985) in the texts describing the MSM.)

2. Determine information requirements: This step uses systems analysis techniques to determine relationships between candidate variables. Specifically, we translate the procedures or the job description of some managerial position — the verbal representation of the plant equivalent of the "what is managed" component — into an *influence diagram.* The influence diagram (also called causal diagram or causal model) is also the starting point of the modern approaches to Forrester's *System Dynamics* studies (Coyle, 1978; Drew 1987).

3. Produce the specification: The organizational context, culture, and the mission scenario determine the inputs and disturbances expected, telling what needs to be done, under what conditions, with what tools, how fast, how accurately, etc. In short, the specification of the management system identifies the required response characteristics (performance). The tasks are:

- Normalize the relationships (a technique borrowed from relational database design (Date, 1982), consisting basically of eliminating redundancies).
- Update the influence diagram to reflect the results of the normalization effort.
- Determine the domain's management element, the single entity common to all the manager's responsibilities (Kurstedt, 1985).

System design

The fundamental design tools in engineering are mathematical models. Engineers use judgment and experience to select applicable models, to assign values to variables, and to determine the range of validity of their calculations. The MSM is the starting point to describe any management situation. Then, to move toward a mathematical model, we establish the analogy between the MSM and a control loop in Figure 1 on page 8. The control loop is complete, because it shows the interactions between a management system and its environment, respectively as inputs (set points), disturbances, and outputs. Like the MSM, the control loop is an apparently simple abstraction.

We start the design of a management system by studying the relationship between the controller and the plant in the control loop, or between the "who manages" and the "what is managed" in the MSM. The next paragraphs show the three main steps in the design stage. These are standard engineering techniques:

1. Build a mathematical model: The model represents the time-varying behavior of the "what is managed" component when no manager is active (controlling). Building it proceeds through the following tasks:

- Select the attributes of the management element as variables.
- Translate the relationships in the influence diagram into a set of (linear) ordinary differential or difference equations.
- Check the (unmanaged) system stability.

2. Build a process control model: This is the first model that actually fits the whole management system. This new set of equations has the parameters of the controller and the observer as unknowns. Recall the controller is the feedback loop element playing the role of the manager and the observer is the element playing the role of the management tools. What we do at this step is to consider the manager's need to maintain (or obtain) a certain behavior from the operation:

- Check the system observability; an unobservable system has an information deficiency.
- Build a state observer; the parameters of the observer give indications about the relative urgency and/or accuracy required from each piece of information.
- Check the system controllability; an uncontrollable system cannot meet the specifications.
- Build a system controller; the parameters of the controller give indications about the relative importance of the managerial actions.

3. Optimize the control model relative to some performance criteria: The study of the control loop will give indications both about the way the operation responds to the manager's directives and about the "management style" that causes a desired response. Very demanding performance criteria may create impossible management situations.

Prototype implementation

The systems engineering process is iterative. This means we may need to revise the original mathematical model of the "what is managed" component based on previous results. When the results are satisfactory from a (preliminary) design standpoint, they still need to be adapted to a set of given circumstances. The dramatic difference between designing a management and a physical system is the impossibility of buying components off-the-shelf or producing them to match a given design.

References

Amey, L.R. (1986). *A conceptual approach to management.* New York: Praeger.

Andersen, D.F. (1981). Kalman filter estimation of system states compared to the general regression problem. *International Journal of Policy Analysis and Information Systems* 5(2), 95-109.

Argyris, C. & Schön, D.A. (1978). *Organizational learning*. Reading, MA: Addison-Wesley.

Ashford, S.J. & Cummings, L.L. (1983). Feedback as an individual resource: personal strategies of creating information. *Organizational Behavior and Human Performance 32,* 370-398.

ASTM (1986). *Standard guide for developing a hazardous materials training curriculum for initial response personnel.* Doc. F 1011-86, The American Society for Testing Materials.

Barlow, D.H. & Hersen, M. (1984). *Single case experimental designs.* New York: Pergamon.

Baybutt, P. (1986). Decision support systems and expert systems for risk and safety analysis, in: *Hazards in the process industries.* London: The Institution of Chemical Engineers Symposium Series No. 97, 261-267.

Belardo, S. *et al.* (1983). Simulation of a crisis management information network: a serendipitous evaluation. *Decision Sciences 14,* 588-606.

Blanchard, B.S. & Fabrycky, W.J. (1981). *Systems Engineering and Analysis.* Englewood Cliffs, NJ: Prentice-Hall.

Blackmore, D.R., Herman, M.N., & Woodward, J.L. (1982). Heavy gas dispersion models. *Journal of Hazardous Materials, 6,* 107-128.

Boyce, W.E. & DiPrima, R.C. (1986). *Elementary differential equations and boundary value problems.* New York: Wiley.

Brasie, W.C. (1976). The hazard potential of chemicals. *Loss Prevention, 10,* 135-140.

Brethower, D.M. (1982). Linking two trends in management, in Duncan, P.K. (ed.) *Current topics in organizational behavior management.* New York: Haworth Press (pp. 21-31). Also in *Journal of Organizational Behavior Management, 3* (3).

Brightman, H.J.; Elrod, R. & Ramakrishna, H. (1988). Matching problem diagnostic tools to managers' decision styles: a contingency approach. *Omega 16*(1), 1-9.

Brinberg, D. & McGrath, J.E. (1985). *Validity and the research process.* Beverly Hills, CA: Sage.

Broekstra, G. (1984). MAMA: management by matching — a consistency model for organizational assessment and change. *Cybernetics and Systems Research 2,* 413-420.

Campion, M.A. & Lord, R.G. (1982). A control systems conceptualization of the goal-setting and changing process. *Organizational Behavior and Human Performance 30,* 265-287.

Carver, C.S. & Scheier, M.F. (1981). *Attention and self-regulation: a control-theory approach to human behavior.* New York: Springer-Verlag.

Catlin, D.E. (1989). *Estimation, control, and the discrete Kalman filter.* New York: Springer-Verlag.

Clancey, V.J. (1982). The effects of explosions. In: *The assessment of major hazards.* London: The Institution of Chemical Engineers Symposium Series No. 71, 87-108.

Chapanis, A. (1988). Some generalizations about generalization. *Human Factors 30*(3), 253-267.

Chatfield, C. (1980). *The analysis of time series: an introduction* (2nd ed.). London: Chapman & Hall.

Chen, C.-T. (1984). *Linear system theory and design.* New York: Holt, Rinehart & Winston.

Chopey, N.P. & Hicks, T.G. (1984). *Handbook of chemical engineering calculations* (pp.6-16). New York: McGraw-Hill.

CMA (1984). *Risk management of existing chemicals.* Chemical Management Association.

Cochin, I. (1980). *Analysis and design of dynamic systems.* New York: Harper & Row.

Cohen, L.J. (1981). Can human irrationality be experimentally demonstrated? *The Behavioral and Brain Sciences, 4,* 317-370.

Comfort, L.K. (1985). Information search processes in emergency management: computer simulation as a means of improving organizational decision making capacity. *Public Administration Review,* Special Issue, 41-45.

Costanza, P.A. *et al.* (1987). Estimation of catastrophic quantities of toxic chemicals by atmospheric dispersion modeling. *Plant/Operations Progress 6*(4). 215-220.

Coulson, J.M. & Richardson, J.F. (1977). *Chemical Engineering* (3rd ed.). Oxford, U.K.: Pergamon.

Coyle, R.G. (1977). *Management system dynamics.* London: Wiley.

Crawley, F.K. (1982). The effects of the ignition of a major fuel spillage, in: *The assessment of major hazards.* London: The Institution of Chemical Engineers Symposium Series No. 71, 125-145.

Crocker, W.P. & Napier, D.H. (1986). Thermal radiation hazards of liquid pool fires and tank fires, in: *Hazards in the process industries.* London: The Institution of Chemical Engineers Symposium Series No. 97, 159-184.

— (1988). Assessment of mathematical models for fire and explosion hazards of liquefied petroleum gases. *Journal of Hazardous Materials, 20,* 109-135.

Daft, R.L. (1983). *Organization theory and design.* St.Paul, MN: West Publishing Co.

Date, C.J. (1982). *An introduction to database systems* (3rd ed.). Reading, MA: Addison-Wesley.

Davies, M.E. & Singh, S. (1985). The phase II trials: a data set on the effect of obstructions. In J. McQuaid (ed.) *op. cit.,* 301-323.

Davis, M.W. (1988). *Applied decision support.* Englewood Cliffs, NJ: Prentice-Hall.

Deaves, D.M. (1984). Application of a turbulence flow model to heavy gas dispersion in complex situations. In S. Hartwig (ed.) *op. cit.*, 91-102.

DePol, D.R. & Chereminisoff, P.N. (1984). *Emergency response to hazardous materials incidents.* Lancaster, PA: Technomic Publ. Co.

DOE 5484.1 (1981). *Environmental protection, safety, and health protection information reporting requirements.* Washington, D.C.: U.S. Department of Energy.

DOE 5550.1A (1987). *Emergency management system.* Washington, D.C.: U.S. Department of Energy.

Drew, D.R. (1987). *System dynamics: modeling and applications.* Unpublished manuscript, Blacksburg, VA: VA Tech.

Earley, P.C. (1986). An examination of the mechanisms underlying the relationship of feedback to performance. *Proceedings of the 46th Annual Meeting of the Academy of Management,* 214-218.

Erez, M. (1977). Feedback: a necessary condition for the goal setting–performance relationship. *Journal of Applied Psychology 62*(5), 624-627.

Falkenhainer, B. & Forbus, K.D. (1988). Setting up large scale qualitative models. *Proceedings of the Seventh National Conference on Artificial Intelligence.* St. Paul, MN: AAAI, 301-306.

Fannelop, T.K. & Zumsteg, F. (1986). Special problems in heavy gas dispersion, in S. Hartwig (ed.) *op. cit.*, 123-135.

Farmer, F.R. (1984). Quantities of hazardous materials, in: Ricci, P. F.; Sagan, L.A. & Whipple, C.G. (eds.) *Technological risk assessment — Proceedings of the NATO Advanced Study Institute on Technological Risk Assessment,* 85-100.

Fink, S. (1986). *Crisis management.* New York: AMACOM.

Fletcher, B. (1982). Sudden discharge of a superheated fluid to atmosphere, in: *The assessment of major hazards.* London: The Institution of Chemical Engineers Symposium Series No. 71, 25-37.

FMPC (1986). *FMPC emergency management reference.* U.S. Department of Energy, Feed Materials Production Center.

FMPC (1987). *FMPC emergency plan.* U.S. Department of Energy, Feed Materials Production Center.

Forrester, J.W. (1961). *Industrial Dynamics.* Cambridge, MA: MIT Press.

— (1980). *Principles of systems* (first published 1968). Cambridge, MA: MIT Press.

Franklin, G.F.; Powell, J.D. & Emami-Naeini, A. (1986). *Feedback control of dynamic systems.* Reading, MA: Addison-Wesley.

Gabarro, J.J. (1987). *The dynamics of taking charge.* Boston: Harvard Business School Press.

Gage, W.L. (1980). Why managers want interrogation facilities in management information systems in F.R. Pichler & F.P. Hanika (eds.) *Progress in cybernetics and systems research, VII.* Washington: Hemisphere Publishing Corp. 137-141.

Galbraith, J. (1973). *Designing complex organizations.* Reading, MA: Addison-Wesley.

Geiger, W. (1984). Present understanding of the explosion properties of flat vapour clouds. In S. Hartwig (ed.) *op. cit.*, 225-236.

Gephart, L. & Moses, S. (1989, January). An approach to evaluate the acute impacts from simulated accidental releases of chlorine and ammonia. *Plant/Operations Progress 8*(1). 8-11.

Glassman, I. (1987). *Combustion* (2nd ed.). Orlando,FL: Academic Press.

Goodwin, G.C. & Payne, R.L. (1977). *Dynamic system identification: experiment design and data analysis.* New York: Academic Press.

Green, S.D. (1980). The engineering response to health hazards, in *Chemical process hazards*. London: The Institution of Chemical Engineers Symposium Series No. 58, 155.

Green, S.G. & Welsh, M.A. (1988). Cybernetics and dependence: reframing the control concept. *Academy of Management Review, 13*(2), 287-301.

Grimble, M.J. (1987). An introduction to Kalman filters, in: O'Reilly, *op. cit.*

Guariso, G. & Werthner, H. (1989). *Environmental decision support systems*. Chichester, U.K.: Ellis Horwood.

Gunn, D.J. (1982). Spreading and dispersion of dense vapours and gases. In: *The assessment of major hazards*. London: The Institution of Chemical Engineers Symposium Series No. 71, 57-68.

Hall, C.A. & Porsching, T.A. (1990). *Numerical analysis of partial differential equations*. Englewood Cliffs, NJ: Prentice-Hall.

Hannan, E.J. & Deistler, M. (1988). *The statistical theory of linear systems*. New York: Wiley.

Harris, N.C. (1982). Problems in hazard analysis and risk assessment, in: *The assessment of major hazards*. London: The Institution of Chemical Engineers Symposium Series No. 71, 267-283.

Hartwig, S. (ed.) (1983). *Heavy gas and risk assessment — II* Dordrecht, FRG: Reidel.

— (1986). *Heavy gas and risk assessment — III* Dordrecht, FRG: Reidel.

Havens, J.A. (1982). A review of mathematical models for prediction of heavy gas atmospheric dispersion, in: *The assessment of major hazards*. London: The Institution of Chemical Engineers Symposium Series No. 71, 1-24.

— (1985). Atmospheric dispersion of heavy gases: an update, in: in: *The assessment and control of major hazards*. London: The Institution of Chemical Engineers Symposium Series No. 93, 143-164.

Heinrich, M.; Gerold, E. & Wietfelt, P. (1988). Large scale propane releases over land at different atmospheric stability classes. *Journal of Hazardous Materials, 20,* 287-301.

Henry, J., Sadikou, Y., & Yvon, J.P. (1989). Identification of parameters in diffusion convection models: application to the analysis of blood flow in digital subtraction angiography. In A. Bermúdez (ed.) *Control of partial differential equations*. Berlin: Springer-Verlag, 156-167.

Hink, R.F. & Woods, D.L. (1987, Fall). How humans process uncertain knowledge: an introduction for knowledge engineers. *AI Magazine,* 41-53.

Hollenbeck, J.R. (1989). Control theory and the perception of work environments: the effects of focus of attention on affective and behavioral reactions to work. *Organizational Behavior and Human Performance 43,* 406-430.

Hunt, D.L.M. & Ramskill, P.K. (1985). The behaviour of tanks engulfed in fire — the development of a computer program, in: *The assessment and control of major hazards*. London: The Institution of Chemical Engineers Symposium Series No. 93, 71-86.

Ijiri, Y. (1988). Momentum accounting and managerial goals on impulses. *Management Science 34*(2), 160-166.

Jacobsen, O. & Magnussen, B.F. (1987). 3-D numerical simulation of heavy gas dispersion. *Journal of Hazardous Materials, 16,* 215-230.

Jagger, S.F. (1983). Formulations of the dense gas dispersion problem in Hartwig (1983) *op. cit.* 27-52.

Johnson, H.T. & Kaplan, R.S. (1987, January). The rise and fall of management accounting. *Management Accounting,* 22-30.

Kahneman, D.; Slovic, P. & Tversky, A. (eds.) (1982). *Judgment under uncertainty: heuristics and biases.* Cambridge, U.K.: Cambridge University Press.

Kalman, R.E.; Falb, P.L. & Arbib, M.A. (1969). *Topics in mathematical system theory.* New York: McGraw-Hill.

Kazdin, A.E. (1984). Statistical analyses for single-case experimental designs, in: Barlow & Hersen, *op. cit.*, 285-324.

Kecman, V. (1988). *State-space models of lumped and distributed systems.* Berlin: Springer-Verlag.

Keeney, R.L. (1988). Facts to guide thinking about life-threatening risks. IEEE CH2556-9, 326-329.

Kerlinger, F.N. (1979). *Behavioral research: a conceptual approach.* New York: Holt, Rinehart & Winston.

Kim-E, M.E. & Reid, R.C. (1983). The rapid depressurization of hot, high pressure liquids or supercritical fluids, in Paulitis, M.E. *et al.* (eds.) *Chemical engineering at supercritical fluid conditions* (pp. 81-100). Ann Arbor, MI: Ann Arbor Science.

Klein, H.J. (1989). An integrated control theory model of work motivation. *Academy of Management Review, 14*(2), 150-172.

Kletz, T.A. (1977-a). Unconfined vapor cloud explosions. *Loss prevention, 11,* 50-58.

— (1977-b). Some myths on hazardous materials. *Journal of Hazardous Materials, 2,* 1-10.

— (1986). Setting priorities in safety, in A. Kandel & E. Avni (eds.) *Engineering risk and hazard assessment.* Boca Raton, FL: CRC Press.

Korn, G.A. (1989). *Interactive dynamic system simulation.* New York: McGraw-Hill.

Kreitner, R. (1982). The feedforward and feedback control of job performance through organizational behavior management (OBM) in P.K. Duncan (ed.) *Current topics in organizational behavior management* (pp. 3-20). New York: Haworth Press. Also in *Journal of Organizational Behavior Management, 3* (3).

Kurstedt, H.A.Jr. (1985). Series of working articles describing the Management System Model. Article #1: The industrial engineer's systematic approach to management. Article #2: The Management System Model helps your tools research for you. Article #3: Managing a management system reduces to concentrating in the interfaces between components. (Drafts available from Management System Laboratories, Virginia Tech, Blacksburg, VA).

— & Mendes, P.M. (1990). Automated performance monitoring provides a strategic management tool for crisis management. *Proceedings of the Twelfth Conference for Computers and Industrial Engineering.* Orlando, FL: IIE (in press).

—; Mendes, P.M. & Lee, K.S. (1988). Engineering analogs in management. *Proceedings of the Ninth Annual Conference of the American Society for Engineering Management.* Knoxville, TN: ASEM, 197-202.

—; Mendes, P.M. & Polk, T.E. (1988). Using control theory to understand management. *Proceedings of 1988 IEEE Engineering Management Conference.* Dayton, OH: IEEE, 194-201.

Langhaar, H.L. (1983). *Dimensional analysis and theory of models.* New York: Wiley.

Lawler, E.E.III & Rhode, J.G. (1976). *Information and control in organizations.* Pacific Palisades, CA: Goodyear.

— (1982). Dysfunctional effects of control systems in D.R. Hampton, C.E. Summer, & R.A. Webber (eds.) *Organizational behavior and the practice of management* (pp. 453-463). Glenview, IL: Scott, Foresman & Co.

Lees, F.P. (1980). *Loss prevention in the process industries.* London: Butterworths.

— (1987). The assessment of major hazards: use of the impact model for injury and damage around a hazard source to determine sensitivity to errors in the constituent models. *Journal of Hazardous Materials, 14,* 259-267.

—, Poblete, B.R. & Simpson, G.B. (1986). The assessment of major hazards: generalization of the impact model for the estimation of injury and damage around a hazard source. *Journal of Hazardous Materials, 13,* 187-196.

LeMay, M. & Wild H. (1988). Why some decision aids work and others don't. pp.227-229.

Longino, H. (1985). Hazardous technologies: how are the hazards measured? *Research in Philosophy & Technology, 8,* 177-188.

Lord, R.G. & Hanges, P.J. (1987). A control system model of organizational motivation: theoretical development and applied implications. *Behavioral Science 32,* 161-178.

Luckritz, R.T. & Schneider, A.L. (1980). Decision making in hazardous materials transportation. *Journal of Hazardous Materials, 14,* 337-363.

Maciariello, J.A. (1984). *Management control systems.* Englewood Cliffs, NJ: Prentice-Hall.

Mackenzie, K.D. & House, R. (1978, January). Paradigm development in the social sciences: a proposed research strategy. *Academy of Management Review,* 7-23.

March, J.G., (1978, Autumn). Bounded rationality, ambiguity, and the engineering of choice. *Bell Journal of Economics,* 587-608.

March, J.G. & Simon, H.A. (1958). *Organizations.* New York: Wiley.

Marchuk, G.I. (1986). *Mathematical models in environmental problems.* Amsterdam: North-Holland.

Marshall, V.C. (1982). Quantification as a means of control of toxic hazards, in: *The assessment of major hazards.* London: The Institution of Chemical Engineers Symposium Series No. 71, 69-85.

— (1987). *Major chemical hazards.* Chichester, U.K.: Ellis Horwood Ltd.

Mason, R.O. & Mitroff, I.I. (1981). *Challenging strategic planning assumptions.* New York: Wiley.

Matsui, T.; Okada, A. & Inoshita, O. (1983). Mechanism of feedback affecting task performance. *Organizational Behavior and Human Performance 31,* 114-122.

McQuaid, J., ed. (1985). *Heavy gas dispersion models at Thorney Island.* Amsterdam: Elsevier.

Meidl, J.H. (1978). *Flammable hazardous materials* (2nd ed.). Encino, CA: Glencoe Publishing Co.

Mendes, P.M. *et al.* (1991). Control theory, giving up, and related concepts: a reinterpretation of the findings. Working draft to submit to *Organizational Behavior and Human Performance.*

— & Kurstedt, H.A.Jr. (1990). Management statics and dynamics. *Proceedings of the Tenth European Meeting on Cybernetics and Systems Research.* Vienna, 617-624.

—; Kurstedt, H.A.Jr. & Koelling, C.P. (1988). Dynamic aspects of decision making. *Proceedings of 1988 IEEE Engineering Management Conference.* Dayton, OH: IEEE, 44-50.

—; Roach, J.W. & Kurstedt, H.A.Jr. (1989). Simulation of management systems. *Proceedings of the 20th Annual Pittsburgh Conference on Modeling and Simulation* (in press).

Meyers, G.C. (1986). *When it hits the fan: managing the nine crises of business.* New York: Mentor.

Miller, D.C. (1983). *Handbook of research design and social measurement* (4the d.). New York: Longman.

Miller, K.S. & Leskiw, D.M. (1987). *An introduction to Kalman filtering with applications*. Malabar, FL: Krieger.

Mintzberg, H. (1975). *Impediments to the use of management information*. New York: National Association of Accountants and Hamilton, Ontario: The Society of Management Accountants of Canada.

Mitroff, I.I.; Shrivastava, P. & Udwadia, F.E. (1987). Effective Crisis Management. *The Academy of Management Executive 1*(3), 283-292.

— (1988, Winter). Crisis management: cutting through the confusion. *Sloan Management Review,* 15-20.

Mize, J.H.; White, C.R. & Brooks, G.H. (1971). *Operations planning and control*. Englewood Cliffs, NJ: Prentice-Hall.

Moodie, K.; Billinge, K. & Cutler, D. P. (1985). The fire engulfment of LPG storage tanks, in: *The assessment and control of major hazards*. London: The Institution of Chemical Engineers Symposium Series No. 93, 87-106.

Mudan, K.S. (1986). Blast waves in partially confined spaces — a numerical simulations model. In S. Hartwig *op. cit.*

Murdick, R.G. (1986). *MIS concepts and design*. Englewood Cliffs, NJ: Prentice-Hall.

Negoita, C.V. (1979). *Management applications of system theory*. Basel, Stuttgart: Birkhauser.

Nunamaker, J.F.Jr.; Weber, E.S.; Smith, C.A.P. & Chen, M. (1988). Crisis Planning Systems: tools for intelligent action. *Proceedings of the Twenty-First Annual Hawaii International Conference on System Sciences,* Vol III, 25-34.

O'Reilly, J. (1987). *Multivariable control for industrial applications*. London: Peter Peregrinus.

Otley, D. (1987). *Accounting control and organizational behaviour*. London: William Heinemann Ltd.

Pasquill, F. & Smith, F.B. (1983). *Atmospheric diffusion*. Chichester, U.K.: Ellis Horwood.

Perrow, C. (1984). *Normal accidents*. New York: Basic Books.

Perry, R.H. & Green, D.W. (1984). *Perry's chemical engineer's handbook*. New York: McGraw-Hill.

Petts, J.I.; Withers, R.M.J. & Lees, F.P. (1987). The assessment of major hazards: the density and other characteristics of the exposed population around a hazard source. *Journal of Hazardous Materials, 14,* 337-363.

Pietersen, C.M. (1984). Calculation of intoxication effects in a risk analysis associated with toxic gases. In S. Hartwig (ed.) *op. cit.,* 183-196.

Platt, J.R. (1964). Strong inference. *Science 146,* 347-353. Also in T.S. Bateman & G.R. Ferris (eds.) *Method and analysis in organizational research*. Reston, VA: Reston Publishing Co., 1984.

Poblete, B.R., Lees, F.P., & Simpson, G.B. (1984). The assessment of major hazards: estimation of injury and damage around a hazard source using an impact model based on inverse square law and probit relations. *Journal of Hazardous Materials, 9,* 355-371.

Podsakoff, P.M. & Farh, J.-L. (1986). Effects of feedback sign and credibility on goal setting and task performance: a preliminary test of some control theory propositions. *Proceedings of the Forty-sixth Annual Meeting of the Academy of Management,* pp. 198-202.

Prugh, R.W. (1985). Mitigation of vapor cloud hazards. *Plant/Operations Progress 4*(2), 95-102.

— (1986). Mitigation of vapor cloud hazards (Part I). *Plant/Operations Progress 5*(3), 169-174.

— (1987). Guidelines for vapor release mitigation (Part II). *Plant/Operations Progress 6*(3), 171-174.

— & Johnson, R.W. (1988). *Guidelines for vapor release mitigation.* New York: American Institute of Chemical Engineers.

Rahmatian, S. (1985). Human rationality as a behavioral postulate. *Systems inquiring, I,* 443-448.

— & Hiatt, C. (1989). Toward an information-based theory of irrational systems behavior. *Systems Research, 6*(1), 7-16.

Ricci, P.F.; Sagan, L.A. & Whipple, C.G. (eds.) (1984). *Technological risk assessment.* The Hague, The Netherlands: Martinus Nijhoff.

Roberts, A.F. (ed.) (1982). The effect of conditions prior to loss of containment on fireball behavior, in: *The assessment of major hazards.* London: The Institution of Chemical Engineers Symposium Series No. 71, 181-190.

Roberts, E.B. (ed.) (1978). *Managerial applications of system dynamics.* Cambridge, MA: MIT Press.

Rottman, J.W., Simpson, J.E., Hunt, J.C.R., & Britter, R.E. (1985). Unsteady gravity current flows over obstacles: some observations and analysis related to the phase II trials. In J. McQuaid (ed.) *op. cit.,* 325-340.

Russel, D.L. (1979). *Mathematics of finite-dimensional control systems.* New York: Marcel Dekker.

Sage, A.P. (1986). Information technology for crisis management. *Large Scale Systems 11,* 193-205.

Sanders, M.S. & McCormick, E.J. (1987). *Human factors in engineering and design* (6th ed.). New York: McGraw-Hill.

Sax, N.I. (1984). *Dangerous properties of industrial materials.* New York: Van Nostrand Reinhold.

Scott, K.D.; Markham, S.E. & Roberts, R.W. (1985). Rewarding good attendance: a comparative study of positive ways to reduce absenteeism. *Personnel Administrator,* August.

Sengupta, J.K. (1987). *Applied mathematics for economics.* Dordrecht: Holland.

Sethi, S.P. & Thompson, G.L. (1981). *Optimal control theory: applications to management science.* Boston: Martinus Nijhoff Publishing.

Simon, H.A. (1952). On the application of servomechanism theory in the study of production control. *Econometrica, 20*(2), 247-268. Also in E.B. Roberts, *op. cit.,* pp. 95-115.

Smith, G.F. (1989). Defining managerial problems: a framework for prescriptive theorizing. *Management Science, 35*(8), 963-981.

Smith, M.E. *et al.* (1983). Atmospheric modeling for emergencies. *Plant/Operations Progress, 2*(1), 61-66.

Smith, R.L. (1987). ASKBUDJr: a precursor of an expert system for the evaluation of fire hazard. *Fire Technology, 23*(1), 5-18.

Sohn, T.-W. & Surkis, J. (1985-a). System dynamics: a methodology for testing dynamic behavioral hypotheses. *IEEE Transactions on Systems, Man, and Cybernetics, SMC-15*(3), 399-408.

— (1985-b). Systems approach for constructing dynamic motivation models. *Cybernetics and Systems, 16,* 145-170

Stark, H. & Woods, J.W. (1986). *Probability, random processes, and estimation theory for engineers.* Englewood Cliffs, NJ: Prentice-Hall.

Sterman, J.D. (1987). Testing behavioral simulation models by direct experiment. *Management Science, 33*(12), 1572-1592.

Stinton, H.G. (1983). Spanish camp site disaster. *Journal of Hazardous Materials, 7,* 393-401.

Szewczak, E.J. & Ramaprasad, A. (1987). Emergency decision support systems design: complementing the impact of stress on cognition. pp. 1017-1021.

Takkenberg, C.A.T. (1982). The applicability of control theory in management science. *Progress in Cybernetics and Systems Research, 10,* 287-292.

Till, J.E. & Meyer, H.R., eds. (1983). *Radiological assessment — A textbook on environmental dose analysis.* Washington, D.C.: United States Nuclear Regulatory Commission.

Tracy, L. (1984). A dynamic living-systems model of work motivation. *Systems Research, 1*(3), 191-203.

Tzafestas, S.G. (ed.) (1982). *Optimization and control of dynamic operational research models.* Amsterdam: North-Holland.

VanAerde, M.; Stewart, A. & Saccomanno, F. (1988). Estimating the impact of L.P.G. spills during transportation accidents. *Journal of Hazardous Materials, 20,* 375-392.

VanAken, J.E. (1982). *On the control of complex industrial organizations.* Boston: Kluwer-Nijhoff.

VanLandingham, H.F. (1985). *Introduction to digital control systems.* New York: MacMillan.

Varela, J.A. (1978). "Solving human problems with human science," *Human Nature, 1*(10), 84-90.

Vesely, W.E. (1984). Engineering risk analysis, in: Ricci, Sagan & Whipple, *op. cit.,* 49-84.

vonKänel, S. & Schäfer, G. (1986). Computer-aided simulation of control processes in enterprises in Trappl, R. (ed.) *Cybernetics and systems.* New York: Reidel, 557-564.

Walker,J.A.; Ruberg, G.E.; Stovall, C.L. & O'Dell, J.J. (1988). Training and validating emergency managers through simulation. *Abstract Book of the 1988 Summer National Meeting on Emergency Response.*

—; Ruberg, G.E. & O'Dell, J.J. (1989, September). Simulation for emergency management: taking advantage of automation in emergency preparedness. *Simulation* (in press).

Wallace, W.A. & DeBalogh, F. (1985). Decision support systems for disaster management. *Public Administration Review,* Special Issue, 134-146.

Wells, J.W. (1989). *The hazard communications standard: an implementation guide.* Lilburn, GA: Fairmont Press.

Wenk, E.Jr. (1979). *Margins for survival.* Oxford, U.K.: Pergamon.

Wiekema, B.J. (1984). Vapour cloud explosions — an analysis based on accidents (Part I). *Journal of Hazardous Materials, 8,* 295-311.

Wierzba, I.; Karim, G.A. & Cheng, H. (1988). The flammability of rich gaseous fuel mixtures including those containing propane in air. *Journal of Hazardous Materials, 20,* 303-312.

Williamson, B.R. & Mann, L.R.B. (1981). Thermal hazards from propane (LPG) fireballs. *Combustion Science and Technology, 25,* 141-145.

Wilson, D.J. (1986). Stay indoors or evacuate to avoid exposure to toxic gas? *Proceedings of the Petroleum Industry Annual Safety Seminar.* Banff, Alberta. Also publ. in *Emergency Preparedness Digest.*

Wilson, E. (1981). A selected annotated bibliography and guide to sources of information on planning for and responses to chemical emergencies. *Journal of Hazardous Materials, 4,* 373-394.

Withers, R.M.J. & Lees, F.P. (1985a). The assessment of major hazards: the lethal toxicity of chlorine — Part 1, review of information on toxicity. *Journal of Hazardous Materials, 12,* 231-282.

— (1985b). The assessment of major hazards: the lethal toxicity of chlorine — Part 2, model of toxicity to man. *Journal of Hazardous Materials, 12,* 283-302.

— (1987). The assessment of major hazards: the lethal toxicity of chlorine — Part 3, crosschecks from gas warfare. *Journal of Hazardous Materials, 15,* 301-342.

Wolfram, S. (1988). *Mathematica: a system for doing mathematics by computer*. Redwood City, CA: Addison-Wesley.

Zeckhauser, R. & Shephard, D.S. (1981). Principles for saving and valuing lives, in: A. Ferguson & E.P. LeVeen (eds.) *The benefits of health and safety regulation.* Cambridge, MA: Ballinger.

Vita

Name

João Pedro M. Mendes

Date

April, 1990

Business Address

Management Systems Laboratories
1900 Kraft Drive
Blacksburg, VA 24060
(703) 231-3501

Home Address

R. Arco Carvalhao, 14, 3/D
1000 Lisboa
Portugal
Intl. (351) 165-9409

Personal

Born February 8, 1950

Married, 2 children

Education

B.S. - Chemical Engineering, 1976 Technical University of Lisbon

Ph.D. - Industrial and Systems Engineering, 1990 Virginia Polytechnic Institute and State University

Experience

Fall'85 - present	Instructor at *Beira Interior University,* Covilhã, Portugal
Since Fall'86	On leave at Virginia Tech
Spring'83 - Fall'85	Planning Engineer at *Hidrocontrato,* Lisbon, Portugal
Fall'80 - Spring'83	Software Coordinator at *Sperry Univac* (now Unisys), Lisbon, Portugal
Fall'79 - Fall'80	Systems Analyst at *TAP—Air Portugal,*
Spring'79 - Fall'79	Computer Systems Manager at *Bertrand* publishers, Lisbon, Portugal (contract job)
Winter'74 - Spring'79	Systems Analyst at *SETENAVE* shipyard, Setubal, Portugal
Winter'72 - Summer'74	Programmer-Analyst at Scientific Research Institute, Angola (part-time job)
Fall'70 - Winter'72	Programmer-Analyst at *NCR*, Angola

Publications

Kurstedt, H.A.Jr.; Berube, D.S. & Mendes, P.M. (1988). We bias information differently for managers at different organizational levels. *Proceedings of the 9th Annual Conference of the American Society for Engineering Management,* pp.43-49.

—; Lee, K.S.; Mendes, P.M. & Berube, D.S. (1988). The responsive system: a new challenge for AI. *Proceedings of The First International Conference on Industrial & Engineering Applications of Artificial Intelligence & Expert Systems,* pp.177-184.

—; Lee, K.S.; Mendes, P.M. & Jones, R.M. (1988). A responsive system operationalizes the management system model concept using distributed AI techniques. *Proceedings of the Conference on the Impact of Artificial Intelligence on Business and Industry,* pp.63-73.

— & Mendes, P.M. (1990). Automated performance monitoring provides a strategic management tool for crisis management. *Proceedings of the Twelfth Conference for Computers and Industrial Engineering*. Orlando, FL: IIE (in press).

—; Mendes, P.M. & Lee, K.S. (1988). Engineering analogs in management. *Proceedings of the Ninth Annual Conference of the American Society for Engineering Management.* Knoxville, TN: ASEM, 197-202.

—; Mendes, P.M. & Polk, T.E. (1988). Using control theory to understand management. *Proceedings of 1988 IEEE Engineering Management Conference.* Dayton, OH: IEEE, 194-201.

Mendes, P.M. & Kurstedt, H.A.Jr. (1990). Management statics and dynamics. *Proceedings of the Tenth European Meeting on Cybernetics and Systems Research.* Vienna, 617-624.

—; Kurstedt, H.A.Jr. & Freeman, H.J. (1988). An information strategy is fundamental for sustained competitive advantage. *Proceedings of the 9th Annual Conference of the American Society for Engineering Management,* pp.237-241.

—; Kurstedt, H.A.Jr. & Gardner, E.J. (1988). Information for strategic manufacturing decisions. *Proceedings of the 1988 S.E. TIMS Annual Meeting,* pp.221-225.

—; Kurstedt, H.A.Jr., & Koelling, C.P. (1988). Dynamic aspects of decision making. *Proceedings of 1988 IEEE Engineering Management Conference,* pp.44-50.

—; Roach, J.W. & Kurstedt, H.A.Jr. (1989). Simulation of management systems. *Proceedings of the 20th Annual Pittsburgh Conference on Modeling and Simulation* (in press).