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A SYSTEMS APPROACH TO CONTAMINATION CONTROL

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Presentation

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SESSION VI

SYSTEMS APPROACH

A SYSTEMS APPROACH TO CONTAMINATION CONTROL

by

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Abstract

Contamination control, in spite of its increasing importance in our technically advanced society, is still a subject suffering from a lack of cohesiveness. This situation obtains because there is no theory of contamination control which applies to all specific contamination control problems and encompasses all types of contamination control techniques. This paper represents an attempt to formulate a framework in which such a theory may be developed. In effect, this is a framework in which contamination control may be planned for on a cost-effectiveness basis.

Introduction

Contamination Control. When contamination control is understood in the broad sense of limiting or removing unwanted material, nearly every human being is involved, to some degree, in this activity. This participation may take the form of placing trash in receptacles or merely limiting one's food to things which are hoped not to be harmful. Because of this "universality" of contamination control, it is easy to view the field as a disjointed collection of relatively unrelated problems. A little reflection, however, must lead to the realization that nearly all contamination control problems have certain similar features: they involve limiting or removing particulate matter, gases or liquids in, on or from solids, gases or liquids.[1] The following abbreviated list gives some indication of the "universality" of contamination control and the similarity of the problems arising in the field.

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[1] Contamination control has been viewed in some detail in this form in a document entitled Principles of Contamination Control. This document was prepared by members of the Planetary Quarantine Department of Sandia Laboratories and was published by the Government Printing Office in late 1967.

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This work was conducted under Contract No. NASA-R-09-019-040, Bioscience Division, Office of Space Science Application, NASA Headquarters.

Area	Problem
Medicine	- Limit (remove) virulent life forms, particulate matter, chemicals and gases on and in (from) instruments, drugs, environments and humans.
Foods	- Limit (remove) viable virulent life forms, harmful chemicals and gross particulate matter in (from) foods and environments.
Drugs	- Limit (remove) certain viable virulent life forms, harmful chemicals and particulate matter in (from) drugs and environments.
Manufacturing	- Limit (remove) certain types of gases, liquids and solids on and in (from) products, environments and raw materials.
Air Pollution	- Limit (remove) certain particulate material and chemicals in (from) air.
Water Pollution	- Limit (remove) certain particulate material, chemicals, life forms in (from) natural water sources.
Planetary Quarantine	- Limit (remove) viable micro-organisms on and in (from) space vehicles, environments, materials and parts.

At least one important observation may be made about contamination control as represented by this list. It is this: a narrow view of contamination control techniques is not possible. It is not possible to view any technique as being exclusively associated with a given area because of the similarity of the problems arising in many areas. The recent use of laminar air flow clean rooms in medicine provides an excellent example of this.[2] Also, it is not possible to equate contamination control with any one technique because of the universality of the field. Cleaning, clean rooms, ultrasonication, and so forth, are all important in addressing the problems of contamination control.

Thus, for purposes of this paper, contamination control is viewed as a broad, important field in which the problems exhibit a similar abstract structure and the many techniques for their resolution may have wide applicability.

[2] McDade, J. J., Whitcomb, J. G., Rypka, E. W., Whitfield, W. J. and Franklin, C. M., The Microbial Profile of a Vertical Laminar Airflow Surgical Theater, Sandia Laboratories Research Report, SC-RR-67-456. This paper presents some specific results indicating the effectiveness of laminar airflow in actual surgical situations and, in addition, has a reasonable bibliography for persons interested in pursuing the subject further.

Planning for Contamination Control. There are several things which influence the author's belief that planning for contamination control is highly desirable. In this context, planning refers to (1) formulating objectives, (2) determining activities which will accomplish the objectives in some "optimal" fashion, and (3) deciding how the activities are "best" undertaken.

If only one means of resolving a problem is available, then planning consists primarily of (1) deciding whether to use it and control contamination or not to use it, with the opposite effect, and (2) making arrangements to use the one means available, if that is the decision. However, when many alternative means of resolving a problem are available, then it is often desirable to choose the "best" from among all alternatives. The view of contamination control expressed above, that is, a broad field of similarly structured problems, techniques for whose resolution may have wide applicability, inevitably leads to the conclusion that there may be many ways of resolving a given problem. With continued technical advances, this will become almost a certainty: leading to an increased need for selecting a "best" means of problem resolution from among the alternatives. Planning plays an important role in doing this.

The cost of contamination control activities in this country today must be enormous. For example, it has been estimated that as much as 275 billion dollars would be necessary over the next 34 years to resolve the air pollution problem.[3] If "best," in the preceding paragraph is related to "lease cost," one can begin to realize the potential importance of planning.

Not unrelated to the question of cost is the question of general "efficiency." Lower costs and, perhaps, greater results (faster, more effective) stem from efficient actions or activities to resolve problems. Both technical and administrative planning tend to encourage this efficiency.

Thus, planning seems desirable because (1) there is an almost inevitable increase in the number of ways of resolving problems (stemming from the broad view of contamination control) and (2) the potential savings and, possibly, technical gains, associated with the efficiency derived from planning seem great.

A theory of contamination control adequate for planning purposes should have several properties:

- a capability of addressing problems before they arise
- few limitations regarding the types of contamination or control techniques considered
- a capability to determine "most effective" means of achieving overall contamination control objectives.

A logical first step toward the development of a theory of contamination control is the formulation of a collection of general objectives

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[3]The cost figure given here is the largest come across by the author. This figure and several others may be found in Hearings before the Subcommittee on Air and Water Pollution of the Committee on Public Works of the United States Senate, Ninetieth Congress. First Session on S 780, Part 2, p. 943.

to which all persons actively engaged in this activity can subscribe. Then some means of deriving "optimal" activities to achieve these objectives should be found. Accordingly, the remainder of this paper is devoted to a discussion of contamination control objectives, a means of relating these objectives to activities sufficient for the achievement of the objectives, and the notion of cost-effectiveness in contamination control.

It should be emphasized that some of the material that follows is subjective in character and represents only the current views of the author.

The Systems Philosophy

In Theory. One philosophy which typically concerns itself with a broad, unified view of the subject being addressed is the "systems philosophy." Rather than appeal to other, often conflicting, definitions of systems analysis, systems studies, systems engineering, operations research, and so forth, a general outline of the "systems philosophy" (as seen by the author) is given below.[4]

A philosophy familiar to men for several centuries is that of the "scientific method." In general, one attempts to determine characteristics of "natural systems" by entering into a logical sequence of actions resembling those shown below.

THE SCIENTIFIC METHOD

Natural System	Observe the System Model the System Verify the Model Analyze the Model Draw conclusions about the System

A few comments about this list are in order. Observation of a natural system clearly depends upon a person's ability to observe. This ability to observe is not only a function of the state of technology and the system being observed, but also of the observer, himself.[5] Thus, subjectivity is inherent in observation. The phrase "Model the system" is often stated "Formulate Hypotheses".[6] "Model," in this context has a broad meaning: an abstract representation of the interrelationships

[4]Numerous similar descriptions of "operations research," "systems analysis" and so forth may be found in the literature. For example:
(i) Ackoff, R. L., "The Development of Operations Research as a Science," Operations Research, June 1956, 4:3, 265-287.
(ii) Hall, A. D., A Methodology for Systems Engineering, Van Nostrand, Princeton, 1962, pp. 19 and 140.
(iii) Optner, S. L., Systems Analysis for Business Management, Prentice-Hall, Englewood Cliffs, N. J., 1960, p. 31.

[5]Weyl, Hermann, Philosophy of Mathematics and Natural Science, Princeton University Press, 1949, Section 17.

[6]For example, (iii) of Footnote 4.

being observed.[7] The choice of a model is, again, a matter of judgment. It represents, in effect, the observer's "hypotheses" stated in some abstract form. The model is very much a function of the observations that are made. Verification of a model is rather difficult; science deals with a series of approximations to reality rather than with "truth." Hence, verification really means that there have been no reliable observations which are in contradiction with the model (insofar as the person doing the modeling knows), and there have been sufficiently many observations to lend credence to the belief that this will continue to be the case as long as one's ability to observe is unchanged. Thus, verification is not absolute. It depends upon personal and scientific judgment and upon one's ability to observe. Analysis of a model is normally an exercise in logic, but the completeness of an analysis can often be questioned. The conclusions are statements about the natural system that can be made as a result of the analysis of the model. As such, they are generally no more reliable than the observations, the model, and so forth.

In practice one may not follow the sequence Observe, Model, Verify, Analyze, Conclude in precisely that order. For example, if verification of the first model is impossible, the sequence may be Observe, Model, Observe, Model, Verify, and so forth. Similarly, if the conclusions are not consistent with the system being observed, the whole original sequence, or some portion of it must be repeated. Thus, the scientific method is a dynamic philosophy which leads to ever better approximations of "reality" based upon judgment and the ability to observe.

In "systems philosophy," as seen by the author, is very similar in character to the "scientific method." The major difference between the two is that the "natural system" of concern to one in the scientific method is replaced by a system over which one has some direct control: a "partially controllable system." Two comments should be made about this notion. First, control may be possible in at least two ways: physical and mental. Physical control refers to the ability to do things such as "control the humidity," "control the airborne particulate matter," and so forth. Mental control refers to the ability to make decisions such as "use a class 100 clean room," "Chemically clean the product," or to a creative sort of control (for example, the ability to design a product so that it is less likely to fail from certain types of contaminants). The second comment about a "partially controllable system" is that this phrase is really undefined. Somehow, the fact that "system," in this context, has yet to be satisfactorily defined causes some persons discomfort. Yet, "natural system" is, it would seem, equally undefined, and this appears to bother few people. This difference in attitude is probably due to the fact that numerous "natural systems" have been investigated by using the scientific method, and this has provided an intuitive base for thinking about "natural systems." On the other hand, it may be that many fewer "partially controllable systems" have been thoroughly analyzed using the "systems philosophy" described below, or it may simply be that such studies are not yet publicized adequately to provide this intuitive base for "partially controllable systems." In any event, it is hoped that the lack of a precise definition of a "partially controlled system" can be compensated for by the recognition of the similarity to the situation existing for a "natural system."

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[7] For an enlightening discussion about models, see Bross, I.D.J., "Models," an article appearing in both: Design for Decision (by I.D.J. Bross), Macmillan, New York, 1953, pp. 161-182, and Scientific Decision Making in Business, (ed. Abe Shuckman) Holt, Rinehart, Winston, New York, 1963, pp. 63-77.

Having some control over a system normally implies that this control should be used to best advantage; that is, if one is dealing with a partially controllable system, he should have objectives stating what he desires as a result of his ability to control parts of the system. This is a fundamental concept in the systems philosophy, which may be outlined in the same form as the scientific method as follows.

SYSTEMS PHILOSOPHY

Partially Controllable System	State Objectives (re control) Observe the System Model the System Verify the Model Analyze the Model Optimize Draw Conclusions (activities)

In outline, the systems philosophy differs from the scientific method in two areas. The first is a statement of objectives occasioned by the existence of some control over the system in question and the second is the possibility of drawing "optimal" conclusions from the modeling representing, in some sense, the "best" way to achieve the objectives. Fundamentally, the difference is deeper because of the various possible types of control and the latitude given in considering some concept or entity a "partially controllable system." Thus, for example, the system may be only an abstraction whose existence is implied by objectives which state its desired properties. Hence, in a real sense, the emphasis in the "systems philosophy" is upon the realization of <u>objectives</u> (dealing with control) through a sequence of actions similar to that occurring in the scientific method. While the conclusions to be drawn may deal with the uncontrollable aspects of the system to some extent, the basic conclusion is a collection of <u>activities</u> that, if implemented, will achieve the objectives "optimally."

The comments made about observation, modeling, and so forth, in the brief description of the scientific method above, apply to them as concepts in the systems philosophy. There are some additional comments appropriate here. Observation, in the application of the systems philosophy, may be an entirely intellectual affair if the system in question is only a concept. In this case, verification of any model is an intellectual activity either until the activities (conclusions) are implemented and the results compared with theory or until a reliable means of simulating the outcome <u>a priori</u> is developed. Sometimes the nature of the system precludes ever verifying the model (e.g., when the necessary testing would be prohibitively expensive). Optimization means essentially "select, from among all possible alternatives, one which best achieves the objectives." Of course, one must determine what "best" means, but even when it is possible to do this, there are several pitfalls. First, <u>all</u> possible alternatives are probably not known. If they are, an "optimum" may not exist because of the nature of the problem. Finally, if an "optimum" choice exists, it may not be possible to find it in practice because of theoretical or computational inabilities. Thus, the word "optimize," in practice, must be understood to imply an "attempt to optimize." The conclusions to be drawn are basically concerned with using the control one has. Thus they have been termed "activities." In essence, they represent a statement of what things must be done in order to "best" achieve the objectives.

The scientific method and the systems philosophy are very similar in intent. There is a distinction between the two in as far as one can distinguish between the investigation of interrelationships *per se* and the control of parameters appearing in such relationships. But this is often difficult, if not impossible, to do. For example, in investigating interrelationships, there is normally an objective: to do so in the "best" possible way. Thus, in investigating, one is in the position of applying the systems philosophy, which surely must have some effect upon the experimentation. Since activities stemming from both philosophies may well stem from the same model, differentiation between the two may be impossible except by a subjective evaluation of "intent." However, it should be emphasized that the *intent in the systems philosophy is to determine activities which allow one to optimally achieve objectives*.

In Practice. The systems philosophy, as outlined above, seems theoretically well-suited to planning: its intent is to answer the question "how should one act in order to optimally achieve his objectives?" But there is another "how" that seems quite apparent. How does one apply the systems philosophy? The final answer, of course, must depend upon circumstances, but some things may be said about this "how." The preceding material was not new - only the wording, and perhaps emphasis, has been altered to conform to the subject of the paper. However, what follows is fairly original, and subject to considerably more scrutiny!

In approaching a system with the systems philosophy, one has given a system and objectives. The objectives need not be precise, but should convey intent about the desired results of control of the system. The approach outlined here will be to operate primarily from the objectives with the system providing constraints upon actions. Before proceeding, a few terms will be defined.

For purposes here, an objective is considered to be a statement which contains or implies the existence of variable factors and which specifies some desirable behavior or value for the variable factors. So, for example, the objective "to cut monthly costs in the future" contains at least two variable factors: cost and time. The objective postulates that these are related, and that at some future time, costs should be lower than at the time the objective was stated. Had the objective been stated "to cut monthly costs $100,000 beginning next month" the existence of the cost and time variables is implied, and this objective specifies values for the variables. In effect then, the word objective will be considered synonomous with a statement indicating desired behavior or values for variable factors which the objective formulator wishes to have controlled, influenced or measured.

It should be remarked that not all statements commonly thought of as objectives completely satisfy this definition. The basic reason for this is the existence of social, environmental, technological, and other norms which make it unnecessary to state the variable factors and specify their desired behavior. For example, the statement "to determine the length of a given room" might be of this type. If a man is already in the room with a tape measure, there is an implied desire for a reasonably immediate answer, for accuracy of measurement compatible with that obtained from a tape measure, and for a cost commensurate with this type of activity.

In attaining an objective, the person responsible for its attainment frequently pays a *penalty*. This penalty may be in the form of a dollar cost or any other expenditure of resources (time, personnel, and so forth). Sometimes the penalty is a loss of other desired goals. When an objective involves a desire for improved efficiency, it may be the case that no penalty is incurred by the person responsible for the attainment of the objective. However, in this case, it may be that other persons, contractors for example, sustain a loss, or penalty, so that the notion of a penalty can depend highly upon one's point of view.

In general, there is a spectrum of types of objectives that may be stated either by an individual or a group acting in unison. These range from free objectives to bound objectives.

Free objectives are usually conceptual in nature and recognize a need for some general outcome or type of behavior without specifying the "amounts." For example, the objective "cut monthly costs in the future" is of this type. The general intent of such a statement is clear, even though one may meet this objective by cutting monthly costs by any amount at any future time. Presumably it is left to the person or persons responsible for achieving the objective to determine what reasonable cost cuts are in any given time period.

A bound objective, on the other hand, is one that is specific in nature. For example, "cut monthly costs $100,000 starting next month" is bound since it requires few if any decisions about the objective itself by those responsible for achieving it.

There are objectives which lie somewhere between these two extremes. These have some elements of constraint and some elements of choice for the implementer. An example of such an objective might be "cut monthly costs beginning next month."

Free objectives, as envisioned here, contain a maximum amount of variable quantities. As such, free objectives may be regarded as abstract statements of intent or desire. The same free objective may assume many bound forms depending upon the values or specific behavior desired for each of the variables. For example, "to cut monthly costs $100,000 beginning next month" and "to cut monthly costs $25,000 beginning in three months" are two bound objectives derived from the free objective "to cut monthly costs in the future."

It is assumed that, whenever the systems philosophy is employed to determine what activities are needed to "best" achieve objectives relating to a partially controllable system, ultimately some objective or objectives must be bound. For example, when a free objective "cut monthly costs in the future" is stated the ultimate determination of activities to accomplish this objective involves either an *a priori* or *a posteriori* statement of the specific amounts (to be) saved in any given month, and this latter statement may be regarded as a bound objective. Because of our interest in planning, it is assumed that an *a priori* bound objective is needed. This is the antithesis of taking some action and then assessing its effectiveness.

Accordingly, the emphasis in the following material is on two items: a possible means of relating objectives to actions which will achieve them with an acceptable penalty, and doing so in such a fashion that a bound objective with an acceptable penalty may be stated before the advent of any action designed to meet the associated free objective.

The objectives associated with the systems philosophy are called primary objectives. These objectives provide the *raison d'etre* for the activities undertaken to control the system and provide also criteria against which the success of the activities may be judged. Normally, in any large program, one would not expect these objectives to be directly achievable, that is, the means for directly controlling the variables occurring in the objectives so that the objectives may be achieved, are not known. When this is the case, the variables occurring in the objective must be analyzed to determine the activities necessary for the attainment of the objective.

The analysis of primary objectives leads to a consideration of the "significant factors" which influence their attainment. For example, it is not unreasonable to imagine that the factors "salaries" and "purchases" influence the monthly cost incurred by an organization. The determination of a set of all such "significant factors" is often a matter of judgment. The relationships between the primary objectives and the "significant factors" influencing their attainment is, similarly, a matter of judgment, and are expressed in the form of a model (or models), with due consideration being given the system being modeled.

The desire to attain primary objectives implies the existence of certain objectives relating to the significant factors associated with the primary objectives. For example, if "salaries" and "purchases" are deemed to be the only significant cost factors of an organization, then a model relating these to organizational cost might take the simple form

$$C = S + P$$

where C represents total organizational dollar cost per month, S represents total organizational salary cost per month and P represents the total purchase cost per month. Each of the quantities C, S and P may vary with time, or

$$C(t) = S(t) + P(t).$$

Then, for example, the objective "cut monthly costs in the future" may be interpreted as specifying that at some time $T > 0$, $C(t)$ should be less than $C(0)$ for $t \geq T$. This, of course, is only one possible interpretation. In this example, $S(t)$ and $P(t)$ represent the factors which influence the achievement of the objective. Depending upon the objective implementer's decision, the original objective, $C(t) < C(0)$ for $t \geq T$, implies either that $S(t) < S(0)$ or that $P(t) < P(0)$ for $t \geq T$ (or both). Thus, the original primary objective implies the existence of objectives dealing with the significant factors influencing the achievement of the primary objective.

The new objectives associated with the significant factors influencing the achievement of the primary objectives are called <u>secondary objectives</u>. In essence, these secondary objectives are statements about the desired mode of behavior or value of the variables representing the significant factors influencing the achievement of the primary objective. The word variables or parameters is appropriate here as long as the significant factors occur in some parametric form. This notion is outlined schematically on the next page.

Primary Objectives {Variables, desired behavior or values}

Significant factors influencing the behavior or values of the primary variables

Models relating primary variables to the significant factors influencing their behavior or values (and specifying the interrelationships among the primary variables.)

Secondary Objectives {Variables, desired behavior or values}

Secondary objectives are highly dependent upon the nature of the primary objective, the choice of significant factors influencing the behavior or possible values of the primary variables and the choice of a model to relate these. The hope is that if the secondary objectives are achieved, the primary objectives will be also. This type of behavior is evident in the simple model used for illustrative purposes above; that is, if

$$\text{(i)} \quad S(t) - S(0) \leq a,$$

$$\text{(ii)} \quad P(t) - P(0) \leq b$$

and

$$\text{(iii)} \quad a + b < 0 \text{ for } t \geq T,$$

then one must have

$$C(t) - C(0) < 0 \text{ for } t \geq T$$

If $S(t)$ and $P(t)$ are the only significant factors influencing $C(t)$, and if the simple model represents the relationship in existence between these, then the attainment of all of the three secondary objectives given above implies the attainment of the primary objective "to cut monthly costs in the future."

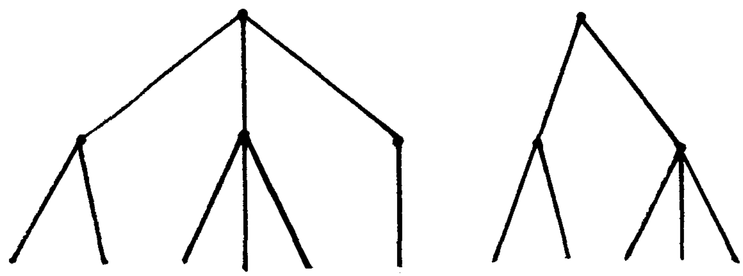
A similar analysis of the secondary objectives may then be undertaken. This analysis yields a collection of tertiary objectives which play the same role to the secondary objectives as the secondary objectives do to primary objectives. This process may be continued to yield 4th level objectives, 5th level objectives, and so forth.

One feature of a process such as this is that it has a tree-like or branching structure. That is, a single primary objective may yield several secondary objectives each of which, in turn, may yield several tertiary objectives, and so forth. Thus the structure is similar to that shown on the next page.

Primary objectives

Secondary objectives

Tertiary objectives



Clearly there is no advantage to a scheme such as that outlined above unless it aids one in determining what activities can be undertaken to achieve the primary objectives with an acceptable penalty.

In order to see how it might do this, the variables associated with any objective are divided into two classes: those variables which are actionable and those which are not. An actionable variable is one which can be directly controlled or measured. As discussed earlier, control may occur in one of two ways and is a fairly subjective matter. Physical action may be taken to control the variables in a predictable fashion, or the variables may be controlled by fiat (e.g., a decision about the magnitude of the variable). There may be variables over which one has no control, and these are actionable if they can be directly measured with an acceptable degree of accuracy. An example of an actionable objective is the objective

$$a + b < 0 \text{ for } t \geq T,$$

above, since this may be controlled by the person performing the analysis.

The intent in constructing a tree-like hierarchy of program objectives is, then, that each branch of the tree should ultimately terminate with an objective each of whose variables is actionable. If this can be done, then one has a scheme which relates the primary objectives of the program to activities that must be taken in order to achieve these primary objectives. Such a statement must be tempered by the realization that its validity depends upon the completeness of the sets of "significant factors" and the appropriateness of the choices of the models occurring throughout the structure.

So far, only the relating of objectives to actions designed to achieve them has been considered. No attention has been given to the possibility that the necessary actions will involve too great a penalty. Formation of a tree-like hierarchy of objectives, each branch of which terminates in objectives containing only actionable variables, may be accomplished independent of the location of the primary objectives on the free-bound scale. The simple illustration "to cut monthly costs in the future" is an example involving a free primary objective.

When one begins with free primary objectives, then all other objectives in the hierarchy are free also. In particular, terminal objectives involve actionable variables whose desired modes of behavior or values are specified abstractly, as for example in the simple model presented earlier where $S(t) < S(0)$ or $P(t) < P(0)$. In this simple example, to have a bound primary objective, one must specify how much less $C(t)$ should be than $C(0)$ when $t \geq T$, and T must also be specified. This can certainly be done directly, or it can be done by specifying T and the relationships between S(t) and S(0) and between P(t) and P(0). If, for example we let

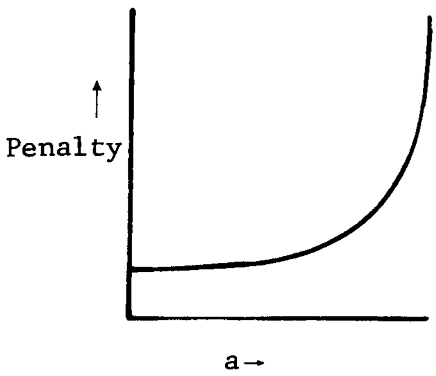
$$S(0) - S(t) = a$$

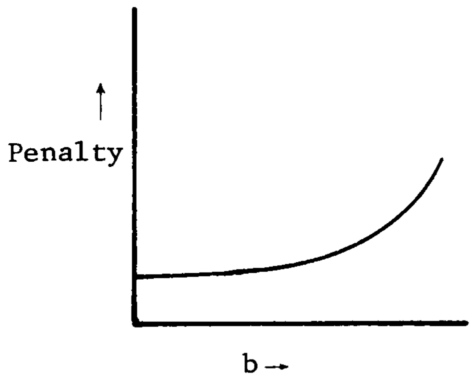
and

$$P(0) - P(t) = b$$

and if there are penalties known for values of a and b as shown below, then an analysis may be performed to obtain the optimum a and b for a given requirement on

$$a + b = C(0) - C(t).$$





There may be a different set of such curves for each specific value of T. Thus for each bound primary objective, that is, specification of C(0) - C(t) = a + b and T, one can determine the minimum penalty that must be incurred to achieve the specific values. If there is then a utility associated with each possible combination of C(0) - C(t) and T, it is possible to choose some combination for which the utility per unit penalty is maximal. In the absence of a well-defined utility measure, it is still possible to choose at least one combination of C(0) - C(t) and T which has an acceptable penalty associated with it. Thus, the objective hierarchy may be useful both in relating objectives to activities designed to achieve them and also in determining bound program objectives which have acceptable associated penalties. When utilities for specific primary objectives are known, an "optimal" solution may be obtainable.

In general, the objective hierarchy terminates in a collection of objectives each of which may be directly achieved (i.e., they possess only actionable variables). These are normally free objectives in that they are stated in some abstract parametric form, as the example above illustrates.

For any assignment of specific parameter values in all of these terminal objectives, one can determine the resources needed to achieve them. Notationally, if $\beta_1,\ldots,\beta_M$ represent the variables occurring in the terminal objectives, in theory one can obtain an approximate penalty function

$$P(\beta_1,\ldots,\beta_M)$$

by (1) determining the "best way of achieving the terminal objectives as a function of the values of the variables occurring in them,
(2) listing the resources needed for the attainment of the terminal objectives individually (as a function of the parameters),
(3) eliminating "redundancy" in resources (for example, if a certain facility may be used to control two variables, possibly occurring in different terminal objectives, it is included in total resources only once)
(4) translating total resource expenditure into penalty units.

Then, for bound (specific) primary objectives, one is attempting to determine specific values for the parameters $\beta_1,\ldots,\beta_M$ so that the primary objectives are achieved and $P(\beta_1,\ldots,\beta_M)$ is minimal. This essentially determines the "optimal" activities needed for the achievement of any bound primary objectives.

Finally, to aid in selecting acceptable bound primary objectives, one may vary the specific values appearing in them and determine the penalty associated with "optimal" attainment of each bound objective so obtained. If utilities for bound primary objectives are known, then a utility-penalty analysis may be performed to determine "best" primary objectives. If utilities are not known, one still may seek a bound primary objective having an "acceptable" penalty associated with its achievement.

The approach to utilization of the systems philosophy outlined above gives one a framework with which to answer the question "how does one implement the systems philosophy?" This is done by changing the problem to one of finding significant factors and models to subproblems. In practice, this seems to provide more order to the use of the systems philosophy. The "model" of the systems philosophy becomes, in this context, a collection of models associated with the objective hierarchy. Optimization takes the form of a utility-penalty analysis of the hierarchy, and the conclusions (activities) are determined by the actionable variables. The "partially controllable system" appears throughout the hierarchy as a constraint upon the "significant factors" and the models that are chosen.

A Systems Approach to Contamination Control

General Comments About an Objective Hierarchy. Early in the paper, it was pointed out that contamination control was generally concerned with limiting or removing solid matter, gases or liquids in, on or from other solids, gases and liquids. But, is this a sufficient description of contamination control planning objectives? The answer is, probably not; since this statement really yields no way of determining the amount of control needed - an essential for planning.

The fact is that contamination control is a field which serves higher objectives, and its role is best understood by considering these objectives. If there were no penalty associated with the existence of contamination in a given situation then there would be no reason for contamination control. The following list gives some indication of the types of penalties encountered in areas where contamination control is practiced.

Area	Penalties
Medicine	- loss of health - death - needless suffering
Foods	- loss of health - death - unfavorable FDA action - loss of business
Drugs	- loss of health - death - unfavorable FDA action - loss of business
Manufacturing	- product failure - unnecessary expense - loss of health - unfavorable government action - loss of business
Air Pollution	- loss of health - human inconvenience - loss of native flora - esthetic loss
Water Pollution	- loss of health - death - loss of native biota - esthetic loss - loss of recreational areas
Planetary Quarantine	- loss of scientific information about planets

Thus, contamination control activities are desired in each area because of the penalty associated with the lack of them. But more than this, in any given situation the penalty that one pays depends upon the amounts of contamination of various kinds that are present. For example, in many medical situations the "normal" environmental infectious contamination for most micro-organisms is acceptable without measurable penalty, whereas in others (severe burns, transplant patients) infectious contamination should be as low as possible because of the severe penalty if the situation is otherwise.

Hence, not only do penalties imply the possible need for control but they also give some insight into "acceptable" levels of contamination. This is important for planning activities in contamination control since the control technique chosen must depend upon the amount of contamination that is permissible, and the cost incurred in contamination control will be a function of the control techniques chosen. Thus, to plan for contamination control, one must have some knowledge of "acceptable" levels of contamination. It might be expected that knowledge of "acceptable" levels of contamination will come from persons outside of the contamination control area. For example, it would probably take a medical specialist to determine "acceptable" levels of types of air contaminants when the penalty for their existence is primarily medical in character. Nevertheless, contamination control is highly dependent upon the existence of penalties incurred in its absence.

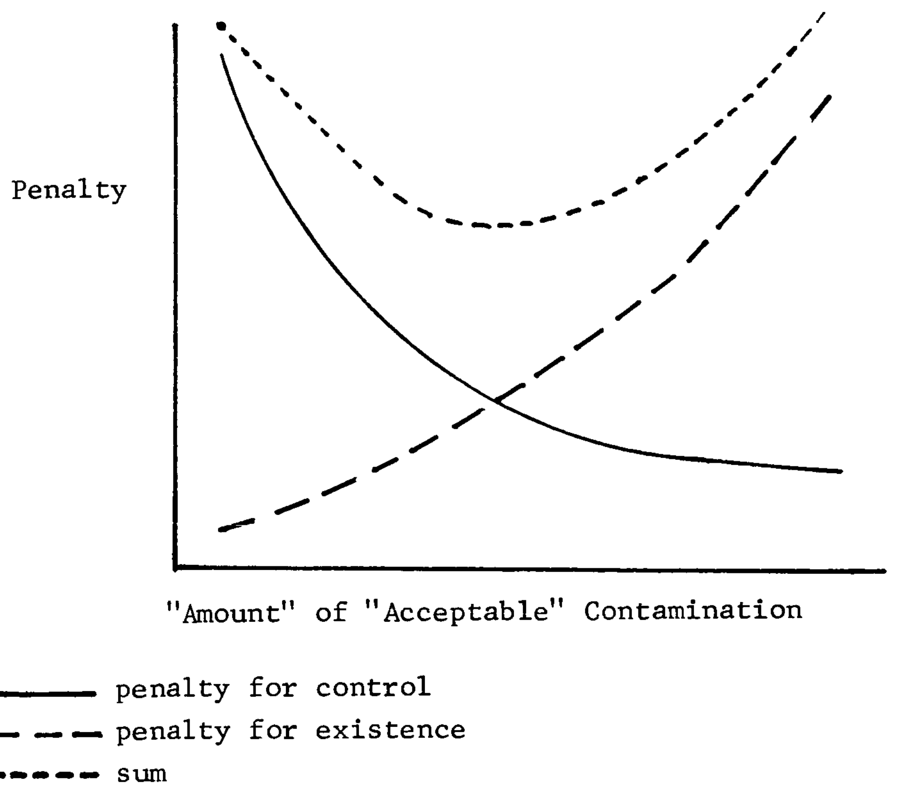
With this in mind, one goal of contamination control activities is:

Goal 1. To control contamination so that the payment of unacceptable penalties due to contamination is avoided.

There are other goals also. For example, there is usually a penalty associated with the control of contamination as well as with its existence since control normally requires an expenditure of resources. Hence, in planning for contamination control, one wishes also:

Goal 2. To achieve Goal 1 so that the penalty associated with the control activities is acceptable.

Not surprisingly, planning must also concern itself with the total acceptability of both of these penalties. If both the penalty for the existence of contamination and the penalty for controlling contamination can be expressed in common units (dollars, for example) then the situation might resemble that shown in the figure below. In this figure, it is assumed that the "amount" of contamination that is acceptable depends not only upon the penalty one pays due to its existence, but also upon the penalty one pays for its control. Thus the "acceptable amount" may be treated as a variable until both these things are known as a function of "acceptable amount."



In this simple illustration, the total acceptable penalty, which, incidentally, is a decision in this setting, must be compared with the curve representing the sum. If that curve is always above (greater than) the total acceptable level, then the problem cannot be resolved without altering the notion of acceptability or finding means of control with a lower associated penalty. Thus, while it is appropriate to consider the penalty from the existence of contamination, and its acceptability, *per se*, these will often be influenced by the penalty paid for control. For example, if the maximum acceptable probability of failure of a device from a contamination failure mode is initially assumed to be 10^{-3}, but it is later found that the cost of attaining this level (by controlling contamination) is ten times that associated with 3×10^{-3}, one might wish to reconsider his original notion of acceptability. Generally speaking, the notion of acceptable penalties associated with the existence of contamination involves some elements of judgment.

Often, curves like those in the above figure are not available: either because the penalty units are different for the existence and control of contamination or because the penalty associated with the existence of contamination is not thoroughly understood. The latter might be the case, for example, in planetary quarantine. In any event, the penalty paid for control should be considered in planning for contamination control.

Before attempting to formulate general primary objectives for contamination control, it is convenient to note that the actual achievement of Goal 1 is often difficult to determine. This is so for at least two reasons. First, it is generally not possible to monitor or measure amounts of contamination exactly because of the inadequacy of measurement techniques, the complexity of the total system (including control environments, nature of contamination) and so forth. Secondly, in many contamination control situations it is not possible to obtain sufficient data about the adequacy of the contamination control undertaken, in terms of results, to *know* with certainty that the goal has been achieved. Planetary quarantine may, again, be such a situation. Thus, it may be more appropriate to speak of the probability of achieving Goal 1, and this goal may be rephrased:

OBJECTIVE 1: To control contamination so that the probability

$\Pr\{\text{payment of unacceptable penalties from contamination}\} \leq \epsilon$.

This form has certain advantages in that it:

- recognizes the possible uncertainty in knowledge about the achievement of Goal 1, and
- allows for trade-offs to be made between ϵ and the penalty for controlling contamination.

Combining Objective 1 with Goal 2 leads to the objective statement

A CONTAMINATION CONTROL OBJECTIVE. To control contamination so that

$\Pr\{\text{payment of unacceptable penalties from contamination}\} \leq \epsilon$ without incurring unacceptable penalties as a result of the control activities.

The nature of the control to be exercised, the control activities, are unknowns in this objective, and the object is, in essence, to determine them. Hence, "control" and "control activities" represent variables in the objective. There are other variables as well. Because of the interdependence of the "acceptable penalties" of both types, it is undesirable to make these specific until the interrelationship is understood. Thus, "acceptable penalties" in both usages in the objective is a variable. Also, the parameter ϵ is a variable since, generally, the penalty incurred from control depends upon the value of ϵ, and it is desirable to understand the functional relationship between the two to aid in deciding what the ultimate value of ϵ should be. Certainly there will be other information available to aid in this also. Its possible that "contamination," itself, is a variable in the sense of the preceding section. Finally, the probability

$$\Pr \{\text{payment of unacceptable penalties from contamination}\}$$

must be regarded as a variable because one presumably has some control over its value.

In constructing an objective hierarchy from the Contamination Control Objective just stated, it is convenient to note that the second part of the objective, corresponding to Goal 2, need not be included in the primary objective of the hierarchy. This occurs because a hierarchy constructed from Objective 1, yields a means of attaining the second part of the Contamination Control Objective as outlined in the previous section. Thus, it is necessary only to construct the objective hierarchy from Objective 1. If P_{un} is used to designate

$$\Pr \{\text{payment of unacceptable penalties from contamination}\},$$

the primary objective to be analyzed takes the form:

$$P_{un} \leq \epsilon \; .$$

As we begin to construct an objective hierarchy from this primary objective, it is worth reiterating that

- the choices of models and significant factors are subjective matters, and
- in actual usage, these choices would be related to the specifics of the situation.

Thus, only a few "levels" of the tree will be constructed as a means of illustrating the relationship between contamination control techniques and activities to general objectives.

What might the significant factors influencing the behavior of P_{un} be? Some factors which must ultimately influence its behavior are

- The ways in which unacceptable penalties may be incurred from contamination,
- Types and amounts of contamination involved in these ways of incurring unacceptable penalties, and
- Sources of the types of contamination being considered.

Suppose there are N independent ways of incurring unacceptable penalties from contamination, and that an unacceptable penalty is incurred over-all if an unacceptable penalty is incurred in any of these N possible ways. "Independent" means, roughly, that incurring an unacceptable penalty in one way does not influence the probability of incurring an unacceptable penalty in any other way. Let

$P_{un}^{(i)}$ - represent the probability of payment of unacceptable penalties from contaminating the i^{th} way.

Here, $i = 1, 2, \ldots, N$. A simple example of this situation might be a system containing two valves in which the system fails whenever either valve fails and in which the failure of one valve does not influence the behavior of the other valve.

Then the $P_{un}^{(i)}$, $i = 1, 2, \ldots, N$, may be regarded as a set of "significant factors" influencing P_{un}. Under the conditions imagined, the relationship between the $P_{un}^{(i)}$ and P_{un} may be expressed

$$P_{un} = 1 - \prod_{i=1}^{N} \left[1-P_{un}^{(i)}\right].$$

Since P_{un} is desired to be no greater than ϵ,

$$1 - \prod_{i=1}^{N} \left[1-P_{un}^{(i)}\right] \leq \epsilon$$

or

$$\prod_{i=1}^{N} \left[1 - P_{un}^{(i)}\right] \geq 1 - \epsilon \ .$$

This requires, in effect, that for $i = 1, 2, \ldots, N$,

$$1 - P_{un}^{(i)} \geq 1 - \epsilon_i$$

where

$$\prod_{i=1}^{N} \left(1-\epsilon_i\right) \geq 1 - \epsilon \ .$$

Thus, there are N + 1 secondary objectives

$$P_{un}^{(i)} \leq \epsilon_i, \ i = 1, 2, \ldots, N$$

and

$$\prod_{i=1}^{N} \left(1-\epsilon_i\right) \geq 1-\epsilon.$$

If these are satisfied, then $P_{un} \leq \epsilon$, as desired.

Hence, the first level of the objective hierarchy may be represented schematically as

<u>Primary Objectives</u>: $P_{un} \leq \epsilon$

<u>Model</u>: $$P_{un} = 1 - \prod_{i=1}^{N} \left[1 - P_{un}^{(i)}\right]$$

$$\left(\text{Significant Factors } P_{un}^{(i)}\right)$$

<u>Secondary Objectives</u>: $P_{un}^{(i)} \leq \epsilon_i, \quad \prod_{i=1}^{M} (1-\epsilon_i) \geq 1-\epsilon.$

The secondary objective $\prod_{i=1}^{N} (1-\epsilon_i) \geq 1-\epsilon$

contains only actionable variables in the sense that one can presumably force this to be the case in his analysis. Thus this objective need undergo no further analysis. Hence, let us proceed to analyze the secondary objective

$$P_{un}^{(i)} \leq \epsilon_i.$$

Let us suppose that there are M_i types of contamination which will contribute to the payment of unacceptable penalties in the i^{th} way. Then, suppose that

$P_{un}^{(i)}$ $a_1, a_2, \ldots, a_{M_i}$

- the probability of incurring unacceptable penalties in the i^{th} way when there is an amount a_j of the j^{th} type of contamination ($j = 1, \ldots, M_i$) <u>available</u> for the i^{th} way of incurring penalties,

and

P_i ($a_1, a_2, \ldots, a_{M_i}$)

- the probability that an amount a_j of the j^{th} type of contamination ($J=1, \ldots, M_i$) <u>is</u> available for the i^{th} way of incurring penalties

are known. If the possible amounts, a_j are discrete valued and lie in ranges

$$0 \leq a_j \leq \alpha_j$$

then

$$P_{un}^{(i)} = \sum_{a_1=0}^{\alpha_1} \sum_{a_2=0}^{\alpha_1} \cdots \sum_{a_{M_i}=0}^{\alpha_{M_i}} P_{un}^{(i)}\left(a_1, a_2, \ldots, a_{M_i}\right)\left(P_i \; a_1, a_2, \ldots, a_{M_i}\right)$$

Hence, one may consider the 2N probabilities

$$P_{un}^{(i)}\left(a_1,\ldots,a_{Mi}\right),\ i = 1,\ldots, N$$

and

$$P_i\ \left(a_1,\ldots,a_{Mi}\right),\ i = 1,\ldots, N$$

as significant factors influencing the attainment of the secondary objectives

$$P_{un}^{(i)} \le \epsilon_i,\ i = 1,2,\ldots, N.$$

The secondary objectives, just stated, imply conditions on the behavior of the probabilities

$$P_{un}^{(i)}\left(a_1,\ldots,a_{M_i}\right) \text{ and}$$

$$P_i\ \left(a_1,\ldots,a_{M_i}\right)$$

as functions of the "amounts" $a_1,a_2,\ldots,a_{Mi}$. These conditions become the tertiary objectives, and usually their exact form will be influenced by the specific nature of the system in question. No attempt will be made to derive them here in any general form. However, the tertiary objectives will involve specifying behavior for these 2N probabilities, so that analysis of them is appropriate.

In order to determine the significant factors influencing the behavior of $P_i(a_1,\ldots,a_{M_i})$, the probability that an amount a_j of the j^{th} type of contamination $(j = 1,\ldots,M_i)$ is available for the i^{th} way of incurring penalties, it seems reasonable to consider <u>sources</u> of contamination. Suppose there are K sources of contamination in the system, each of which may supply any or all pertinent types of contamination. Suppose further that they are independent sources in the sense that the effect of any one source upon the i^{th} way of incurring penalties in no way influences the effect of any other source. Then, if from the k^{th} source one gets an amount b_{jk} of the j^{th} type of contamination, this determines an array

$$\begin{matrix} b_{11}, & b_{21}, \ldots, & b_{M_i1} \\ b_{12}, & b_{22}, \ldots, & b_{M_i2} \\ \vdots & \vdots & \vdots \\ b_{1K}, & b_{2K}, \ldots, & b_{M_iK} . \end{matrix}$$

Suppose one has knowledge of the probabilities

$$P_{ik}\left(b_{1k},\ldots,\ b_{M_ik}\right)$$

- the probability that amounts, b_{jk}, of the j^{th} type of contamination from the k^{th} source are available for the i^{th} way of incurring penalties,

(where $k = 1,\ldots,K$) for all possible arrays of the type above for which

$$\sum_{k=1}^{K} b_{jk} = a_j,\ j = 1,\ldots,\ M_i.$$

Then

$$P_i\ \left(a_1,\ldots,a_{M_i}\right) = \sum_{\Omega} \prod_{k=1}^{K} P_{ik}\ \left(b_{1k},\ldots,b_{M_ik}\right)$$

where the summation extends over the set Ω of all K-by-M_i arrays $\left|\left|b_{jk}\right|\right|$ for which

$$\sum_{k=1}^{K} b_{jk} = a_j,\ j = 1,\ldots,\ M_i.$$

At this point, the objective hierarchy is adequately developed to allow some insight into the relationships existing between general objectives and contamination control activities. While these relationships are to be viewed as a consequence of a number of assumptions (N,M_i and K: known, ways of incurring penalties, sources: independent) it is very likely the case that a similar hierarchy exists when the assumptions are not valid. In this case, different models would be needed, but the nature of the parameters would probably not undergo "significant" change.

Referring to the objective hierarchy reproduced on the next page, it may be viewed intuitively as follows. The primary objective is of a general nature: control contamination to keep the likelihood of incurring unacceptable penalties arising from its existence small (less than "ϵ"). It was then postulated that unacceptable penalties could be incurred in several ways, and the secondary objectives are statements implying a desire to maintain the likelihood of incurring unacceptable penalties in any way small (the i^{th} way less than ϵ_i). The "smallness," ϵ_i, in this case, is directly related to the original quantity ϵ. At the third level, it was postulated that the penalty incurred in any of the possible ways depended upon the type and amount of contamination available (for each way). Accordingly, the third level objectives become statements about (a) the likelihood of incurring unacceptable penalties in each way from defined types and amounts of contamination, and (b) the likelihood of actually having certain amounts of various types of contamination available for the i^{th} way of incurring unacceptable penalties. These objectives were not explicitly stated because the nature of the system will influence their exact form. Finally, at the fourth level, the existence or availability of certain amounts of various types of contamination was postulated to depend upon the sources

<u>Primary Objective</u>: $P_{un} \leq \varepsilon$

<u>Model</u>: $$P_{un} = 1 - \prod_{i=1}^{N} [1 - P_{un}^{(i)}]$$

<u>2nd Objectives</u>: $P_{un}^{(i)} \leq \varepsilon_i, \; i = 1,\ldots,N$

<u>Model</u>: $$P_{un}^{(i)} = \sum_{a_1=0}^{\alpha_1} \cdots \sum_{a_{M_i}=0}^{\alpha_{M_i}} P_{un}^{(i)}(a_1,\ldots,a_{M_i}) \, P_i(a_1,\ldots,a_{M_i})$$

<u>3rd Objectives</u>(re): $P_{un}^{(i)}(a_1,\ldots,a_{M_i})$ and $P_i(a_1,\ldots,a_{M_i})$

$i = 1,\ldots,N$ $\qquad$ $i = 1,\ldots,N$

<u>Model</u>: $$P_i(a_1,\ldots,a_{M_i}) = \sum_{\Omega} \prod_{k=1}^{K} P_{ik}(b_{1k},\ldots,b_{M_i k})$$

<u>4th Objectives</u> (re): $P_{ik}(b_{1k},\ldots,b_{M_i k})$,

$i = 1,\ldots,N, \quad k = 1,\ldots,K$

Sources, <u>per se</u> $\qquad$ From source to way of incurring penalties $\qquad$ Types

System Characteristics $\qquad$ Control Techniques of contamination. As a result, the fourth level objectives become statements about the likelihood of certain amounts of contamination of various types being (i) available at each source, and (ii) capable of "reaching" the various ways of incurring unacceptable penalties. At each level, the postulates just mentioned represented the assumption of the "significant factors" appearing in Section II. In each case, mathematical models were used to relate these significant factors to the preceding variables. At one point, an actionable objective (containing only actionable variables) was found, and, in all probability, there would have been others had the third and fourth level objectives been stated precisely. In general, the objective hierarchy is compatible with the theory outlined in the section on "The Systems Philosophy."

Let us examine the consequences of developing the hierarchy this far. Down the right branches of the hierarchy (through "sources"), one's only concern is with sources of various types of contamination, and the availability of contamination from these sources for the various ways of incurring unacceptable penalties. Objectives associated with these items (at, in fact, the fifth level) are attainable in one or both of two broad ways. The first is physical control of contamination. This may be accomplished at its source or somewhere "between" the sources and the ways of incurring unacceptable penalties. The second is a "design" control to be discussed later. The fifth level objectives, in any specific problem, would pertain to the "allowable" amounts (parametrically) from any source or between any source and any way of incurring unacceptable penalties. Thus, hopefully, one could determine the "best" means of control as a function of the original ϵ. Then ϵ could be determined as a function of the penalty paid for control.

This "optimization" cannot be accomplished, however, without consideration of the left branches of the tree. In this branch, one is concerned with the likelihood of incurring unacceptable penalties from each way of doing so when there is a certain amount of each pertinent type of contamination present. In any specific problem, one would hope to be able to determine this through further analysis coupled with experimentation. But there is a potential contamination control problem here that is often overlooked. If the system is not completely designed, the possibility of control in these branches exists. That is, one may be able to design the system so that the likelihood of incurring unacceptable penalties from various types of contamination is small even though the amount of many or all types of contamination is large.

Similarly, the number and nature of sources, number and nature of the ways in which unacceptable penalties may be incurred, and types and modes of transport of contamination available may possibly be controlled through design. Thus, as might be intuitively obvious, system characteristics influence the complete tree. When these may be controlled through decisions, these decisions should be made so that the final physical control of contamination has a small penalty associated with it (insofar as possible).

To reiterate, using an approach such as this, it should be possible, at least in theory, to

- determine "optimal" means (activities, equipment, etc.) needed to achieve the contamination control objective for a given ϵ (allowable uncertainty in incurring unacceptable penalties),
- allow one insight into the dependence of ϵ, and, indeed, the definition of an "unacceptable penalty from contamination," upon the penalty paid for controlling contamination,

- help one assess the effect of system design upon contamination control problems,
- aid in recognizing areas in need of investigation, and
- provide a common framework in which many, if not all, contamination control problems may be viewed.

Two Partial Examples. To illustrate the above, somewhat abstract, approach to resolving contamination control problems, two somewhat more specific problems in which this approach has been partially implemented will be briefly discussed.

Tierney and the author have considered the probability of failure from contamination of a valve.[8] In this instance, the primary objective might be stated: To control contamination so that the probability of failure of a valve before time T from particulate contamination should be less than ϵ. In this primary objective, an "unacceptable penalty" appears in the form "failure before time T." In the situation envisioned, an unacceptable penalty was incurred in only one way: failure of one valve before time t. Thus the secondary objective was merely a rephrasing of the primary objective, i.e.,

$$P_F(t) \leq \epsilon \text{ for } t < T,$$

where $P_F(t)$ represents the probability of failure (from particulate contamination) at time t.

In the next level, it was hypothesized that failure occurred as a result of having certain amounts a_i of M types of particulate contamination (here, i = 1,2,...,M), and the analysis was much the same as the general case above with $\alpha_i = \infty$. That is

$$P_F(t) = \sum_{a_1=0}^{\infty} \sum_{a_2=0}^{\infty} \cdots \sum_{a_M=0}^{\infty} P_F(a_1,\ldots,a_M:t)\ P(a_1,\ldots,a_M:t)$$

where

$P_F(a_1,\ldots,a_M:t)$ is the probability of failure of the valve at time t if amount a_i of the i^{th} type of contamination is present in the valve at time t (i = 1,2,...,M),

and

$P(a_1,\ldots,a_M:t)$ is the probability that there will be amounts a_i of the i^{th} type of contamination present in the valve at time t.

In analyzing $P(a_1,\ldots,a_M:t)$, it was assumed that there were N sources of contamination for the valve during its operation: contamination sealed in the certain sites of the system to which the valve was attached. No consideration was given to the analysis of specific sources of contamination before operation of the system, i.e., the environment before the system was sealed, contamination from materials in the system, and so forth. Thus, the analysis of $P(a_1,\ldots,a_M:t)$ was in terms of (a) a probability distribution, P_i, representing the initial (after

[8] Tierney, M. S. and Trauth, C. A., Jr., A Model for Determining the Probability of Failure of a Valve Having a Particle Contamination Failure Mode, Sandia Laboratories Research Report, SC-RR-67-772.

sealing) contamination in the i^{th} site and (b) the probability, $\Pi_{iv}^{(j)}(t)$, that a single particle of type j in the i^{th} site, initially, would be found in the valve at time t. These latter probabilities were further analyzed by assuming that certain "transition" probabilities were known (significant factors at the sixth level).

While the authors had no specific system involving a valve in mind, so that the analysis was not carried beyond this level, the approach parallels the general approach presented above, and was not, incidentally, undertaken with the general approach in mind.

The second example of an analysis of a contamination control problem which resembles the general approach presented in this paper is the analysis of the planetary quarantine problem. In planetary quarantine one form of the primary objective may be stated as follows:

> To control contamination so that the probability of biasing life detection and analysis experimentation on a given planet before time T should not exceed ϵ.

In this objective, an "unacceptable penalty" becomes "biasing life detection and analysis experimentation before time T." Unfortunately T must be regarded as unknown. One possible definition of "biasing" in this context is "obtaining results one would otherwise not obtain." This, again, presents some problem since what one would obtain without any contamination is unknown.

An analysis of essentially the above primary objective may be found in a report in which an "unacceptable penalty" was actually left undefined.[9] The ways of incurring unacceptable penalties (biasing experimentation) were assumed to be the missions launched in the vicinity of the planet in question. The missions were divided into "classes" - each class having a possibly different mode of delivering contamination (e.g., landers, flybys and orbiters). Because it was deemed prudent to consider the number of missions in any class unknown (as well as the time period, T, referred to in the primary objective), a simple model of the form found in the general contamination control tree (p.38) could not be used. The model developed was one allowing periodic estimates to be made of the number of missions to be launched in each class. The significant factors influencing the attainment of the primary objective were of the form

> P_{ik} - the probability that a mission of the i^{th} class whose launch is deemed necessary as a result of the k^{th} estimate will "contaminate" the planet in question.

Here, "contaminate" may be understood to mean "deposit contamination in such a way that life detection and analysis experimentation is biased." The exact nature of the model will be found in the report, and need not be elaborated upon here. The secondary objectives arising from the model are of the form

$$P_{ik} \leq \epsilon_{ik} ,$$

[9] Trauth, C. A., Jr., A Sequential Decision Model of Planetary Quarantine Primary Objectives, Sandia Laboratories Research Report, SC-RR-67-462.

where the ϵ_{ik} can be directly related to the ϵ appearing in the primary objective.

A complete analysis leading to tertiary objectives has yet to be performed; however, enough is known to show that one of the significant factors appearing at approximately the third level is of the form

$P_L \{n(t) = k\}$ - the probability that the bioburden of a mission at launch is equal to k (for k = 0,1, 2,...).

To attempt to analyze this probability distribution, a model has been developed which may be used to predict microbial survival (or death)[10] in thermal environments. The significant factors appearing in the model include

- The temperature of the thermal environment,
- Time the capsule is exposed to the thermal environment, and
- The number of micro-organisms on the capsule just before its exposure to the thermal environment (or an initial distribution, if more appropriate.).

A first attempt has been made to analyze this last factor in terms of certain assembly contamination parameters,[11] and further work is underway to analyze these parameters in terms of environmental parameters in the hope of obtaining some actionable variables.

Thus, in planetary quarantine, the primary objective has a form like the general contamination control objective. The secondary objectives relate to ways of incurring penalties and are similar in form to those stated earlier in the general context of contamination control. Third level objectives which are known at this time are related to quantities or amounts of micro-organisms present on missions, and those fourth level objectives currently being investigated relate to sources of contamination (assembly, manufacture, etc.). Thus, again, planetary quarantine is another problem area which insofar as it has been analyzed, parallels the general analysis presented earlier in this section. Admittedly, some portions of the hierarchy will differ from the general abstract case presented earlier, but basically, planetary quarantine follows this pattern.

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[10]Brannen, J. P., A Rational Model for Spacecraft Sterilization Requirements, Sandia Laboratories Research Report, SC-RR-67-256.
__________, "A Rational Model for Thermal Sterilization of Microorganisms," Mathematical Biosciences, to appear.
__________, "On Logarithmic Extrapolation of Microbial Survivor Curves for Planetary Quarantine Requirements," Journal of Space Life Sciences, to appear.

[11]Sherry, E. J. and Trauth, C. A. Jr., An Assembly Contamination Model, Sandia Laboratories Research Report, SC-RR-66-421.

Incidentally, the "left branches" of the general tree developed on on page does not yield only measurable variables for planetary quarantine. The actual consequences of contaminating a planet cannot be known a priori, so that many of the variables occurring in these branches will present decision situations. Analysis of these left branches is currently underway.[12]

Conclusions and Comments

The intent of this paper was to develop a theory of contamination control with the following properties. It should be

(1) broad enough to encompass all contamination control problems,

(2) capable of aiding in the formulation of specific contamination control objectives in any given situation,

(3) helpful in determining the activities needed for the achievement of contamination control objectives on some "optimal" utility-penalty basis.

The desirability of such a theory may be attributed to two things. First, the "universality" of contamination control problems, and second, the similar abstract character of many contamination control problems. These lead, inevitably, to the conclusion that there will be many possible ways of solving contamination control problems. The potential gains associated with making a "best" choice from among alternative means of resolving a given problem seem great, so that a theory having the above named attributes seems desirable.

The "systems philosophy" was introduced as an approach to problem resolution primarily concerned with determining activities which "best" achieve some given set of objectives. As a philosophy, it is in many ways analogous to the "scientific method," and is, therefore, not a specific problem resolution scheme but, rather, a point of view. To actually implement the systems philosophy, a framework in which primary objectives (original problem objectives) are linked to "actionable" objectives (directly achievable objectives) was developed. This framework was termed an "objective hierarchy," and the elements occurring in it may be directly related to those occurring in the "systems philosophy." The objective hierarchy appears to be a framework possessing properties (1), (2) and (3), listed above, provided that primary objectives for contamination control are known.

Finally, primary objectives for contamination control were stated, and a partial abstract analysis of these in the objective hierarchy framework was carried out. To examine the validity of this approach, two rather dissimilar specific contamination control problems were presented. Each seemed to be capable of formulation within the framework

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[12] This research was evidenced by the presentations of N. H. Horowitz and R. W. Davies at the meeting of the Spacecraft Sterilization Advisory Committee of the American Institute of Biological Sciences held in Los Angeles June 19-21, 1967. These gentlemen were addressing themselves to the questions of the nature of contamination and the penalties that might be incurred for its existence in certain spacecraft components. Not unrelated, the article by Horowitz, Davies and R. W. Sharp entitled "Planetary Contamination I: The Problem and the Agreements," Science, Vol. 155, No. 3769, pp. 1501-1505.

developed in this paper, allowing for some variations in specific parameters because of the specific nature of the problems.

While the general approach to contamination control presented in this paper seems applicable to most contamination control situations, it must be understood that it is not a tested theory. To the author's knowledge, no problem in contamination control has been analyzed in this fashion to a complete set of actionable objectives. Thus it is a matter of believing that this can be done. Since a complete set of actionable variables has not been obtained in any contamination control situation, it follows that the theory is equally untried in its ability to obtain "best" means of problem resolution. Nevertheless, with this reservation (and others mentioned below) the approach to contamination control developed in this paper seems, in theory, to satisfy the goals set forth in this paper.

Aside from the untested nature of the approach presented here, there are at least two other reservations about the approach that should be mentioned. The first is that the "true" nature of resource allocation for control has not been thoroughly treated. The method outlined in this paper is an approximate method: a more "realistic" method requires the solution of a rather complex resource allocation problem constrained by the results of solving a number of resource scheduling problems. This occurs when the control of terminal or actionable variables is not independent, i.e., when the method of control of one may influence the control of another. For example, if a clean room is needed for the achievement of one actionable objective and a less costly cleaning facility is needed for the achievement of another, it may be possible, schedule permitting, to use the clean room (which one <u>must</u> have) to replace the cleaning facility, thereby reducing the <u>total</u> resource expenditure. Thus, a need for the "usual" tools of <u>planning</u> is evidenced in the approach presented in this paper. The solution of allocation and scheduling problems is, at times, very difficult,[13] so that the complete success of the approach to contamination control presented here may depend upon one's ability to resolve other difficult problems. The second reservation about the approach outlined in this paper is that it does not consider the organizational and educational aspects of planning. The organizational role that contamination control groups play, the number of groups involved, and the way in which they are coordinated must influence the effectiveness of contamination control actions as well as have some effect on the penalties associated with contamination control activities. Educational factors will influence contamination control "acceptance," effectiveness, activities and so forth. For example, only when the engineering community accepts contamination control as a vital consideration in product design will the potential gains in this area be realized.

Both the educational and organizational aspects of contamination control planning tend to be associated with the implementation of a technical plan derived, possibly, within a framework similar to that presented here. Their importance may be secondary in any relatively short time frame, but, long term, their consideration may well be necessary, and certainly desirable.

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[13]Pierce, J. F., Jr., <u>Some Large-Scale Production Scheduling Problems in the Paper Industry</u>, Prentice-Hall, Englewood Cliffs, N. J., 1964.

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