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A CHANCE-CONSTRAINED GOAL PROGRAMMING MODEL TO EVALUATE RESPONS--ETC(U)
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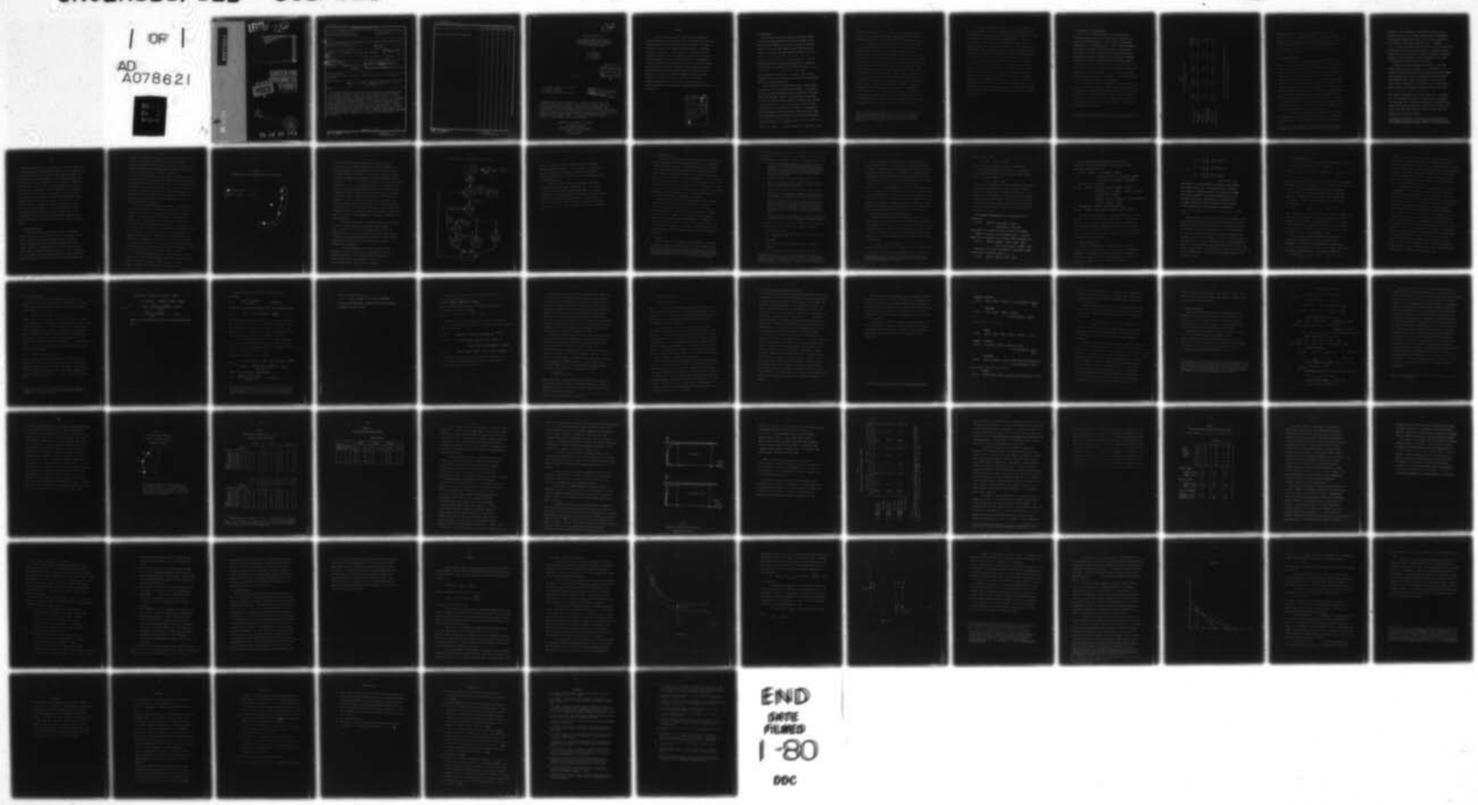

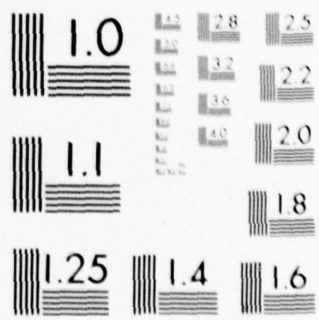

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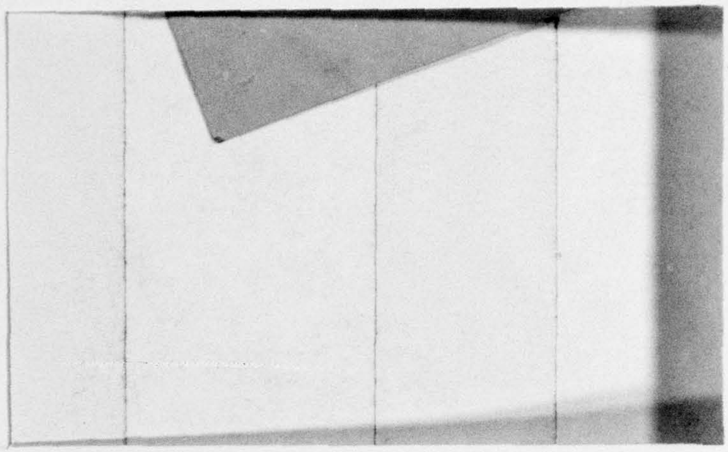

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This paper develops a model to aid Coast Guard managers in formulating appropriate policies with respect to planning for various types of equipment required to contain major pollution incidents. The model is elaborated in terms of three primary stages of response: offloading, containment, and removal. The zero order rule of chance-constrained programming is used to obtain a deterministic equivalent of the original chance-constrained model. This is then replaced by a goal programming formulation to allow for plans that come "as close as possible" to desired quality and risk levels for each pertinent region and type of incident. Numerical examples illustrate potential uses of the model with special emphasis on its value for budgetary (equipment) planning by central management that extends to evaluation of risk and performance quality levels, as well as the usual dual evaluator approaches for evaluating initially prescribed levels of equipment and their efficiency coefficients.

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A CHANCE-CONSTRAINED GOAL PROGRAMMING MODEL TO EVALUATE RESPONSE RESOURCES FOR MARINE POLLUTION DISASTERS

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ABSTRACT

This paper develops a model to aid Coast Guard managers in formulating appropriate policies with respect to planning for various types of equipment required to contain major pollution incidents. The model is elaborated in terms of three primary stages of response: offloading, containment, and removal. The zero order rule of chance constrained programming is used to obtain a deterministic equivalent of the original chance constrained model. This is then replaced by a goal programming formulation to allow for plans that come "as close as possible" to desired quality and risk levels for each pertinent region and type of incident. Numerical examples illustrate potential uses of the model with special emphasis on its value for budgetary (equipment) planning by central management that extends to evaluation of risk and performance quality levels, as well as the usual dual evaluator approaches for evaluating initially prescribed levels of equipment and their efficiency coefficients.

1. Introduction

Several spectacular maritime disasters in the late 1960's, including the highly publicized Torrey Canyon incident off the coast of England in March 1967, served to focus both public and political attention on the problem of marine environmental protection. As a result, the early seventies witnessed considerable legislative activity directed toward both prevention and response to major maritime pollution incidents.[2] The Coast Guard, in particular, was granted sweeping powers to establish regulations for the prevention of pollution as well as to provide for effective action to control and remove discharges of oil and hazardous substances in U.S. waters. This, in turn, prompted the Coast Guard to establish its own Marine Environmental Protection (MEP) Program in 1971.

Several years later, considerable attention is again being focused on the risk of major pollution incidents. In a period of less than one month--beginning with the grounding of the Liberian tanker Argo Merchant off the coast of Massachusetts on December 15, 1976-- no fewer than eight tankers went aground, sunk, exploded or were involved in collisions in U.S. waters[3]. Major questions have now been raised concerning (1) the adequacy of existing pollution regulations, (2) the Coast Guard's ability to enforce them and (3) the sufficiency of available response teams and equipment

[2] The most prominent of the resulting laws are the Federal Water Pollution Control Act and its Amendments.

[3] See, e.g., Newsweek accounts for the week of January 17, 1977.

to combat the major spills. These issues are of even greater importance today due to the proposed development of deepwater ports and increased offshore drilling for oil, two potential sources of catastrophic spills.

Our attention in this paper will be focused on only one of the above issues--the availability of resources to the Coast Guard and other groups to combat a major oil spill or multiple spills that occur simultaneously. To completely address this issue would require detailed discussions of (1) the extensive research and development effort in cleanup technology that is presently being conducted by government and industry [2] and (2) the financing of pollution response and compensation for damages through means such as the Coast Guard's Pollution Fund.[4] We will limit ourselves, however, to a modeling effort designed to assist in planning for the effects of increased resources in the light of their "best" allocations to various types of equipment while taking account of the ways in which they might, or must, be utilized in various types of incidents. We should specifically note that such equipment needs ought to be considered in terms of specified levels of performance and the associated risks of not achieving them. That is, unlike the situation in [9], the probability of achieving specified performance levels plays a prominent role that must be addressed explicitly when dealing with the large spill problem.

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[4]This is a revolving fund used to defray cleanup costs where the polluter cannot or will not effect cleanup, or where the polluter cannot be identified. The fund is revolving in that, under certain liability limitations, the polluter must reimburse the fund for actual costs incurred by the U.S. government.

One way of summarizing all this is to say that we shall be concerned with formulating a model for "budgetary" planning under risk and indicating how it may be applied to evaluating--and hence planning for-- these risks and their associated levels of performance quality. Actually we shall bypass a variety of issues such as the financial dimensions of budgetary planning since (a) these conditions may be readily adjoined for implementation when desired--see [3]-- and (b) their inclusion would tend to divert attention from the related physical-technical requirements which are presently of major concern. We shall want to develop our models for use in formulating presidential directives as well as agency planning. For this reason, too, we shall want to free these models for possibly separate use with respect to equipment considerations and related risk-quality evaluations as well as for use as one component for budgetary planning that extends not only to equipment costs but also to manpower, training, facility planning, maintenance, etc. In any case, the effort presented here may be viewed as a first step in a larger process involving data collection and decision making as well as modeling wherein all three (data collection, decision making and modeling) are viewed as a continually interacting process.

2. The Incidence of Major Pollution

For a variety of planning purposes, the Coast Guard has arbitrarily defined a major pollution incident to be any spill of greater than 100,000 gallons in coastal waters or greater than 10,000 gallons on the inland waterways. For the period 1973-1976, the number of occurrences of major spills has averaged about 9 per year (out of a total of 8500) for coastal waters and approximately 80 per year (out of 2600) for the inland waters.[5] The large majority of incidents are extremely small and contribute a relatively small portion of the total spill volume. On the other hand, major discharges, which are relatively rare, nevertheless make up the preponderance of the total volume. This raises a host of problems which range from data treatment to the kinds of risk characterizations and concepts that are suited to such situations.

For statistical-analytic purposes one experiences difficulty even at a conceptual level since the usual statistical measures, such as the mean and standard deviation, can be shown to be of very little practical value. (See Paulson et.al., [20] for further discussion.) In Table I, for example, observe that the median spill size for the time period 1973 to the present is only 12 gallons. Yet the average (mean) spill size is almost

[5]Source: U.S. Coast Guard's Pollution Incident Reporting System.

TABLE I

Oil Pollution Summary Statistics[a]
1973 - 1977

	1973	1974	1975	1976	TOTAL 1973-1977
Number of Spills	11,022	11,882	10,848	11,353	50,296
Total Volume[b] Spilled	19,359,808	16,809,129	23,149,054	23,257,422	80,028,562
Mean Spill Size	1,756	1,415	2,134	2,049	1,691
Standard Deviation of Spill Size	48,019	23,778	67,137	86,990	57,634
Largest Spill	4,000,080	1,680,000	6,000,000	7,500,000	7,500,000
Median Spill Size	12	15	14	10	12

[a]Source: Coast Guard's Pollution Incident Reporting System

[b]All spill sizes are stated in gallons

1700 gallons, and a 7.5 million gallon spill did in fact occur! It is clear that a strategy aimed at prevention or response for the vast majority of incidents as in [9] will not necessarily address the issue of major spills and evidently a model formulated only in terms of customary measures of risk such as means, variances, etc., will fall short of what is required.

3. Response Strategies

Concern over the incidence of pollution has given rise to what has been termed the "Oil Spill Clean-Up Industry." Though all sources of pollution removal and amelioration are considered to be part of this industry, it is useful to classify them into four sectors: the commercial firms (for hire), the private firms (for use by own firm), the non-profit cooperatives and the government sector [22]. The first three of these refer to cleanup capabilities maintained by various groups outside the public sector, such as industry, private marinas, etc. The key role of the public sector cleanup, other than for spills from government vessels, is in terms of a specialized capability which must be maintained for incidents where adequate cleanup services are not otherwise available. This characterization is especially apt since the small number of major incidents is insufficient to economically justify the maintenance of a large cleanup capability by any of the other sectors.[6]

The Coast Guard is responsible for responding to spills from unidentified sources and where the spiller will not or cannot perform adequate cleanup. The MEP Program's role in the National Pollution

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[6]This is also the "firehouse problem" where seldom used resources, perhaps in large amount, must be maintained for emergency purposes.

Contingency Plan is manifested in two ways: (1) supervision of a contingency fund to finance cleanup operations and (2) maintenance of specialized equipment and trained response teams to provide support, advice and assistance at major spills [15]. Equipment acquired by the Coast Guard for pollution removal has been (and will be) distributed to units at major ports and those in areas with limited commercial and private resources. For added flexibility, specialized equipment is also maintained by Coast Guard "National Strike Force Teams" located on the East, West and Gulf coasts.

A variety of types of equipment are available to local[7] and Strike Force units in order to combat major pollution incidents [21]. Examples of Coast Guard equipment for such use are; high seas skimmers and containment booms, a self contained high speed pumping system called ADAPTS, various chemical dispersants, etc. The need for these resources depends, of course, upon the type of spill, environmental conditions surrounding it, and the available cleanup capability from sectors in the area of the spill. The strategies for Coast Guard use of this equipment can be enumerated as: (1) containment and removal, (2) removal without containment, (3) containment only, (4) sinking or breaking up the pollutant with chemicals (including ignition), (5) cleaning of shoreline and (6) no action. Of course, more than one of these strategies can be employed for any particular incident.

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[7]The Coast Guard maintains a network of multi-mission field units. The majority of these are usually designated as Captain of the Ports (COTPs), Marine Safety Offices (MSOs) or Port Safety Stations.

Unfortunately, much of the data necessary to relate the effectiveness of response strategies to the incidence of pollution are not available even from PIRS, the Coast Guard's Pollution Incident Reporting System. Information concerning the effectiveness of overall cleanup operations (e.g., the total amount of oil recovered from particular spills) is maintained in PIRS. This information, however, is not subdivided by the various sectors of the cleanup industry and it is impossible to ascertain the effectiveness of the various types of equipment used by each sector. Furthermore, no record appears to be presently available of the cleanup equipment maintained by the private sector. This is not to say that models for effective contingency planning are not needed, of course, or that they should be delayed. It is to say rather these efforts should be guided by considerations of data availability not only for their present use as decision aids but also for their further use as guides to appropriate collections of data needed to improve the decision process.

4. The Response Scenario

We can indicate some of what is involved in formulating a response scenario along the following lines. For background to such a scenario we first note that the President's directive (message to the Congress, March 18, 1977) indicates a desired goal of maintaining a capability to respond to spills of up to 100,000 tons of oil within 6 hours. Statistical analyses such as those in [16] and [20] can help to determine the probability that spills on the order of 100,000 tons will occur, of course, but greater detail on spill information is necessary (in terms of types and locations of spills and rate of spillage) in order to give meaning to the phrase "response within 6 hours." For example, this might mean having an initial monitor on site within 6 hours. It might mean having all necessary containment equipment on site within 6 hours plus necessary personnel and other resources, etc.

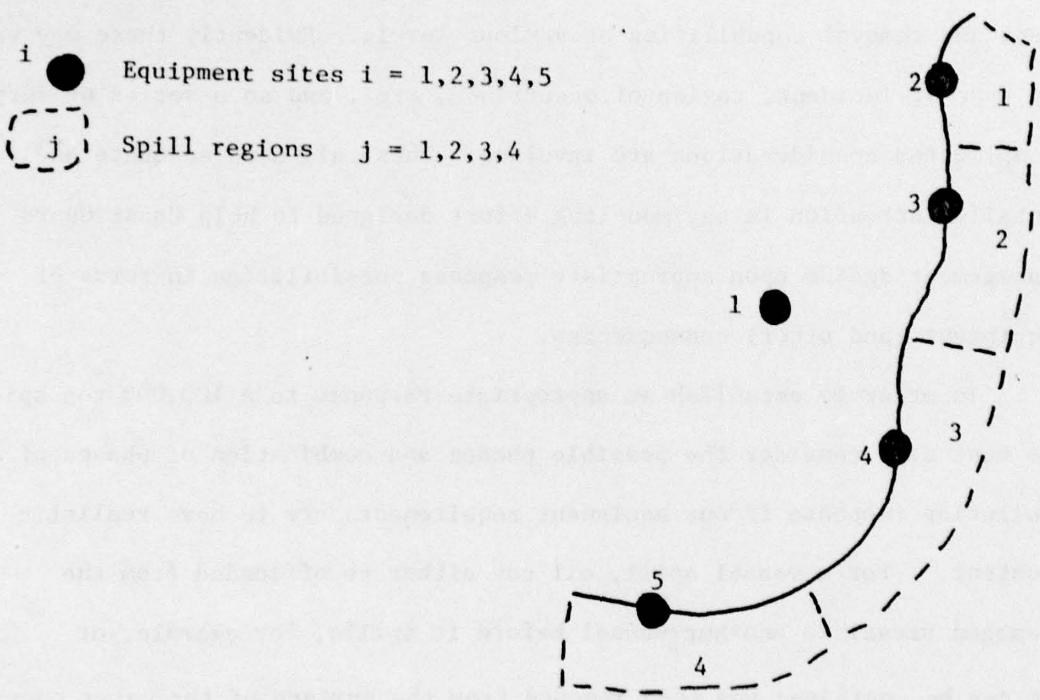
Also, even though it does not appear explicitly, attention must be given to the various risks of failure to achieve all of the wanted containment and removal capabilities at various levels. Evidently these may vary by type of incident, region of occurrence, etc., and so a series of very complicated considerations are involved. These all need adequate and detailed attention in any modeling effort designed to help Coast Guard management decide upon appropriate response possibilities in terms of equipment (and other) consequences.

In order to establish an appropriate response to a 100,000 ton spill we must also consider the possible phases and combination of phases of a pollution response if our equipment requirements are to have realistic content. For a vessel spill, oil can either be offloaded from the damaged vessel to another vessel before it spills, for example, or it can be contained and then removed from the surface of the water once it has already spilled. Such phases of pollution response are relevant because it is not sufficient to have "cleanup capability for 100,000 tons of spillage" available when the responses to various "100,000 ton spills" might differ according to the type of spill, its location, rate of spill, etc. In short, a model such as we are considering must allow for different scenarios that are appropriate to different major spill incidents as well as the various combinations of responses that might be required.

The following diagrams will help to clarify what is involved. Figure 1 depicts a hypothetical planning situation with 5 potential equipment sites and 4 spill regions. Equipment sites 2, 3, 4 and 5 might be considered as local Coast Guard units and site 1

FIGURE 1

A HYPOTHETICAL MAP OF EQUIPMENT SITES AND SPILL REGIONS



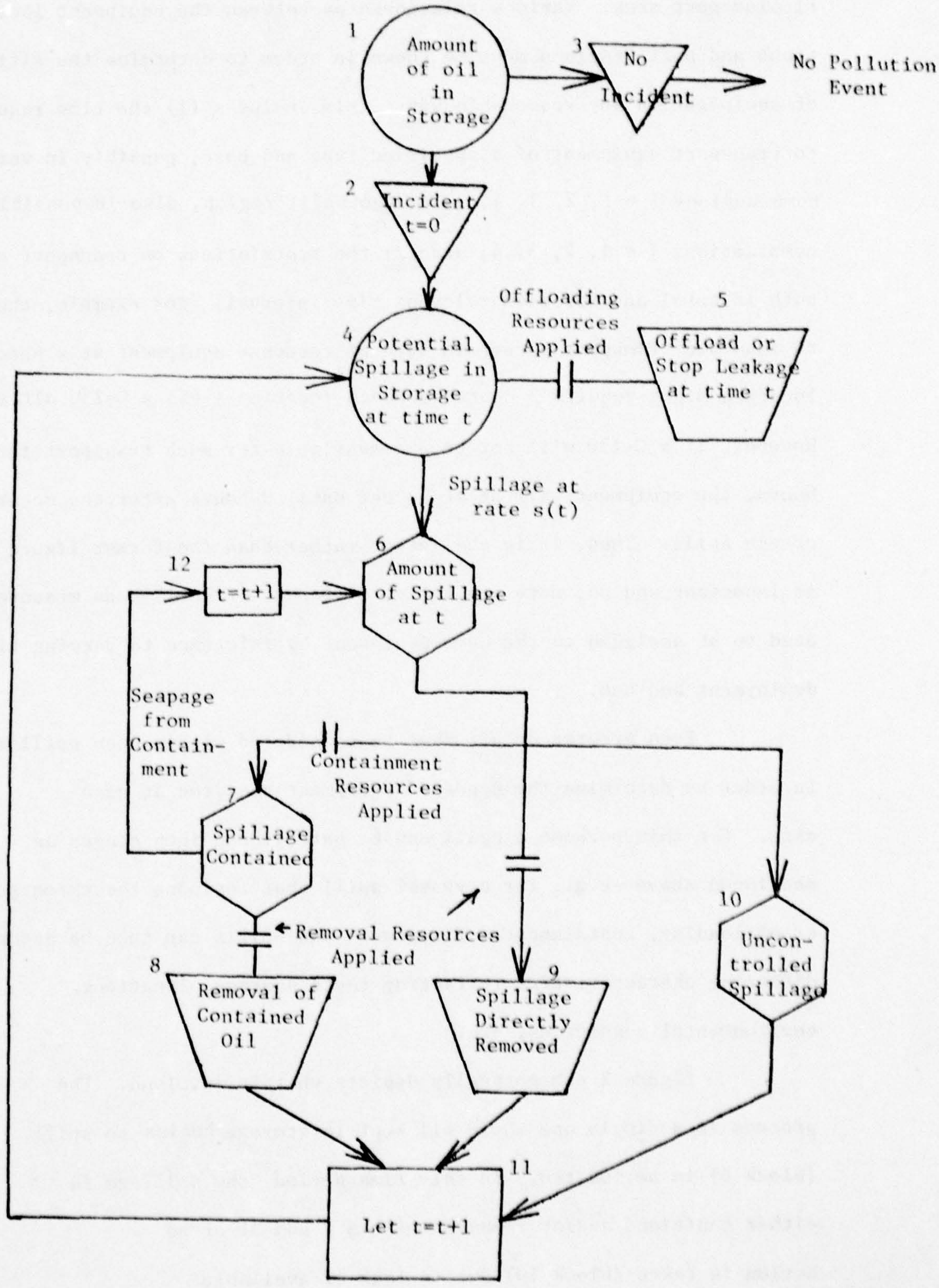
as a Strike Force location, not necessarily located near any particular port area. Various relationships between the equipment locations and spill regions must be known in order to determine the siting of equipment in any reasonable way. This includes (1) the time required to transport equipment of a specified type and base, possibly in varying combinations i = 1, 2, 3, 4, 5, to the spill region, also in possible varying combinations j = 1, 2, 3, 4; and (2) the restrictions on transport capacity both in total and for each relevant time interval. For example, the time to load and transport a certain type of response equipment at a specified location might require 3 hours to reach location j via a C-130 aircraft. However, if a C-130 will not become available for such transport for 6 hours, the equipment will be of no use until 9 hours after the occurrence of the spill. Thus, it is the latter rather than the former figure which is important and so, more generally, different effectiveness measures will need to be assigned to the same equipment by reference to varying times of deployment and use.

Even greater detail must be considered within each spill region in order to determine the types of equipment required at each site. For this purpose a spill can be partitioned into stages as mentioned above--e.g., for a vessel spill that includes the three stages of offloading, containment and removal--and spills can then be accorded differing characteristics reflecting their sources, locations, environmental conditions, etc.

Figure 2 schematically depicts what is involved. The process is a simple one where oil kept in storage begins to spill (block 6) in period t=0. In this time period, the spillage is either contained and/or removed (blocks 7 and 9) or no action is taken (block 10) due to lack of available

FIGURE 2

THE FLOW OF OIL DURING RESPONSE TO A VESSEL SPILL



resources or because extreme environmental conditions render the available equipment inoperative. In the meantime, oil that has not yet been spilled can be off-loaded to another storage facility (block 5) during the same time period. The process then moves forward one period (block 11).

Observe in Figure 2 that the availability of equipment directs the flow into the blocks denoted  , i.e., oil that is controlled via offloading, containment and removal. A goal for response to such an incident might be to minimize the amount of spillage in block 10 at a particular time period but, of course, a variety of other goals, such as minimizing the amount of oil reaching the water, might also be employed -- either separately or in various combinations.

5. Modeling Strategy

The process described in the preceding section must be incorporated into any model adequately designed to determine the level and siting of pollution response resources. The formulation here will be a combined chance constrained-goal programming model. The model, which will be called the Spill Incidence Model (SIM), will be discussed in terms of a major vessel spill though it is readily generalizeable to all major incident types.[8] In any case we shall regard this as typical of what is involved for purposes of central office or "presidential directive" planning - in advance of the occurrence of the indicated incidents - while allowing for subsequent elaboration, as desired, when more than one prototypical incident is to be included for separate or simultaneous consideration.

The details of the model to be described below will be developed in subsections as follows: (1) model notation, (2) accounting constraints for each time period, that keep track of the oil still in storage and oil spilled, spilled oil that is contained, oil offloaded from storage and oil removed, (3) constraints that relate equipment deployed to oil contained, removed and offloaded, (4) limitational constraints on available resources for various time periods, and in toto, (5) probabilistic constraints to the kinds of equipment needs these constraints imply, and (6) goal constraints derived from these probabilistic constraints.

5.1 Notation

Since our model is to be developed "prototypically" to correspond to the various stages of response to major pollution incidents, and in

[8] We will deal primarily with vessel spills since they have historically constituted the majority of all "catastrophic" spills and because spills of this type potentially involve all of the possible "stages" of pollution response that are likely to enter into any other large-spill scenario.

particular, for spills from vessels we proceed as follows. First we assume three prototypical stages which we shall designate as: (1) offloading, (2) containment, and (3) removal.[9] Then, for notational purposes, we let

i denote the location and equipment type available at that location, e.g., an ADAPTS pump located at Elizabeth City, N.C. Note that i is a composite subscript that incorporates both equipment siting and type since, in general, location as well as the type of equipment must be considered simultaneously. See Table II in section 6 below for an example of such a simultaneous designation.

ℓ denote an equipment site such as Elizabeth City, N.C.

I_ℓ denote the set of all indices i common to a particular location. For example, if $\ell=1$ in Table II of section 6 then the $i \in I_1$ consist of $i=1$, $i=4$ and $i=7$.

e denote a type of equipment such as skimmers, pumps or booms.

J_e denote the set of all indices i common to a particular type of equipment. For example, if $e=1$ represents pumps in Table II of section 6, then $i \in J_1$ consists of $i=1$, $i=2$, and $i=3$.

j denote the location and environmental conditions of a spill at that location, e.g., a crude oil spill off the coast of Massachusetts in five-foot seas. Note that each such index refers only to some environmental condition for which operations are assumed to be possible, and other environmental conditions (e.g., ten-foot seas) are eliminated from consideration.

d_j denote the amount of spillage of type j, i.e., the spillage at a certain location and corresponding to particular environmental conditions such as need to be considered for planning purposes.

We next define spillage in terms of response stages by reference to d_j^k values which are generally random variables as follows:

1. Pumping (offloading)

   d_j^1 corresponds to potential spillage to be pumped out or offloaded (in gallons).

2. Containment

   d_j^2 corresponds to leakage (in gallons) to be contained.

3. Removal

   d_j^3 corresponds to spillage to be removed (in gallons).

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[9] One further stage that may merit future consideration involves beach cleanup of spillage that has not been contained and removed and washes up on the shoreline. To date, this stage has been of less interest to the Federal Government because it appears to have been adequately managed by private contractors and local groups.

Observe that d_j^k is simply a "demand" on available resources at stage k, where k=1 refers to offloading, k=2 to containment, and k=3 to removal. Similarly, we will define r_j^k as the amount of oil offloaded, contained, and removed for k=1, 2, 3 respectively. These r_j^k values are the <u>results</u> of the decision variables that we shall shortly introduce - see the expression (5.3) in the section that follows - and each such r_j^k represents the results of decisions by Coast Guard managers with respect to each of the designated location and environmental conditions. For example $r_j^2 = 100{,}000$ might indicate a total containment capability of 100,000 gallons for a spill such as was indicated in the above definition of j. This 100,000 gallon capability is available from some underlying combination of equipment and delivery capability, of course, but this same combination of equipment may have quite a different value for other types of incidents and locations. See (5.3) ff., below.

5.2 <u>Demand on Resources Broken Down by Stages</u>

The analysis must now be further refined to account for different time periods, e.g., a time period might represent 6 hours as suggested in the President's directive. Thus let the total amount of oil (potential spillage) at location and environmental condition j in time t be $d_j(t)$. Then the total amount to be offloaded in the first time period (time t) is that proportion that will not leak out by the end of the period, i.e.,

$$(5.2.1) \qquad d_j^1(t) = (1-s_j)d_j(t)$$

where s_j is a proportion $0 \leq s_j \leq 1$ determined by the spillage rate.[10]

The total amount to be contained is determined by the proportion

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10 We assume that the total amount of spillage in any time period is directly proportional to and depends <u>only</u> upon the potential spill volume at the beginning of that period.

that will leak out, viz.,

$$(5.2.2) \qquad d_j^2(t) = s_j\, d_j(t).$$

where d_j^2 is as already defined in the preceding section.

From the amount which has leaked out, it is usually the case that only that proportion which has been contained can be removed. We therefore write

$$(5.2.3) \qquad d_j^3(t) = r_j^2(t)$$

for this amount. Note that we are here determining this in advance by referral to an amount $r_j^2(t)$. This means that we are determining $r_j^2(t)$ and hence $d_j^3(t)$ in a non-stochastic manner from the models that we shall shortly be developing in terms of "zero order decision rules." See [5] and [6]. Thus, in this paper the $d_j^3(t)$ are not random variables although, more generally, when the $r_j^k(t)$ are defined through stochastic decision rules then the $d_j^3(t)$ will also be random variables.

In the <u>second time period</u>, (t+1), the amount left to be offloaded is

$$(5.2.4) \qquad d_j^1(t+1) = (1-s_j)\,[d_j^1(t) - r_j^1(t)]$$
$$= (1-s_j)^2\, d_j(t) - (1-s_j)\, r_j^1(t)$$

where $r_j^1(t)$ is the amount pumped out in the first time period.

Similarly, the amount to be contained is equal to the total amount that has leaked out less the amount already contained, i.e.,

$$(5.2.5) \qquad d_j^2(t+1) = s_j[d_j^1(t) - r_j^1(t)] + d_j^2(t) - r_j^2(t)$$
$$= [s_j(1-s_j) + s_j]\, d_j(t) - s_j\, r_j^1(t) - r_j^2(t).$$

The amount to be removed is assumed to be that amount already contained but not previously removed, i.e.

$$(5.2.6) \qquad d_j^3(t+1) = r_j^2(t+1) + r_j^2(t) - r_j^3(t).$$

In the third time period, (t+2), the amount left to be pumped out is that amount not leaked out less the amount pumped out in the previous period, i.e.,

(5.2.7) $$\begin{aligned} d_j^1(t+2) &= (1-s_j)\,[d_j^1(t+1) - r_j^1(t+1)] \\ &= (1-s_j)\,[(1-s_j)^2 d_j(t) - (1-s_j)r_j^1(t) - r_j^1(t+1)] \\ &= (1-s_j)^3 d_j(t) - (1-s_j)^2 r_j^1(t) - (1-s_j)r_j^1(t+1). \end{aligned}$$

The amount to be contained is

(5.2.8) $$\begin{aligned} d_j^2(t+2) &= s_j[d_j^1(t+1) - r_j^1(t+1)] + d_j^2(t+1) - r_j^2(t+1) \\ &= s_j[(1-s_j)^2 d_j(t) - (1-s_j)r_j^1(t)] + [s_j(1-s_j) + s_j]d_j(t) \\ &\quad - s_j r_j^1(t) - r_j^2(t) - r_j^2(t+1) \\ &= [s_j(1-s_j)^2 + s_j(1-s_j) + s_j]d_j(t) - [s_j(1-s_j) + s_j]r_j^1(t) \\ &\quad - s_j r_j^1(t+1) - r_j^2(t+1) - r_j^2(t). \end{aligned}$$

The amount to be removed is that amount contained

(5.2.9) $$d_j^3(t+2) = r_j^2(t) + r_j^2(t+1) + r_j^2(t+2) - r_j^3(t) - r_j^3(t+1).$$

The analysis can be extended to as many time periods as are deemed necessary to fit any of the various horizons which Coast Guard management uses for its planning purposes. Further, the time periods need not be of the same length--though this would necessitate some changes in the form of the above constraints - and so the time period conditions used can be adjusted to those used by others (e.g., OMB or EPA) in their evaluation or planning processes.

5.3 Controlling the Spill

Cleanup is effected by levels of equipment type i deployed to incident j at time t in amount $x_{ij}(t)$. These $x_{ij}(t)$ are the decision variables. The results of these decisions, or, the total amount of pollution offloaded, contained or removed respectively in period t is equal to some $r_j^k(t)$, as in the following expressions:

$$r_j^1(t') = \sum_{\tau=t}^{t'} \sum_{i=1}^{m} \varepsilon_{ij}^1(t'-\tau)\, x_{ij}(\tau)$$

$$(5.3) \quad r_j^2(t') = \sum_{\tau=t}^{t'} \sum_{i=1}^{m} \varepsilon_{ij}^2(t'-\tau)\, x_{ij}(\tau)$$

$$r_j^3(t') = \sum_{\tau=t}^{t'} \sum_{i=1}^{m} \varepsilon_{ij}^3(t'-\tau)\, x_{ij}(\tau)$$

for $t' = t, t+1, \ldots, T$,

where $\varepsilon_{ij}^k(t)$ is the "effectiveness" of equipment i on spill type j for response stage k, e.g., a skimmer maintained at the Strike Force base near San Francisco used for a certain spill in Puget Sound might be capable of removing 10,000 gallons of oil in a particular time period. Observe that the total amount of oil offloaded, contained or removed in any period t' is a function of all equipment that has been allocated to the spill in question in previous time periods, $\tau \leq t'$. Thus, we sum on τ from t to t'.

The effectiveness coefficients, $\varepsilon_{ij}^k(t)$, are time dependent so that, in particular, we can allow for cases in which equipment allocated in time period t is not necessarily available for use during that period. More generally, $\varepsilon_{ij}^k(t)$ will be interpreted as an effectiveness measure (per unit resource) t periods after the allocation of equipment type and site i for spill type and location j. Thus, at time t', equipment allocated at time τ, i.e., $t'-\tau$ periods ago, has a unit effectiveness of $\varepsilon_{ij}^k(t'-\tau)$. The total results of all allocations are then the sum of all $\varepsilon_{ij}^k(t'-\tau)\, x_{ij}(\tau)$ terms, as in equations (5.3), wherein, we may note, $\varepsilon_{ij}^k = 0$ for any x_{ij} which cannot be used in the operation indicated by k. See Table II in section 6.

5.4 Available Resources

Resources of type i are available in finite quantities for any spill, or set of simultaneous spills, which we may write as

$$(5.4.1)\quad \sum_{j=1}^{n} \sum_{\tau=t}^{T} x_{ij}(\tau) \equiv \sum_{j=1}^{n} x_{ij}(t) + \sum_{j=1}^{n} x_{ij}(t+1) + \ldots + \sum_{j=1}^{n} x_{ij}(T) \leq x_i$$

$i = 1, 2, \ldots, m,$

where x_i is the total amount of resource i (given by type of resource and location). x_i is here represented as a variable since the total allocation of type i is to be determined optimally as part of our problem (e.g. the number of containment booms to be located in New York harbor). Furthermore, the total amounts of each equipment type, e.g. pumps or booms, are limited in toto. Thus, we also have the constraints

$$(5.4.2)\quad \sum_{i \in J_e} x_i \leq b_e, \qquad e=1,2,\ldots,E,$$

where the constants b_e, will differ for each of these E equipment types. Note that these constraints may be omitted or included, as desired for different types of studies. See section 6, below. They can also be varied parametrically or studied even more conveniently by ordinary dual evaluators -- by virtue of the reductions we shall shortly make to achieve an ordinary linear programming problem.

Other resource constraints are possible on sums such as $\sum_j x_{ij}(t)$. This might indicate that only so much delivery capability (C-130 aircraft, delivery sleds, etc.) is available in any particular time period by reference to equipment needed to deploy the required cleanup equipment. For example, we might have

$$(5.4.3)\quad \sum_{j=1}^{n} \sum_{i \in I_\ell} c_i x_{ij}(t) \leq D_\ell(t) \qquad \ell = 1, 2, \ldots, L,$$

where c_i is the required delivery capacity (measured in relevant units such as, for example, cubic feet of space) needed per unit of the i^{th} equipment type. Similarly, $D_\ell(t)$ is the total amount of delivery capacity available at equipment location ℓ in time period t as prescribed by various managerial (and other) considerations from past history and future projected availabilities which include, perhaps, recommendations by port Captains or study teams as a basis for initial study and evaluation. See also the remarks following (5.4.2).

We have now achieved part of the flexibility that was set forth as a desideratum in our model design. We can, for instance, include or exclude certain constraints according to the purposes of a study as we have just indicated. We can also include all of the many details required for a complete depiction of the resource constraints when, for instance, we want to study the effects on the decision variables x_{ij} needed to attain prescribed $r_j^k(t)$ values with different applicable assumptions for the $\varepsilon_{ij}^k(t)$. Such a course could be useful, for instance, to secure guidance for technological and/or managerial-organizational research pointed in these directions. Alternatively we can single out the $r_j^k(t)$ for separate study as we shall do in the next section. There, as we shall see separation is convenient for embedding all of the above in a probabilistic context. This is also useful for policy purposes such as the development of a presidential directive in which one wants to avoid cluttering details. On the other hand the $r_j^k(t)$ values associated with various levels of risk and performance quality indicators can be brought into contact with the decision variables and effectiveness coefficients which together provide the resource implications via (5.3).

5.5 Chance Constraints

We now turn to the relevant risk consideration which we will develop by chance constrained formulations for period t+1. Recall that $d_j^1(t+1)$ is the amount of potential spillage of the j^{th} incident type to be offloaded in period t+1 so that

$$d_j^1(t+1) = (1-s_j)^2\ d_j(t) - (1-s_j)\ r_j^1(t).$$

We will suppose that the probability distributions for $d_j^1(t+1)$ are known or can be satisfactorily approximated. Then we shall suppose that a "fractile quality level," $q_j^1(t+1)$, to offload oil in period t+1 is imposed which will be sufficient to handle $d_j^1(t+1)$ with probability at least $\alpha_j^1(t+1)$. We want to formulate our model so that we will be able to determine what such quality levels need to be to match the corresponding α's or, conversely, how large the α's can be for prescribed q's. See the Appendix. Therefore, using ideas from chance constrained programming [5], we introduce the chance constraint

$$\text{(5.5.1)} \qquad P\ [d_j^1(t+1) \leq q_j^1(t+1)] \geq \alpha_j^1(t+1)$$

to mean that we desire a probability of at least $0 \leq \alpha_j^1(t+1) \leq 1$ that the amount to be offloaded will be less than or equal to $q_j^1(t+1)$ where the $\alpha_j^1(t+1)$, like the $q_j^1(t+1)$, are policy stipulations. In other words, this double inequality represents a policy constraint[11] which prescribes a desired quality level, $q_j^1(t+1)$, and a risk $1 - \alpha_j^1(t+1)$ of failing to meet it.

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[11] In the sense described on p. 260 of [11] wherein α=0.5 indicates "indifference" to servicing the stipulated quality level and α=1.0 converts the "policy" into a "rule".

Substituting for $d_j^1(t+1)$ in the above, we obtain

$$P\ [(1-s_j)^2 d_j(t) - (1-s_j) r_j^1(t) \le q_j^1(t+1)] \ge \alpha_j^1(t+1)$$

or

(5.5.2)
$$P\ [\ d_j(t) \le \frac{q_j^1(t+1) + (1-s_j) r_j^1(t)}{(1-s_j)^2}\ ] \ge \alpha_j^1(t+1)$$

or
$$F_j\ [\ \frac{q_j^1(t+1) + (1-s_j) r_j^1(t)}{(1-s_j)^2}\ ] \ \ge \ \alpha_j^1(t+1)$$

where F_j is the distribution function of the potential spill volume $d_j(t)$.

If the distribution is invertible, or via approximation, we then have

$$(5.5.3) \qquad \frac{q_j^1(t+1) + (1-s_j)r_j^1(t)}{(1-s_j)^2} \geq F_j^{-1}(\alpha_j^1(t+1))$$

for the case of the zero order decision rule.[12] Now rearranging, we get

$$(5.5.4) \qquad r_j^1(t) \geq (1-s_j)F_j^{-1}(\alpha_j^1(t+1)) - \frac{q_j^1(t+1)}{(1-s_j)} \quad ,$$

which establishes the minimum required level of offloading capability in period t, $r_j^1(t)$. Thus, we are now conveniently positioned to study these $r_j^1(t)$ not only in terms of their relation to the decision variables in (5.3) but also in terms of the resource consequences which may attend a variation of these $\alpha_j^1(t+1)$ and $q_j^1(t+1)$ policy conditions.

For a full-scale parametric study of these resource consequences we also need to consider them simultaneously with other policy conditions. Therefore, for the analogous period t+1 containment policy we write

$$(5.5.4) \qquad P\,[d_j^2(t+1) \leq q_j^2(t+1)] \geq \alpha_j^2(t+1) \; .$$

Then, by substitution from (5.2.5) we obtain

$$(5.5.5) \qquad P\,[\,(s_j(1-s_j)+s_j)\,d_j(t) - s_j r_j^1(t) - r_j^2(t) \leq q_j^2(t+1)] \geq \alpha_j^2(t+1)$$

or

$$P\,[\,d_j(t) \leq \frac{q_j^2(t+1) + r_j^2(t) + s_j r_j^1(t)}{s_j(1-s_j) + s_j}\,] \geq \alpha_j^2(t+1)$$

and, if F is invertible, or by approximation,

$$(5.5.6) \qquad \frac{q_j^2(t+1) + r_j^2(t) + s_j r_j^1(t)}{s_j(1-s_j) + s_j} \geq F_j^{-1}(\alpha_j^2(t+1)),$$

[12] See, e.g., [6], for a discussion of decision rules and the conditions for effecting the indicated inversions in the context of chance constrained programming. An example of the kind of decision rule that might be employed in real time operating contexts may be found in [12].

which may also be represented by

$$(5.5.7) \qquad r_j^2(t) + s_j r_j^1(t) \geq [s_j(1-s_j)+s_j]\ F_j^{-1}(\alpha_j^2(t+1)).$$

Note that this uses the same distribution function as before, but different risk levels, $\alpha_j^2(t)$.

For removal in period t+1 the route we have already traced for the other constraints would yield

$$(5.5.8)\quad P\,[\, d_j^3(t+1) \leq q_j^3(t+1)\,] \geq \alpha_j^3(t+1)$$

However, by virtue of the discussion accompanying (5.2.3) we replace this with the deterministic constraint

$$(5.5.9)\qquad r_j^2(t+1) + r_j^2(t) - r_j^3(t) \leq q_j^3(t+1)\ .$$

Evidently we can study the above constraints singly or in combination for our equipment planning purposes. Proceeding in an entirely analogous manner we would obtain

$$(5.5.10)\qquad (1-s_j)r_j^1(t) + r_j^1(t+1) \geq (1-s_j)^2 F_j^{-1}(\alpha_j^1(t+2)) - \frac{q_j^1(t+2)}{1-s_j}\ .$$

$$(5.5.11)\qquad [s_j(1-s_j)+s_j]r_j^1(t) + s_j r_j^1(t+1) + r_j^2(t) + r_j^2(t+1) \geq$$

$$[s_j(1-s_j)^2+s_j(1-s_j)+s_j]F_j^{-1}(\alpha_j^2(t+2)) - q_j^2(t+2),$$

$$(5.5.12)\qquad r_j^2(t) + r_j^2(t+1) + r_j^2(t+2) - r_j^3(t) - r_j^3(t+1) \leq q_j^3(t+2),$$

for studying offloading, containment and removal, respectively, in any desired combination with respect to both risk and quality levels and their possible resource consequences.

Thus far we have focused only on the constraints where--unlike the case for the earlier GIP models [9]--we were required to give explicit attention to the risk considerations that play such a prominent role in the problem of large oil spills. Note, however, that we have produced a formulation in which these risks are associated with fractile functions. Hence we have achieved one of our study objectives in that we are not confined to the usual measures of risk such as the mean and variance, etc., which (as was noted earlier) are not up to the task of dealing with the kinds of statistical distributions that are involved in this class of problems. We have, instead, oriented our development toward the tails where the risks of large spill incidents are located.

Nothing has been lost, moreover, since we can deal with any part of the underlying statistical distributions in the indicated manner either separately or in an iterated manner. For instance, as we shall later see, we can deal with the means and other parameters of these distributions by associating them with fractiles. We can illustrate this by reference to the usual mean-variance relations as follows. Let $q_j = Ed_j$ and $\sigma_j^2 \equiv E(d_j - q_j)^2$ where "E" is the expected value operator and $q_j \equiv q_j^k(t+1)$, $d_j \equiv d_j^k(t+1)$ for some $k = 1, 2, 3$. Then assuming that these parameters exist, we can meaningfully use them to represent a commonly employed mean-variance constraint in the form [13]

$$P\left[\frac{|d_j - q_j|}{\sigma_j} \le k_j\right] \ge \alpha_j ,$$

wherein the vertical strokes represent an absolute value for the thus enclosed expression and k_j is some suitably specified positive constant for the indicated interval. But then we can replace this one absolute value condition with the two conditions

[13] Recall that d_j contains decision variables r_j.

$$P[d_j \geq q_j + k_j\sigma_j] \leq \gamma_j$$

$$P[d_j \leq q_j - k_j\sigma_j] \leq \delta_j$$

where $\gamma_j = \delta_j = \frac{1-\alpha_j}{2}$ if the distribution is symmetric about the mean. The latter pair is evidently also in the form of the same kind of chance constraints as before and therefore can be readily adjoined to the preceding ones for use in cases where behavior in the central regions of the distributions are also of interest.

Other interactions will produce what might be wanted for other distributions and risk situations. See [5] and [6] for further details. Furthermore, in a manner suited to central office planning (i.e., with zero order decision rules), we have also been able to replace the chance constraints (5.5.1) ff. with deterministic equivalents such as (5.5.4) which are ordinary linear inequalities. Indeed substitution from (5.3) into (5.5.4) and like expressions makes it clear that we have arranged matters so that the pertinent decision variables can be directly related to their risk-quality consequences, and vice versa.

There are still further possibilities which emerge from these formulations. These include possible guidance for research efforts directed to improving the ε_{ij}^k coefficients in (5.3). Finally, we have formulated the model so that issues of grand policy, as incorporated in Presidential directives, can be studied separately and then related to their implementation requirements for equipment and delivery capabilities. See section 6, below. Hence, any or all of the above can be used separately or in varying combinations, as was stipulated when outlining our modeling strategy at the start of section 5, above.

5.6 Goal Constraints and Objective Functions

The above formulations are advantageous from the standpoint of clarifying the kinds of risk and quality conditions that need to be considered in selecting and evaluating "policies" with respect to their equipment (and regional location) consequences. They are, however, "too sharp" for many of the applications that we are considering. For instance, the chance constraints require attention to the consistency requirements for the choices of q_j and α_j in various inequalities. Consistency between constraints is evidently also required and this may represent an undue burden to impose on even intermediate level decision makers who might thereby be required to effect these ab initio choices for simultaneous consideration over a great variety of possible incidents.

We need to ease these burdens and so we shall now essay another approach that will build upon what we have already accomplished. This will also enable us to address yet another facet for practical implementation in that, by and large, the prescribed quality and risk levels are not really susceptible of precise specification. Furthermore, a failure to achieve them need not have dire consequences if the resulting deviations are not "too serious." In any case we will, in general, only be able to do "as well as possible" in these kinds of planning situations and therefore would like to arrange for a model that will (a) help us assess whether "as well as possible" is satisfactory with the resources we are planning to use and (b) enable us to effect tradeoff analyses and/or explore resource expansion possibilities in a fairly straightforward manner.

For this new phase of our modeling strategy we propose to employ an approach which will get "as close as possible" to all indicated goals. After this has been done one can assess whether this is sufficiently satisfactory for every subset of goals. When the latter is not the case the model will then be available to study tradeoffs, e.g., via goal alterations or by increasing resource availabilities, etc., until such a state is achieved.

Following Naslund [19] [14] we can give form to these ideas in a way that joins heretofore separate developments from "chance constrained programming" and "goal programming" as follows. First we replace the conditions we have just derived with the following types of goal constraints:

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[14] See also Contini [14] and Ijiri [17] for other possible approaches.

PERIOD 1 OFFLOADING

$$(5.6.1)\quad r_j^1(t) - y_j^{1+}(t+1) + y_j^{1-}(t+1) = (1-s_j)F_j^{-1}(\alpha_j^1(t+1)) - \frac{q_j^1(t+1)}{1-s_j}$$

CONTAINMENT

$$(5.6.2)\quad r_j^2(t) + s_j r_j^1(t) - y_j^{2+}(t+1) + y_j^{2-}(t+1) = z_j(t+1)F_j^{-1}(\alpha_j^2(t+1)) - q_j^2(t+1)$$

where $z_j(t+1) = s_j(1-s_j) + s_j$

REMOVAL

$$(5.6.3)\quad r_j^2(t+1) + r_j^2(t) - r_j^3(t) - y_j^{3+}(t+1) + y_j^{3-}(t+1) = q_j^3(t+1)$$

PERIOD 2 OFFLOADING

$$(5.6.4)\quad (1-s_j)r_j^1(t) + r_j^1(t+1) - y_j^{1+}(t+2) + y_j^{1-}(t+2) = (1-s_j)^2F_j^{-1}(\alpha_j^1(t+2)) - \frac{q_j^1(t+2)}{1-s_j}$$

CONTAINMENT

$$(5.6.5)\quad [s_j(1-s_j)+s_j]r_j^1(t) + s_j r_j^1(t+1) + r_j^2(t) + r_j^2(t+1) - y_j^{2+}(t+2) + y_j^{2-}(t+2) = z_j(t+2)F_j^{-1}(\alpha_j^2(t+2)) - q_j^2(t+2)$$

where $z_j(t+2) = s_j(1-s_j)^2 + s_j(1-s_j) + s_j$

REMOVAL

$$(5.6.6)\quad r_j^2(t) + r_j^2(t+1) + r_j^2(t+2) - r_j^3(t) - r_j^3(t+1) - y_j^{3+}(t+2) + y_j^{3-}(t+2) = q_j^3(t+2)$$

where the values for y_j^{k+} and y_j^{k-} are constrained to be non-negative so that they may represent the over- and underachievements that the $r_j^k(t)$ values (and their associated decision variables) yield with respect to the right-hand sides.

Having replaced each chance constraint by a goal constraint, we now seek to achieve "as closely as possible," the goals which are indicated on the right. We give a precise interpretation to this by writing our objective as

$$(5.6.7) \qquad \min \sum_{\tau=t+1}^{T} \sum_{j=1}^{n} (w_j^{1-}(\tau)y_j^{1-}(\tau) + w_j^{2-}(\tau)y_j^{2-}(\tau) + w_j^{3+}(\tau)y_j^{3+}(\tau))$$

where T is the number of time periods under consideration and $w_j^k \geq 0$ are weighting factors, specified by MEP managers, on the underachievement of containment and offloading goals and on the overachievement of removal goals.

A variety of considerations, some of them very complex, can enter into a choice of these weights. As observed in the Appendix such choice considerations can be meaningfully discussed only to a very limited extent without reference to the constraints and other "in-context" considerations. The latter may be illustrated by reference to the course of development we have followed. Note, for instance, that we have allowed deviations both above and below goals for the $r_j^k(t)$ choices in constraints (5.6.1) - (5.6.6) but have used only one-sided weights in the objective (5.6.7). This was done to bias program choices in the direction indicated by the inequalities (5.5.1) ff. in the preceding section. Furthermore, the technological relations between offloading, containment and removal make it fairly clear that one will ordinarily have $w_j^1, w_j^3 \geq w_j^2 \geq 0$ since containment cannot really function effectively without the presence of adequate removal and offloading capacity.

5.7 Review of the Model

Beyond the kinds of considerations set forth above (and in the Appendix) we cannot say much more about a choice of weights for the objective functional.[15] We will, therefore, hereafter assume that $w_j^{1-} = w_j^{2-} = w_j^{3+} = 1$ all j, and all <u>other</u> $w_j = 0$ so we can turn to other aspects of our model and its possible uses in what follows.

We assume that the Coast Guard's budgetary planning for this class of cases is guided by prototypical situations in which notice is received of a spill at the time of its occurrence so that action can be initiated at time t=0. For concreteness we shall suppose that three time periods are of interest so that for t=0, 1, 2, we can rewrite the general model for this class of cases as

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[15] Such choices are not necessarily decisive in producing anything more than a figure-of-merit alteration and, in fact, one may erect examples in which all possible sets of positive weights have only this effect. See [13] and [10]. A detailed discussion which includes a review of the many standard approaches from economics, psychology, etc., for their possible uses and shortcomings in this class of problems may be found in [18].

SIM = Spill Incidence Model

$$\min. \sum_{j=1}^{n} \sum_{t=1}^{2} y_j^{1-}(t) + y_j^{2-}(t) + y_j^{3+}(t)$$

subject to:

OFFLOADING CONSTRAINTS: $j=1,2,\ldots,n.$

$$r_j^1(0) - y_j^{1+}(1) + y_j^{1-}(1) = (1-s_j)F^{-1}(\alpha_j^1(1)) - \frac{q_j^1(1)}{1-s_j}$$

$$r_j^1(1) + (1-s_j)r_j^1(0) - y_j^{1+}(2) + y_j^{1+}(2) = (1-s_j)^2F^{-1}(\alpha_j^1(2)) - \frac{q_j^1(2)}{1-s_j}$$

CONTAINMENT CONSTRAINTS: $j=1,2,\ldots,n.$

$$r_j^2(0) + s_j r_j^1(0) - y_j^{2+}(1) + y_j^{2-}(1) = z_j(1)F_j^{-1}(\alpha_j^2(1)) - q_j^2(1)$$

$$z_j(1)r_j^1(0) + s_j r_j^1(1) + r_j^2(0) + r_j^2(1) - y_j^{2+}(2) + y_j^{2-}(2) =$$

$$z_j(2)F_j^{-1}(\alpha_j^2(2)) - q_j^2(2)$$

where $z_j(1) = [s_j(1-s_j)+s_j]$ and $z_j(2) = [s_j(1-s_j)^2+s_j(1-s_j)+s_j]$

REMOVAL CONSTRAINTS: $j=1,2,\ldots,n.$

$$r_j^2(1) + r_j^2(0) - r_j^3(0) - y_j^{3+}(1) + y_j^{3-}(1) = q_j^3(1)$$

$$r_j^2(2) + r_j^2(1) + r_j^2(0) - r_j^3(1) - r_j^3(0) - y_j^{3+}(2) + y_j^{3-}(2) = q_j^3(2)$$

EQUIPMENT CONSTRAINTS:

$$\sum_{j=1}^{n} x_{ij}(0) + \sum_{j=1}^{n} x_{ij}(1) + \sum_{j=1}^{n} x_{ij}(2) \leq x_i \qquad i=1,2,\ldots,m$$

and

$$\sum_{i \in J_e} x_i \leq b_e \qquad e=1,2,\ldots,E.$$

DELIVERY CAPABILITY CONSTRAINTS: $\ell=1,2,\ldots,L;\ t=0,1,2$

$$\sum_{j=1}^{n} \sum_{i \in I_\ell} c_i(t)\, x_{ij}(t) \leq D_\ell(t)$$

EFFECTIVENESS CONSTRAINTS: $k=1,2,3;\ t=0,1,2;\ j=1,2,\ldots,n.$

$$r_j^k(t) = \sum_{\tau=0}^{t} \sum_{i=1}^{m} \varepsilon_{ij}^k(t-\tau)\, x_{ij}(\tau)$$

NON-NEGATIVITY CONSTRAINTS: for all i,j,k,t,

$$x_{ij}(t),\ x_i,\ y_j^{k+}(t) \text{ and } y_j^{k-}(t) \geq 0.$$

In this form, the problem can be solved by available linear programming codes, either directly as stated above, or after first substituting the effectiveness constraints of (5.3) into the offloading, containment and removal (goal) constraints. Thus, we have therefore now satisfied another one of our desiderata in that the whole complex of considerations ranging from varying risks and quality levels in different dimensions together with favored directions for program deviations are now joined together in an ordinary linear programming model. The requisite computing power for dealing with the thousands of variables and constraints that need to be considered is therefore readily available, together with an already developed body of mathematical theory that includes access to an extraordinarily sharp and flexible duality theory. The latter provides us not only with a convenient way for effecting evaluations of risk and quality levels, together with other constraint stipulations, but also with direct access to other mathematical disciplines (such as game theory) as well as to the main body of economic theory, where it is assumed that price and quantity variations can be considered separately[16] in the same manner that dual variables can be separately employed to evaluate primal program possibilities -- a property which is virtually unique among all mathematical programming models. Hence, we have achieved what we were seeking in the form of a very conveniently manipulated planning guide.

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[16] Cf., e.g., W. Baumol [1].

6. Numerical Illustrations and Uses of the Spill Incidence Model (SIM)

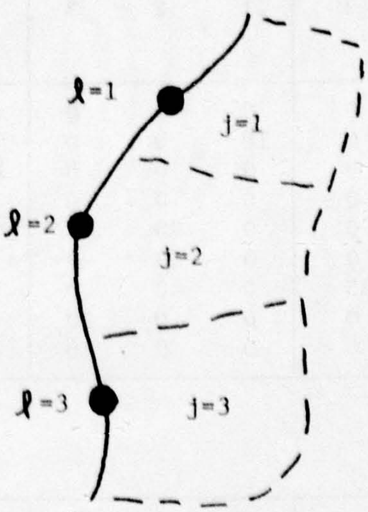
For illustrative purposes we will consider a simplified hypothetical example using the model for the three time periods (t=0, 1, 2) given in the preceding section. We shall assume that there is only one spill type but three regions (j=1, 2, 3) in which such a spill can occur. See Figure 3. We shall also assume that each region contains an equipment location (ℓ=1, 2, 3) where the following three types of equipment may be positioned: (1) pumps for offloading, (2) booms for containment and (3) skimmers for removal of spillage. Thus, in total, i runs from 1 to 9 where i = 1 represents pumps at equipment site 1, i=2 booms at site 1, i=3 skimmers at site 1, i=4 pumps at site 2, ..., i=9 skimmers at site 3. See the stub of Table II, for which the body gives numerical values corresponding to $\varepsilon_{ij}^{k}(t)$, the effectiveness of each equipment type i for a spill in region j at stage k. I.e., these $\varepsilon_{ij}^{k}(t)$ rate each of the indicated equipment types at each site to the amount of oil (in thousands of gallons offloaded, contained, or removed) per unit resource by reference to the stages and possible response times as well as to incident types and regions where they might apply.

FIGURE 3

DIAGRAM OF SPILL REGIONS AND

POTENTIAL EQUIPMENT SITES FOR

HYPOTHETICAL EXAMPLE[a]



[a]Assumptions: Equipment can reach spills in the same region immediately. Equipment at site 2 can reach regions 1 and 3 after one period. Equipment at 1 and 3 can similarly reach 2 in one period. Equipment cannot be moved between 1 and 3 in less than 3 periods. See Table II.

TABLE II

EQUIPMENT EFFECTIVENESS FOR j = 1, 2, 3

AT INDICATED TIMES AND STAGES[a]

Equipment and Site	i	$\varepsilon_{i1}^k(0)$ k=1	k=2	k=3	$\varepsilon_{i2}^k(0)$ k=1	k=2	k=3	$\varepsilon_{i3}^k(0)$ k=1	k=2	k=3
Pumps at site 1	1	20	0	0	0	0	0	0	0	0
Pumps at site 2	2	0	0	0	18	0	0	0	0	0
Pumps at site 3	3	0	0	0	0	0	0	15	0	0
Booms at site 1	4	0	20	0	0	0	0	0	0	0
Booms at site 2	5	0	0	0	0	20	0	0	0	0
Booms at site 3	6	0	0	0	0	0	0	0	25	0
Skimmers at site 1	7	0	0	35	0	0	0	0	0	0
Skimmers at site 2	8	0	0	0	0	0	30	0	0	0
Skimmers at site 3	9	0	0	0	0	0	0	0	0	30

Equipment and Site	i	$\varepsilon_{i1}^k(1)$, $\varepsilon_{i1}^k(2)$ k=1	k=2	k=3	$\varepsilon_{i2}^k(1)$, $\varepsilon_{i2}^k(2)$ k=1	k=2	k=3	$\varepsilon_{i3}^k(1)$, $\varepsilon_{i3}^k(2)$ k=1	k=2	k=3
Pumps at site 1	1	20	0	0	18	0	0	0	0	0
Pumps at site 2	2	20	0	0	18	0	0	15	0	0
Pumps at site 3	3	0	0	0	18	0	0	15	0	0
Booms at site 1	4	0	20	0	0	20	0	0	0	0
Booms at site 2	5	0	20	0	0	20	0	0	25	0
Booms at site 3	6	0	0	0	0	20	0	0	25	0
Skimmers at site 1	7	0	0	35	0	0	30	0	0	0
Skimmers at site 2	8	0	0	35	0	0	30	0	0	30
Skimmers at site 3	9	0	0	0	0	0	30	0	0	30

[a]Numerical values correspond to $\varepsilon_{ij}^k(t)$, the effectiveness of equipment type i for spill type j at response stage k. Figures in units of demand satisfied (i.e., thousands of gallons of oil offloaded, contained or removed) per unit resource. See Figure 3 for assumptions.

TABLE III

SPILLAGE RATES AND QUALITY LEVELS

Incident Types and Region j	Spillage rate s_j	Quality Levels: Stage 1 $q_j^1(1)$	Stage 1 $q_j^1(2)$	Stage 2 $q_j^2(1)$	Stage 2 $q_j^2(2)$	Stage 3 $q_j^3(1)$	Stage 3 $q_j^3(2)$
1	.20	300	200	50	0	100	50
2	.24	200	100	50	0	100	50
3	.25	200	100	50	0	100	50

Recall that these terms are time dependent. For example, note that $\varepsilon^1_{12}(0)=0$ in column one row one, under $\varepsilon^k_{i2}(0)$ at the top of the table but that $\varepsilon^1_{12}(1)=18$ in this same column and row under $\varepsilon^k_{i2}(1)$ in the lower portion of the table. This is intended to indicate that pumps sent from equipment site 1 to the specified type of spill in region j=2 are not available for deployment until at least 1 period after allocation. See assumptions under Figure 3 and recall that $\varepsilon^k_{ij}(t)$ is the effectiveness t periods after allocation.

Table III gives other parts of the requisite input to this hypothetical example in the form of spillage rates s_j and quality levels, $q^k_j(t)$. The solution to the problem is heavily dependent upon the simultaneous choice of risk and quality levels-- just as the choice of goals is a key factor in more classical goal programming applications. Furthermore, the quality levels must be chosen by Coast Guard managers with knowledge of the spill process and appropriate probability distributions. For example, in this case Table III indicates that the decision maker has provisionally specified $q^1_1(1)=300$ and $q^1_1(2)=200$ which means that in period 1 he would like to have no more than a demand of 300 (thousand) gallons to be offloaded, with a decrease to 200 (thousand) during the second time period. His primary control over these numbers is exerted by offloading in prior time periods, i.e. a quality level of $q^1_1(1)=300$ can be achieved for a potential spill if, during time period 0, a sufficient amount of oil either has already leaked from the vessel or is offloaded. (See constraint (5.6.1).) Of course, too much leakage is not beneficial in that quality levels at subsequent stages must also be met. Observe, as in this example, that designated quality levels, $q^k_j(t)$, should decrease with time so as to promote greater control over the spill with each succeeding interval.

We can now use SIM to illustrate a variety of questions that can be addressed by means of the above data together with the portrayal in Figure 4 below. The latter are supposed to represent graphs that correspond to probability distributions for spill sizes in the indicated regions. To simplify matters we have provided only two different probability distributions by assuming that the same probability distribution (in the lower portion of Figure 4) is applicable to Regions 2 and 3.

As a start we might consider how SIM might be used to aid in developing a Presidential directive. For this situation we omit the Equipment and Delivery Capability constraints in SIM and study the possible equipment consequences for different α and q combinations that might be considered.

We might begin with prior equipment capabilities as one source of comparison. Another source of possible comparison which provides added perspective, however, can be secured by proceeding from what we shall refer to as the "median" and "mean problems" as follows.

We obtain the "median problem" by setting each $\alpha_j^k(t) = .5$ and therefore $F_j^{-1}(.5) = 1$ for each of j=1, 2, 3, as in Figure 4. For this situation almost no equipment is necessary, and this will be true even if quality levels, q, are all set equal to 0 because the median spill is so small. See Table 1.

Throughout this analysis we are assuming that the presidential directive will prescribe the same value α_j^k and the same values q_j^r for all j and will not be concerned with other parts of the distribution. Thus, turning to the "mean problem" we shall specify that version of SIM where each $\alpha_j^k(t)$ is chosen such that $F_j^{-1}(\alpha_j^k(t))$ is equal to the mean of the distribution for its $d_j(0)$. In Figure 4, the means of the spill distribution are shown to be 150 for j=1 and 125 for j=2 or 3. As is approximately the case for spill statistics that have been recorded, these means are shown to occur

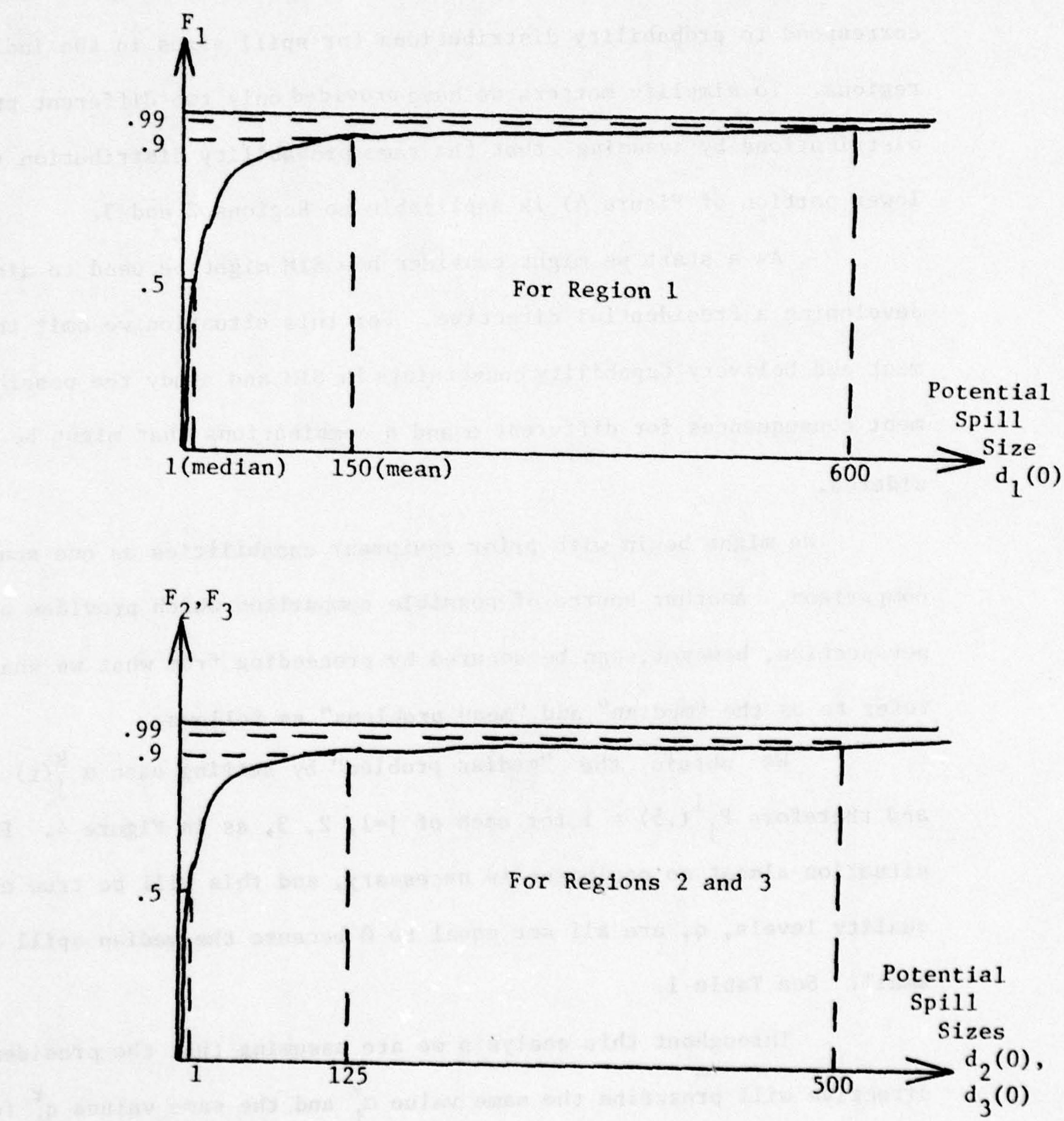


FIGURE 4

PROBABILITY DISTRIBUTION FUNCTIONS OF

POTENTIAL SPILL SIZES

at α_j^k = .90. See [18]. If we now solve the unconstrained "mean problem," a considerable increase in resources is now required (see Table IV) and a total of 0 pumps, 9.6 booms and 5.6 skimmers would be required to meet the specified goals. Here no pumps are needed since, for example, the total volume in region 1 to be controlled is only 150 (i.e. $F_j^{-1}(\alpha_1^1(t)) = 150$) and yet the acceptable quality levels for pumping, $q_1^1(1) = 300$ and $q_1^1(2) = 200$, are both greater than this potential volume.

Finally we turn to the major spill problem which we can study at least provisionally by setting all α_j^k=.99. This then moves the total number of pumps, booms and skimmers to 19.0, 19.7 and 17.6, respectively, when the associated x_i values are optimally sited to the positions noted in Table IV.

In comparing the three solutions, it is interesting to note the quite sizeable consequences in comparison to the median and mean risks which occur when $\alpha_j^k(t)$ = .99. In this example, the $\alpha_j^k(t)$ = .99 percentiles of the distributions occur at spill sizes that are <u>five and six hundred times</u> the medians and <u>four times</u> the means.

TABLE IV

RESOURCES ALLOCATED FOR UNCONSTRAINED PROBLEMS[a]

	Median Problem			Mean Problem			Large Spill Problem		
	$x_{ii}(0)$	$x_{ii}(1)$	Total x_i	$x_{ii}(0)$	$x_{ii}(1)$	x_i	$x_{ii}(0)$	$x_{ii}(1)$	Total x_i
1. Pumps at site 1	.04	0	.04	0	0	0	5.3	0	5.3
2. Pumps at site 2	.04	0	.04	0	0	0	6.5	0	6.5
3. Pumps at site 3	.05	0	.05	0	0	0	7.2	0	7.2
Total Pumps			.13			0			19.0
4. Booms at site 1	.02	0	.02	.2	3.3	3.5	7.3	0	7.3
5. Booms at site 2	.02	0	.02	.1	3.3	3.4	6.7	0	6.7
6. Booms at site 3	.02	0	.02	.2	2.5	2.7	5.7	0	5.7
Total Booms			.06			9.6			19.7
7. Skimmers at site 1	.01	0	.01	0	2.6	2.6	5.5	0	5.5
8. Skimmers at site 2	.02	0	.02	1.5	0	1.5	5.8	0	5.8
9. Skimmers at site 3	.02	0	.02	1.5	0	1.5	6.3	0	6.3
Total Skimmers			.05			5.6			17.6

---

[a]The allocations are shown for time periods 0 and 1 and in total. All positive allocations which occurred were from equipment sites to spill regions containing these sites, i.e., no $x_{ij}(t)$'s were positive for $i \neq j$. Thus only the values for $x_{ij}(t)$ where $i = j$ are shown.

Recall, however, from Table I, that the distributions of oil spill statistics are much more skewed than this.[17] Whereas the median spill is approximately 12 gallons and the mean near 1,700 gallons, 7.5 million gallon spills have actually occurred. This suggests that a large-spill strategy might involve preparing for spills over 625,000 times the median spill or over 4,400 times the average spill! The implication is that an enormous amount of "excess capacity" is required in preparing for the major spills.

Evidently the various types of equipment can be accorded significance for planning purposes only when positioned in a particular location. This is to say that the same equipment in a different location may have different risk-quality consequences and this suggests another question that might be asked by Coast Guard managers. Thus, keeping the above size consequences in mind we might want to study the potential benefits that might be accrued by positioning resources in varying amounts in different regions. Suppose, for instance, that resources were presently at the level given in the "mean problem" discussed above, i.e., that the Coast Guard maintained no pumps but owned 10 booms and 6 skimmers. If the Coast Guard were willing to purchase new equipment to have a total of 19 pumps, 20 booms, and 18 skimmers, what configuration of this equipment would be most effective?

More generally we might phrase this as a question for study by parametric variation to compare risk-quality consequences against other properties that need to be considered by Coast Guard management. Thus using the data in the last column of Table IV we now use SIM to study the x_i allocations associated with $\sum_{i \varepsilon J_e} x_i \leq b_e$ for these particular b_1, b_2, b_3 values by means of the arrays shown in Table V. The solution which optimally allocates these x_i values for the $\alpha_j^k(t) = .99$ is recapitulated

[17] The statistics remain skewed in this fashion even when broken down by source, e.g., by vessels, marine facilities, etc. See [23].

from Table IV to provide the display shown as Alternative 1 in Table V. The other two alternatives may have properties (not necessarily capable of explicit statement) which may commend them to Coast Guard management and to others. Nevertheless something may be obtained in the way of insight by displaying their risk-quality consequences as in Table V. Apparently the risks are quite insensitive to these variations since changes occur only in the third position after the decimal point. Whether this will continue to be the case for variations besides those studied here can, of course, also be determined from the SIM model. In any case, these and other alternatives may be displayed for balancing other considerations against the risk-quality consequences not only for the levels $b_1 = 19.0$, $b_2 = 19.7$ and $b_3 = 17.6$ but for other levels as well.

TABLE V

SOME ALTERNATIVE SOLUTIONS UNDER VARYING RISK

LEVELS WHERE $b_1 = 19.0$, $b_2 = 19.7$ AND $b_3 = 17.6$

		Alternatives I	II	III
Risk Levels (Same for all time periods)	$\alpha_1^{1}(t)$	.99	.987	.985
	$\alpha_2^{1}(t)$	.99	.992	.993
	$\alpha_3^{1}(t)$	.99	.992	.993
	$\alpha_1^{2}(t)$	.99	.988	.986
	$\alpha_2^{2}(t)$	.99	.992	.993
	$\alpha_3^{2}(t)$	.99	.992	.993
From 19 Pumps				
	Pumps to site 1	5.3	3.8	2.9
	Pumps to site 2	6.5	7.2	7.6
	Pumps to site 3	7.2	8.0	8.5
From 19.7 Booms				
	Booms to site 1	7.3	7.0	6.8
	Booms to site 2	6.7	6.8	6.9
	Booms to site 3	5.7	5.9	6.0
From 17.6 Skimmers				
	Skimmers to site 1	5.5	5.2	5.1
	Skimmers to site 2	5.8	6.0	6.0
	Skimmers to site 3	6.3	6.4	6.5

One further aspect of the SIM model is of particular significance in analyzing the Coast Guard "response problem". Interestingly, in practice to date, the ability of the Coast Guard to reach the scene of major pollution incidents has been severely constrained by a lack of sufficient delivery and auxiliary deployment capability. In order to meet all goals (such as directed by the President and interpreted by the Coast Guard), it might well be necessary to purchase not only more cleanup equipment, but also more delivery equipment or, what is almost the same, to ensure that delivery capability is dedicated to pollution response and not available for other Coast Guard purposes. The Coast Guard, for instance, has already decided to purchase several high-speed delivery sea sleds to transport equipment from onshore debarkation points to spill sites. Other capabilities such as air delivery of certain equipment types may be necessary, however, to achieve desired goals.

Recall that the SIM model deals with delivery capabilities in terms of changes in equipment effectiveness across time periods as well as changes in total delivery capacity. **Effectiveness** rates per unit resource are increased in particular time periods whenever equipment can be delivered earlier in the period. For example, an effectiveness of $\varepsilon_{ij}^{k}(2) = 10$ might represent the fact that equipment of type i arrives at j halfway through the second period following allocation. If it could now be made available immediately following the first period after allocation due to faster delivery, e.g. air transport, $\varepsilon_{ij}^{k}(2)$ might be increased to as much as, say, 20. Thus we see that by parametrically varying the $\varepsilon_{ij}^{k}(t)$ coefficients in an appropriate fashion, SIM could be employed to evaluate the increase in goal attainment due to improved delivery capabilities as well as increasing equipment allocations.

This leads us to one further point concerning the illustrations presented earlier in this section. The exclusive allocation of equipment from equipment sites to spills in the same region as occurred in Table IV is by no means a general result. It would be possible, even while employing the zero order decision rule, to allocate resources from equipment sites to distant spill sites. For example, if air delivery is only possible from a single equipment site, it may only be possible to meet various goals in certain (or all) regions by locating equipment at that site -- even though the equipment is to be used primarily in other regions.

7. Data Collection - Implementation of the Model

Of course, a great variety of additional possibilities are available from such uses of SIM. There are other factors, however, which also require consideration. Before such models can be fully implemented appropriate data will have to be collected not only as decision aids for MEP managers but also to help provide answers to Presidential directives, etc. Moreover, these data collections will need to be modified continuously as the following undergo change: (1) oil transport routes and volumes, (2) response technology, and (3) prevention measures, such as improved construction standards.

SIM, the Spill Incidence Model described in section 5, can be accommodated to each of these kinds of developments with the following minimal information requirements for full-scale use:

(1) Determining the appropriate levels of aggregation at which to analyze the problem. For example, it can probably be taken as given that Coast Guard response equipment will be located either at Strike Force locations or near COTP (Captain of the Port) bases. The grouping of possible spills, however, can be made either at district, COTP, or other geographical areas.

(2) The distribution of potential spill volumes, d_j, due to accidents, collisions, etc., by "location", i.e., broken down by general region as discussed in (1) above. A lower bound for potential spill volumes could be chosen in various ways including actual spill volumes as reported in PIRS, the Coast Guard's Pollution Incident Reporting System. The potential

spills, however, include the volume of oil that has been prevented from being spilled, e.g., by offloading from a vessel.

(3) The rates of spillage, s_j, for various pollution incident types. This information is provided in PIRS and could be verified through individual incident reports. Average values could be determined though a range of possible rates must be examined in the model context.

(4) Effectiveness rates $\{\varepsilon_{ij}^{k}(t)\}$ of the various available types of equipment. PIRS data were found to be inadequate for determining these values. Unless PIRS is revised these data must be obtained in other ways such as by interview with users and manufacturers of response equipment.

(5) The availability of delivery capability such as aircraft and sleds. Some of this could be considered as exogenous input (uncontrollable) since, for example, Coast Guard aircraft are usually available on a multi-mission basis and not employed solely as MEP equipment. Also, the time required to transport the response equipment via these delivery systems must be calculated for all possible origin-destination (equipment site-spill site) pairs. This information is also needed to calculate the effectiveness rates as a function of time.

Now we may observe that only a minimum of input from MEP decision makers is required for reasonably intelligent uses of SIM. Managers must assist in the provision of weighting factors to reflect the relative importance of deviations from goals for spills of different types and locations, of course, but a great deal of the burden can be assumed by analysts in the way of providing carefully selected alternatives with their equipment and other consequences. Similarly, although quality levels, $q_j^k(t)$, and risk levels, $\alpha_j^k(t)$, must be determined in principle by MEP managers, a knowledgeable analyst can help to focus attention on significant issues and the kinds of consequences that need managerial attention in these cases, too.

8. Concluding Remarks

As data needs become known and as appropriate data become available, SIM and further related models should be developed for implementation in a framework for parametric variation of the weighting factors and quality and risk levels. Establishing appropriate risk levels, must of course, be done by consideration of the characteristics of appropriate probability distributions, particularly since the more common distributions do not accurately model the process of oil pollution [20]

Furthermore, we note that other developments and model refinements should seek to incorporate further factors that are of importance in combatting marine pollution. This includes factors such as possible alternative deployments, e.g., with Strike Force and other reserves for back up of day-to-day response operations. Mathematically, this will require the use of more sophisticated decision rules than that employed in this study. It will also lead into issues of organization and coordination which tie together routine Coast Guard activities with the ability to deal with catastrophic pollution incidents, both in terms of prevention and response, in ways that will evolve naturally from central office planning before the relevant incidents occur and extend to the response decisions that should occur after the incident has occurred. Still further progress will include prevention as well as response models, of course, but in any case SIM has provided a start which should facilitate progress in these dimensions as well. This, however, is only an "in principle" start, we should specifically note, since, unlike the predecessor GIP model [9], SIM has yet to be used in actual Coast Guard decision making.

APPENDIX

The following geometric portrayals may help to illuminate the more complex developments needed to deal with the multifarious aspects of the problem discussed in the text. Figure A.1, for example, deals only with the single chance constraint

$$P\,[d_j^1(t+1) \leq q_j^1(t+1)] \geq \alpha_j^1(t+1)$$

and the associated deterministic equivalent -- viz.,

$$r_j^1(t) \geq (1-s_j)\, F_j^{-1}(\alpha_j^1(t+1)) - \frac{q_j^1(t+1)}{(1-s_j)}$$

represented by (5.5.4) in the text.

The values such as $r_{j_o}^1$ are supposed to minimally satisfy the latter constraint. Evidently an increase in α_j^1 or a decrease in q_j^1 for the above expression implies a further increase in this minimal value to, say, $r_{j_1}^1$ in order to service them. This means that values smaller than $r_{j_o}^1$ are associated with points to the north and east of the curve for $r_{j_o}^1$.

These curves are derived in a loose qualitative manner from distributions like those of Figure 4 with allowance for the fact that $\beta_j^1 = 1$ and $\alpha_j^1 = 1$ are both attainable, since tanker spill sizes are bounded on both ends. Points like the latter which are of interest in the applications will not, however, be treated in detail here. Instead we shall focus on intermediate ranges of values such as the point $(\hat{\beta}_j^1, \hat{q}_j^1)$ shown in Figure A.1.

Only points within the shaded region will satisfy the double inequality of the above chance constraint when "policy values" $(\hat{\beta}_j^1, \hat{q}_j^1)$ are specified. The curve for $r_{j_o}^1$ has no points in common with this region. Hence this resource level is not adequate to satisfy this constraint.

The curve for $r_{j_1}^1$ does have points in common with this region. Hence it may be employed so that in conjunction with specified optimality (or other choice) criteria selections may be effected from among the available x_{ij} values as determined in (5.3) in association with other $r_j^k(t)$ values for the other pertinent constraints.

The x_{ij} values for $r_{j_1}^1$ may appear excessive as they are portrayed in Figure A.1, e.g., from a financial budgeting standpoint, since within the range of intersection between the shaded region and the $r_{j_1}^1$ curve the resulting program values will strictly satisfy both of the double inequalities in the above chance constraint. Note, however, that this degree of satisfaction for this one constraint may be a consequence that flows from the x_{ij} choices needed to satisfy other constraints.

Among the points of intersection between the shaded region and the $r_{j_1}^1$ curve there are a range of possible choices and it is an objective of the model to help select the best of these admissible choices. Furthermore the model may be turned around, so to speak, and via parameterization and other techniques the possibility of program choices along the $r_{j_1}^1$ curve may also be explored. And this does not exhaust the possibilities that this model offers for such program-policy studies since, evidently, we need not confine ourselves only to variations in the (β_j, q_j) values--as the discussion and the examples in the text serve to illustrate.

We do not propose to carry the discussion of these possibilities for the chance constrained programming model any further since, as in the text, we propose to replace it with a new goal programming formulation. Replacement of the above chance constraint by the corresponding goal

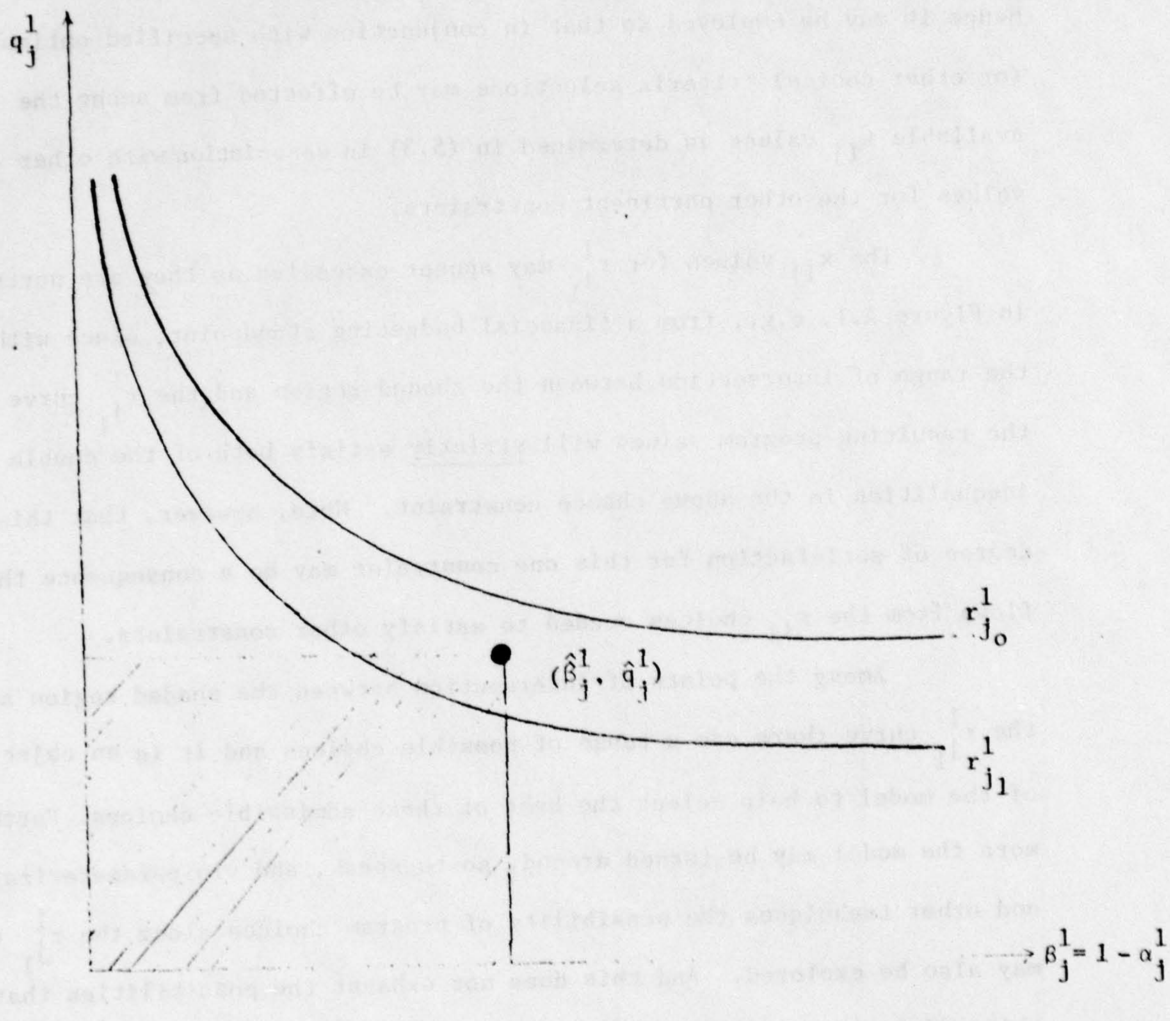


Figure A.1

programming formulation results in a situation which can be portrayed in a diagram such as Figure A.2. Observe, for example, that the 2-dimensional representations of Figure A.1 are replaced by points on the axis for r_j^1. Furthermore, the solution value $r_{j_o}^1$ is also now admissible--as is true for any other r_j^1 choice--with the issue now turning on whether the resulting deviation

$$y_j^{1-} = \hat{F}_j^{-1}(\alpha_j^1) - r_{j_o}^1 \equiv (1-s_j)\, F_j^{-1}(\alpha_j^1(t+1)) - \frac{q_j^1(t+1)}{1-s_j} - r_{j_o}^1(t)$$

is "satisfactory."

To determine this, one will, of course, generally need to consider this deviation in the light of other deviations as well. In order to highlight this aspect of the problem of choosing goals and the associated decision variable possibilities--see (5.3)--we have matched this underattainment of an offloading goal in Figure A.2 with an overattainment of the associated containment goal, <u>viz.</u>,

$$y_j^{2+} = r_j^2 - \hat{F}_j^{-1}(\alpha_j^2) \equiv r_j^2(t) - z_j(t+1)\, F_j^{-1}(\alpha_j^2(t+1)) + q_j^2(t+1)$$

where

$$z_j(t+1) \equiv s_j(1-s_j) + s_j.$$

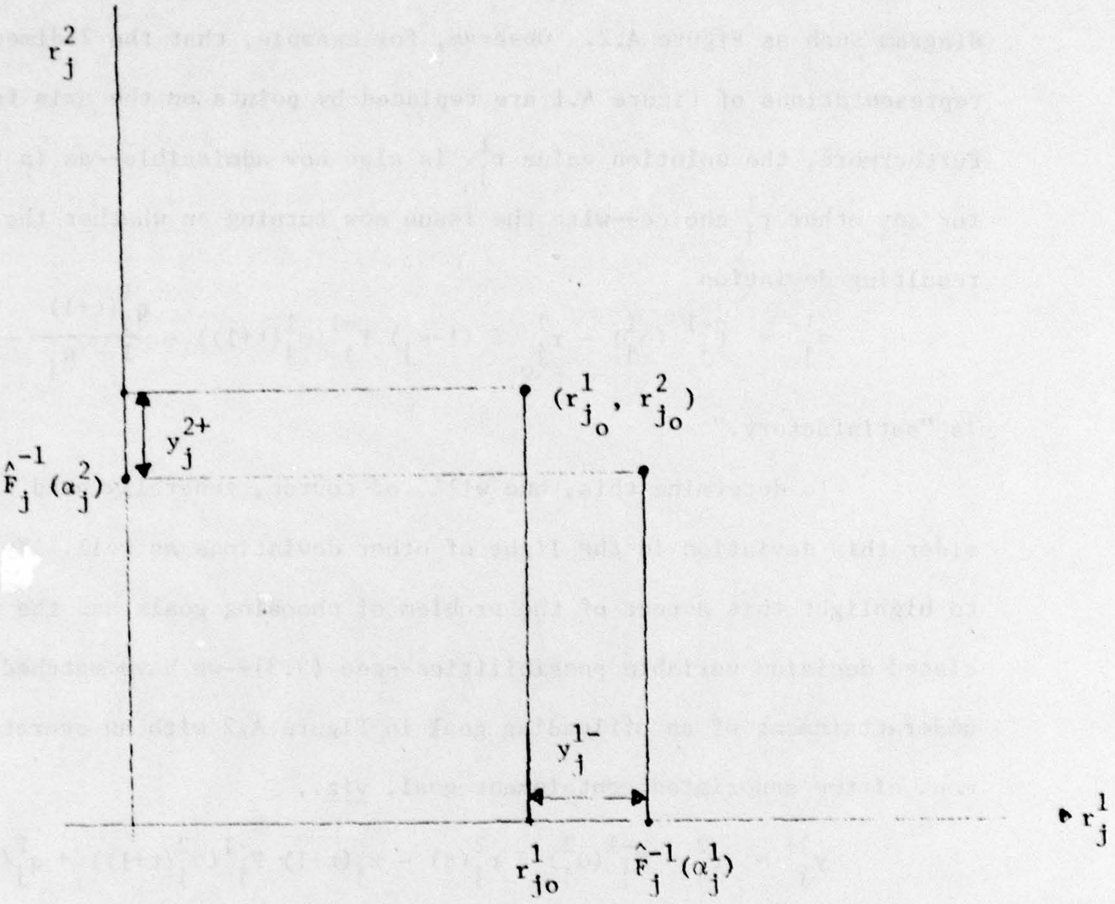

r_j^2
$(r^1_{j_o}, r^2_{j_o})$
y_j^{2+}
$\hat{F}_j^{-1}(\alpha_j^2)$
y_j^{1-}
r_j^1
r^1_{jo}
$\hat{F}_j^{-1}(\alpha_j^1)$

Figure A.2

To some extent, as noted in the text, the issue of choosing between deviation values like these may be resolved by suitably chosen weights. E.g., the fact that containment is incidental to offloading and removal suggest that it should be given the lowest "relative" weight.[18] In situations such as the ones that the Coast Guard confronts in its management planning problems, however, an in-context approach to these weight possibilities relative to other approaches should be used, we think, rather than the kind of out-of-context approaches such as might be used to ascertain the preferences of an individual decision maker bent on satisfying himself.[19] For instance, a choice between weights in the functional and goal variations in the constraints might be considered for separate or joint use as analytical convenience and psychological appeal to various decision makers may suggest. This may include specifying certain balances which need to be maintained, at least approximately, and may also include the insertion of maximum allowable deviations from particular goals. These and other such extentions are easily effected for the models in the text.[20]

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[18] We will not consider the further issues involved in a use of "absolute" and "pre-emptive" priorities such as are discussed in Ijiri [17].

[19] See Karwan [18] for further detailed discussions and developments.

[20] It has been the authors' experience that decision makers are likely to think more easily and be more directly responsive to questions about balance conditions between goals and/or maximum permitted deviations for particular goals than when such decision makers are restricted to choosing between different sets of weights. See the discussion of "goal focusing" approaches, etc., in A. Charnes, W. W. Cooper, A. Schinnar and N. Terleckyj [10].

As experience develops, one might turn to other functionals of a goal programming variety.[21] This could certainly include the piecewise linear extensions that proved successful for segmenting the different degrees of goal discrepancy in the GIP applications[9]. It would also include the minimax and maximin considerations that are involved in a Chebychev metric since algorithms now exist for use in multi-dimensional goal programming contexts. See [8].

Of course, when the equipment and delivery capability limitations are removed from SIM -- so that the goals are all attainable -- then different choices of positive weights or even different choices of functional in the objective will not affect the optimum set of solutions. A focus on a "weights only" approach would thus seem to rank fairly low among the candidates from an almost embarrasing number of alternatives.[22] Nevertheless the choice of weights is a topic of interest. Therefore to conclude this Appendix we now sketch some of what is involved in such weight variations with special reference to the ℓ_1 metric.[23]

The two sets of arrows portrayed orthogonally in head-to-tail fashion in Figure A.3 both terminate on the line labelled $\mathcal{L}_1$. Here we are using the so-called ℓ_1 metric for which only the one segment in the positive quadrant is shown since this is the only segment of the usual "baseball-diamond" portrayal of this metric which will be of interest to us.[24] All points on this line are equidistant from the origin. That is, the two solid arrows and the two broken line extensions both terminate on this line, which means that for each pair the sums of their absolute values

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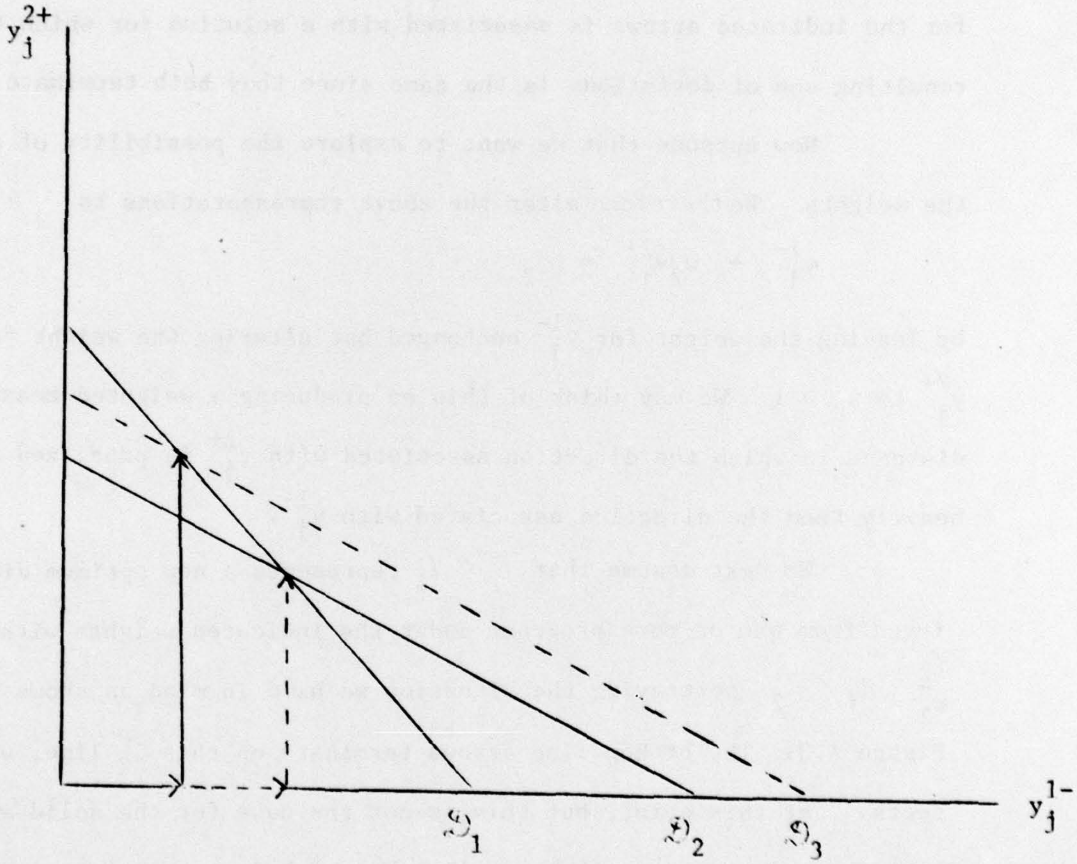
[21] See, e.g., the discussion of "proper" goal functionals in [8].

[22] Another trouble with the "weights only" choice is that many different weights may yield the same (optimal) program choices with, as in goal programming, only an alteration in the figure of merit to show for whatever effort was expended. See, e.g., pp. 130-136 in [13].

[23] For further discussion of these metrics and their relation to goal programming see Appendix A and Chapter X in [4].

[24] See Appendix A in [4].

Figure A-3



is the same. Since we are restricting our considerations to non-negative values, we can dispense with the absolute value signs and write

$$y_j^{1-} + y_j^{2+} = \delta_1$$

to mean that the values (y_j^{1-}, y_j^{2+}) are at a distance δ_1 for all coordinates of this line.

We may think of the two sets of values (y_j^{1-}, y_j^{2+}) explicitly portrayed in Figure A.3 as alternate optima. That is, each pair of values for the indicated arrows is associated with a solution for which the resulting sum of deviations is the same since they both terminate on $\mathcal{D}_1$.

Now suppose that we want to explore the possibility of altering the weights. We therefore alter the above representations to

$$y_j^{1-} + w_2 y_j^{2+} = \delta_2$$

by leaving the weight for y_j^{1-} unchanged but altering the weight for y_j^{2+} to $w_2 > 1$. We may think of this as producing a weighted measure of distance in which the direction associated with y_j^{2+} is penalized more heavily than the direction associated with y_j^{1-}.

We next assume that $\delta_2 < \delta_1$ represents a new optimum distance achieved from one or more programs under the indicated weights with also $\frac{\delta_2}{w_2} < \delta_1 < \delta_2$ portraying the situation we have in mind as shown by $\mathcal{D}_2$ in Figure A.3. The broken line arrows terminate on this $\mathcal{D}_2$ line, which intersects $\mathcal{D}_1$ at this point, but this is not the case for the solid arrows. The latter terminate on another new line $\mathcal{D}_3$ which is parallel to $\mathcal{D}_2$ but further away from the origin and hence not optimal.

Evidently the solution with the solid arrows has lost its optimality property relative to the broken line alternative which shortens the arrow for y_j^{2+} in exchange for a lengthening[25] of the arrow for y_j^{1-}.

The fact that the program which generates the distance for the broken line arrows is optimal under both the old and the new weights is of special interest. Thus in this case the new figure of merit, α_2, replaces the old α_1 value without any change in the underlying values of the decision variables. This shows that it will generally be necessary to consider all alternate optima (usually a great number are present) for each set of weights before deciding whether one set is preferred to another. Finally, we might observe that the availability of alternate optima may itself be a desideratum, which is to say, again, that these matters are best approached in context with a variety of other approaches to the problems of choice evaluations in management planning.

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[25] We are eliding the separate mathematical concepts of "distance" and "length" in the interests of brevity. See Appendix A in [5]. We have also not expressed our distance functions in a wholly rigorous manner in that we have omitted dividing through by the appropriate norming constants since (a) this would require additional, possibly distracting, explanations from the main points we wanted to make, and (b) these norming constants would be eliminated in any case en route to making these points. See, e.g., pp. 262-263 in [5].

FOOTNOTES

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FOOTNOTES

2. The most prominent of the resulting laws are the Federal Water Pollution Control Act and its Amendments.
3. See, e.g., Newsweek accounts for the week of January 17, 1977.
4. This is a revolving fund used to defray cleanup costs where the polluter cannot or will not effect cleanup, or where the polluter cannot be identified. The fund is revolving in that, under certain liability limitations, the polluter must reimburse the fund for actual costs incurred by the U.S. government.
5. Source: U.S. Coast Guard's Pollution Incident Reporting System.
6. This is also the "firehouse problem" where seldom used resources must be maintained for emergency purposes. We observe that these resources provided by the public sector are essentially "excess capacity" from the standpoint of "normal" operations.
7. The Coast Guard maintains a network of multi-mission field units. The majority of these are designated as Captain of the Ports (COTPs), Marine Safety Offices (MSOs) or Port Safety Stations.
8. We will deal primarily with vessel spills since they have historically constituted the majority of all "catastrophic" spills and because spills of this type potentially involve all of the possible operational "stages" of pollution response that are likely to enter into any other large spill scenario.

FOOTNOTES (cont.)

9. One further stage that may merit future consideration involves beach cleanup of spillage that has not been contained and removed and washes up on the shoreline. To date, this stage has been of less interest to the Federal Government because it appears to have been adequately managed by private contractors and local groups.

10. We assume that the total amount of spillage in any time period is directly proportional to and depends only upon the potential spill volume at the beginning of that period.

11. In the sense described on p. 260 of [11] wherein $\alpha=0.5$ indicates "indifference" to servicing the stipulated quality level and $\alpha=1.0$ converts the "policy" into a "rule".

12. See, e.g. [6], for a discussion of decision rules and the conditions for effecting the indicated inversions in the context of chance constrained programming. An example of the kind of decision rule that might be employed in a real time operating context may be found in [12].

13. Recall that d_j contains decision variables r_j.

14. See also Contini [14] and Ijiri [17] for other possible approaches.

FOOTNOTES (cont.)

15. Such choices are not necessarily decisive in producing anything more than a figure-of-merit alteration and, in fact, one may erect examples in which all possible sets of positive weights have only this effect.

    See [13] and [10]. A detailed discussion which includes a review of many of the standard approaches from economics, psychology, etc., for their possible uses and shortcomings for this class of problems may be found in [18].

16. Cf., e.g., W. Baumol [1].

17. The statistics remain skewed in this fashion even when broken down by source, e.g., by vessels, marine facilities, etc. See [23].

FOOTNOTES (cont.)

18. We will not consider the further issues involved in a use of "absolute" and "pre-emptive" priorities such as are discussed in Ijiri [17].
19. See Karwan [18] for further detailed discussions and developments.
20. It has been the authors' experience that decision makers are likely to think more easily and be more directly responsive to questions about balance conditions between goals and/or maximum permitted deviations for particular goals than when such decision makers are restricted to choosing between different sets of weights. See the discussion of "goal focusing" approaches in [10].
21. See, e.g., the discussion of "proper" goal functionals in [8].
22. Another trouble with the "weights only" choice is that many different weights may yield the same (optimal) program choices with, as in goal programming, only an alteration in the figure of merit to show for whatever effort was expended. See, e.g., pp. 130-136 in [13].
23. For further discussion of these metrics and their relation to goal programming, see Appendix A and Chapter X in [4].
24. See Appendix A in [4].
25. We are eliding the separate mathematical concepts of "distance" and "length" in the interests of brevity. See Appendix A in [5]. We have also not expressed our distance functions in a wholly rigorous manner in that we have omitted dividing through by the appropriate norming constants since (a) this would require additional, possibly distracting explanations from the main points, and (b) these norming constants would be eliminated in any case en route to making these points. See, e.g., pp. 262-263 in [5].

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