PD-AAX-277 54568

[redacted]

AGENCY FOR INTERNATIONAL DEVELOPMENT

PROJECT PAPER FACESHEET

TO BE COMPLETED BY ORIGINATING OFFICE

1. TRANSACTION CODE ("X" appropriate box)
[X] Original [ ] Change [ ] Add [ ] Delete

PP

DOCUMENT CODE 3

2. COUNTRY/ENTITY: INTERREGIONAL

3. DOCUMENT REVISION NUMBER

4. PROJECT NUMBER: 931-11-590-0260

5. BUREAU: a. Symbol: TAB; b. Code: 6

6. ESTIMATED FY OF PROJECT COMPLETION: FY 79

7. PROJECT TITLE (SHORT (stay within brackets)): EFFICIENCY OF HEALTH MEASURES

8. ESTIMATED FY OF AUTHORIZATION/OBLIGATION: a. INITIAL mo. 7 yr. 75; b. FINAL FY 78

9. ESTIMATED TOTAL COST ($000 or equivalent, $1 =)

a. FUNDING SOURCE	FIRST YEAR FY T.Q. b. FX	c. L/C	d. Total	ALL YEARS e. FX	f. L/C	g. Total
AID APPROPRIATED TOTAL			192			296
(Grant)	( )	( )	(192)	( )	( )	(296)
(Loan)	( )	( )	( )	( )	( )	( )
Other U.S. 1.						
Other U.S. 2.						
HOST GOVERNMENT						
OTHER DONOR(S)						
TOTALS						

10. ESTIMATED COSTS/AID APPROPRIATED FUNDS ($000)

a. Appropriation (Alpha Code)	b. Primary Purpose Code	c. Primary Tech. Code	FY T.Q. d. Grant	e. Loan	FY 77 f. Grant	g. Loan	FY 78 h. Grant	i. Loan	ALL YEARS j. Grant	k. Loan
PH	594	520	192		-		104		296	
TOTALS									296	
11. ESTIMATED EXPENDITURES			20		89		109			

12. PROJECT PURPOSE(S) (stay within brackets) [ ] Check if different from PID/PRP

To increase current knowledge concerning the effectiveness with which alternative health sector technologies influence health status of target groups of infants and children under five years of age in selected LDCs.

13. WERE CHANGES MADE IN BLOCKS 12, 13, 14, or 15 OF THE PID FACESHEET? IF YES, ATTACH CHANGED PID FACESHEET.

[ ] Yes [X] No

14. ORIGINATING OFFICE CLEARANCE

Signature: Lee M. Howard, M.D.

Title: Director, Office of Health

Date Signed: mo. 06 day 15 yr. 76

15. Date Received in AID/W, or For AID/W Documents, Date of Distribution: mo. day yr.

AID 1330-4 (7-75)

Block 10. Estimated Costs/AID Appropriated Funds (Continued)

	FY 79
	Grant
	-

Block 11. Estimated Expenditures (Continued)

	FY 79
	Grant
	78

Drafter: JHDavis, TA/H 6/22/76
JWJacobs, TA/H 6/22/76

Originating Office: HRCordova, TA/H 6/22/76
RDNewman, TA/H 6/22/76

Other Offices: M. Reohcigl, TA/RES 7/14/76
L. Wakefield, TA/PPU 7/13/76
C. Fritz, TA/PPU

PROPOSED BUDGET

Personnel Positions	Annual Salary Rate	mm	Year 01 Salary	Benefits	mm	*Year 02 Salary	Benefits
Project Director	22,667	6.5	12,278	2,087	8.75	17,354	2,950
Project Officer	29,035	2.0	4,839	823	2.0	5,081	864
Pediatrician (Local national)	14,769	6.5	8,000	-	6.5	8,400	-
Research Assistant	6,410	12.0	6,410	1,090	12.0	6,730	1,144
Secretary	8,975	5.0	3,740	635	5.0	3,926	667
			35,267	4,635		41,491	5,625

*Calculation based upon 5% p.a. increase

		Year 01		Year 02
Personnel		39,902		47,116
Consultants @ $100/day	10 days	1,000	30 days	3,000
Travel & Per Diem				
International Travel @ $1180/trip	2 trips	2,360	3 trips	3,540
Per Diem @ $45/day	60 days	2,700	240 days	10,800
Domestic Travel @ $135/trip, (3 DC-Ann Arbor R/T and 3 Ann Arbor-Los Angeles R/T)	6 trips	810	As Year 01	810
Per Diem @ $35/day	150 days	5,250	60 days	2,100

PROPOSED BUDGET - continued

Other Direct Costs	Year 01	Year 02
Telephone	300	350
Supplies	1,200	1,300
Printing & Reproduction	300	350
Contract Services (Computer usage)	1,300	1,300
Survey	-	5,000
Field Research Costs	-	6,500
Overhead	24,612	30,100
TOTAL	79,734	112,266

MEMORANDUM TO THE ASSISTANT ADMINISTRATOR

TO : AA/TA, Mr. Curtis Farrar DATE: July 13, 1976

FROM: : TAB/PPU, Carl R. Fritz

SUBJECT: PP Approval - "Efficiency of Health Measures"

Problem: Your approval is requested of the attached Project Paper(PP) "Efficiency of Health Measures" authorizing the obligation of $192,000 in the Transitional Quarter for implementation of Phases I and II of the three-year project and providing $104,000 FY 78 funds for Phase III subject to satisfactory completion of the first two phases. Total cost of the proposed project is $296,000.

Discussion: The general purpose of the project is to increase current knowledge about the effectiveness with which alternative health technologies influence infant and childhood health and mortality. The specific products to be obtained are: (1) a state of the art analysis of the literature, (2) a simulation model of infant and childhood morbidity and mortality, (3) a linear programming model specifying the most cost effective interventions to ameliorate morbidity and mortality and (4) a final report summarizing findings and describing their policy implications. The project will be implemented by means of a contract with the University of Michigan if the request of TA/H for a predominant capability determination is approved.

Phase I of the project will consist of: (1) an extensive literature search and (2) the preparation and development of a simulation model describing infant and childhood mortality and identifying the variables to be considered in subsequent stages.

Phase II of the project will consist of: (1) an estimation of the costs of alternative interventions, (2) a preliminary assessment of the effectiveness of various interventions from the literature surveys and (3) the development of prior estimates of these variables by experts using techniques like Delfi.

Phase III will consist of the development and implementation of the linear programming model and preparation of the final report.

The project was considered and approved at the March 10 R&D Committee meeting. However, you had stated that this proposal, which was presented as a General Technical Services (GTS) project, was borderline research in nature and suggested that it be forwarded to the RAC for comments. On May 25, 1976, the RAC reviewed the proposed project. The RAC found the research area an important one but felt that the proposal lacked specificity. The RAC took no formal action, since it was not requested to do so, but offered the services of Dr. Earl Heady to review the project with the proposed contractors and the project monitor. On June 14, Drs. Heady and Davis met with the University of Michigan contractors and reviewed their methodology. Drs. Heady and Davis were satisfied as to the appropriateness

of the methodology proposed and the capabilities of the contractors to do the tasks outlined in the project proposal.

TA/H is submitting the original PP, as approved by the R&D Committee and considered by RAC, for your approval. Implementation of Phase I and II will be completed and evaluated prior to initiation of Phase III. TA/H has extracted from the research proposal the financial requirements for Phases I and II and presented this budget for TQ funding as an attachment to the PP face sheet.

Recommendation: That you approve the attached "Efficiency of Health Measures" PP authorizing the obligation of $192,000 TQ funds for implementing Phase I and II of the project and providing $104,000 of the first two phases.

Attachments:
PP - Efficiency of Health Measures
Tab A Minutes of RAC May 26 Meeting

Approved: M Belche for C Farman

Disapproved: _____

Date : July 22 '76

Clearances:
TA/PPU:JGunning (Draft) Date 7/21/76
TA/RES:MRechcigl (Draft) Date 7/21/76

b

ENVIRONMENTAL THRESHOLD DETERMINATION

TO: AA/TA, Mr. Curtis Farrar

THRU: TA/PPU

FROM: TAB/PPU, Carl R. Fritz

SUBJECT: Environmental Threshold Determination

Project Title: Efficiency of Health Measures
Project #: 260
Specific Activity (if applicable) _____
REFERENCE: Mr. Printz, the Environmental Coordinator, has reviewed the PP for project proposal and discussed it with Ms. Wakefield. He and TA/PPU concur that a negative environmental threshold determination is appropriate for this project.

On the basis of the Initial Environmental/Examination (IEE) referenced above and attached to this memorandum I recommend that you make the following determination:

X 1. The proposed agency action is not a major Federal action which will have a significant effect on the human environment.

___2. The proposed agency action is a major Federal action which will have a significant effect on the human environment, and:

___a. An Environmental Assessment is required; or

___b. An Environmental Impact Statement is required.

The cost of and schedule for this requirement is fully described in the referenced document.

___3. Our environmental examination is not complete. We will submit the analysis no later than _____ with our recommendation for an environmental threshold decision.

Approved: MS Belcher

Disapproved: _____

Date: July 22 '76

TA/OST, ACPrintz (Subs)

I. B.1 Recommendations (Supersededby attached Proposed Budget)

Grant	$300,726.00 $295,880.00	Ghana Assumption Colombia Assumption
Total new AID obligations	$300,726.00 $295,880.00	Ghana Assumption Colombia Assumption

I. C.1 Description of the Project

The project will review the literature on the inter-action between the socio-economic environment and infant and toddler mortality. On the basis of an extensive survey of expert opinion, and a field study, a simulation model of this inter-action will be created. Using the results of the simulation model, a linear programming model will be developed to find the least cost method of reducing infant and toddler mortality.

The project will last for three years and will require an estimated 8 man-years of labor.

I. C.2

The project will be organized and carried out by a U.S. contractor.

I. C.3

The assurance of project completion rests to a considerable extent on the quality of the U.S. contractor selected. The "physical products" of the work will be the reports they produce: A survey of the literature, a simulation model and a linear programming model.

Results will be disseminated by (1) dissemination of final report through AID Health Planning network, (2) by the wide network of professional journals published in this area and (3) by a series of planned regional conferences in health planning.

I. D. Summary Findings

The project proposed relates directly to the goals of the Key Problem Area of Health Planning. These goals are to bring about a more efficient allocation and more equitable distribution of health sector resources. This project is expected to yield significant new information concerning the efficiency with which alternative interventions reduce infant and childhood mortality.

The external reviews of this project have been favorable (See Annex I). It is the opinion of the technical office that the project as a whole is both feasible and useful.

It is assumed that the project will be ready for implementation in CY 1976. A contractor will be selected and contacts made with potential LDC collaborators in July or August.

The project meets all apllicable statutory criteria.

I. E. Project Issues

The single project issue as identified by our external reviewers is the feasibility of using Bayesian estimates for simulation model variables. It is proposed that the project be initiated under the assumption that this method of estimating project variables is feasible and schedule an intensive review at month 15-20 of the project to review this aspect of project implementation. If the use of Bayesian estimators has not proven feasible, the remainder of the project should be cancelled at the juncture. The proposed use of Bayesian estimators is described in Annex II.

II. Project Background and Detailed Description

A. Background

A salient aspect of the underdevelopment of the Third World is the persistence of a high rate of morbidity and mortality from diseases largely eradicated in the developed world. This is a matter of pressing concern to the developing world, both because it stands as one measure of their poverty and underdevelopment, and because it looms as a fundamental obstacle to a structural transformation of the social and economic environment. The large share of government resources devoted to the medical and health sector reflect the urgency and importance attached to these problems.

Among health problems, the high rates of morbidity and mortality among the under-five population are perhaps the most serious. The death of children saps the motivation of parents and inspires a fatalistic perspective on efforts at changing their economic environment of their behavior. High infant mortality rates appear to lead to high fertility levels and may even contribute to the large family sizes desired by families in less-developed areas. The social burden of high rates of population growth is well-known, but the impact of high fertility on the state of maternal health and productivity, and on childhood malnutrition is of equally pressing and perhaps more immediate concern. Similarly, the factors underlying high infant mortality suggest the concommitant debilitating effect of morbidity on the potenial productivity of the children who survive.

Economic policymakers have only recently begun to recognize the gravity and portent of health problems for development. Yet efforts

to mobilize resources effectively to address these problems have been stymied by a dearth of research which could provide health policy guidance and by the non-problem oriented approach of health ministries. Planning is a new and very recent development in the health ministries of the developing world and where it is present, it is focused on implanting a more rational and effective distribution of health infrastructure and resources. In few countries does the pattern of health resource allocation derive from a prior evaluation of how best to attack the country's principal health problems. As a consequence, where a cohesive integrated set of policies is required to attack a pressing disease problem, one usually observes fragmented, uncoordinated and often counterproductive efforts by the separate agencies controlling the instruments of policy interventions. No single agency or ministry is in a position to pull together all the pieces of an integrated program. The result is extensive inefficiency in the allocation of health sector resources in most developing countries.

Efforts by economic planners to influence the direction of government policy are equally stymied by the dearth of health policy-oriented research from which they could draw guidance. Though they may be aware of the pressing health problems, they have nowhere to turn but to the health ministries for guidance as to the effective ways of attacking these problems. Until recently, economic analyses of the health problems of the developing world have been largely nonexistent.

The significance and rationale of this project arises from our perception of these critical bottlenecks to rational health sector decision-making and the importance of the infant and toddler mortality problem in the developing world. Pursuing the line of research begun by

* Feldstein, et al., this project will further develop an analytical framework within which disease processes and appropriate intervention strategies may be modelled. Unlike their research on tuberculosis this study will focus on a health problem which arises from the interaction of a complex of disease problems and for which policy actions may be both medical and nonmedical.

the project should also test the validity of the hypothesis that it is possible to estimate "Bayesian" measures, through survey analysis, of the impact of alternative policy interventions on the probability of incidence or survival from different disease problems. Such measures are probably not as accurate as the results derived from careful, controlled medical research, but the latter kind of research is a slow, time-consuming and expensive process. Yet the problems are of such importance and urgency, that policy decisions cannot be indefinitely postponed. If this approach is successful, it would allow decision makers to make policy judgements based on the integration of the best judgements of the medical profession into a coherent analytic model. Where professional uncertainty is great, the sensitivity of alternative assumptions for policy outcomes can be explored. Moreover, this approach can be easily applied to the analysis of other health sector problems.

Finally, the project should yield valuable insights into the set of policies which are most likely to be effective in attacking the problem of high levels of infant and toddler mortality. For example, what is the relative cost-effectiveness of policies to provide potable water or pit latrines relative to the provision of curative health services? The

impact of the various maternal-child health programs? Of mass-immunization campaigns? At the present time, there is no clear sense of which programs are the most cost-effective, and in what mix they should be provided. This project should prove rough but reasonable answers to these questions.

This project is the logical outgrowth of four strands of health and medical research relating to the problem of infant mortality or health sector analysis. First, several economists have sought, through econometric research, to determine the principal factors underlying high levels of infant and toddler mortality. The AID-financed study by Louise Russell on the Pan American Health Organization infant-mortality data bank represents the most current and ambitious effort. An earlier work by Frank Sloan of RAND and current research by the project director are similar attempts to explore the factors explaining the variance in infant and toddler mortality rates within countries, particularly as they relate to models of fertility.

These studies can yield useful qualitative insights to policy makers into some of the behavioral, environmental and medical determinants of child survivorship. It is obviously important to know whether female illiteracy rates and low birth weights are significant in explaining infant mortality, or whether physicians or hospital beds per capita are insignificant. However, although these results are helpful, they are probably not sufficient for a choice of policy actions to remedy the infant and toddler mortality problem. Questions persist; for example, how strong are the observed relationships? What specific policy interventions may be used to influence these principal

determinants? These are not easy questions when the policy maker is also confronted with striking financial and skilled manpower constraints. Hence, this strand of research will be valuable in guiding the present project, but it will by no means be duplicative.

A second strand of research is the recent intensive and extensive work of the Pan American Health Organization in describing the characteristics of infant and child mortality in Latin America. Summarized in the recent work by Ruth R. Puffer and Carlos V. Serrano, Patterns of Mortality in Childhood, a massive volume of data has been collected on the associated and underlying causes of infant mortality in seventeen areas of South and North America, with information on the demographic, epidemiological and socioeconomic correlates of approximately 33,000 infant deaths. It provides the kind of data which could be easily used as the baseline data for the type of analysis proposed in this project, and is one of the reasons why Colombia has been suggested as a feasible country for the proposed study. It does not, however, attempt to focus on the analytical issues underlying the choice among alternative policies. A similarly large data-collection effort has been mounted in connection with the Danfa Rural Health and Family Planning Project in Ghana. Although not wholly focused on the infant mortality problem, a large volume of data has been collected on the epidemiological characteristics of the child population, as well as on socio-economic, demographic and health-behavioral variables. This work could also provide the baseline data required for our project.

An equally important strand of work relates to the operational and theoretical research, past or currently underway, in many LDC's on the treatment and prevention of maternal and childhood disease problems. There is a large literature on the problems of infant mortality, as is clear from the annotated bibliography. Of particular interest is the work by Drs. Ofosou-Amaah and Nicholas with the Danfa Project in Ghana, David Morley and Dr. Ransome-Kuti in Lagos, Nigeria, Nevin Scrimshaw in Guatemala, D. Jellife and Cicely Williams, and of the WHO Maternal-Child Health Team in Colombia under Dr. Agualimpia. These research efforts provide a rich source of data and experience which will be vitally important as inputs for our task of quantifying the effect of different policies. It is precisely the wealth of medical research experience which suggests that it is feasible to estimate measures of the impact of alternative policy interventions which may be usefully integrated into an analytic policy model.

Finally, a fourth strand of work is the linear programming model of alternative tuberculosis policies in Korea developed by Feldstein, *et. al.* In many respects, this provides a basic framework for the proposed research, in that many of the methodological problems involved in our project are quite similar. An equally ambitious effort at developing a linear programming model of the nutrition sector is currently underway by AID in Colombia (Colombia Sector Assessment Activity).

B. Detailed Description

The project design and resource requirements may be considered in three phases of one year's duration each.

1. A review of the literature, the final choice of a country with sufficient baseline data on the under-five population for the

subsequent empirical phases, and the modeling and simulation of the interaction between alternative policy interventions and the health status of the target child population;

2. Empirical estimation of (a) the impact of alternative policy interventions on the incidence of a set of priority health and disease problems and on the probability of child survivorship, and (b) the cost of alternative policy interventions; and,

3. Empirical specification and analysis of a linear programming model to determine the optimal mix of intervention strategies for reducing the risk of mortality in the under-five population; the model will be simulated for alternative objective functions, technological parameters, degrees of budget constraint and combinations of specific medical problems.

Phase 1

Project Design

A fundamental premise underlying this project is that it is possible to model the processes by which a child is exposed, as a fetus, infant or toddler, to health and medical problems carrying significant risks of mortality. Through such a model, one may explore the impact of alternative policy interventions on the probability that a child will contract and succumb to these disease processes over the course of its early years. Such a model may then be empirically specified and applied for an evaluation of the optimality of alternative health sector policies aimed at reducing the rate of neo-natal, infant and toddler mortality in a target child population. Principal emphasis here will be on this problem as mainfested in the rural areas.

Phase 1 will concentrate on three principal tasks: (a) an extensive literature review on the role, interaction and relative importance of the medical and socioeconomic factors underlying infant mortality from specific disease processes, intra-utero and by year for first three years after birth; (b) development and simulation of a model of the infant mortality process which, in subsequent phases, may be empirically specified as a linear programming model for evaluation of alternative intervention strategies; and (c) the final choice of a baseline population in a less developed country for which sufficient epidemiological, socioeconomic and demographic data exist to serve as the focus of the empirical research in Phases 2 and 3. At the present time, Ghana or Colombia appear the most suitable for this effort.

The nature of the modeling problem encompasses medico-technological and economic issues and may be briefly outlined. The nature of the disease problems to which a child or fetus is susceptible and their potential severity will differ as a child passes through different phases of its early life span. The <u>ante-natal</u>, <u>peri-natal</u>, <u>neo-natal</u>, <u>infant</u> and <u>toddler</u> phases characterize distinct periods associated with different complexes of medical problems with specific risks of mortality. It is likely that the optimal mix of the policy measures to reduce these risks will probably also differ in each period. The optimal policy mix for the child population will obviously be influenced by the relative fraction of the child population in each age group, a demographic characteristic heavily influenced by fertility levels. The proposed model will primarily focus on the possible interventions associated with the four or five

principal causes of infant mortality in each of these periods in the target country's childhood population. The selected causes would include diarrheal diseases, low infant birth weight, pneumonia and child spacing.

In each of these periods, the probability that a child will contract a given illness or survive it, will obviously differ across children, as will the impact of any policy intervention on these probabilities of incidence or survival. Children begin each period of their lives with different endowments of family resources (the quantity and quality of maternal attention, the level of family income), in environments of varying quality (the availability of potable water or sewage, the prevalence of dangerous disease vectors) and in their own level of health (initial birth weight, prematurity), calendar month of birth. These "endowment" variables are obvious factors which influence whether a child will be exposed to certain disease problems, whether a disease is likely to be severe with risk of mortality, and the degree of the child's responsiveness to treatment. As a child moves from one period to another, its susceptibility to diseases and to the risk of mortality is obviously also influenced by its past history of morbidity and by the effects of that morbidity. For example, an infant of low birth weight that has been weakened by a gastro-intestinal disease is likely to be more susceptible and more in jeopardy of not surviving subsequent respiratory ailments. The potential efficacy of treatment cannot be independent of a child's initial state of health.

One implication is that the impact of policy actions on the probability of incidence or survival are a function of the child's endowment variables. Con-

commitantly, policy actions taken during any given period will not only influence the probability of survival in that period but also the probabilities of being susceptible to disease and morbidity in subsequent periods.

Policy actions may be preventive -- lowering the probability of contracting various disease problems -- or curative, raising the probability of survival with any illness, once contracted. Policy actions may be directly focused on the child or may be focused on improving the quality and quantity of inputs (for example, maternal-child health education) to the child. Finally, in any population pool, there is an obvious interdependence between the state of health of different individuals. A substantial boosting in the probability of survival for one set of children, by explicit policy actions, is likely to have positive expernality effects on the probability of survival of other children.

Economic issues emerge in the specification of the model's objective function and of the constraints which delimit the range and magnitude of policy actions. At one level, the goal may be to raise the probability of survivorship for population pool of children, which is the equivalent of a fall in infant and toddler mortality rates. At another level, it is important for policy makers to evaluate the economic value to society of any changes induced in the probability of survivorship. This involves complex issues, relating both to the economic value of the individual child as well as to the complex demographic effects of a reduction in infant mortality rates, such as on fertility. The specification of the constraints on the model involves economic and demographic

factors. The level of budget resources, the availability of skilled medical and paramedical manpower, and the existing institutional structure sharply constrain the feasible set of policy actions.

In Phase 1, the structure of this model will be specified in terms of delimiting: (a) the relationship between the various endowment variables and the probability of alternative disease problems and survivorship during the different phases of the child's first five years; (b) the set of relevant policy interventions; (c) the direction and structure of their impact; (d) the interdependencies between the probability of disease and survivorship across children; (e) the objective function, and (f) the economic, institutional and demographic constraints. The initial modeling is a crucial and complex task, since it will significantly shape the research design issues in the subsequent phases of the project. The comprehensive review of the medical and socioeconomic literature during this phase will be instrumental in clarifying many of the model's relationships, and will reveal knowledge gaps that yet remain to be addressed in Phase 2. However, it is expected that most of the empirical quantification of the model's structure will occur in Phase 2 of the project.

The model will be simulated in Phase 1, in order to evaluate the potential sensitivity of the model to alternative specifications, and assumptions, particularly assumptions concerning the timing of the relationship between policy actions and changes in the probability of disease and survivorship. Ultimately, it will be necessary to specify the model in a linear form (although this does not preclude non-linear assumptions) to facilitate the linear programming analysis of Phases 2 and 3.

The other principal task of Phase 1 will be the final choice of the country to be used as the focus for the empirical analysis of the later phases. It is clear that an empirical application of such a model has enormous data requirements in order even to structure the problem. Demographic data are needed to determine the size of the relevant child population pool and the age, parity and fertility characteristics of the maternal population. Epidemiological data on the structure and character of the disease problems afflicting the child population crucially shape the model's focus, delimiting the set of relevant disease problems and the way in which they are manifested. Economic data on the incomes, occupations and nutritional consumption characteristics of the population will indicate the set of the economic endowment variables. The range and cost of feasible policy actions will be influenced, though not exclusively, by the structure of the public health and medical system. It is clear that this is a wealth of data which could not be generated, within a reasonable time period, by this project. Consequently, it will be necessary to use a population that has already been studied in such detail. Within the last five years, population groups with high infant mortality rates in several LDC's have been intensively examined and could provide sufficient data for our analysis. For example, projects in Ghana (Danfa), Colombia, and India (Narangwal) have accumulated significant data in this form. In conjunction with the interests of AID, negotiations on acquiring data for the limited needs of the model will be undertaken.

The most suitable countries would be Ghana and Colombia. Significant survey and vital registration efforts have been undertaken in the Danfa Rural Health and Family Planning Project in 4 rural areas (with a population of 50,000)

outside of Accra, Ghana. These encompass socioeconomic, environmental, health behavior and utilization, epidemiological and demographic variables. Moreover, several of the Ghanians in the University of Ghana Medical School (notably Dr. Ofosu-Amaah) are intensely interested in the problems of childhood mortality. In Colombia, and at this stage this seems to be the preferable site, several projects are underway in the health and medical sector which would provide sufficient data for such a study. The PAHO study collected detailed data on the circumstances surrounding the deaths of 4,200 children under age 5 in Cali, Cartagena and Medellin. The AID-financed health and nutrition sectoral models will undoubtedly provide some overlap with the research of our project, thus economizing on the research requirements. A certain amount of cost analysis has already been undertaken in the health sector. Finally, the WHO Maternal-Child Health project under Dr. Agualimpia could offer useful inputs to this project.

A critical factor in choosing a country will be the interest of the Ministry of Health and/or the country's medical school in such a project. Even with an existing data base, Phase 2 will require additional field work to estimate the cost of alternative policy actions for the empirical estimation of the technological relationships in the model. The methodology used for the latter will require the guidance of the medical practitioners in the country with experience in the rural areas. The final choice will be made in conjunction with the views of AID and its health sector program efforts.

Phase 2

Project Design

During Phase 2, the following activities aimed at empirically estimating the economic and medical relationships in the model will be carried out: (a) analysis of results from ongoing operational research on the provision of health and medical services in maternal-child health, (b) estimation of the cost of providing alternative policy actions, and (c) development, implementation and analysis of a survey of medical practitioners with pediatric experience in the rural areas of LDC's. The survey instrument would be designed to develop Bayesian estimates of the model's medical parameters.

As a consequence of the review in Phase 1, the structure of the model will have been specified. The critical problem will then be to quantify the relationship between the (1) different endowment variables and various policy interventions, and (2) the probability of contracting the surviving different disease problems. Many of these technological relationships are not fully understood, and if understood, are not firmly specified on the basis of controlled and careful medical research. This has been the principal stumbling block of any previous research along the lines of this project. It is also clear that providing the full set of technological parameters through the normal process of medical research would delay any comprehensive analysis of alternative policy interventions until the distant future.

It is a fundamental premise of this project that a sufficient wealth of practical experience and knowledge exists at the present time to provide estimates

of these relationships at a level of accuracy sufficient for policy analyses. The key problem is to conceptualize and specify the precise technological relationships at a level with which operational practitioners can relate and react. Specifically, the way in which any medical or health action relates to the probability of contracting or surviving an illness can be specified in terms of a discrete chain of physiological-behavioral relationships. Each link in the chain is an operationally relevant causal relationship with which a medical practitioner is likely to have had experience, whereas the combined effect of all links in the chain are not as readily experienced and perceived. By focusing on these discrete links in the chain for various levels of a child's resource endowment variables, and for specific health and disease problems, it should be possible to elicit informed and reasonable judgments as to the magnitude of each relationship.

There are two possible sources of this information. One source is the increasing number of ongoing operational research projects in medical care delivery in many developing countries. This would include the functional analysis research by Johns Hopkins in Taiwan and India, the Danfa Rural Health Project in Ghana, the work of Dean Wilson in Guatemala, of David Morley and Dr. Ransome-Kuti in Nigeria, and comparable projects currently underway in Colombia, Indonesia, Thailand and Kenya.

These projects are amassing at a very micro-level considerable experience and knowledge on the operational problems in delivering health services to the maternal-child population and on the problems in effecting change in health related environmental and behavioral variables.

Second, the project would undertake a survey of approximately 200 to 300 medical and health practitioners with considerable experience in the problems of delivering pediatric services in the rural areas of LDC's. The survey would be designed to yield "Bayesian" estimates of the effect of different health and medical actions on a child's probability of contracting and surviving different diseases. The survey instrument will emerge as an outgrowth of the modeling process in Phase 1, and would have to be in a form which relates to the type of cause and effect relationships that an operational medical practitioner would normally encounter.

For any given disease problem, it would have to carefully specify (a) the physiological characteristics of the child for whom an action is taken, (b) the environmental situation and the average level of family inputs provided to the child, (c) the precise nature of the medical or health action taken. The respondent would be asked, for each of these "situations," the likely effect of the policy action on the probability of contracting and surviving the given disease or health problem. It is probable that the combination of policy actions, disease problems and human and nonhuman resource slates will yield between 100 and 200 "situations" for which a probabilistic judgment would be required. The individual probability estimates of the respondents will be combined to come up with a "best" judgment of the magnitude of these technological relationships. As important as the careful design of the survey instrument is the choice of the sample of physicians. Considerable discussion will be undertaken with different international agencies and universities in order to draw a sample of individuals

with a considerable experience in the problems of delivering pediatric health services in the context of rural less developed country environments.

Finally, one of the professional investigators will spend approximately four months in the host country gathering the supplementary data necessary for the estimation of the model. Precise estimates must be made of the financial costs of providing alternative services, as well as the foreign exchange and skilled manpower requirements. Where some services would have to be provided in the context of larger programs with multiple outputs, the joint cost requirements would have to be estimated. Similarly, estimates would be required of the pattern of health service utilization, in order to account for the large fraction of the child population that conceivably would not be reached by specific types of policy actions.

Phase 3

Project Design

By the beginning of Phase 3, most of the data necessary for the empirical specification of the model will have been assembled. The principal task of Phase 3 will be to complete the specification of the model, and to do a linear programming analysis of the range of possible policy actions, given the epidemiological and demographic characteristics of the population, and the resource constraints that impinge on policies. The analysis should reveal the optimal mix of policy actions required to yield either the greatest increase in the probability of survival and/or the greatest gain in terms of the economic benefits to be derived. The model can be simulated by varying the objective function;

the magnitude of the technological parameters, the budget constraint or the cost of alternative actions. Similarly, a test can be made of the sensitivity of the optimal policy mix to changes in the baseline disease mix in the population or to the demographic characteristics of the population. In this way, the model may provide useful policy guidance to other countries interested in formulating an integrated cohesive policy to attack the infant mortality problems. The final results of the survey, the specification of the model, and an evaluation of the linear programming analysis will be published and distributed to relevant operating agencies in the health field.

Narrative Synopsis of Proposed Project

Sector goal - The increased efficiency of utilization and more equitable distribution of LDC resources to improve health.

Project purpose - To increase current knowledge concerning the effectiveness with which alternative health sector technologies influence health status in the target groups of infants and children under five.

End of project status - Identification of optimal activity mixes to improve maternal and child health in different epidemiological, social and environmental situations.

Assumption for achieving project purpose:

(1) That the analytical instruments proposed can be made operational with existing empirical data sources.

Project outputs:

(1) A summary of existing literature concerning effectiveness of alternative health sector interventions to influence infant and childhood mortality.

(2) A validated model which simulates the interaction of epidemiological, environmental and technical factors in the causality of infant and childhood mortality.

(3) A linear programming model which combines results of the simulation model of disease causality and resources required for intervention to identify least cost intervention alternatives.

Output indicators:

(1) Completion of literature review.

(2) Completion of validated simulation model.

(3) Completion of linear programming model.

(4) Identification of least cost interventions for typical LDC situations.

Assumptions for achieving outputs:

(1) That the use of Bayesian estimators will suffice in the production of valid inputs for the simulation model.

Progress to date:

(1) A bibliography has been prepared.

Inputs:

-- U.S. Contractor -- estimated 96 m.m. professional personnel

-- AID - funding, monitoring and evaluation

-- Host country - access to data sources.

III. A. Technical Analysis

As previously stated in I.B., the project proposal was submitted to three external experts for comment. In general, they found the project both useful and feasible, and their comments are attached as Annex II.

Both Drs. Piot and Weisbrod identified the same principal technical concern with the project. Their concern was not with the modeling techniques to be employed which they both considered to be appropriate for the problem to be solved, but was with the method of developing estimates for the model variables. They thought that the use of expert judgments for many of the effectiveness variables could introduce significant error into the model and its results. Their final opinion was that (1) the model results are critically needed in the short run to better plan health programs, (2) empirical field research for more definitive estimates of the effectiveness variables would be quite costly and time consuming, and (3) the proposed project is modest in cost when compared to the insight it could deliver into the selection of least cost alternatives for MCH services. They felt that the tradeoff between these factors was one which favored project implementation at this time, and that the approach taken was the preferable one.

The project would have no negative environmental impacts. In fact, it is expected that the results of the project would focus greater attention on the impacts of an improved environment on health status of infants and children.

The amounts of effort proposed and the technical design appear adequate with the proviso that if the problems of reliability of data prove more difficult than expected, the project should <u>not</u> proceed to Phase 3, but should be terminated at the end of Phase 2.

The project will have no immediate employment effect. An anticipated result of the project, however, is shifting responsibilities for health care from a few health care professionals to a larger number of paraprofessionals.

The project meets FAA Section 611 requirements.

B. Financial Analysis and Plan

The attached financial plan tables indicate the financing required by phases listed under III.A. above. There will be no recurrent costs accruing to the implementing agency.

The project is divided into three phases:

Phase 1 - An extensive literature survey and development and simulation of an infant mortality model.

Phase 2 - Development of empirical estimates for the model resulting from Phase 1.

Phase 3 - Linear programming model development and analysis of data resulting from Phase 2.

Resource Requirements Phase I

Phase 1 is expected to be completed within 12 months. Three principal investigators will devote a combined total of approximately 20 man months to this phase. Two of the principal investigators will be economists with experience in the analysis of health in developing countries and in the modeling of health economic relationships. The third will hopefully be a physician of the project country with significant pediatric experience in the rural areas.

During Phase 1, several trips to Washington will be necessary for discussions and exchange of resource materials. Additional domestic trips will be required to obtain or copy research materials available in other U.S. institutions. One of the principal investigators will need to spend at least a month in the country chosen in order to discuss and negotiate the research with the host government, to make arrangements for the field research in Phase 2 and to gather additional primary data available in government offices and the Medical School. It will also be necessary for the physician member of the project to spend 3-4 months in the U.S. in collaboration on the modeling process.

During all three phases of the project, the investigators will be supported by a full-time graduate student research assistant, secretarial, administrative and clerical services, phone and computer. It is hoped that the graduate student research assistant will be a Ph.D. student interested in developing a dissertation centered on aspects of this research.

Phase 1 cost is estimated at $78,000.

Resource Requirements Phase II

The activities in Phase 2 would be carried out in the next 12 months of the project and would involve the same professional investigator staff as in Phase 1. One of the U.S.-based principal investigators would spend approximately 4 months in the developing country in order to collect the supplementary data discussed above and to apply the survey instrument to a separate sample of medical practitioners in the host country. The physician member of the team will be heavily involved in the development, implementation and analysis of the

survey instrument as applied to our larger international sample of medical practitioners. One of the principal investigators will also visit several of the ongoing health research projects in order to collect additional data on the technological linkages. This would include a trip to WHO as part of the development of a sample frame. It is also expected that the project would hire LDC professionals in the host country, on a consultant basis, to assist in certain aspects of the field research.

As in Phase 1, it is also likely that the professional investigators would need to make several trips to domestic U.S. institutions to obtain data and research materials.

The principal additional costs in Phase 2 will be the per diem and project cost of the four months of field study of the professional investigator and of the survey. It is not expected that the cost of this survey will be very great.

Phase 2 cost is estimated at $116,000.

Resource Requirements Phase III

Phase 3 will involve the last 9-12 months of the project. Approximately 13 man months of professional investigator time will be required, and most of this work will be in the U.S. The principal non-staff cost will be for computer time and programming. Linear programming analysis is expensive and for an adequate number of computer runs for sensitivity analysis, it will be necessary to have a far larger computer budget than in the earlier phases. Allowances

will also be necessary for final preparation and distribution of reports, and travel to discuss these reports with AID personnel.

Phase 3 cost is estimated at $105,000.

COLOMBIA ASSUMPTION

FINANCIAL PLAN - INFANT MORTALITY STUDY

	PHASE A Man Months	Dollars	PHASE B Man Months	Dollars	PHASE C Man Months	Dollars	Total Dollars
Principal Investigators:							
Project Director	6.5	14,365	8.75	21,250	6.5	17,400	53,015
Project Officer	2	5,662	2	6,230	2	6,853	18,745
Pediatrician from host country	6.5	6,000	6.5	8,800	4.5	6,525	23,325
Research Assistants	12	7,500	12	8,000	12	10,000	25,500
Secretary	5	4,375	5	4,812	5	5,293	14,480
TOTAL SALARIES		39,892		49,092		46,071	135,055
University Overhead		25,588		31,713		30,200	87,501
Subtotal I		65,480		80,805		76,271	221,556
	Item	Dollars	Item	Dollars	Item	Dollars	
Copying		300		350		400	1,050
Telephone		300		350		400	1,050
Supplies		1,200		1,300		1,400	2,700
International Travel	3 trips	2,000	4 trips	2,648	2 trips	1,324	5,972
International per diem	2 mm.	2,400	8mm.	9,576	1 mo.	1,200	13,176
Domestic travel	6 trips	800	6 trips	880	6 trips	800	2,480
Domestic per diem	150 m/days	3,750	60 m/days	1,600	50 m/days	1,250	6,600
Computer		1,300		1,300		20,000	12,000
Consultants	10 m/days	1,000	30 m/days	3,000	10 m/days	1,000	5,000
Survey		—		5,000		—	5,000
Field Research Cost				6,500			6,500
Subtotal II		13,050		32,504		27,773	83,328
TOTAL		78,530		113,291		104,059	295,440

(See new Proposed Budget which is attached to PP Facesheet.)

Ghana Assumption

COST ESTIMATES (REVISED) INFANT MORTALITY STUDY

	PHASE A Man Months	Dollars	PHASE B Man Months	Dollars	PHASE C Man Months	Dollars	Total Dollars
Principal Investigators:							
Project Director	6.5	14,365	8.75	21,250	6.5	17,400	53,015
Project Officer	2	5,662	2	6,230	2	6,853	18,745
Pediatrician from host country	6.5	8,000	6.5	8,800	4.5	6,525	23,325
Research Assistants	12	7,500	12	8,000	12	10,000	25,500
Secretary	5	4,375	5	4,812	5	5,293	14,480
TOTAL SALARIES		39,892		49,092		46,071	135,055
University Overhead		25,588		31,713		30,200	87,501
Subtotal I		65,480		80,805		76,271	221,556
	Item	Dollars	Item	Dollars	Item	Dollars	
Copying		300		350		400	1,050
Telephone		300		350		400	1,050
Supplies		1,200		1,300		1,400	3,900
International Travel	3 trips	3,000	4 trips	5,500	2 trips	2,500	11,000
International per diem	2 mm.	2,400	8 mm	9,576	1 mm.	1,200	13,176
Domestic travel	6 trips	800	6 trips	880	6 trips	800	2,480
Domestic per diem	150 man days	3,750	60 mdys	1,600	50 mdys	1,250	6,600
Computer		1,300		1,300		20,000	22,600
Consultants	10 m/days	1,000	30 mdys	3,000	10 mdys	1,000	5,000
Survey		--		5,000		--	5,000
Field Research				6,500			6,500
Subtotal II		14,050		35,356		28,950	78,356
TOTAL		78,428		116,161		105,221	299,912

(See new Proposed Budget which is attached to PP Facesheet)

Notes for Financial Plan

1. Salary entries include 17% addition for fringe benefits, and 10% inflation per year.

2. Overhead is estimated at 69% of salaries plus fringe paid individuals on campus, and 45% of salaries plus fringe paid individuals off-campus.

3. Copying costs are based on an estimate of 500 copies per month at $.05 per copy.

4. Supply costs are estimated at $67 per month.

5. International per diem is estimated at an average of $40.

6. Domestic travel in phases 1 and 2 is based on an estimate of three round trips between a U.S. university and Washington; and one trip each to MIT-Harvard in Boston, UCLA in Los Angeles, and Yale in New Haven. Domestic travel in phase 3 is based on an estimate of three round trips between a U.S. university and Washington and one trip to UCLA in Los Angeles.

7. Domestic per diem is based on the assumption that the LDC investigator spends 120, 30, and 30 man days, respectively, in the U.S. at $25 per day. The remaining days relate to periods spent collecting materials at other U.S. based institutions.

8. Consultant costs are based on an estimate of $100 per day.

9. Field research cost includes the cost of transportation, LDC research assistant, secretary and supplies for 6 months in phase 2.

10. The cost of equipment and supplies is assumed to rise by approximately 10% per year by inflation.

C. Social Analysis

The intended beneficiaries of the project are initially health sector planners and decision makers but the project results are all specific to the ultimate target group of infants and children under the age of five.

The ultimate target group was selected due to the disparate disease and health problems they suffer in relationship to other population groups in LDC's and the fact that many of these health problems are completely avoidable with existing preventive technologies, many of which fall within the capability of LDC's to deliver within current resources.

The target group should benefit in the form of improved health status upon implementation of the most effective program mixes identified by this project. There is no assurance that the project results will be implemented spontaneously and indeed there are serious impediments to the implementation of expected findings of the most effective interventions being preventive medicine, environmental sanitation and simplest curative medicine in character. This project idea, however, has grown out of the repeatedly expressed felt need of LDC health planners for information on effectiveness of alternative interventions in order to present more convincing cases for orienting health sector investments toward simple preventive interventions. This project will form a part of a broader effort to strengthen national planning capability and provide the information to identify and describe the most effective use of national health sector resources.

III. D. Economic Analysis

Current literature indicates there are no valid techniques available for conducting cost-benefit or cost-effectiveness analyses of projects like this. Some studies, such as Weisbrod's study of poliomyelitis research, have found high cost-benefit ratios for research, but they have not, as he admitted, included

the likelihood for failure in their calculations. The uncertainty of implementation of project findings for reasons described under C above make impossible a cost-effective analysis of this project or even a cost-effective analysis of the combined efforts being brought to bear on increasing national health planning capability to plan more effective health programs. It is to be expected that LDC's have available to them alternative health sector programs which would probably have 10 times the impact on health as those programs they are currently investing in.

At least one linear programming model -- that done for tuberculosis control -- has made a substantial contribution to the rational planning of health programs in developing countries.

IV. A. Analysis of Administrative Arrangements

The project will be carried out in its entirety under a contract presumably with a U.S. university. The contractor then will establish relationships with LDC personnel and identify and mobilize data sources in LDC's in order to carry out the research.

The technical office has experience in working with some of the individuals and institutions already identified for Colombia and will assist the contractor but no complex monitoring or administrative problems for AID are envisioned.

IV. B. Implementation Arrangements

The contractor must develop a relationship with an LDC pediatrician and a group of LDC researchers. The project manager has made initial contacts with a group in Cali, Colombia.

The implementation procedure involves five steps:

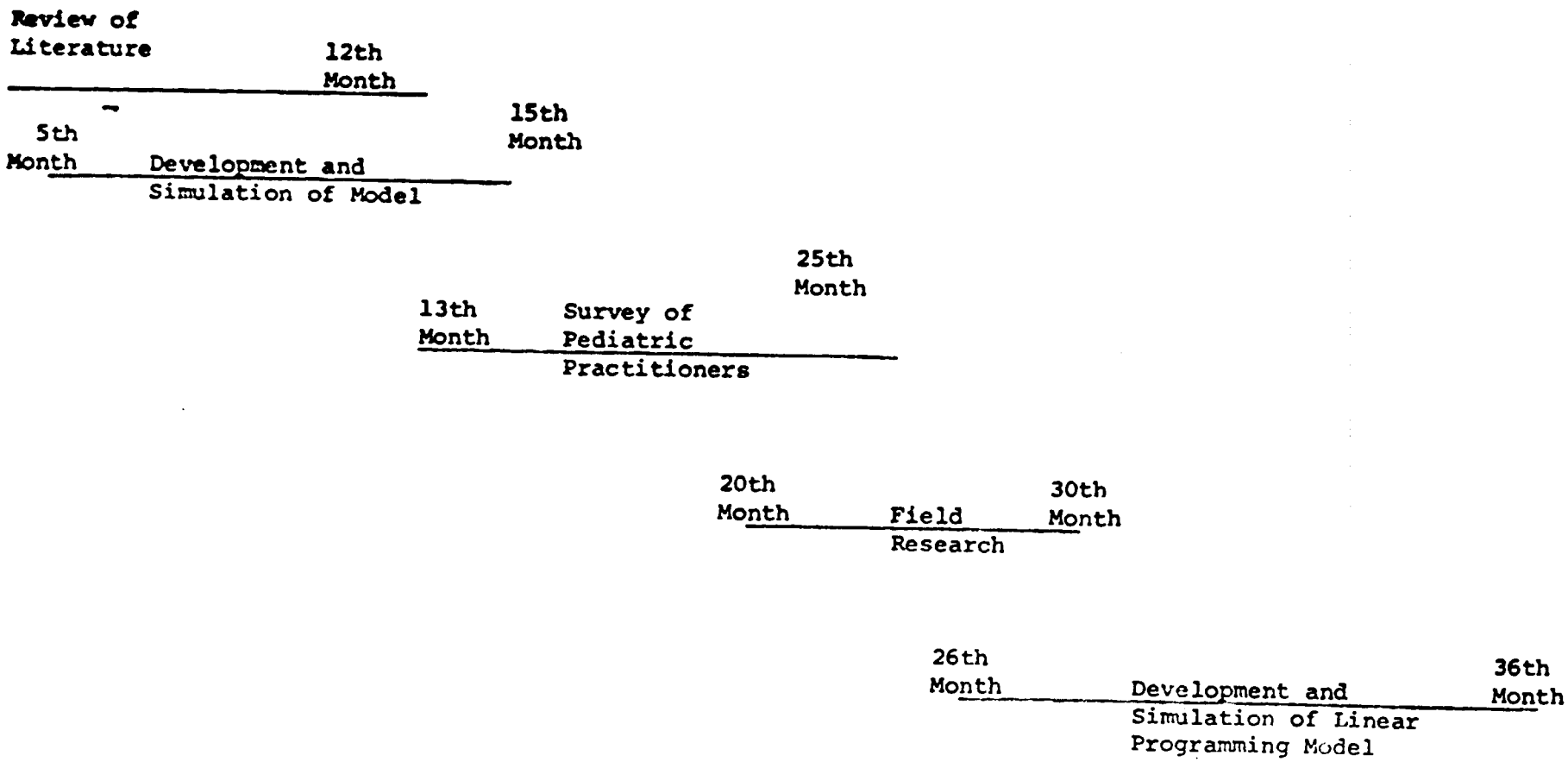
Phase 1: A. Review of the literature.

B. Development of a simulation model.

Phase 2: A. Survey of pediatric practitioners and the development of prior estimates.

B. The conduct of field surveys and the development of revised estimates.

Phase 3: A. Development of a linear programming model based on the improved estimates.



Month One is assumed to be the month of project approval.

IV. C. Evaluation

The project will be evaluated in stages. A number of intermediate reports will be demanded at each major stage. These reports will be reviewed by consultants with expertise in the field. At present the following sequence of reports is envisioned:

1. After the 12th month a critical review of the literature will be submitted.
2. In the 12th month, the survey instrument to be used in the pediatric survey will also be submitted for evaluation.
3. A report on the survey of pediatricians will be submitted in the 25th month.
4. The protocol for the field research will be submitted for review before the field research is undertaken.
5. A report on the equations, assumptions, and reasoning involved in the simulation model will be submitted.
6. The final project report will contain the results of the simulation and linear programming model.

Current plans are to establish a board of consultants in the key problem area of Health Planning. These consultants will be used for project review and evaluation. If not, then additional funds will be required to obtain expert evaluation services.

IV. D. Conditions, Comments and Negotiating Status

No special conditions, covenants or negotiating status concerns are applicable.

COSTING OF PROJECT OUTPUTS/INPUTS
(In $000 or equivalent)
Project Paper

_____ New
_____ Rev # _____

Project # _____ Title Efficiency of Health Measures

Project Inputs	Project Outputs					
	#1 literature review	#2 simulation model	#3 pediatrician review	#4 field surveys	#5 linear programming model	TOTAL
AID Appropriated						
Personnel	19	22	29	23	47	140
Overhead	12	14	18	13	30	87
Supplies	1	1	1	1	2	6
Travel		9	7	8	5	29
Data processing		1	1	12	20	34
Other U.S. *						
Host Country						
Other Donors *						
Total	32	47	56	57	104	296

* Single line entree is acceptable unless this item is more than 25% of the project or more than $1 million.

AID 1020-2015-72D

PROJECT DESIGN SUMMARY
LOGICAL FRAMEWORK

Project Title & Number: Efficiency of Health Measures

Life of Project:
From FY 76 to FY 79
Total U. S. Funding $281,000
Date Prepared: 12/11/75

NARRATIVE SUMMARY	OBJECTIVELY VERIFIABLE INDICATORS	MEANS OF VERIFICATION	IMPORTANT ASSUMPTIONS
Program or Sector Goal: The broader objective to which this project contributes: The increased efficiency of utilization and more equitable distribution LDC resources to improve health.	Measures of Goal Achievement: 1. Improved health status. 2. Increased availability of health services to currently disenfranchised groups.	1. national statistics 2. national statistics	Assumptions for achieving goal targets:
Project Purpose: To increase current knowledge concerning the effectiveness with which alternative health sector technologies influence health status in the target groups of infants and children under five.	Conditions that will indicate purpose has been achieved: End of project status. Identification of optimal activity mixes to improve maternal and child health in differing epidemiological, social and environmental situations.	Expert evaluation.	Assumptions for achieving purpose: That the analytical instruments proposed can be made operational with existing empirical data sources.
Outputs: 1. Summary of existing literature concerning effectiveness of alternative health sector interventions to influence infant and childhood mortality. 2. Validated model which simulates the interaction of epidemiological, environmental and technical factors in the causality of infant and childhood mortality. 3. Linear programming model which combines results of the simulation model of disease causality & resources required for intervention to identify least cost intervention alternatives.	Magnitude of Outputs: 1. Completion of literature review. 2. Completion of validated simulation model. 3. Completion of linear programming model. 4. Identification of least cost interventions for typical LDC situations.	1. direct 2. direct 3. direct 4. expert evaluation	Assumptions for achieving outputs: That the use of Bayesian estimators will suffice in the production of valid inputs for the simulation model.
Inputs: University of Michigan - 45.25 mm professional personnel. AID - funding, monitoring and evaluation. Host country - access to data sources.	Implementation Target (Type and Quantity) 1. 45.25 m.m. 2. $281,000		Assumptions for providing inputs:

country: Inter-regional	project no:	project title: Efficiency of Health Measures	date: 12/15/75	/X/ original / /revision

FY:
CY: / ------ FY 1976 ---------- / ------ FY 1977 ---------- / ------ FY 1978 ------

month: Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar

0 12 24 36

prior actions

completion of bibliography

identification of LDC collaborators

1 init. lit. rev.

2 init. model dev.

3 comp. lit. rev.

4. comp. model dev.

5 init. simultns. with model

6 init. ped. surv. instr.

7 comp. model simultns.

8 init. quest. of ped.

9 comp. surv. analy. results

10 init. work on linear programming model

11 init. pediatric surv. in selected country

12 anal. results pediatric surv.

13 init. itrtns. of LP model

14 cond. sensit. analys.

15 comp. model dvlpmt.

16 final report

17 eval. comple

financial plan:

evaluation plan:

PROJECT PERFORMANCE NETWORK

Country:	Project No:	Project Title:	Date:	/X/ original / / revision	Approved:
Interregional		Efficiency of Health Measures	12/15/75		

CPI NARRATIVE

1.	4/1/75	Initiate literature review of costs and effects on health status of obstetric and pediatric intervention
2.	9/1/75	Initiate development of simulation model for impacts of alternative interventions on infant and child health
3.	3/31/76	Complete literature survey report (required report)
4.	3/31/76	Complete development simulation model
5.	4/1/76	Initiate simulation model iterations
6.	4/1/76	Initiate development pediatrician survey instrument
7.	6/30/76	Complete simulation model (required report)
8.	7/15/76	Initiate international pediatrician survey
9.	10/15/76	Complete international survey and analysis of results
10.	11/1/76	Initiate elaboration of linear programming model of costs and impacts on health of alternative obstetric and pediatric interventions
11.	12/15/76	Initiate survey of pediatricians in selected LDC
12.	4/1/77	Complete analysis of pediatrician survey (required report)
13.	5/1/77	Initiate iterations of LP model
14.	8/1/77	Conduct sensitivity analysis of model
15.	12/1/77	Complete LP model
16.	3/30/78	Final report

WORLD HEALTH ORGANIZATION

1211 GENEVA 27 - SWITZERLAND
Telegr.: UNISANTE-Geneva

Tél. 34 60 61 Télex. 27821

ORGANISATION MONDIALE DE LA SANTÉ

1211 GENÈVE 27 - SUISSE
Télégr.: UNISANTÉ-Genève

In reply please refer to
Prière de rappeler la référence:

PERSONAL

10 June 1975

Dear Dr Davis,

Thank you for sending me Professor Heller's research proposal for review. On return from Pakistan I have had little or no time to consult all those of my colleagues in WHO who would no doubt be interested in commenting. What follows is primarily mine and PSA's views.

First of all, let me say that I support fully the purpose of the proposed research. This area of child health is one in which expenditure of considerable amounts of public money is being decided upon on rather weak grounds by most governments at various levels of development. Considerable savings could result from even the smallest element of rationality being introduced into the decision-making process. I also subscribe to the fundamental premise that there is sufficient wealth of diffuse knowledge and experience to warrant the formal study of the impact of alternative policies on the child health problem.

On the three stages of the proposed study, I have the following comments. As I see it, the kingpin of stage A is, beyond an analysis of determinants, the structuring of a technology matrix making explicit the strength of relationship between policy-controlled determinants - like the medical ones - and risks to child health. The design of such a technology matrix will no doubt have a strong bearing on the ensuing survey: the extent to which environmental and behavioural determinants are included in the technology matrix will determine the scope of the proposed survey in stage B.

In respect of stage B, I have some doubts as to the productivity of an international survey - beyond a review of published data - in respect of obtaining empirical estimates of either marginal effectiveness or unit cost of the available technology. The approach focussing on an already known population like the Colombian one, would seem more profitable for the purpose of such research. The above reference to structure of the technology matrix also raises the question of the validity of a survey based on medical practitioners (pediatricians) alone in order to quantify effect of non medical determinants - let alone their cost. No doubt stage B will be quite an exercise in delphic techniques, and from past experience I would venture a guess that the broader and more multidisciplinary the team of national consultants is, the more meaningful the empirical estimates will be.

Dr Joe H. Davis
Health Planning Officer
Office of Health
Technical Assistance Bureau
Department of State

46 [illegible]

Dr Joe H[illegible]vis
Agency f[illegible] International Development
Washington

10 June 1975

About stage C, I would return to the issue of the objective function of the model. The authors propose the dimension "Infant survival" as a basis for setting an economically meaningful objective function, with reference to demographic and other externalities. This is where, in my view, the crux of the study lies. The validity of the model and the credibility of its conclusions will depend on the acceptability of the objective function. I would be tempted to suggest that the closer the objective function is to satisfying the requirements of a real life decision situation, the more meaningful the results - at least to one set of readers. Also, as most decisions are about the next marginal dollar, and as the weight of the past and current situation on the productivity of the marginal dollar makes every decision highly dependent on the locale as well as the rationale, this pleads for the study to focus on supporting a real decision process in a well-defined situation. In addition to the interest of academic circles, Government commitment to some major child health investment should guide the choice of the country.

In summary, I have no reservation towards the general design of this study, which I feel with confidence deserves to be financed. My minor points of comment concern more the process and the setting in which the study is conducted, and are motivated by my wish to see it succeed fully, i.e. to the point of actually influencing the situation in child health.

I shall now take the liberty to show the proposal to interested colleagues in WHO, from whom Professor Heller might want to obtain support in due course.

Yours sincerely,

With best regards

Dr M. Piot
Project Systems Analysis

47 a1

UNITED STATES GOVERNMENT

Memorandum

TO : Memorandum of telephone conversation from Dr. Burton Weisbrod to Dr. Joe Davis

DATE: January 29, 1976

FROM : TA/H, Dr. Joe H. Davis

SUBJECT: Proposal to study Efficiency of Health Measures to Prevent Infant and Toddler Mortality

Dr. Weisbrod felt that (1) the project addressed an area where more accurate information on the costs and impacts of alternative policies was critically needed, and that to his knowledge no research had previously addressed this particular problem; (2) that the methods and techniques of simulation modeling and linear programming were correctly applicable to this type of analysis; (3) that the principal contractors who authored the proposal were quite competent in the area of proposed activity and (4) that the major area of uncertainty in successful completion of the project was in the method of developing estimates of impacts on health of alternative policies, i.e., the use of expert judgement refined using Delfi techniques to obtain the numerical estimates of effectiveness of options to be used in the models. He indicated that there is no way to assure that estimates developed in this way are accurate estimators of the true values. He indicated, however, that the multistep process for developing the estimators proposed in this project is probably the best way to develop expert judgement estimates.

In general he thought that the project warranted support due to the importance of the policy area it addressed. Even though the proposed method of developing model numerical parameters involved considerable uncertainty concerning the accuracy of the parameters, this was such a low cost way of collecting information in comparison to the alternatives of actual field collection of information that it was the preferable choice for this project.

Buy U.S. Savings Bonds Regularly on the Payroll Savings Plan

DEPARTMENT OF STATE

Washington, D.C. 20520

June 26, 1975

MEMORANDUM

To: AID/TA/H - Dr. Joe H. Davis

From: S/P - Charles R. Frank, Jr., CRF

I apologize for taking so long to review the proposal put forth by Peter Heller and Robin Barlow that you asked me to review in your memoranda of May 2.

I have no problem with the proposal to develop a fertility and survival model for infants and to use linear programming techniques to evaluate policies. I do not feel qualified to judge the crucial intermediate step -- gathering of data by means of a survey of LDC pediatricians. I feel that the authors might be asked to elaborate more precisely what kinds of data they intend to get and how they intend to get it in this survey.

ANNEX II

Source: Ronald J. Wonnacott and Thomas H. Wonnacott, Econometrics . New York : Wiley, 1970.

chapter 10

Decision Theory

With our discussion of systems of equations completed in the last chapter, we now turn to an entirely different topic: decision making in the face of uncertainty. A large part of the discussion involves Bayesian methods, which are not only useful for their own sake, but also sharpen our understanding of the limitations of classical statistics. The best introduction is a simple example.

10-1 AN EXAMPLE: THE PRIOR AND POSTERIOR DISTRIBUTION

In a certain country, it rains 40% of the days and shines 60% of the days. A barometer manufacturer, in testing his instrument, has found that it sometimes errs: on rainy days it erroneously predicts "shine" 10% of the time, and on shiny days it erroneously predicts "rain" 20% of the time.

The best prediction of tomorrow's weather *before* looking at the barometer[1] would be the prior distribution in Table 10-1. But *after* looking at

TABLE 10-1 Prior Probabilities, $p(\theta)$

State θ	Rain (θ_1)	Shine (θ_2)
Prior probability $p(\theta)$	.40	.60

the barometer and seeing it predict "rain," what is the posterior distribution? That is, with this new information in hand, can't we quote better odds on rain than Table 10-1?

[1] In this analysis, it is assumed that there is no other available information (such as a weather report, or visual observation of how the weather is developing).

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The answer is, of course, yes. To see why, we first formally set out the reliability of the barometer in Table 10-2. This information is combined with

TABLE 10-2 Conditional Probabilities, $p(x/\theta)$

Prediction x \ State θ	Rain (θ_1)	Shine (θ_2)
"Rain" (x_1)	.90	.20
"Shine" (x_2)	.10	.80
Σ	1.00	1.00

the prior probabilities in Table 10-1 to define the sample space shown as the entire large rectangle in Figure 10-1. It has four subdivisions, each representing the probability of a specific state of nature, and a barometric prediction. Thus, for example, the probability of the state of nature θ being rain and the barometric prediction (x) being "rain" is[2]

$$p(\theta_1, x_1) = p(\theta_1) \cdot p(x_1/\theta_1) \tag{10-1}$$

$$= (.4)(.9) = .36 \tag{10-2}$$

Similarly, the probability of the state shine, and the prediction "rain" is

$$p(\theta_2, x_1) = p(\theta_2) \cdot p(x_1/\theta_2) \tag{10-3}$$

$$= (.6)(.2) = .12 \tag{10-4}$$

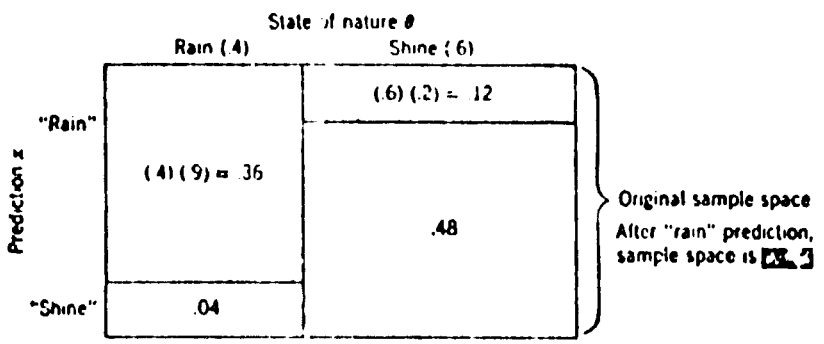


FIG. 10-1 How posterior probabilities are determined.

[2] We use the conditional probability theorem

$$p(y, z) = p(y) \cdot p(z/y) \tag{10-5}$$

For reference, see for example Wonnacott and Wonnacott, *op. cit.*, Chapter 3.

Of course, after "rain" has been predicted, this sample space is no longer relevant. It is replaced by the new, shaded sample space; now rain is seen to be three times as probable as shine (.36 versus .12). This leads us directly to our posterior distribution in Table 10-3. Comparing this with Table 10-1, we

TABLE 10-3 Posterior Probabilities, $p(\theta/x)$

State θ	Rain (θ_1)	Shine (θ_2)
Posterior probability $p(\theta/\text{"rain"})$	.75	.25

see, as expected, just how the odds on rain improve once the barometer has predicted it.

Since this is so important, we now write down its full formal confirmation. From (10-2) and (10-4)

$$p(\text{prediction "rain"}) = p(x_1) = .36 + .12 = .48 \tag{10-6}$$

Using (10-5) again

$$p(\theta_1/x_1) = \frac{p(\theta_1, x_1)}{p(x_1)} = \frac{.36}{.48} = .75$$

Similarly

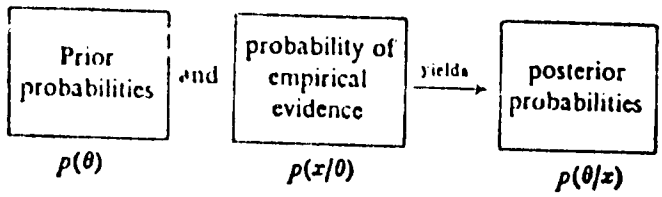
$$p(\theta_2/x_1) = \frac{p(\theta_2, x_1)}{p(x_1)} = \frac{.12}{.48} = .25 \tag{10-7}$$

In this way, the new (shaded) sample space in Figure 10-1 has its probabilities blown up by using the divisor $p(x_1)$; the result is the posterior probability distribution in Table 10-3. This is often written in the more convenient and general form

$$p(\theta/x) = \frac{p(\theta, x)}{p(x)} = \frac{p(\theta)p(x/\theta)}{p(x)} \tag{10-8}$$

To keep the mathematical manipulations in perspective, we repeat the physical interpretation for emphasis. Before the evidence (barometer) is seen, the prior probabilities $p(\theta)$ give the proper betting odds on the weather. But after the evidence is in, we can do better; the posterior probabilities $p(\theta/x)$ now give the proper betting odds. (This may be intuitively grasped by appealing to the relative frequency interpretation. Of all the times the barometer registers "rain," in what proportion will rain actually occur? The answer: 75%.) As a simple summary, we note that the prior probability distribution is adjusted by the empirical evidence to yield the posterior

distribution. Schematically:



(10-9)

PROBLEMS

10-1 Suppose another barometer is used: on shiny days it erroneously predicts "rain" 30% of the time, but on rainy days it always correctly predicts "rain."

(a) With the prior probabilities in Table 10-1, calculate the posterior probability of rain, once this barometer has predicted "rain." What is the posterior probability of shine?

(b) What do you think of this argument: "Since the barometer always predicts 'rain' when it does rain, a 'rain' prediction means that it is dead certain that it will rain."

(c) Explain why the posterior probability of rain is now *less* than in Table 10-3, even though this new barometer is a better predictor when it rains.

10-2 In a population of workers, suppose 40% are grade school graduates, 50% are high school graduates, and 10% are college graduates. Among the grade school graduates, 10% are unemployed, among the high school graduates, 5% are unemployed, and among the college graduates 2% are unemployed. If a worker is chosen at random and found to be unemployed, what is the probability that he is:

(a) A grade school graduate?

(b) A high school graduate?

(c) A college graduate?

10-3 A factory has three machines (θ_1, θ_2, and θ_3) making bolts. The newer the machine, the larger and more accurate it is, according to the following table:

Machine ⟶	θ_1 (Oldest)	θ_2	θ_3 (Newest)
Proportion of total output produced by this machine	10%	40%	50%
Rate of defective bolts it produces	5%	2%	1%

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Thus, for example, θ_3 produces half of the factory's output, and of all the bolts it produces, 1% are defective.

(a) Suppose a bolt is selected at random; *before* it is examined, what is the chance it was produced by machine θ_1? by θ_2? by θ_3?

(b) Suppose the bolt is examined and found to be defective; *after* this examination, what is the chance it was produced by machine θ_1? by θ_2? by θ_3?

⇒10-4 Suppose a man is drawn at random from a group of ten people, whose heights θ have the following distribution:

θ (Inches)	$p(\theta)$
70	.1
71	.3
72	.2
73	.2
74	.1
75	.1

(a) Graph this (prior) distribution of θ.

(b) Suppose also that a crude measuring device is available that makes errors with the following distribution:

e (Error in Inches)	$p(e)$
−2	.1
−1	.2
0	.4
1	.2
2	.1

Surely this can help us a little in estimating the man's height. For example, suppose his measured height using this crude device is $x = 74''$. We now have further information about θ; that is, this measurement changes the probabilities for θ from the prior distribution $p(\theta)$ to a posterior distribution $p(\theta/x = 74)$. Calculate and graph this posterior distribution.

10-2 OPTIMAL DECISIONS

(a) Example

Suppose a salesman regularly sells umbrellas or lemonade on Saturday afternoons at football games. To keep matters simple, suppose he has just three possible options (actions, a_i):

a_1 = sell only umbrellas.

a_2 = sell some umbrellas, some lemonade.

a_3 = sell only lemonade.

If he chooses a_1 and it rains, his profit is \$20; but if it shines, he loses \$10. It will be more convenient to describe everything as a loss (negative profit); thus his losses will be -20 or $+10$ respectively.

If he chooses action a_2 or a_3, there will also be certain losses. All this information may be assembled conveniently in the following loss table:

TABLE 10-4 Loss Function $l(a, \theta)$

Action a \ State θ	Rain (θ_1)	Shine (θ_2)
a_1	-20	10
a_2	5	5
a_3	25	-7

Suppose further that the probability distribution (long-run relative frequency) of the weather is as follows:

TABLE 10-5 Probability Distribution of θ

State θ	Rain (θ_1)	Shine (θ_2)
Probability $p(\theta)$	.20	.80

What is the best action for the salesman to take? (You are urged to work this out, before reading on; it will be easier that way.)

Solution. If he chooses a_1, what could he expect his loss to be, on average? Intuitively, we calculate the average (expected) loss if he chooses a_1

Formally[3]
$$L(a_1) = -20\,(.20) + 10\,(.80) = 4 \tag{10-10}$$

$$L(a_1) = l(a_1, \theta_1)\,p(\theta_1) + l(a_1, \theta_2)\,p(\theta_2) = \sum_\theta l(a_1, \theta)\,p(\theta) \tag{10-11}$$

Similarly, we evaluate

and
$$L(a_2) = 5(.20) + 5(.80) = 5 \tag{10-12}$$

In general
$$L(a_3) = 25(.20) - 7(.80) = -.6 \tag{10-13}$$

$$L(a) = \sum_\theta l(a, \theta)\,p(\theta) \tag{10-14}$$

The optimal action is seen to be a_3, which minimizes the expected loss; in fact, this is the only option that allows any expected profit. All our information and calculations are summarized in Table 10-6.

TABLE 10-6 Calculation of the Optimal Action a

$p(\theta)$	.20	.80	
a \ θ	θ_1	θ_2	$L(a)$ = expected loss
a_1	−20	10	4
a_2	5	5	5
a_3	25	−7	−.6 ← minimum

Loss function $l(a, \theta)$

(b) Generalization

It hardly seems necessary to state that this problem can be generalized to any number of states θ or actions a (even an infinite number, as in the next

[3] This is just an application of the concept of expected value. It has the following justification. In, say, 100 days the salesman would get about 20 rainy days at $5−20 each, yielding $−400; and about 80 shiny days, at $5+10 each, yielding $5+800—for a sum of about $+400 in 100 days, or an average of $4 per day.

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section). The objective remains the same: to minimize expected loss. We now pause to reconsider in detail:

1. The probabilities $p(\theta)$.
2. The loss function $l(a, \theta)$.

1. *The probabilities* $p(\theta)$, of course, should represent the best possible intelligence on the subject. For example, suppose the salesman moves to another state, with weather probabilities as given in Table 10-1. If he has no barometer, he will have to use the (prior) probabilities in this table. But if he can consult the barometer (described in Table 10-2), then of course the posterior probabilities $p(\theta/x)$ in Table 10-3 should be used. (See Problem 10-5 below.)

The logic of Bayesian inference is laid out in the block diagram, Figure 10-2. Incidentally, in the calculation of the average loss $L(a)$ in (10-14) it would not hurt to use $kp(\theta)$ instead of $p(\theta)$ as weights, where k is any constant (independent of θ and a). For $kp(\theta)$ would generate losses $kL(a)$, which would rank in the same order as the true losses $L(a)$ and, hence, point to the same correct optimizing action. This is a very useful observation. Thus, for example, our umbrella salesman need not undertake the last step in calculating the posterior probabilities of rain in (10-7); he can forget about

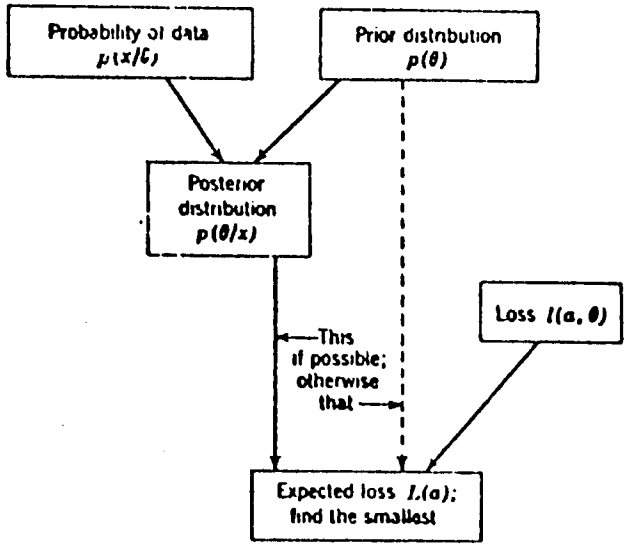


FIG. 10-2 The logic of Bayesian decisions to minimize expected loss.

the denominator $p(x_1)$, and use (10-2) and (10-4) instead—without affecting his decision.[4]

2. *The loss function*, $l(a, \theta)$. In our example, we assumed that monetary loss is the appropriate consideration. This may be valid enough if the decision is made ("game is played") over and over again: whatever minimizes the expected loss in each game will minimize total expected loss in the long run.

Yet there are some decisions that are made only once, and then expected monetary loss may not be the right criterion. To illustrate: suppose you were offered (tax-free) a choice between

$$\left.\begin{array}{l}\text{(a) \$100,000 for sure, or}\\ \text{(b) a 1/2 chance (lottery ticket) on a \$210,000 prize.}\end{array}\right\} \qquad (10\text{-}15)$$

Most people would prefer choice (a), even though its expected monetary value is less than that of choice (b):

$$\left.\begin{array}{r}\$100{,}000\ (1) = \$100{,}000\\ \$210{,}000\ (1/2) = \$105{,}000\end{array}\right\} \qquad (10\text{-}16)$$

The reason is that most people value the first hundred thousand more than the second. (You can easily speculate on how you would spend the first hundred thousand. Once these purchases have been made, there would be less exciting opportunities for spending the second hundred thousand; the sports car has already been bought, and so on.) Such a decision should be

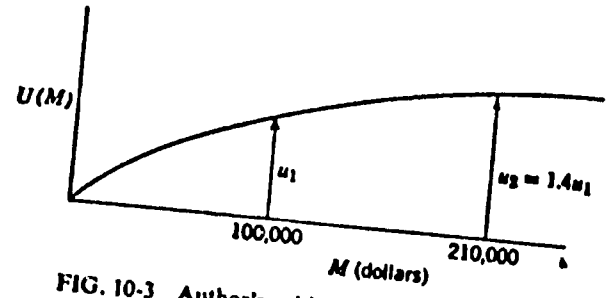


FIG. 10-3 Author's subjective evaluation of money.

[4] That is, attaching weights of .36 and .12 to his losses would yield the same result as weights of .75 and .25.

based not on money itself as in (10-16), but rather on a subjective valuation of money, or the "utility" of money. As an illustration, Figure 10-3 shows one author's subjective evaluation[5] $U(M)$. Since utility is the more appropriate measure, the decision should be based on *expected utility*, rather than expected money. Using Figure 10-3, the expected utilities of the two choices are:

$$\begin{aligned} &(a) \quad u_1(1) = u_1 \\ &(b) \quad u_2(\tfrac{1}{2}) = 1.4u_1(\tfrac{1}{2}) = .7u_1 \end{aligned} \tag{10-17}$$

which is a clear victory for choice (a). In decision situations, a *loss-of-utility* function of this kind should typically be used as our loss function $l(a, \theta)$; hereafter we shall interpret losses in this way.

PROBLEMS

10-5 Using the losses of Table 10-4, calculate the optimal action if:

(a) The only available probabilities are the prior probabilities of Table 10-1.

(b) The barometer reads "rain" (so that the posterior probabilities of Table 10-3 are relevant).

(c) The barometer reads "shine."

(d) Is the following a true or false summary of questions (a) to (c) above? If false, correct it.

If the salesman must choose his action (order his merchandise) before consulting a barometer, then a_2 (umbrellas and lemonade) is best.

However, if the barometer can be consulted first, then the salesman should

Choose a_1 (umbrellas) if the barometer predicts "rain."
Choose a_3 (lemonade) if the barometer predicts "shine."

But a bright salesman could have seen this obvious solution without going to all the trouble of learning about Bayesian decisions.

10-6 A farmer has to decide whether to sell his corn for use A or use B. His losses depend on its water content, (determined by the mill during processing, after the farmer's decision has been made) according

[5] This utility curve is highly personal, and temporary. It is defined empirically for an individual by asking him which bets he prefers. In other words, many bets like (10-15) are used to define utility.

to the following table:

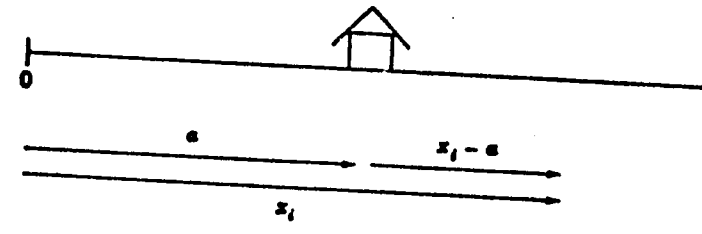
Action a \ State θ	Dry	Wet
Use A	−10	30
Use B	20	10

(a) If his only additional information is that, through long past experience his corn has been classified as dry one third of the time, what should his decision be?

(b) Suppose he has developed a rough-and-ready means of determining whether it is wet or dry—a method which is correct 3/4 of the time regardless of the state of nature. If this indicates that his corn is "dry" what should his decision be?

(c) How much is the method of part (b) worth, that is, how much does it reduce his expected loss?

⇒ 10-7 A school is to be built to serve 125 students, who live along a single road.



Let x_i = distance student i lives from origin
a = distance of school from origin

Thus

$$(x_i - a) = \text{distance of student } i \text{ from school.}$$

(a) Where is the optimum place (mean, median, mode, midrange?) to build the school in order to

1. Minimize the distance that the farthest student has to walk.
2. Minimize the total walking done, that is, minimize the sum of the absolute deviations:

$$\sum |x_i - a|$$

*3. Minimize the sum of the squared deviations:

$$\sum (x_i - a)^2$$

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(*Hint.* Calculus suggests differentiating with respect to a, setting the result equal to zero.)

4. Maximize the number of students who live where the school is built, and do not have to walk at all.

(b) Does the following accurately reflect your conclusions in question (a) above? If not, correct it.

In (2) we are concerned only about the total walking done; walking is considered a loss, no matter who does it. In (1), on the other hand, only the walking done by the two extreme people is considered a loss; walking done by any others is of no concern whatsoever. (3) is a compromise; we imply that although all walking is some kind of loss, the more a student has walked, the greater his loss in walking one more mile. Thus the person who walks 3 miles ($x_i - a = 3$) contributes 9 to the loss function, whereas the person who walks 1 mile contributes only 1.

10-3 ESTIMATION AS A DECISION

In our earlier example the states θ (rain and shine) and actions a were categorical (i.e., nonnumerical). But this was not an essential part of the theory; in this section we consider a numerical example.

Example

Suppose the judge at a beauty contest is asked to guess the height θ of the first contestant, whom he has never seen. Yet he is not in complete ignorance; suppose he knows that the heights of contestants follow the probability distribution $p(\theta)$ shown in Figure 10-4.

(i) Suppose, in order to encourage an intelligent guess, the judge is to be fined \$1 if he makes a mistake (no matter how large or small); "a miss is as good as a mile." What should the rational judge guess?

θ (inches)	$p(\theta)$
64	.1
65	.1
66	.2
67	.2
68	.3
69	.1

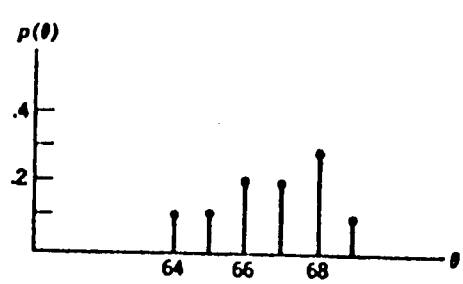

FIG. 10-4 Prior distribution of heights θ.

(ii) Suppose the rules become more severe, by fining the judge $\$x$ for an error of x inches; the greater his error, the greater his loss. What is his rational guess?

(iii) Suppose the rules are made even more severe, by fining the judge $\$x^2$ for an error of x inches; this is the same as (b), except that the loss becomes more severe as his error increases. What is his rational guess now?

TABLE 10-7 How the Optimal Estimator of θ Depends on the Loss Function

If the Loss Function $l(a, \theta)$ is:	Then the Corresponding Optimal Estimator a is:
(i) 0 if $a = \theta$ exactly, 1 otherwise ("the 0–1 loss function")	Mode of $p(\theta)$
(ii) $\lvert a - \theta \rvert$	Median
(iii) $(a - \theta)^2$	Mean

Solution. (i) The most likely (modal) value 68.

(ii) The median value 67.

(iii) The mean value 66.8.

Thus (i), (ii), and (iii) are like (4), (2), and (3) in the schoolhouse Problem 10-7, with the same solution.

To translate this into the familiar language of decision theory, the girl's height is the state of nature θ, and the guessed height (estimate) is the action a to be taken. The fine the judge must pay is the loss function $l(a, \theta)$; since a and θ are numerical, the loss function is most conveniently given by a formula, rather than a table. Each of the three loss functions, along with its corresponding optimal estimator, is shown in Table 10-7.

The quadratic loss function (iii) is the one that is usually used in decision theory. It is graphed in Figure 10-5. It is justified not only by its

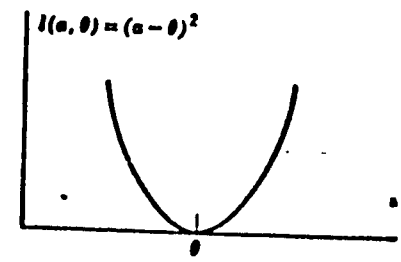

FIG. 10-5 The quadratic loss function.

intuitive appeal, but also by its attractive mathematical properties. For example, it is easily differentiated (an important requirement in minimization problems); on the other hand (i) obviously cannot be differentiated, nor can (ii), since it is an absolute value function.

We reemphasize that the probability distribution $p(\theta)$ used in the decision process ought to reflect the best available information. Thus we may be forced to use the prior distribution $p(\theta)$ if we have not yet collected any data, but after data is collected, the posterior distribution $p(\theta/x)$ is appropriate.

PROBLEMS

These are extensions of Problem 10-4.

10-8 Suppose you have to guess the height of the man drawn in Problem 10-4, with only the prior distribution $p(\theta)$ known. Find the optimal estimate of θ

(a) Assuming $l(a, \theta) = 0 \quad \text{if } a = \theta$

$\qquad\qquad\qquad = 1 \quad \text{otherwise.}$ (10-18)

(b) Assuming $l(a, \theta) = |a - \theta|$. (10-19)

(c) Assuming $l(a, \theta) = (a - \theta)^2$. (10-20)

10-9 Repeat Problem 10-8, *after* the man's height has been crudely measured as $x = 74$, so that the posterior distribution $p(\theta/x)$ is relevant.

10-4 ESTIMATION FOR NORMAL DISTRIBUTIONS: BAYESIAN VERSUS CLASSICAL

This comparison is best shown with an extended example, illustrated in Figure 10-6; from this we shall draw conclusions later.

(a) Example

Suppose it is essential to estimate the length θ of a beetle accidentally caught in a delicate piece of machinery. A measurement x is possible, using a device which is subject to some error; suppose x is normally distributed about the true value θ, with $\sigma = 1$. Suppose x turns out to be 20 mm.

Question (a). What is the classical 95% confidence interval for θ?

Solution. Our information on the sampling distribution of x, that is,

$$p(x/\theta) = N(\theta, \sigma^2), \quad \text{specifically } N(\theta, 1) \tag{10-21}$$

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can be "turned around" to construct the following confidence interval for θ:

$$\theta = 20 \pm 1.96(1)$$
$$= 20 \pm 1.96 \tag{10-22}$$

and, of course,

$$\text{point estimate of } \theta = 20 \tag{10-23}$$

Question (b). Suppose we take the effort to find out from a biologist that the population of all beetles has a normally distributed length, with mean $\theta_0 = 25$ mm and variance $\sigma_0^2 = 4$. How can this be used to define a posterior distribution of θ?

Solution. It will be useful to develop a general formula applying for any θ_0, σ_0, etc., and then solve it for our specific example. Since our prior distribution is

$$p(\theta) = N(\theta_0, \sigma_0^2) \tag{10-24}$$

and the distribution of our empirical evidence x is

$$p(x/\theta) = N(\theta, \sigma^2) \tag{10-21 repeated}$$

it can be shown[6] that the posterior distribution is also normal; specifically:

$$p(\theta/x) = N(ab, a) \tag{10-36}$$

---

[6] (10-24) and (10-21) may be written

$$p(\theta) = K_1 e^{-(1/2\sigma_0^2)(\theta-\theta_0)^2} \tag{10-25}$$

$$p(x/\theta) = K_2 e^{-(1/2\sigma^2)(x-\theta)^2} \tag{10-26}$$

where K_1 and K_2 and other similar constants introduced in this footnote are of a form not critical to the argument. Since

$$p(x, \theta) = p(\theta)\, p(x/\theta) \tag{10-27}$$

we can use (10-25) and (10-26) to write

$$p(x, \theta) = K_1 K_2 e^{-(1/2)\{(1/\sigma_0^2)(\theta^2-2\theta\theta_0+\theta_0^2)+(1/\sigma^2)(x^2-2x\theta+\theta^2)\}} \tag{10-28}$$

Now consider only the exponent, which may be rearranged to

$$-\tfrac{1}{2}\left[\theta^2\left(\frac{1}{\sigma_0^2}+\frac{1}{\sigma^2}\right) - 2\theta\left(\frac{\theta_0}{\sigma_0^2}+\frac{x}{\sigma^2}\right) + K_3\right] \tag{10-29}$$

Let

$$\frac{1}{\sigma_0^2}+\frac{1}{\sigma^2} = \frac{1}{a} \tag{10-30}$$

$$\frac{\theta_0}{\sigma_0^2}+\frac{x}{\sigma^2} = b \tag{10-31}$$

(cont'd)

where

$$\frac{1}{a} = \frac{1}{\sigma_\theta^2} + \frac{1}{\sigma^2} \tag{10-37}$$

$$b = \frac{\theta_0}{\sigma_\theta^2} + \frac{x}{\sigma^2} \tag{10-38}$$

Now apply this to our example. Since

$$\sigma_\theta^2 = 4$$
$$\sigma^2 = 1$$
$$\theta_0 = 25$$
$$x = 20$$

it follows that

$$\frac{1}{a} = \frac{1}{4} + \frac{1}{1} = \frac{5}{4}$$

and

$$b = \frac{25}{4} + \frac{20}{1} = \frac{105}{4}$$

Thus

$$\text{mean} = ab = 21.0$$
$$\text{variance} = a = .8$$

Hence the posterior distribution may be formally written

$$p(\theta/x = 20) = N(21, .8) \tag{10-39}$$

compared with the prior

$$p(\theta) = N(25, 4) \tag{10-40}$$

Using these definitions, the exponent (10-29) can be written

$$-\frac{1}{2a}[\theta^2 - 2ab\theta + K_6] \tag{10-32}$$

$$= -\frac{1}{2a}[(\theta - ab)^2 + K_8] \tag{10-33}$$

Finally we use this to write (10-28) as

$$p(x, \theta) = K_9 e^{-(1/2a)(\theta - ab)^2} \tag{10-34}$$

and

$$p(\theta/x) = \frac{p(x, \theta)}{p(x)} = K_7 e^{-(1/2a)(\theta - ab)^2} \tag{10-35}$$

This means that θ, given x, is a normal variable with mean ab and variance a, provided a appears appropriately in K_7. But it must, since $p(\theta/x)$ is a bona fide probability function (integrating to 1), and K_7 is just the scale factor necessary to ensure this.

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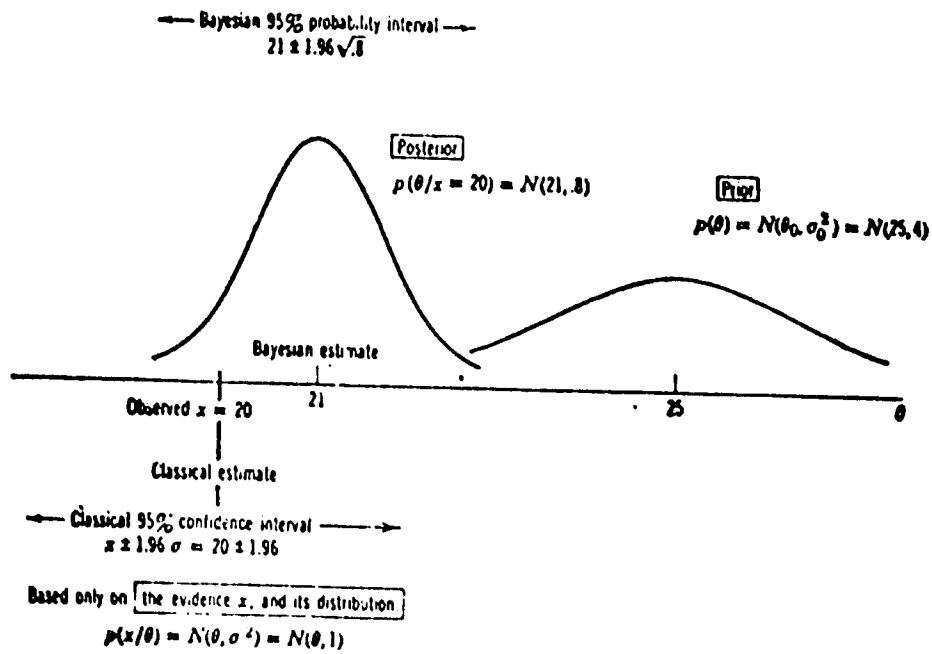

FIG. 10-6 Bayesian versus classical estimation.

The Bayesian logic is shown in Figure 10-6. A prior distribution is adjusted to take account of observed data (x), with the weight attached to the observed x depending on its probability $p(x/\theta)$. The result is the posterior distribution, with mean (21) falling, as expected, between the prior mean (25) and the observed value (20). (As a bonus, variance is reduced in the posterior distribution. Although this does not always happen, it is evident that it must happen for normal distributions; for (10-37) shows that the posterior variance σ is less than σ_0^2, and also less than σ^2 incidentally.)

Question (*c*). With the posterior distribution (10-39) now in hand, defining a Bayesian estimate of θ requires only a loss function. Suppose this is the quadratic loss function: what is the Bayesian point estimator of θ? Find also the 95% probability interval for θ.

Solution. For the quadratic loss function, the posterior mean (21) is the optimum estimator. (Note that because $p(\theta/x)$ is normal, this is also the posterior median and mode, so that all the loss functions in Table 10-7 yield the same answer. This is reassuring, and frequently happens in practice.)

To construct a 95% probability interval, we know from (10-39) that, given the observation $x = 20$, there is a 95% probability that θ will fall in the interval

$$21 \pm 1.96\sqrt{8}.$$
$$= 21 \pm 1.76$$

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Note that this is narrower (more precise) than the classical interval (10-22), reflecting the value of the prior information $p(\theta)$.

PROBLEMS

10-10 As our method of measuring (beetles) becomes more and more precise ($\sigma^2 \to 0$), show that in the posterior distribution $p(\theta/x)$,

$$\text{the mean} \to x$$
$$\text{variance} \to 0 \tag{10-41}$$

In other words, if we use an errorless measuring device, we can be certain that the true θ will be its measured value x.

⇒ 10-11 Using Figure 10-6, what would you expect intuitively of the posterior mean if two independent measurements of the beetle had yielded an average of 20 mm? (For an extension of your answer, see the section immediately following.)

(b) Generalization

Suppose that a sample of n independent measurements $x_1, x_2, \ldots, x_n$ can be taken rather than just a single x. Using the sample mean $\bar{x}$, what now is the Bayesian estimate of θ? In particular, what happens as we get more and more observations ($n \to \infty$)?

This problem may be solved, using (10-36) to (10-38) with one important change. Since our data now is $\bar{x}$ instead of x we must make this substitution in (10-38), and also substitute

$$\sigma_{\bar{x}}^2 = \frac{\sigma^2}{n} \tag{10-42}$$

for σ^2 in (10-37) and (10-38). [Of course, (10-42) is just the variance of a sample mean when σ^2 is the variance of a single observation.] Thus, our generalized definition of a and b in (10-36) is

$$\frac{1}{a} = \frac{1}{\sigma_0^2} + \frac{n}{\sigma^2} \qquad \text{for } n = 1, \text{ this reduces to (10-37)} \tag{10-43}$$

$$b = \frac{\theta_0}{\sigma_0^2} + \frac{n\bar{x}}{\sigma^2} \qquad \text{for } n = 1, \text{ this reduces to (10-38)} \tag{10-44}$$

In the limit, as sample size $n \to \infty$:

$$\frac{1}{a} \simeq \frac{n}{\sigma^2} \tag{10-45}$$

$$b \simeq \frac{n\bar{x}}{\sigma^2} \tag{10-46}$$

Incidentally, exactly these same results follow, whether $n \to \infty$, or

$$\sigma_0^2 \to \infty \tag{10-47}$$

Thus, evaluating (10-36)

$$\text{posterior mean} = ab \simeq \bar{x} \tag{10-48}$$

$$\text{posterior variance} = a \simeq \frac{\sigma^2}{n} \tag{10-49}$$

Again the normality of this posterior distribution ensures that its mean, mode, and median coincide. Hence, regardless of which loss function we may use:

$$\text{Bayesian estimator of } \theta \simeq \bar{x} \tag{10-50}$$

$$95\% \text{ probability interval} \simeq \bar{x} \pm 1.96 \frac{\sigma}{\sqrt{n}} \tag{10-51}$$

We conclude that, as $n \to \infty$, Bayesian estimation approaches the classical. This is exactly as it should be: as more and more data are collected, less and less weight need be attached to prior information; and with an unlimited sample, prior information is completely disregarded, as in classical estimation. The classical and Bayesian approaches are compared in more detail in Table 10-8.

We now turn to the other condition that leads to the same result. Bayes estimators also approach the classical if prior information is very vague (i.e., if $\sigma_0^2 \to \infty$, as stated in (10-47)). Thus the less the prior distribution tells us,

Table 10-8 Relation of Classical and Bayesian Estimation. (Although Normality is Assumed, Results are Instructive for Other Cases Too)

Procedure to Estimate θ	Point and Interval Estimates	Requires, Along With Observed x	And Gets the Answer: In Our Example ($n = 1$)	And Gets the Answer: In the Limit, as $n \to \infty$ or $\sigma_0^2 \to \infty$
Classical	Point estimate		20	$\bar{x}$
	Confidence interval	$p(x/\theta)$	20 ± 1.96	$\bar{x} \pm 1.96 \frac{\sigma}{\sqrt{n}}$
Bayesian	Point estimate	$p(x/\theta)$, $p(\theta)$ and loss function	21	Same as classical
	Probability interval	$p(x/\theta)$, $p(\theta)$	21 ± 1.76	Same as classical

the less weight we attach to it. To sum up, the two reasons for completely disregarding prior information are (1) if present data is in unlimited supply, or (2) if prior information is useless.

(c) Is θ Fixed or Variable?

In this chapter we regard the target to be estimated as a random variable—for example, the beetle's length θ in Figure 10-6. Yet in all preceding chapters, we have regarded the target as a fixed parameter—for example, the true regression coefficient β. Nevertheless, we may often find it useful to think of β as having a *subjective* probability distribution—with this being a description of the betting odds we would give that β is bracketed by any two given values. It may be helpful to boil down our best prior knowledge of β into a prior subjective distribution of β. Then the posterior subjective distribution of β would reflect how the sampling data changed the betting odds.

PROBLEMS

10-12 Following the beetle example in Section 10-4(b), suppose that:

$$\sigma_\theta^2 = 100$$
$$\theta_0 = 25$$
$$\sigma^2 = 1$$

and a sample of four independent observations on the trapped beetle yields an average length $\bar{x}$ of 20 mm.

(a) Calculate the Bayesian point estimate for θ, the length of the beetle. For two reasons this estimate is closer to the observed value of 20 than the Bayesian estimate (21) in Figure 10-6. Explain.

(b) Calculate the Bayesian 95% probability interval for θ.

⇒ 10-13 Suppose that, in a random sample of ten students on an American college campus, you find only one is a Democrat. Which would you rather quote as your "best estimate" of the proportion π of Democrats in the population (whole campus):

(a) The classical estimate,

$$P = \frac{x}{n} = \frac{1}{10} = .10$$

or

(b) The Bayesian estimate which, assuming this subjective prior

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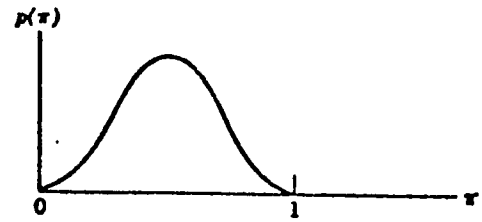
distribution:



and a quadratic loss function, yields[7] the estimate

$$\frac{x+3}{n+6} = \frac{4}{16} = .25$$

10-5 CRITIQUE OF BAYESIAN METHODS

(a) Strength

Bayesian inference is the optimal statistical method (in the sense of minimizing loss of utility) if there is a known prior distribution $p(\theta)$ and loss function $l(a, \theta)$. Compared to classical methods, Bayesian methods often yield shorter interval estimates (e.g. Table 10-8), more credible point estimates (e.g. Problem 10-13), and more appropriate hypothesis tests (e.g. Problem 10-15 below). Bayesian methods may be increasingly useful in economics because sample size is often very small.

(b) Weakness

The major criticism of Bayesian estimation is that it is highly subjective. The prior $p(\theta)$ and loss function $l(a, \theta)$ are usually not known[8]—nor is there often any hope at all of specifying them exactly. For example, what is the loss function for an economist measuring a population's unemployment rate, with inevitable statistical error? We have already seen that this is not as serious a difficulty as it seems at first glance, since in many problems any of the three loss functions of Table 10-7 lead to the same Bayesian estimator. Hence, selecting the "wrong" one involves no error in the final estimate.

[7] For proof, see for example, B. W. Lindgren, *Statistical Theory*, 2nd Ed. New York: Macmillan, 1967.

[8] The other required information for Bayesian inference is $p(x/\theta)$, the distribution of sample data x. But this can often be borrowed from classical statistics. [For example, recall how we borrowed a classical deduction in (10-42).]

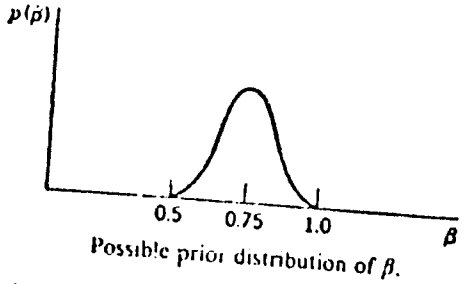
The other information required—the prior distribution $p(\theta)$—usually remains unknown too. Moreover, there are often difficulties in interpreting θ as a random variable; an economist cannot regard the unemployment rate θ as a random variable (as though it were drawn from a bowlful of chips). Instead, he must think of $p(\theta)$ as a subjective distribution reflecting his prior betting odds on θ. But he may not view even this as entirely satisfactory.

(c) Compromise

These issues may be clarified by considering the dilemma an economist may face. Suppose he is estimating β, the marginal propensity to consume.

At hand is a good deal of prior knowledge (drawn from economic theory, previous studies, or the like) before he collects data. For example, previous studies may indicate β to be close to .75; moreover, he may be almost certain that $.5 < \beta < 1$. He now has several options:

1. Ignore this prior knowledge, and opt for the classical estimate regardless.
2. Use prior knowledge informally to truncate his classical estimate at .5 and 1. For example, if he gets an estimate $\hat{\beta} = .23$, quote instead $\hat{\beta} = .5$; if he gets an estimate $\hat{\beta} = .52$, quote it as is.
3. A variant on this truncation option is simply to ignore the result if the estimated $\hat{\beta}$ exceeds 1, or is less than .5.
4. Use prior knowledge formally by postulating a subjective prior distribution such as:



Possible prior distribution of β.

It is evident that none of these options is entirely satisfactory; yet one option must be chosen [just doing nothing with the prior knowledge is a decision—decision (1) in fact]. Judgment on which of these options is best involves examining the consequence of each.

Option (1) implies that if the data are particularly unreliable, so that for example $\hat{\beta} = .23$, this implausible answer would be used regardless. This seems to be the least attractive option.

Option (2) implies that an unfortunate estimate like $\hat{\beta} = .23$ would be

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pulled up to the more "respectable" value of .5. Furthermore, any estimate less than .5 is handled in exactly the same way; thus, $\hat{\beta} = .47$ would be pulled up to .5. This raises two questions: (a) Should not the estimate .47 be pulled up higher than the estimate .23? (b) Should not an estimate $\hat{\beta} = .51$ be pulled up some also, toward our prior expectation .75? It is evident that truncation is in the spirit of Bayesian inference, since it does use prior information. The difficulty is that it is bad Bayesian inference, because it involves a "switching" decision procedure:

(a) If $.5 < \hat{\beta} < 1$, it completely ignores the prior restriction, placing complete faith in the data; on the other hand,

(b) If $\hat{\beta} > 1$ or $\hat{\beta} < .5$, it completely ignores the data, placing complete faith in the prior restriction. In this case, there is just a playback of an arbitrary assumption, without adjustment.

Option (3) involves discarding an estimate that your judgment (prior information) tells you is unreliable. This is a better approach than (2) in the sense that you avoid using a figure[9] that *appears* to be the product of statistical analysis, but is in fact just an arbitrary initial assumption.

Option (4) is the Bayesian compromise: in *all* instances the final estimate reflects both prior information and the statistical evidence; thus the unfortunate switching decision procedure in (2) or (3) is avoided. Like these other methods, (4) does involve a (somewhat arbitrary) prior specification—using a functional form that may make some economists uncomfortable. Yet it is less arbitrary than the prior restriction used in (2) or (3).

The two "lesser evils" among these four options seem to be (3) or (4). Which is more appropriate in any specific case will depend on the outlook of the statistician and the use to which the result must be put. Thus, a conservative statistician may be inclined to bury a result out of line with his good judgment, while publishing unaltered a result that is in line. Thus, he can let his statistical results "speak for themselves" (while still reserving the right to muzzle them completely in special instances). On the other hand, a less conservative statistician will incline to (4) on the grounds that all new statistical information should be presented, rather than buried—even though it may be misleading (after all, maybe it is *not* misleading). While both agree that a statistical result should be restricted in *some* way by prior information, this statistician will feel that the Bayesian approach is more reasonable and better justified mathematically.

A final, and often very important, reason for choosing (4) rather than (3) is if the statistician cannot "opt out" of estimating β. For example, an econometrician building a many-equation model of an economy must use

[9] For example, .23 adjusted to .5.

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some consumption function. Thus, if he estimates an implausible value of β, he cannot just forget about it. He must use some $\hat{\beta}$, in the same way that an auto manufacturer must use some carburetor, even though he feels none is fully satisfactory. The model won't run without it.

In such circumstances there is one additional option. The econometrician may choose to discard the implausible $\hat{\beta}$, in favor of reestimating it. This may be a reasonable enough approach in certain circumstances; but it raises the practical difficulty of where he will find another sample in the nonexperimental world of economics. There is also a major theoretical difficulty: if his estimator has a substantial spread (variance), the econometrician may be able to confirm a preconceived notion of what the marginal propensity to consume should be, simply by reestimating until such a $\hat{\beta}$ turns up. This, of course, would represent an even more rigid application of prior knowledge.

Again we conclude: statistical analysis *must* be tempered by good common sense. Moreover, there is no single approach, infallible in all circumstances. But if an estimate must be derived, the two most reasonable options seem to be: the Bayesian method, with the problem it raises of specifying a prior distribution; or simply reestimating an implausible $\hat{\beta}$, recognizing that this procedure tends to lose its statistical validity as it is repeated.

*(d) Classical Methods as Bayesian Methods in Disguise

Suppose a Bayesian wishes to estimate θ with no prior knowledge. In desperation he might use the "equiprobable" prior

$$p(\theta) = c, \text{ a constant} \tag{10-52}$$

Further suppose that, rather than using the familiar and attractive quadratic loss function, he opts for the 0-1 loss function. He thus will estimate θ with the mode of the posterior distribution

$$p(\theta/x) = \frac{p(\theta)\,p(x/\theta)}{p(x)} \tag{10-53}$$

(10-8) repeated

But because of (10-52)

$$= \left[\frac{c}{p(x)}\right] p(x/\theta) \tag{10-54}$$

To find the mode, he finds the value of θ which makes $p(\theta/x)$ largest. But since the bracketed term $[c/p(x)]$ doesn't depend on θ, he only needs to find:

$$\text{the value of } \theta \text{ that makes } p(x/\theta) \text{ largest} \tag{10-55}$$

But this statement is recognized as just the definition of the classical MLE.

From this, we conclude that a classical statistician who uses MLE is getting the same result as a Bayesian using the 0-1 loss function and an "equiprobable" prior. This seems a very unflattering description of MLE, since neither this prior nor this loss function is easy to justify. But in many cases, MLE is not nearly this restrictive. If $p(\theta/x)$ is unimodal and symmetric, as it often is, then its mean, mode and median coincide; in such circumstances MLE is equivalent to Bayesian estimation using *any* of our three loss functions.

As if the discussion of MLE above has not been damaging enough, we consider an even more questionable application. Suppose we are estimating a population proportion π (as in Problem 10-13). It has been proved[10] that a classical statistician using MLE will arrive at the same result (estimating π with x/n) as a Bayesian using the quadratic loss function and the prior distribution shown in Figure 10-7.

This prior distribution is obviously hopeless, the worst we have yet encountered. (It means that a huge majority of students are Republican, or a huge majority are Democratic.) We recall that we may have been uncomfortable about the prior distribution graphed in Problem 10-13; but it was vastly better than this. This explains why MLE can occasionally give a very strange result in a small sample; our intuition was correct in leading us to reject it in Problem 10-13.

In conclusion, although MLE has many attractive characteristics,

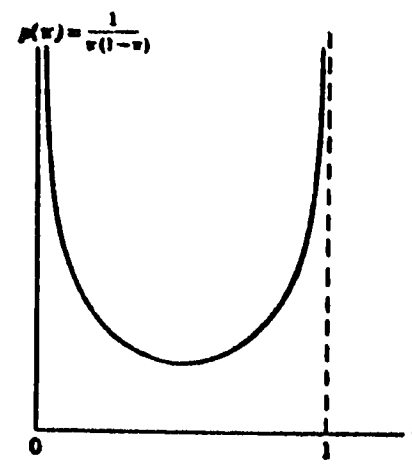

FIG. 10-7

[10] Again, see for example, B. W. Lindgren, *Statistical Theory*, 2nd Ed., New York: Macmillan 1967.

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these are large sample properties; in small sample estimation, it should be used with great caution.

*10-6 HYPOTHESIS TESTING AS A BAYESIAN DECISION

(a) Example

Suppose there are two species of beetle. Species S_0 is harmless, while species S_1 is a serious pest, requiring an expensive insecticide. A beetle is sighted in a new, as yet uninfested territory; but this sighting provides no information useful in establishing whether the beetle was S_0 or S_1. Should insecticide be used or not?

TABLE 10-9 Probabilities of States of Nature, and Loss Function

$p(\theta)$	.7	.3
State θ / Action a	S_0 (Harmless Species)	S_1 (Harmful Species)
a_0 (don't spray)	5	100
a_1 (spray)	15	15

To answer this question, we need to know the costs $l(a, \theta)$ of a wrong decision, and the probabilities $p(\theta)$ of it being one species or the other; these are given in Table 10-9. Obviously action a_0 (don't spray) is appropriate if the state of nature is S_0 (harmless beetle) while a_1 is appropriate if the state is S_1.

Question (a). Should we spray, or not?

Solution. It will be convenient to generalize the loss table, calling $l(a_i, \theta_j) = l_{ij}$, for short. As always, we calculate the expected losses $L(a)$, by weighting elements in each row of this table by their appropriate probabilities:

$$L(a_0) = p(\theta_0)\, l_{00} + p(\theta_1)\, l_{01}$$
$$= (.7)\,5 + (.3)\,100 = 33.5 \qquad (10\text{-}56)$$

and

$$L(a_1) = (.7)\,15 + (.3)\,15 = 15 \leftarrow \min$$

Thus the optimal action is a_1: spray.

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We see that this problem may be expressed in terms of hypothesis testing: action a_0 (don't spray) may be interpreted as accepting H_0 (harmless beetle), while action a_1 (spray) may be interpreted as accepting H_1 (harmful beetle).

Question (*b*). Suppose that prior information about the beetles is that species S_0 is 9 times as common as S_1. Given this new information about $p(\theta)$, what is the optimum action?

Solution. Don't spray, as shown in Table 10-10.

TABLE 10-10 Calculation of Optimal Action, a priori

$p(\theta)$	.9	.1	
State θ / Action a	S_0 (H_0)	S_1 (H_1)	$L(a)$
a_0 (don't spray)	5	100	14.5 ← min
a_1 (spray)	15	15	15

In this case the harmful species is so rare, that it is better to "take the risk," that is, assume the beetle is harmless as our working hypothesis.

Question (*c*). So far we have assumed no statistical information on the beetle that has been sighted. Now suppose it has been captured, with its length measured as 27 mm. Suppose further that the two species are distinguishable by their lengths, which are normal random variables with $\sigma = 4$, and means $\theta_0 = 25$ and $\theta_1 = 30$ respectively. What now is the best action, a posteriori? [Assume $p(\theta)$ and losses given in Table 10-9.]

Solution. It will be most instructive to develop a general solution, leaving substitution of particulars to the end. Losses are calculated as in (10-56), substituting the appropriate posterior probabilities $p(\theta/x)$ for $p(\theta)$:

$$L(a_0) = p(\theta_0/x)\, l_{00} + p(\theta_1/x)\, l_{01} \tag{10-57}$$

Similarly

$$L(a_1) = p(\theta_0/x)\, l_{10} + p(\theta_1/x)\, l_{11} \tag{10-58}$$

We choose action a_0 iff (if and only if)

$$L(a_0) < L(a_1) \tag{10-59}$$

Substituting (10-57) and (10-58) into (10-59), and collecting like terms, we obtain the criterion: choose a_0 iff

$$p(\theta_1/x)\,[l_{01} - l_{11}] < p(\theta_0/x)\,[l_{10} - l_{00}] \tag{10-60}$$

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The bracketed quantities

$$r_0 \triangleq l_{10} - l_{00} \tag{10-61}$$

and

$$r_1 \triangleq l_{01} - l_{11} \tag{10-62}$$

are called regrets. It is easy to see why: the regret if the beetle is harmless (r_0) is the extra loss incurred if we used the wrong action—that is, sprayed (a_1), rather than not sprayed (a_0). Evaluating (10-61) we see that r_0 is $15 - 5 = 10$, the difference in column elements in Table 10-9. Our much larger regret $r_1 = 100 - 15$ represents our act loss if we employ the wrong action (don't spray) on a beetle that turns out to be harmful.

Returning to (10-60), it may now be written in terms of regrets:

$$p(\theta_1/x)\, r_1 < p(\theta_0/x)\, r_0 \tag{10-63}$$

that is

$$\frac{p(\theta_1/x)}{p(\theta_0/x)} < \frac{r_0}{r_1} \tag{10-64}$$

The posterior probabilities in this equation can now be expressed in full using (10-8), and noting that $p(x)$ cancels,

$$\frac{p(\theta_1)\, p(x/\theta_1)}{p(\theta_0)\, p(x/\theta_0)} < \frac{r_0}{r_1} \tag{10-65}$$

Recall that this is our criterion for action a_0 (don't spray), interpreted as acceptance of H_0: (beetle harmless, $\theta = \theta_0$). An appropriate cross-multiplication of (10-65) leads us to an important theorem, called the

Bayesian Likelihood-Ratio Criterion:

Accept H_0 iff

$$\frac{p(x/\theta_1)}{p(x/\theta_0)} < \frac{r_0\, p(\theta_0)}{r_1\, p(\theta_1)} \tag{10-66}$$

where r_i is the regret if θ_i is true, $p(\theta_i)$ is the prior distribution, and $p(x/\theta_i)$ is the distribution of the observed data.

As stated earlier, $p(x/\theta_i)$ is often borrowed directly from classical deduction, and is the distribution of the estimator x, given the parameter θ_i. Specifically, it appears in maximum likelihood estimation as the likelihood function. Thus the left-hand side of (10-66) is called the "likelihood ratio."

This criterion is certainly reasonable. If θ_1 is a sufficiently implausible explanation of the data [i.e. $p(x/\theta_1)$ is sufficiently less than $p(x/\theta_0)$], then the likelihood ratio will be small enough to satisfy this inequality. Thus H_0 will be accepted, as it should be.

To illustrate further, consider the very simple case in which the regrets

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distribution. Then criterion (10-66) reduces to

$$\text{Accept } H_0 \text{ iff } x \text{ is observed closer to } \theta_0 \text{ than } \theta_1 \tag{10-67}$$

Again, a very reasonable result.

Evaluating (10-66) when $r_0 \neq r_1$ or $p(\theta_0) \neq p(\theta_1)$ is obviously a more complicated matter. To keep things simple, we assume that $\theta_0 < \theta_1$, and that $p(x|\theta_0)$ and $p(x|\theta_1)$ are normal with a common σ. Then (10-66)—our criterion for accepting H_0—becomes

$$\frac{e^{-(1/2\sigma^2)(x-\theta_1)^2}}{e^{-(1/2\sigma^2)(x-\theta_0)^2}} < \frac{r_0\, p(\theta_0)}{r_1\, p(\theta_1)} \tag{10-68}$$

This may be reduced[12] to: accept H_0 iff

$$x < \frac{\sigma^2}{\theta_1 - \theta_0} \log\left[\frac{r_0\, p(\theta_0)}{r_1\, p(\theta_1)}\right] + \frac{\theta_1 + \theta_0}{2} \tag{10-69}$$

(The logarithms used throughout this section are natural logarithms, to the base e. The common logarithms of Appendix Table VIII can be converted to natural logarithms by multiplying by 2.30.) We note that the right-hand side of (10-69) is independent of x; as in all hypothesis tests, this can be evaluated prior to observing x. At the same time it does depend, as expected, on background information $p(\theta)$ and regrets. Moreover, when $r_0 = r_1$ and $p(\theta_0) = p(\theta_1)$, then the log term disappears and this reduces to the special case (10-67).

Finally, the particular problem of the beetle spray can now be solved. Substituting the information given in question (c) and Table 10-9 into

[12] Details: taking logarithms of (10-68):

$$-\frac{1}{2\sigma^2}(x - \theta_1)^2 + \frac{1}{2\sigma^2}(x - \theta_0)^2 < K \tag{10-70}$$

where

$$K = \log\left[\frac{r_0\, p(\theta_0)}{r_1\, p(\theta_1)}\right] \tag{10-71}$$

Rearranging (10-70):

$$\frac{1}{2\sigma^2}(2\theta_1 x - 2\theta_0 x - \theta_1^2 + \theta_0^2) < K \tag{10-72}$$

that is, accept H_0 iff:

$$2(\theta_1 - \theta_0)x - (\theta_1^2 - \theta_0^2) < 2\sigma^2 K \tag{10-73}$$

$$x < \frac{\sigma^2}{\theta_1 - \theta_0} K + \frac{(\theta_1^2 - \theta_0^2)}{2(\theta_1 - \theta_0)} \tag{10-74}$$

Using the definition of K in (10-71), (10-74) may be written as (10-69).

distribution. Then criterion (10-66) reduces to

$$\text{Accept } H_0 \text{ iff } x \text{ is observed closer to } \theta_0 \text{ than } \theta_1 \tag{10-67}$$

Again, a very reasonable result.

Evaluating (10-66) when $r_0 \neq r_1$ or $p(\theta_0) \neq p(\theta_1)$ is obviously a more complicated matter. To keep things simple, we assume that $\theta_0 < \theta_1$, and that $p(x/\theta_0)$ and $p(x/\theta_1)$ are normal with a common σ. Then (10-66)—our criterion for accepting H_0—becomes

$$\frac{e^{-(1/2\sigma^2)(x-\theta_1)^2}}{e^{-(1/2\sigma^2)(x-\theta_0)^2}} < \frac{r_0\, p(\theta_0)}{r_1\, p(\theta_1)} \tag{10-68}$$

This may be reduced[12] to: accept H_0 iff

$$x < \frac{\sigma^2}{\theta_1 - \theta_0} \log\left[\frac{r_0\, p(\theta_0)}{r_1\, p(\theta_1)}\right] + \frac{\theta_1 + \theta_0}{2} \tag{10-69}$$

(The logarithms used throughout this section are natural logarithms, to the base e. The common logarithms of Appendix Table VIII can be converted to natural logarithms by multiplying by 2.30.) We note that the right-hand side of (10-69) is independent of x; as in all hypothesis tests, this can be evaluated prior to observing x. At the same time it does depend, as expected, on background information $p(\theta)$ and regrets. Moreover, when $r_0 = r_1$ and $p(\theta_0) = p(\theta_1)$, then the log term disappears and this reduces to the special case (10-67).

Finally, the particular problem of the beetle spray can now be solved. Substituting the information given in question (c) and Table 10-9 into

[12] Details: taking logarithms of (10-68):

$$-\frac{1}{2\sigma^2}(x-\theta_1)^2 + \frac{1}{2\sigma^2}(x-\theta_0)^2 < K \tag{10-70}$$

where

$$K = \log\left[\frac{r_0\, p(\theta_0)}{r_1\, p(\theta_1)}\right] \tag{10-71}$$

Rearranging (10-70):

$$\frac{1}{2\sigma^2}(2\theta_1 x - 2\theta_0 x - \theta_1^2 + \theta_0^2) < K \tag{10-72}$$

that is, accept H_0 iff:

$$2(\theta_1 - \theta_0)x - (\theta_1^2 - \theta_0^2) < 2\sigma^2 K \tag{10-73}$$

$$x < \frac{\sigma^2}{\theta_1 - \theta_0} K + \frac{(\theta_1^2 - \theta_0^2)}{2(\theta_1 - \theta_0)} \tag{10-74}$$

Using the definition of K in (10-71), (10-74) may be written as (10-69).

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The bracketed quantities

$$r_0 \triangleq l_{10} - l_{00} \tag{10-61}$$

and

$$r_1 \triangleq l_{01} - l_{11} \tag{10-62}$$

are called regret. It is easy to see why: the regret if the beetle is harmless (r_0) is the extra loss incurred if we used the wrong action—that is, sprayed (a_1), rather than not sprayed (a_0). Evaluating (10-61) we see that r_0 is $15 - 5 = 10$, the difference in column elements in Table 10-9. Our much larger regret $r_1 = 100 - 15$ represents our net loss if we employ the wrong action (don't spray) on a beetle that turns out to be harmful.

Returning to (10-60), it may now be written in terms of regrets:

$$p(\theta_1/x)\, r_1 < p(\theta_0/x)\, r_0 \tag{10-63}$$

that is

$$\frac{p(\theta_1/x)}{p(\theta_0/x)} < \frac{r_0}{r_1} \tag{10-64}$$

The posterior probabilities in this equation can now be expressed in full using (10-8), and noting that $p(x)$ cancels,

$$\frac{p(\theta_1)\, p(x/\theta_1)}{p(\theta_0)\, p(x/\theta_0)} < \frac{r_0}{r_1} \tag{10-65}$$

Recall that this is our criterion for action a_0 (don't spray), interpreted as acceptance of H_0: (beetle harmless, $\theta = \theta_0$). An appropriate cross-multiplication of (10-65) leads us to an important theorem, called the

$$\boxed{\begin{array}{c}\text{Bayesian Likelihood-Ratio Criterion:}\\ \text{Accept } H_0 \text{ iff}\\ \dfrac{p(x/\theta_1)}{p(x/\theta_0)} < \dfrac{r_0\, p(\theta_0)}{r_1\, p(\theta_1)}\end{array}} \tag{10-66}$$

where r_i is the regret if θ_i is true, $p(\theta_i)$ is the prior distribution, and $p(x/\theta_i)$ is the distribution of the observed data.

As stated earlier, $p(x/\theta_i)$ is often borrowed directly from classical deduction, and is the distribution of the estimator x, given the parameter θ_i. Specifically, it appears in maximum likelihood estimation as the likelihood function. Thus the left-hand side of (10-66) is called the "likelihood ratio."

This criterion is certainly reasonable. If θ_1 is a sufficiently implausible explanation of the data [i.e. $p(x/\theta_1)$ is sufficiently less than $p(x/\theta_0)$], then the likelihood ratio will be small enough to satisfy this inequality. Thus H_0 will be accepted, as it should be.

To illustrate further, consider the very simple case in which the regrets

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(penalties for error) are assumed equal, and the prior probabilities $p(\theta_0)$ and $p(\theta_1)$ are also assumed equal. The right-hand side of (10-66) becomes 1; thus H_0 is accepted if the likelihood of θ_0 generating the sample $[p(x/\theta_0)]$ is greater than the likelihood of θ_1 generating the sample $[p(x/\theta_1)]$. Otherwise, the alternative H_1 is accepted. In simplest terms: we select the hypothesis which is more likely to generate the observed x. In this sense, this could be viewed as hypothesis testing, within a maximum likelihood context, shown in Figure 10-8*a*. In *b* we make the further assumption that the two likelihood functions (centered on θ_0 and θ_1 respectively) have the same normal[11]

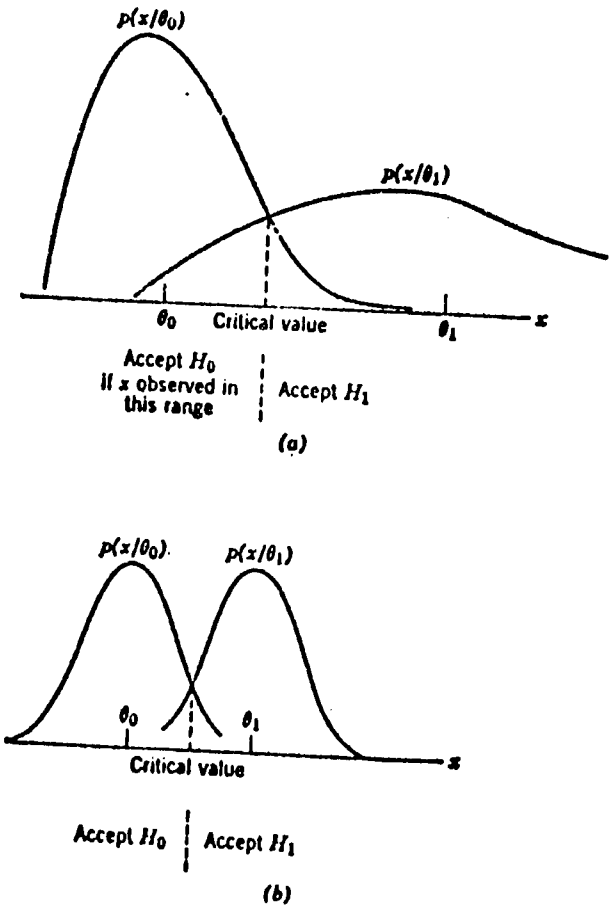

FIG. 10-8 Hypothesis testing, using the Bayesian likelihood ratio [special case when $r_0 = r_1$ and $p(\theta_0) = p(\theta_1)$]. (*a*) For any $p(x/\theta_i)$. (*b*) If $p(x/\theta_i) = N(\theta_i, \sigma)$.

[11] In fact, normality is not required; the two distributions need only be unimodal and symmetric.

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distribution. Then criterion (10-66) reduces to

$$\text{Accept } H_0 \text{ iff } x \text{ is observed closer to } \theta_0 \text{ than } \theta_1 \tag{10-67}$$

Again, a very reasonable result.

Evaluating (10-56) when $r_0 \neq r_1$ or $p(\theta_0) \neq p(\theta_1)$ is obviously a more complicated matter. To keep things simple, we assume that $\theta_0 < \theta_1$, and that $p(x/\theta_0)$ and $p(x/\theta_1)$ are normal with a common σ. Then (10-66)—our criterion for accepting H_0—becomes

$$\frac{e^{-(1/2\sigma^2)(x-\theta_1)^2}}{e^{-(1/2\sigma^2)(x-\theta_0)^2}} < \frac{r_0\, p(\theta_0)}{r_1\, p(\theta_1)} \tag{10-68}$$

This may be reduced[12] to: accept H_0 iff

$$x < \frac{\sigma^2}{\theta_1 - \theta_0} \log\left[\frac{r_0\, p(\theta_0)}{r_1\, p(\theta_1)}\right] + \frac{\theta_1 + \theta_0}{2} \tag{10-69}$$

(The logarithms used throughout this section are natural logarithms, to the base e. The common logarithms of Appendix Table VIII can be converted to natural logarithms by multiplying by 2.30.) We note that the right-hand side of (10-69) is independent of x; as in all hypothesis tests, this can be evaluated prior to observing x. At the same time it does depend, as expected, on background information $p(\theta)$ and regrets. Moreover, when $r_0 = r_1$ and $p(\theta_0) = p(\theta_1)$, then the log term disappears and this reduces to the special case (10-67).

Finally, the particular problem of the beetle spray can now be solved. Substituting the information given in question (c) and Table 10-9 into

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[12] Details: taking logarithms of (10-68):

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Rearranging (10-70):

$$\frac{1}{2\sigma^2}(2\theta_1 x - 2\theta_0 x - \theta_1^2 + \theta_0^2) < K \tag{10-72}$$

that is, accept H_0 iff:

$$2(\theta_1 - \theta_0)x - (\theta_1^2 - \theta_0^2) < 2\sigma^2 K \tag{10-73}$$

$$x < \frac{\sigma^2}{\theta_1 - \theta_0} K + \frac{(\theta_1^2 - \theta_0^2)}{2(\theta_1 - \theta_0)} \tag{10-74}$$

Using the definition of K in (10-71), (10-74) may be written as (10-69).

(10-69) yields: accept H_0 iff

$$x < \frac{16}{5} \log \left[\frac{10(.7)}{85(.3)}\right] + 27.5 \tag{10-75}$$

$$< 3.2 \log \left(\frac{7}{25.5}\right) + 27.5 \tag{10-76}$$

$$< 3.2(-1.29) + 27.5 \tag{10-77}$$

$$< 23.4 \tag{10-78}$$

Since we observed a 27 mm beetle, this condition is violated, and we reject H_0. But what does seem strange is the critical value in (10-78): even if the beetle were 25 mm--exactly θ_0, the length we would expect of a *harmless* beetle---we would still spray. With further thought we see that this answer is, after all, reasonable. The heavy damage involved if the beetle turns out to be harmful induces us to spray to avoid this risk. [From (10-75) we confirm that it is in fact the relative size of the two regrets that explains this result.]

(b) Comparison with Classical Methods

Bayesian testing is more complicated than classical testing, yet often more satisfactory. Classical testing uses only the probability function $p(x/\theta)$, while the Bayesian method also exploits the prior distribution $p(\theta)$ and regrets (the loss function); we have seen in the last section how important both these can be in setting up an appropriate test. Restated, the classical method sets the level of significance (probability of type I error) at 5% or 1%—sometimes arbitrarily, sometimes with implicit reference to vague considerations of loss and prior belief. Bayesians would argue that these considerations should be explicitly introduced---with all the assumptions exposed, and open to criticism and improvement.

PROBLEMS

10-14 Using $p(\theta)$ and losses given in Table 10-10:

(a) Reconstruct the hypothesis test of question (c) above. With your measurement of 27 mm, what would you do? Why does our previous argument (spray even if beetle is 25 mm) no longer hold?

(b) Suppose that species S_0 and S_1 were equally frequent. Would that alter your decision?

(c) How frequent would species S_0 have to be in order to alter your decision?

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The Decision to Seed Hurricanes

On the basis of present information, the probability of severe damage is less if a hurricane is seeded.

R. A. Howard, J. E. Matheson, D. W. North

The possibility of mitigating the destructive force of hurricanes by seeding them with silver iodide was suggested by R. H. Simpson in 1961. Early experiments on hurricanes Esther (1961) and Beulah (1963) were encouraging (*1*), but strong evidence for the effectiveness of seeding was not obtained until the 1969 experiments on Hurricane Debbie (*2*). Debbie was seeded with massive amounts of silver iodide on 18 and 20 August 1969. Reductions of 31 and 15 percent in peak wind speed were observed after the seedings.

Over the last 10 years property damage caused by hurricanes has averaged $440 million annually. Hurricane Betsy (1965) and Hurricane Camille (1969) each caused property damage of approximately $1.5 billion. Any means of reducing the destructive force of hurricanes would therefore have great economic implications.

Decision to Permit Operational Seeding

In the spring of 1970 Stanford Research Institute began a small study for the Environmental Science Service Administration (ESSA) (*3*) to explore areas in which decision analysis (*4, 5*) might make significant contributions to ESSA, both in its technical operations and in its management and planning function. At the suggestion of Myron Tribus, Assistant Secretary of Commerce for Science and Technology, we decided to focus the study on the decision problems inherent in hurricane modification (*6*).

The objective of the present U.S. government program in hurricane modification, Project Stormfury, is strictly scientific: to add to man's knowledge about hurricanes. Any seeding of hurricanes that threaten inhabited coastal areas is prohibited. According to the policy currently in force, seeding will be carried out only if there is less than a 10 percent chance of the hurricane center coming within 50 miles of a populated land area within 18 hours after seeding.

If the seeding of hurricanes threatening inhabited coastal areas is to be undertaken, it will be necessary to modify the existing policies. The purpose of our analysis is to examine the circumstances that bear on the decision to change or not to change these existing policies.

The decision to seed a hurricane threatening a coastal area should therefore be viewed as a two-stage process: (i) a decision is taken to lift the present prohibition against seeding threatening hurricanes and (ii) a decision is taken to seed a particular hurricane a few hours before that hurricane is expected to strike the coast. Our study is concentrated on the policy decision rather than on the tactical decision to seed a particular hurricane at a particular time. It is also addressed to the experimental question: What would be the value of expanding research in hurricane modification, and, specifically, what would be the value of conducting additional field experiments such as the seedings of Hurricane Debbie in 1969?

Our approach was to consider a representative severe hurricane bearing down on a coastal area and to analyze the decision to seed or not to seed this "nominal" hurricane. The level of the analysis was relatively coarse, because for the policy decision we did not have to consider many geographical and meteorological details that might influence the tactical decision to seed. We described the hurricane by a single measure of intensity, its maximum sustained surface wind speed, since it is this characteristic that seeding is expected to influence (*7*). The surface winds, directly and indirectly (through the storm tide), are the primary cause of the destruction wrought by most hurricanes (*8*). The direct consequence of a decision for or against seeding a hurricane is considered to be the property damage caused by that hurricane. (Injuries and loss of life are often dependent on the issuance and effectiveness of storm warnings; they were not explicitly included in our analysis.)

However, property damage alone is not sufficient to describe the consequence of the decision. There are indirect legal and social effects that arise from the fact that the hurricane is known to have been seeded. For example, the government might have some legal responsibility for the damage caused by a seeded hurricane (*9*). Even if legal action against the government were not possible, a strong public outcry might result if a seeded hurricane caused an unusual amount of damage. Nearly all the government hurricane meteorologists that we questioned said they would seed a hurricane threatening their homes and families—if they could be freed from professional liability.

The importance of the indirect effects stems in large part from uncertainty about the consequences of taking either decision. A hurricane is complex and highly variable, and at present meteor-

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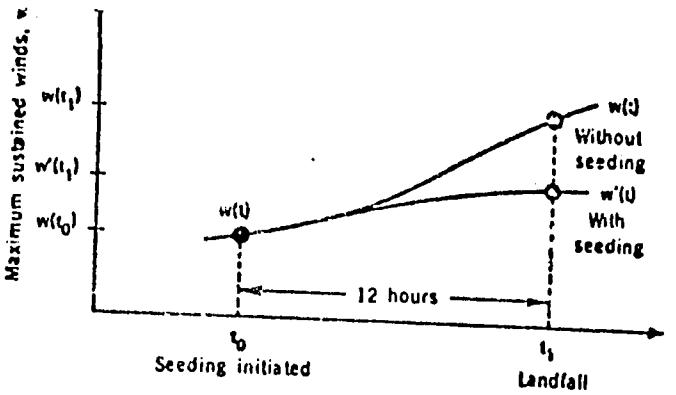


Fig. 1. Maximum sustained winds over time.

stems in large part from uncertainty about the consequences of taking either decision. A hurricane is complex and highly variable, and at present meteorologists cannot predict accurately how the behavior of a hurricane will evolve over time. The effect of seeding is uncertain also; consequently, the behavior of a hurricane that is seeded will be a combination of two uncertain effects: natural changes and the changes induced by seeding.

The seeding decision would remain difficult even if the uncertainty were removed. Suppose that, if the hurricane is not seeded, the surface wind intensifies as shown by the curve $w(t)$ in Fig. 1 and that, if the hurricane is seeded, the behavior of the wind is that shown by the curve $w'(t)$. The effect of the seeding has been to diminish the wind, thus reducing property damage, yet the wind speed $w'(t_1)$ when the hurricane strikes land at time t_1 is higher than the wind speed when the seeding was initiated at time t_0. Even if the decision-maker were certain of $w(t_1)$ and $w'(t_1)$, he would still have a difficult choice. If he chooses not to seed, the citizens may have more property damage. On the other hand, if he chooses to seed, the citizens may not perceive themselves as better off because of his decision. Instead, they may perceive only that the storm became worse after the seeding and they may blame the decision maker for his choice. The trade off between accepting the responsibility for seeding and accepting higher probabilities of severe property damage is the crucial issue in the decision to seed hurricanes.

Decision under Uncertainty

The decision to seed a threatening hurricane would be taken about 12 hours before the hurricane is predicted to strike the coast. At this time the consequences are uncertain for both alternatives; the decision-maker does not know what amount of property damage will be sustained if the hurricane is seeded or is not seeded. We may illustrate the situation facing him in the form of a decision tree, as shown in Fig. 2. The decision-maker must select one of the two alternatives, seeding or not seeding. The decision cannot be avoided for inaction is equivalent to selecting the alternative of not seeding. Each alternative leads to a set of possible consequences: property damage caused by the hurricane and the responsibility incurred by the government. These consequences are, in turn, related to the intensity of the hurricane and whether or not it was seeded. The consequences for each alternative are uncertain at the time the decision is made; the uncertainty will be resolved after the decision-maker selects his choice. This decision under uncertainty may be examined according to the usual procedures of a decision analysis. We use the information that is currently available to develop a probability distribution over changes in the intensity of the hurricane as measured by its maximum sustained surface wind speed for each of the two decision alternatives. Then we use data from past hurricanes to infer a relation between wind speed and property damage. By assessing the consequences in property damage and government responsibility and the probability that these consequences will be achieved, we are able to determine which of the decision alternatives is the preferred choice.

Uncertainty in Hurricane Wind Changes

We began our analysis by considering the change in maximum sustained surface winds over a 12 hour period for a hurricane that is not seeded. If enough data had been available on the changes in hurricane wind speeds with time, a probability distribution for wind changes could have been based largely on these past data. Wind-change data were not available, but data were available for changes over time in the central pressure of hurricanes. The central pressure and the maximum wind speed of a hurricane are closely related; Holliday has shown that the available data can be summarized fairly well by a linear relation (*10*). We combined this relation with observations of the change in central pressure over a 12-hour period, using the assumption that the discrepancies from the Holliday relation are independent over a 12-hour period and independent of the change in central pressure. These assumptions imply a probability distribution on wind changes over a 12-hour period that is normal with a mean of zero and a standard deviation of 15.6 percent (*11*).

Therefore, present information is consistent with rather large natural changes in hurricane intensity over a 12-hour period. There is about one chance in six that a hurricane whose maximum sustained wind speed is 100 miles per hour will intensify over a 12-hour period to a maximum wind speed of over 115 miles per hour; there is also about one chance in six that the winds would naturally diminish to less than 85 miles per hour. In assessing these probabilities only general historical and meteorological information has been used. In a specific hurricane situation additional meteorological information might indicate that the hurricane would be more likely to intensify or more likely to diminish.

Effect of Seeding

The next step is to develop a probability distribution for the wind speed if the hurricane is seeded. The change in wind speed over 12 hours would then be a combination of the natural change occurring in the hurricane and the change caused by seeding. With the limited data available it is reasonable to assume that the two effects would be independent of each other and act in an additive fashion; for example, if the natural change is an intensification such that the maximum sustained wind speed is increased from 100 to $(100+x)$ percent, and if the effect of seeding is to diminish the maximum sustained wind speed from 100 to $(100-y)$ percent, the net observed change over 12

noots is from 100 to $(100 + x - y)$ percent. A probability distribution has already been assigned for natural changes; we need to assign a probability distribution for the change caused by seeding. In developing this probability distribution it is necessary to distinguish between the effect of seeding on one hurricane and the average effect of seeding on many hurricanes. The effect of seeding on a particular hurricane might be quite different from its average effect.

After discussion with meteorologists associated with Project Stormfury, we concluded that the major uncertainty about the effect of seeding would be resolved if we knew which of the following mutually exclusive and collectively exhaustive hypotheses described the effect of seeding:

1) H_1, the "beneficial" hypothesis. The average effect of seeding is to reduce the maximum sustained wind speed.

2) H_2, the "null" hypothesis. Seeding has no effect on hurricanes. No change is induced in maximum sustained wind speed.

3) H_3, the "detrimental" hypothesis. The average effect of seeding is to increase the maximum sustained wind speed.

The scientific basis for the "beneficial" hypothesis, H_1, had its origins in the original Simpson theory (*1*). It has been modified and strengthened by Project Stormfury studies involving a computer model of hurricane dynamics (*1, 12*). This hypothesis, in fact, motivated the formation of the Project Stormfury research program. A possible basis for the "null" hypothesis, H_2, is that seeding does not release enough latent heat to affect the dynamics of the hurricane. The "detrimental" hypothesis, H_3, has been added to complete the set. Meteorologists do not have a basis in physical theory for H_3 that is comparable to that for H_1 or H_2.

Even if we know which of the hypotheses is true, there remain uncertainties about the effects of seeding. We now describe the approach we followed in creating a model to formalize existing knowledge about these uncertainties. Then we shall return to the hypotheses.

Let us suppose we have access to a clairvoyant who can tell us which hypothesis, H_1, H_2, or H_3, represents the actual effect of seeding on hurricanes. What probability would we assign to the 12-hour change in the maximum sustained winds of a seeded hurricane for each of his three possible answers? If the clairvoyant says H_2 is true, the assignment process is simple. Seeding has no effect, and the same probabilities are assigned to the wind speed w' if the hurricane is seeded as to the wind speed w if the hurricane is not seeded (*13*).

$$P(w'|H_2) = P(w) = f_N(100\%, 15.6\%) \quad (1)$$

If H_1 is the clairvoyant's answer, the process is more difficult. The average effect is known to be a reduction in storm intensity, but the amount of this average reduction is uncertain. The Simpson theory and the computer studies indicate that a reduction of 10 to 20 percent in wind speed should be expected, with 15 percent as the most likely value. This information was summarized by assigning to the change in wind speed a normal probability distribution with a mean of -15 percent and a standard deviation of 7 percent. An average reduction greater than 15 percent is considered as likely as an average reduction less than 15 percent, and the odds are about 2 to 1 that the average reduction will lie between 22 and 8 percent rather than outside this interval.

The effect of seeding on an individual hurricane would be uncertain even if the average effect of seeding were known. Odds of about 2 to 1 were considered appropriate that the effect of seeding would not differ from the average effect by more than about 7 percent; thus, a normal distribution centered at the average value with a standard deviation of 7 percent was judged an adequate summary of the information available on fluctuations in seeding effects. Combining the uncertainty about fluctuations with the uncertainty about the average effect leads to a probability distribution for the effect of seeding a specific hurricane that is normal with a mean equal to -15 percent and a standard deviation of 10 percent (*14*).

Adding the natural change in the hurricane over a 12-hour period to the change resulting from seeding gives the total 12-hour change occurring in a seeded hurricane if hypothesis H_1 is true. The probability distribution assigned to w' is then normal with a mean of 85 percent and a standard deviation of 18.6 percent (*15*):

$$P(w'|H_1) = f_N(85\%, 18.6\%) \quad (2)$$

The development of a probability distribution for w', if it is considered that H_3 is true, proceeds in a similar way. The average change effected by seeding is described by a normal probability distribution with a mean of $+10$ percent and a standard deviation of 7 percent. The fluctuations expected when an individual hurricane is seeded are normally distributed around the average with a standard deviation of 7 percent. Combining these uncertainties

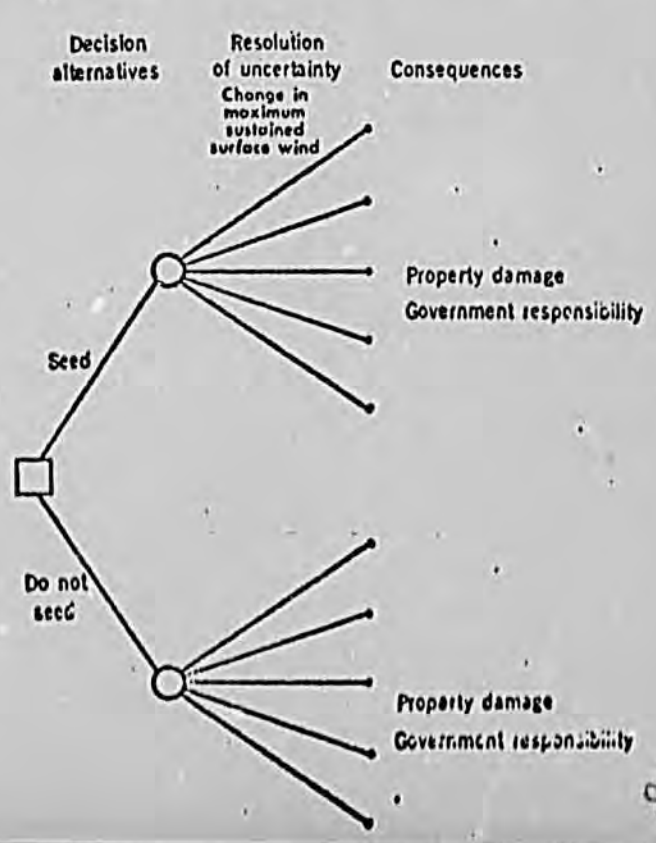
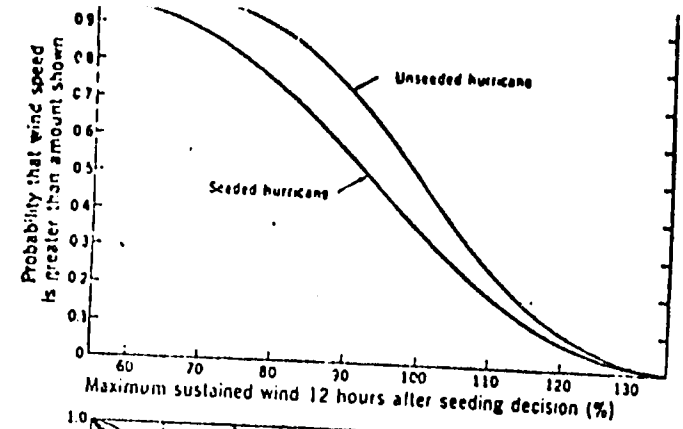
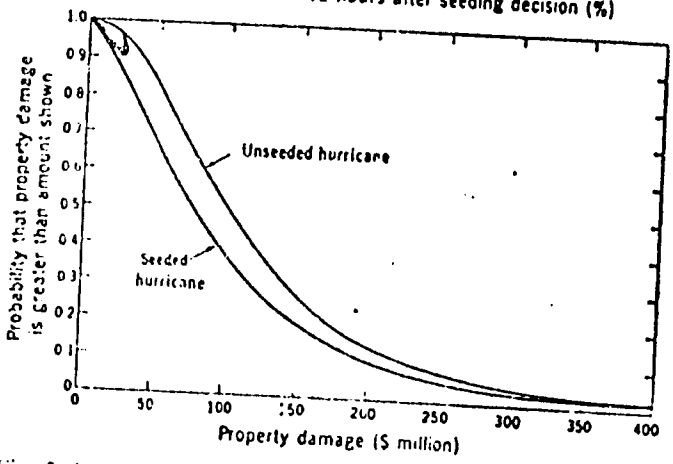


Fig. 2. The seeding decision: decision tree.





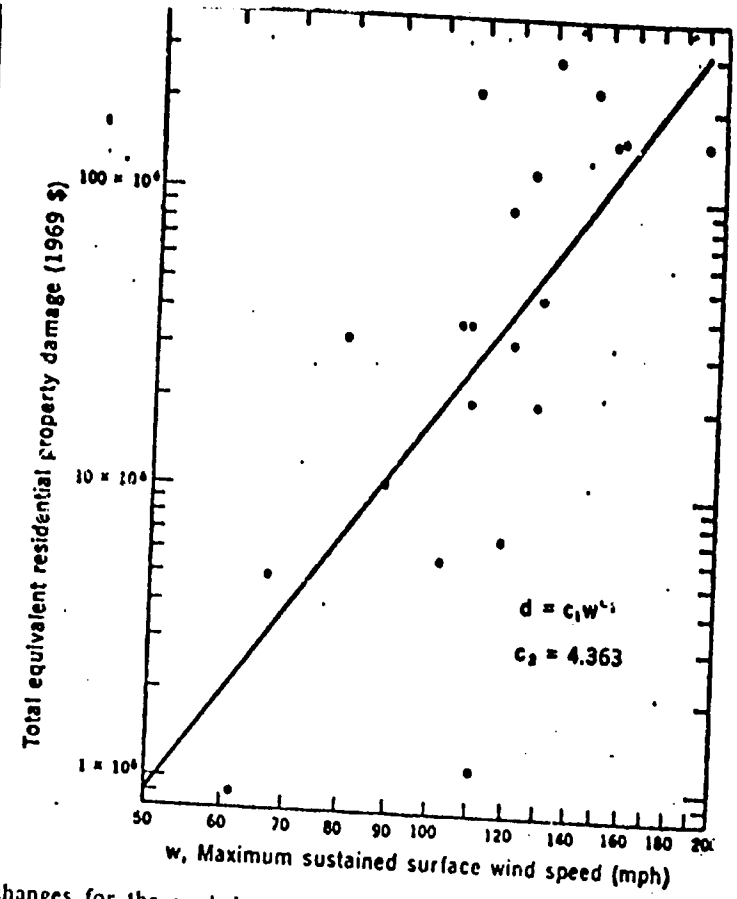


Fig. 3 (upper left). Probability distributions on 12-hour wind changes for the seeded and unseeded hurricane. Fig. 4 (right) Property damage plotted against maximum sustained wind speed. Fig. 5 (lower left). Probability distributions on property damage for the seeded and unseeded hurricane.

with the uncertainty about the natural change in the hurricane over a 12-hour period, we obtain a probability distribution for w' that is normal with a mean of 110 percent and a standard deviation of 18.6 percent:

$$P(w'|H_3) = f_N(110\%, 18.6\%) \quad (3)$$

We have now developed probability distributions for the wind speed w' over a 12-hour period following the initiation of seeding for each of the three hypotheses. To obtain the probability distribution for w' that represents present information about the change in a seeded hurricane, we multiply each of the above distributions by the probability that is presently assigned to each of the hypotheses being true and sum over the three hypotheses:

$$P(w') = \sum_{i=1}^{3} P(w'|H_i)P(H_i) \quad (4)$$

Assigning Probabilities to the Hypotheses

The last element in developing a probability distribution for w' is to assign the probabilities $P(H_1)$, $P(H_2)$, and $P(H_3)$. These probabilities should take into account both present meteorological information and meteorological information before the results of the 1969 Debbie experiments. The models we have just constructed allow us to examine the effect of experimental observations, such as the Debbie results, in revising the probabilities assigned to the three hypotheses. If a wind speed $w' = u$ has been observed after a seeding experiment, the posterior probabilities $P(H_i|u)$ are related to the probabilities $P(H_i)$ assigned before the experiment by Bayes' equation (*5, 16, 17*):

$$P(H_i|u) = \frac{P(u|H_i)P(H_i)}{P(u)} \quad (5)$$

where the denominator is

$$P(u) = P(w' = u) = \sum_{i=1}^{3} P(w' = u|H_i)P(H_i) \quad (6)$$

The extension to several independent experiments is straightforward. The Debbie results are considered as two independent experiments in which reductions of 31 and 15 percent in wind speed were observed over a 12-hour period. The posterior probabilities assigned to the hypotheses are computed by multiplying together the appropriate values of two normal probability density functions. The probability density function for the Debbie results if hypothesis H_i is true, $P(u_1 = 69$ percent $u_2 = 85$ percent$|H_i)$, is

$$P(69\%, 85\%|H_1) = 1.50 \times 2.14 = 3.21$$
$$P(69\%, 85\%|H_2) = 0.372 \times 1.64 = 0.61$$
$$P(69\%, 85\%|H_3) = 0.195 \times 0.886 = 0.173 \quad (7)$$

These numbers can be used to compute the posterior probabilities appropriate after the Debbie results from any set of probabilities assigned to the hypotheses before the Debbie results were known. For example, suppose that before the Debbie experiments the three hypotheses H_1, H_2, and H_3 were considered to be equally likely, that is, each had a probability of 1/3. Then, after the Debbie results are incorporated through Bayes' equation, the corresponding posterior probabilities assigned to the hypotheses are

$$P(H_1|\text{Debbie}) = \frac{3.21 \times 1/3}{3.21 \times 1/3 + 0.61 \times 1/3 + 0.173 \times 1/3} = .81$$

$$P(H_2|\text{Debbie}) = .15$$
$$P(H_3|\text{Debbie}) = .04$$

However, meteorologists did not believe that H_1, H_2, and H_3 were equally likely before the Debbie experiments. They thought that seeding was unlikely to have any effect but that, if seeding did have an effect, it was more likely to be a reduction in wind speed than an increase, because a reduction was expected from both the Simpson theory and the computer model studies. Further, the four field experiments that were conducted before Debbie all led to no change or to reductions in the maximum wind speeds (*1*).

We determined probability assignments for the three hypotheses to reflect present information by two conditions: (i) Before Debbie, meteorologists believed that H_1 was more likely than H_3 if seeding had any effect on a hurricane. (ii) Since Debbie, meteorologists believe that H_1 and H_2 are equally likely.

These conditions led us to use the probabilities

$$P(H_1) = .49 \qquad P(H_2) = .49 \qquad P(H_3) = .02 \tag{9}$$

in our analysis. These posterior probabilities correspond to the pre-Debbie probabilities

$$P(H_1) = .15 \qquad P(H_2) = .75 \qquad P(H_3) = .10 \tag{10}$$

This set of probability assignments implies that prior to Debbie the odds were 3 to 1 that seeding would have no effect but that, if seeding did have an effect, the odds were 3 to 2 for wind reduction rather than wind intensification. Since the Debbie results, the chance of seeding causing an average intensification of hurricanes is assessed at 1 in 50, and the "null" hypothesis, H_2, of no effect and the "beneficial" hypothesis, H_1, of an average reduction are judged equally likely.

The probability assignments (Eq. 9) representing present information were reviewed with Project Stormfury officials before being used in the analysis. However, the results of the analysis are not particularly sensitive to the specific numbers, as we discuss below.

Probability Distributions on Wind Speed

We now can compute the probability distributions on wind speed for the seeding and not-seeding alternatives (from Eqs. 1–4 and Eq. 9). These distributions are plotted in Fig. 3 as complementary cumulative distribution functions. By reading the ordinate values corresponding to an initial wind intensity of 100 percent, we find that the probability assigned to intensification if a hurricane is seeded is .36; if the hurricane is not seeded, the probability is .50. The probability of intensification by 10 percent or more is .18 if a hurricane is seeded and .26 if it is unseeded. For any particular wind speed, the probability that this speed will be exceeded is always greater if the hurricane is unseeded than if it is seeded because the complementary cumulative distribution function for the not-seeding alternative is always above the curve for the seeding alternative. This result is called stochastic dominance of the seeding alternative.

We have now specified the uncertainties about the outcome of the decision to seed. The same methods could be applied if the outcome were specified by several variables rather than simply by the relative change in maximum sustained wind speed. Much of the uncertainty in the outcome is the result of uncertainty about the natural change in hurricane behavior, not about the effect of seeding. This characteristic holds even more strongly if other aspects of hurricane behavior are examined, such as the trajectory of a hurricane or the precipitation it generates. Although it is considered unlikely that seeding would have a significant effect on these features of hurricanes, substantial variations may occur from natural causes.

The uncertainty about the natural behavior of a hurricane makes the issue of government responsibility of paramount importance. The intensification after seeding illustrated in Fig. 1 is a distinct possibility. Even if further experiments confirm that the "beneficial" hypothesis, H_1, is true, there would still be about one chance in ten that a seeded hurricane will intensify by 10 percent or more. Meteorological advances and improved computer models may eventually allow many of the natural changes in a hurricane to be predicted accurately, but this capability may require many years to achieve.

Wind Changes and Property Damage

The winds of a hurricane cause property damage directly and indirectly, the latter by creating a high storm tide that can flood low-lying coastal areas. The data available for past hurricanes do not distinguish wind and storm-tide damage; consequently, a detailed basis is lacking for a causal model relating wind and property damage. In our analysis, we assumed a general power law of the form

$$d = c_1 w^{c_2} \tag{11}$$

where d is property damage in millions of dollars, w is the maximum sustained wind speed in miles per hour, and c_1 and c_2 are empirical constants to be determined from historical data on hurricanes. We estimated c_2 from data obtained from the American Red Cross on residential damage from 21 hurricanes. Since the Red Cross data were available for counties, we could isolate the damage caused by precipitation-induced flooding rather than by the wind or the storm tide by assuming that such damage occurred well inland. (The Red Cross data are the only statistics available that permit even this crude distinction between causes of damage.) Corrections for construction cost inflation and population growth were included, and c_2 was determined as 4.36 by a linear least-squares fit of the logarithms (Fig. 4). Thus, a change in the wind speed by a factor x implies a change in property damage by the factor x to the power 4.36. If x is 0.85, corresponding to a 15 percent reduction in maximum wind speed, the corresponding reduction in property damage is 51 percent (*18*).

The approximations of this method and the limited data indicate that broad limits are appropriate in a sensitivity analysis. If c_2 is 3, the reduction in damage corresponding to a 15 percent reduction in wind speed is 39 percent; if c_2 is 6, the corresponding damage reduction is 62 percent.

Since the probability assignments to wind changes were made on relative rather than absolute changes in maximum sustained wind speeds, the scaling factor c_1 can be assigned as the last step in the analysis. We assume a nominal hurricane whose maximum wind speed at the time of the seeding decision is such that, if no change occurs in the 12 hours before landfall, the property damage will be $100 million. The analysis for a more or a less severe hurricane can be obtained by a suitable change in scale factor (*19*).

Using this relationship between property damage and maximum wind speed, we can develop the probability distributions for property damage for the nominal hurricane, whether seeded or unseeded. Figure 5 shows that the seed-

ing alternative stochastically dominates the not-seeding alternative: the probability of exceeding a particular amount of property damage is always greater if the hurricane is not seeded than if it is seeded. Hence, if property damage is the criterion, the better alternative is to seed.

Further Analysis of the Decision to Seed

The decision to seed is shown in the form of a decision tree in Fig. 6. The decision to seed or not to seed is shown at the decision node denoted by the small square box; the consequent resolution of the uncertainty about wind change is indicated at the chance nodes denoted by open circles. For expository clarity and convenience, especially in the later stages of the analysis, it is convenient to use discrete approximations to the probability distributions for wind change (*20*) (Table 1).

As a measure of the worth of each alternative we can compute the expected loss for each alternative by multiplying the property damage for each of the five possible outcomes by the probability that the outcome will be achieved and summing over the possible consequences. The expected loss for the seeding alternative is $94.33 million (including a cost of $0.25 million to carry out the seeding); the expected loss for the not-seeding alternative is $116 million; the difference is $21.67 million or 18.7 percent.

These results should be examined to see how much they depend on the specific assumptions in the model. Stochastic dominance is a general result that does not depend on the specific form of the relationship between property damage and maximum wind speed (see Eq. 11); rather, it depends on the probabilities assigned to hypotheses H_1, H_2, and H_3. The probability of H_3 must be raised to .07 before stochastic dominance no longer holds. Even if the probability of H_3 is raised much higher, seeding still results in the least expected property damage. If $P(H_1)$ is .40, $P(H_2)$ is .40, and $P(H_3)$ is .20, the expected loss for the seeding alternative is $107.8 million—7 percent less than for the not-seeding alternative. Variation of the exponent c_2 from 3 to 6 does not change the decision: if c_2 is 3, the expected property damage with seeding is 14 percent less; if c_2 is 6, the expected reduction in damage is 22 percent. If the criterion of expected cost is replaced by a nonlinear utility function reflecting aversion to risk, the relative advantage of the seeding alternative is even greater (*21*). The results of extensive sensitivity analysis may be summarized as follows: The expected loss in terms of property damage appears to be about 20 percent less if the hurricane is seeded. Varying the assumptions of the analysis causes this reduction to vary between 10 and 30 percent but does not change the preferred alternative.

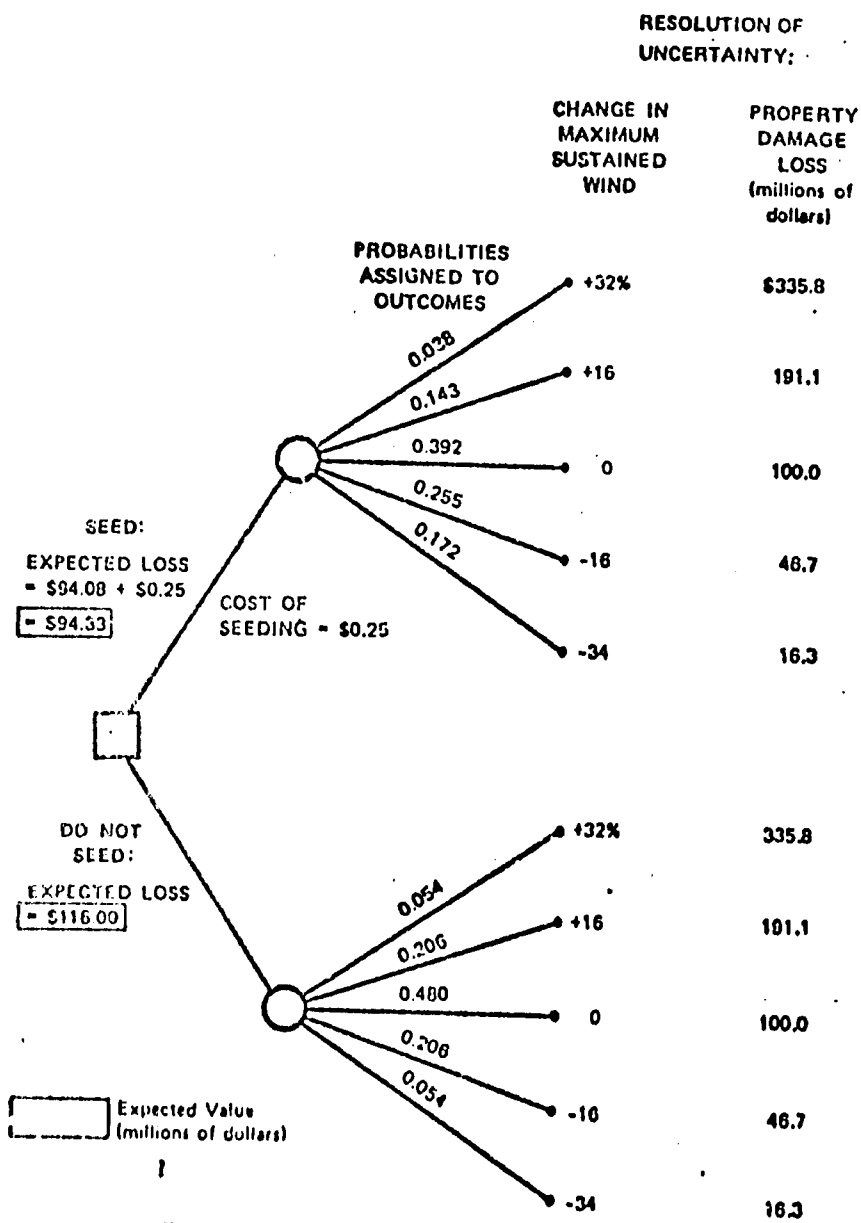


Fig. 6. The seeding decision for the nominal hurricane.

Government Responsibility

The analysis in the section above indicates that, if minimizing the expected loss in terms of property damage (and the cost of seeding) is the only criterion, then seeding is preferred. However, an important aspect of the decision—the matter of government responsibility—has not yet been included in the analysis. We have calculated a probability of .36 that a seeded hurricane will intensify between seeding and landfall and a probability of .18 that this intensification will be at least 10 percent. This high probability is largely the result of the great natural variability in hurricane intensity. It is advisable to consider both the legal and the social consequences that might

occur if a seeded hurricane intensified.

The crucial issue in the decision to seed a hurricane threatening a coastal area is the relative desirability of reducing the expected property damage and assuming the responsibility for a dangerous and erratic natural phenomenon. This is difficult to assess, and to have a simple way of regarding it we use the concept of a government responsibility cost, defined as follows. The government is faced with a choice between assuming the responsibility for a hurricane and accepting higher probabilities of property damage. This situation is comparable to one of haggling over price: What increment of property-damage reduction justifies the assumption of responsibility entailed by seeding a hurricane? This increment of property damage is defined as the government responsibility cost. The government responsibility cost is a means of quantifying the indirect social, legal, and political factors related to seeding a hurricane. It is distinguished from the direct measure—property damage—that is assumed to be the same for both modified and natural hurricanes with the same maximum sustained wind speed.

We define the government responsibility cost so that it is incurred only if the hurricane is seeded. It is conceivable that the public may hold the government responsible for not seeding a severe hurricane, which implies that a responsibility cost should also be attached to the alternative of not seeding. Such a cost would strengthen the implication of the analysis in favor of permitting seeding.

The assessment of government responsibility cost is made by considering the seeding decision in a hypothetical situation in which no uncertainty is present. Suppose the government must choose between two outcomes:

1) A seeded hurricane that intensifies 16 percent between the time of seeding and landfall.

2) An unseeded hurricane that intensifies more than 16 percent between the time of seeding and landfall. The property damage from outcome 2 is x percent more than the property damage from outcome 1.

If x is near zero, the government will choose outcome 2. If x is large, the government will prefer outcome 1. We then adjust x until the choice becomes very difficult, that is, the government is indifferent to which outcome it receives. For example, the indifference point might occur when x is 30 percent. An increase of 16 percent in the intensity of the nominal hurricane corresponds to property damage of $191 million, so that the corresponding responsibility cost defined by the indifference point at 30 percent is (.30) ($191 million), or $57.3 million. The responsibility cost is then assessed for other possible changes in hurricane intensity.

The assessment of government responsibility costs entails considerable introspective effort on the part of the decision-maker who represents the government. The difficulty of determining the numbers does not provide an excuse to avoid the issue. Any decision or policy prohibiting seeding implicitly determines a set of government responsibility costs. As shown in the last section, seeding is the preferred decision unless the government responsibility costs are high.

Let us consider an illustrative set of responsibility costs. The government is indifferent, if the choice is between:

1) A seeded hurricane that intensifies 32 percent and an unseeded hurricane that intensifies even more, causing 50 percent more property damage.

2) A seeded hurricane that intensifies 16 percent and an unseeded hurricane that causes 30 percent more property damage.

Table 1. Probabilities assigned to wind changes occurring in the 12 hours before hurricane landfall. Discrete approximation for five outcomes.

Interval of changes in maximum sustained wind	Representative value in discrete approximation (%)	Probability that wind change will be within interval: If seeded	Probability that wind change will be within interval: If not seeded
Increase of 25% or more	+32	.038	.054
Increase of 10 to 25%	+16	.143	.206
Little change, +10 to −10%	0	.392	.480
Reduction of 10 to 25%	−16	.255	.206
Reduction of 25% or more	−34	.172	.054

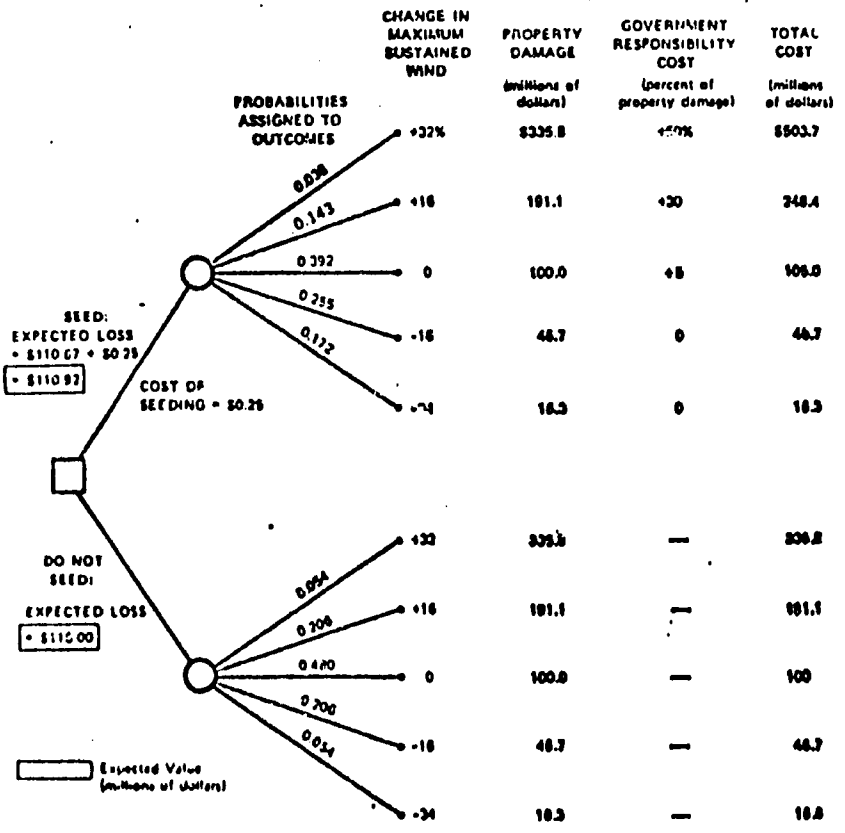


Fig. 7. The seeding decision for the nominal hurricane (government responsibility cost included).

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intensifies nor diminishes (0 percent change in the maximum sustained wind speed after the seeding) and an unseeded hurricane that intensifies slightly, causing 5 percent more property damage.

4) A seeded hurricane that diminishes by more than 10 percent and an unseeded hurricane that diminishes by the same amount. (If the hurricane diminishes after seeding, everyone agrees that the government acted wisely; thus, responsibility costs are set at zero.)

with these government responsibility costs included is diagramed in Fig. 7. Even with these large responsibility costs, the preferred decision is still to seed.

The responsibility costs needed to change the decision are a substantial fraction of the property damage caused by the hurricane. For the $100-million hurricane chosen as the example for this section, the average responsibility cost must be about $22 million to change the decision. If the hurricane were in the $1-billion class, as Camille

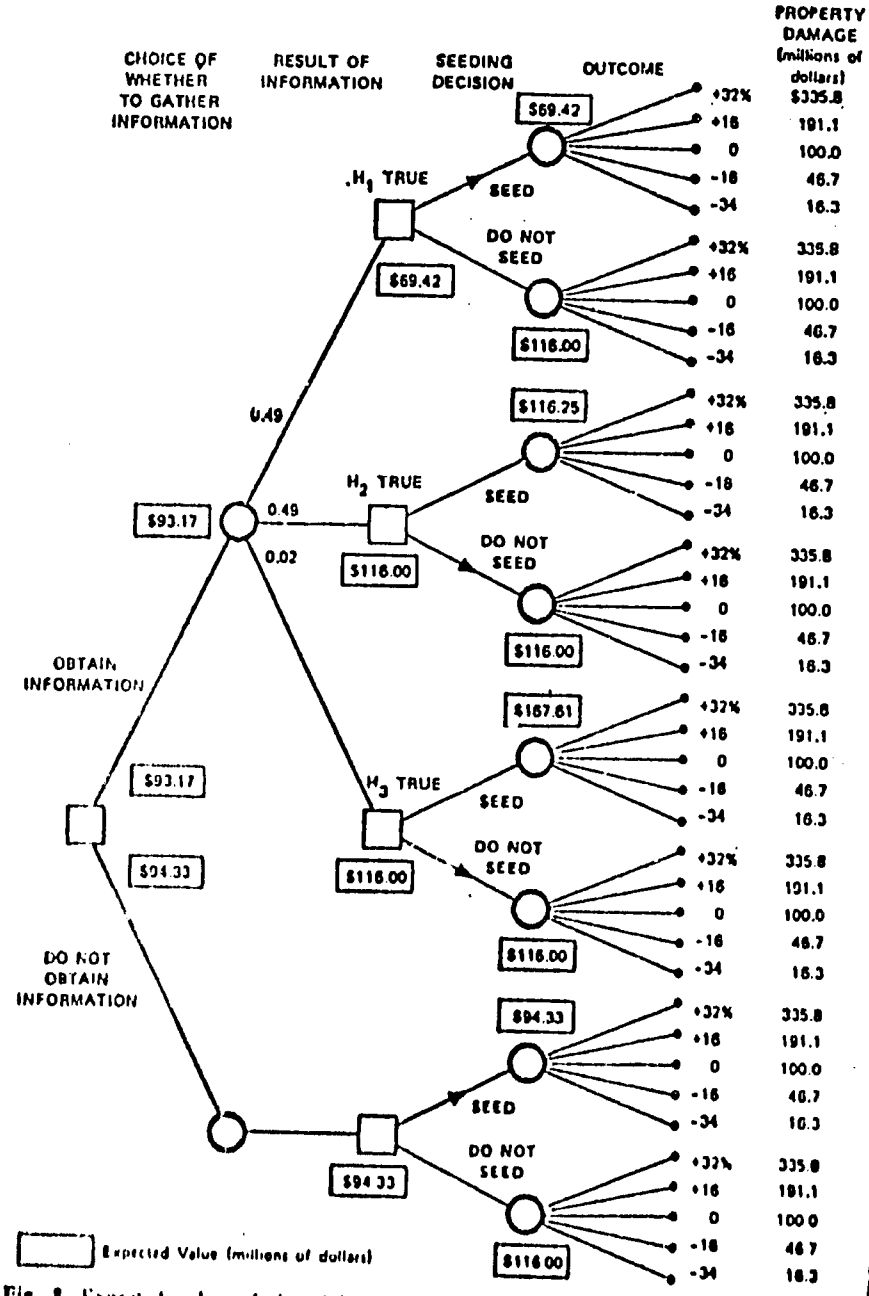

Fig. 8. Expected value of the clairvoyant's information—which hypothesis describes the effect of seeding? (There is no government responsibility cost.)

average responsibility cost of $200 million would be needed. In other words, an expected reduction of $200 million in property damage would be foregone if the government decided not to accept the responsibility of seeding the hurricane.

The importance of the responsibility issue led us to investigate the legal basis for hurricane seeding in some detail. These investigations were carried out by Gary Widman, Hastings College of the Law, University of California. A firm legal basis for operational seeding apparently does not now exist. The doctrine of sovereign immunity provides the government only partial and unpredictable protection against lawsuits, and substantial grounds for bringing such lawsuits might exist (*22*). A better legal basis for government seeding activities is needed before hurricane seeding could be considered other than as an extraordinary emergency action. Specific congressional legislation may be the best means of investing a government agency with the authority to seed hurricanes threatening the coast of the United States.

Value of Information

One of the most important concepts in decision analysis is the value of information: How much it would be worth to make the decision after rather than before uncertainty is resolved? In the case of hurricane modification, how much should be the government pay to learn which of the three hypotheses H_1, H_2, or H_3, is actually true (*23*)? We imagine that the government has access to a clairvoyant who has this information and is willing to sell it to the government, if he is paid before he makes the information available. It is easiest to understand the calculation in terms of the decision to seed one hurricane threatening a coastal area.

Let us consider the choice between the two decision situations shown in Fig. 8. The government can choose to buy the information and make the decision after it has learned which hypothesis is true, or it can choose not to buy the information and can make the seeding decision on the basis of the present uncertainty.

Let us, for the moment, consider only property damage and the cost of seeding and disregard government responsibility costs. If H_1 is true, the preferred decision is to seed because the expected

loss of $116.00 million for the alternative of not seeding. If H_2 is true, then by choosing not to seed, the government saves the $0.25-million cost of seeding; the loss expected from property damage is the same for both alternatives: $116.00 million. If H_3 is true, seeding is a poor choice: the expected loss from property damage is $167.61 million, $51.61 million more than for the alternative of not seeding. At the present time, the government does not know what the clairvoyant will say, but probabilities have been assigned to his answers:

$$P(H_1) = .49$$
$$P(H_2) = .49 \qquad (12)$$
$$P(H_3) = .02$$

The expected loss corresponding to the decision situation in Fig. 8 is then computed by multiplying the probability of each of the clairvoyant's answers by the expected loss associated with that answer and summing over the three possible answers:

$$(.49)\ ($69.42) + (.49)\ ($116.00) + (.02)\ ($116.00) = $93.17 \text{ million} \qquad (13)$$

Comparing this with the expected loss for the best alternative (seed) without the clairvoyant's information, which was $94.33 million, we see that it is $1.16 million less. This difference represents the expected value of the clairvoyant's information in allowing the government to make a better decision. It is a relatively small number compared with the expected losses because the information is not expected to be of much value—the probability assignments indicate that seeding is already a good idea. Without the clairvoyant's information the government should seed, with the clairvoyant's information, with probability .49, the government will save the cost of seeding ($0.25 million), and with the low probability .02 it will avert the potentially disastrous intensification expected from H_3, saving $167.61 million − $116 million = $51.61 million. By this reasoning we get the same answer as before for the value of information

$$(.49)\ ($0.25) + (.02)\ ($51.61) = $1.16 \text{ million} \qquad (14)$$

and we can see that the value is very sensitive to the small probability assigned to H_3.

Now suppose that the government responsibility costs assumed previously are included. The expected value of perfect information is then much higher responsibility costs can be saved by not seeding. If the decision without perfect information is to seed, the expected saving from engaging the clairvoyant is

$$(.49)\ ($0.25 + $23.28) + (.02)\ ($51.61 + $53.57) = $13.63 \text{ million} \qquad (15)$$

This figure represents 11.75 percent of the expected property damage if the alternative of not seeding is taken for the nominal hurricane.

The value of information largely derives from the fact that it allows the government to avoid the responsibility for seeding if seeding turns out to have no effect. The large increase over the value computed in Eq. 13 is due to the contribution of the government responsibility costs. Most of the increase of $12.47 million, namely $11.41 million, comes from the first or H_2 term.

The value of information depends on the extent to which the government is willing to assume responsibility for seeding a hurricane. If responsibility were not an issue, the government would seed operationally now, and information would have a comparatively low value in the context of this decision. The value of information is great costs are large enough to make the decision essentially even between seeding and not seeding. Still higher responsibility costs cause the value of information to decrease (*24*).

Value of Further Seeding Experiments

The analysis of the value of a seeding experiment is similar to the determination of the value of the clairvoyant's information. The difference is that the resolution of uncertainty is only partial. The information obtained in the experiment is used in Bayes' equation (Eq. 5) to revise the prior probability assignments to the hypotheses. The original decision is then reevaluated with the posterior probabilities (Fig. 9). The result of the experiment is uncertain when the decision to experiment is made; consequently, the value of experimentation must be computed as an expectation over the possible posterior decision situations. The situation can be diagramed in tree form as shown in Fig. 9.

The analysis for two experimental seedings is given in Table 2 (*25*). The values assumed above for the govern-

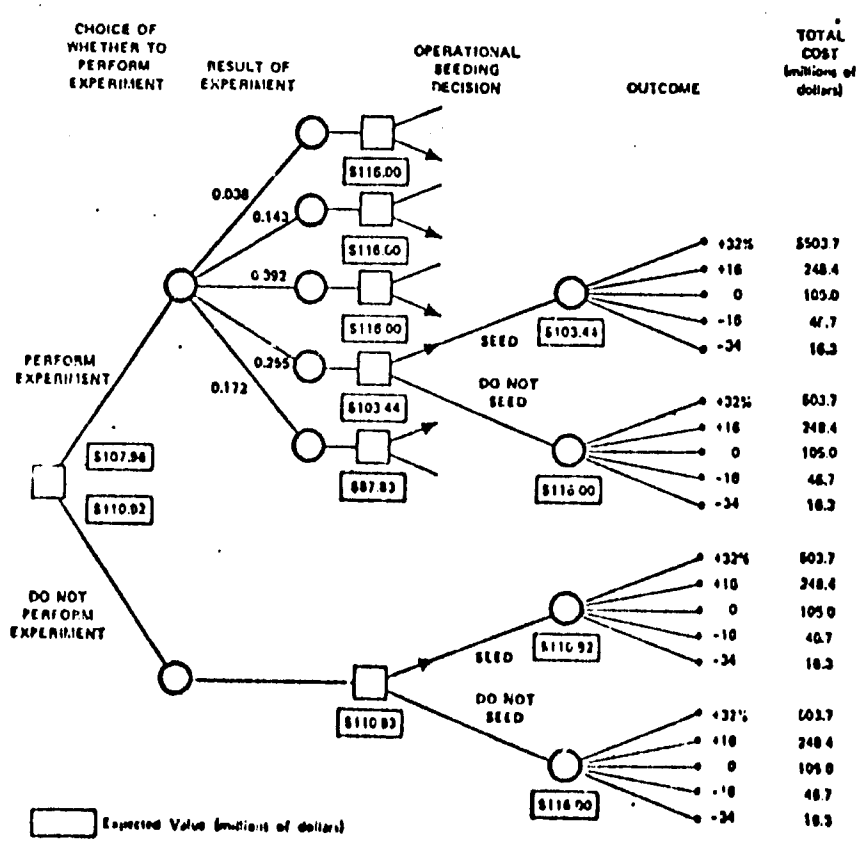

Fig. 9. Value of a seeding experiment (government responsibility cost included).

single hurricane but to all hurricanes that might be seeded operationally. The numerical results for the single nominal hurricane are summarized in the extreme left column of Table 3 and are extended to multiple hurricanes in the remaining columns.

Even if only half the hurricanes could be seeded because of tactical considerations having to do with precipitation, hurricane trajectory, and so on, the expected annual benefit from perfect information is $26 million. If we assume that only half the hurricanes could be seeded, and discount the expected benefits of perfect information for all future hurricane seasons at a discount rate of 7 percent, we arrive at $370 million. This figure represents the value of a "perfect" experiment that would determine whether H_1 is true.

A single repetition of the 1969 Hurricane Debbie experiment has an expected value of $5.39 million in the context of the nominal hurricane, or about 4.7 percent of expected property damage. For the decision to seed a single hurricane in the billion-dollar range, the expected value of the experiment is ten times as high, about $50 million. For one hurricane season the value is 4.7 percent of $220 million, or $10.2 million (it is assumed again that various tactical considerations might preclude seeding in half of the cases). For all future hurricane seasons, with a discount rate of 7 percent, the value is $146 million compared with an experimental cost of about $500,000. The benefit to cost ratio is therefore about 300. Even if only a single hurricane season is considered, the expected benefits are 20 times greater than the cost of the experiment and ten times the present annual budget for Project Stormfury.

percent of hurricanes that are assumed to be possible candidates for seeding on the basis of tactical considerations are considered. If all hurricanes are assumed to be candidates for operational seeding, the figures of the last two columns should be doubled.

Item	Nominal hurricane used in analysis		Single hurricane season (million dollars)	All future hurricane seasons, discounted at 7% (million dollars)
	Million dollars	Percentage		
Expected property damage without seeding	116.0	100	220.0	3142
Expected value of perfect information	13.6	11.8	26.0	370
Expected value of a field experiment consisting of two experimental seedings	5.4	4.7	10.2	146
Expected value of field experiments:*				
With government responsibility costs	8.8	7.6	16.6	238
Government responsibility costs ≅ 0	12.4	10.7	23.5	335

* If it is assumed that prior operational seeding is not permitted.

Experimental Capability Decision

The occurrence of hurricanes is a random phenomenon. Therefore, it is uncertain whether there will be an opportunity for an experimental seeding before the arrival of a threatening storm that might be operationally seeded. Opportunities for experimental seeding have been scarce. In the last few years there have been only six experimental seedings, and these have been conducted on three hurricanes, Esther (1961), Beulah (1963), and Debbie (1969) (*7*). Experimental seedings have been limited to a small region of the Atlantic Ocean accessible to aircraft based in Puerto Rico, and few hurricanes have passed through this region.

There are many other regions of the ocean where hurricanes might be found that satisfy the present criterion for experimental seeding—that is, the hurricane will be seeded only if the probability is less than .10 that it will come within 50 miles of a populated land area within 18 hours after seeding. However, a decision to expand the present experimental capability of Project Stormfury would need to be made well before the experiment itself. Whereas the seeding itself requires only that an aircraft be fitted with silver iodide pyrotechnic generators, the monitoring of the subsequent development of the hurricane requires other aircraft fitted with the appropriate instrumentation. The requirements in equipment, crew training, and communications and support facilities are substantial. In addition, permission may be needed from nations whose shores might be threatened by the seeded hurricane. The experimental decision, then, involves an investment in the capability to perform an experimental seeding. Whether an experiment is performed depends on the uncertain occurrences of hurricanes in the experimental areas.

The expected time before another experimental opportunity for Project Stormfury's present capability is about one full hurricane season. There was no opportunity during 1970. Preliminary estimates of the cost of a capability to seed hurricanes in the Pacific are about $1 million (*27*). The incidence of experimentally seedable hurricanes in the Pacific appears to be more than twice that in the Atlantic (*28*). Therefore, it appears advisable to develop a capability to conduct experimental hurricane seeding in the Pacific Ocean since the benefits expected from this capability outweigh the costs by a factor of at least 5 (*29*).

Conclusions from the Analysis

The decision to seed a hurricane imposes a great responsibility on public officials. This decision cannot be avoided because inaction is equivalent to a decision not to permit seeding. Either the government must accept the responsibility of a seeding that may be perceived by the public as deleterious, or it must accept the responsibility for not seeding and thereby exposing the public to higher probabilities of severe storm damage.

Our report to the National Oceanic and Atmospheric Administration recommended that seeding be permitted on an emergency basis. We hope that further experimental results and a formal analysis of the tactical decision to seed a particular hurricane will precede the emergency. However, a decision may be required before additional experimental or analytical results are available. A hurricane with the intensity of Camille threatening a populous coastal area of the United States would confront public officials with an agonizing but unavoidable choice.

The decision to seed hurricanes can not be resolved on strictly scientific grounds. It is a complex decision whose uncertain consequences affect many people. Appropriate legal and political institutions should be designated for making the hurricane-seeding decision, and further analysis should be conducted to support these institutions in carrying out their work.

Role of Decision Analysis

The results of a decision analysis depend on the information available at the time it is performed. Decision analysis should not be used to arrive at a static recommendation to be verified by further research, rather it should be used as a dynamic tool for making necessary decisions at any time. Various sensitivity analyses included here indicate how new information might be expected to influence policy recommendations. However, the advent of a severe hurricane will necessitate a decision on the basis of the information then available.

The analysis of hurricane modification points up a difficulty that is common in public decision-making on complex technological issues. When the consequences of deploying new technology are uncertain, who will make the choice? While many individuals or groups may share responsibility, decision analysis conceptually separates the roles of the executive decision-maker, the expert, and the analyst. The analyst's role is to structure a complex problem in a tractable manner so that the uncertain consequences of the alternative actions may be assessed. Various experts provide the technical information from which the analysis is fashioned. The decision-maker acts for society in providing the basis for choosing among the alternatives. The analysis provides a mechanism for integration and communication so that the technical judgments of the experts and the value judgments of the decision-maker may be seen in relation to each other, examined, and debated. Decision analysis makes not only the decision but the decision process a matter of formal record. For any complex decision that may affect the lives of millions, a decision analysis showing explicitly the uncertainties and decision criteria can and should be carried out.

References and Notes

1. R. H. Simpson and J. S. Malkus, *Sci. Amer.* 211, 27 (Dec. 1964).
2. R. C. Gentry, *Science* 168, 473 (1970).
3. Now incorporated in the National Oceanic and Atmospheric Administration.
4. R. A. Howard, *Proceedings of the Fourth International Conference on Operational Research* (Wiley, New York, 1966).
5. ———, *IEEE Trans. Syst. Sci. Cyberm.* 4 (1968), p. 211.
6. A detailed discussion of the research is to be found in the project's final report [D. W. Boyd, R. A. Howard, J. E. Matheson, D. W. North, *Decision Analysis of Hurricane Modification* (Project 8501, Stanford Research Institute, Menlo Park, Calif., 1971)]. This report is available through the National Technical Information Service, U.S. Department of Commerce, Washington, D.C., accession number COM-71-00784.
7. The meteorological information leading to this approximation is discussed in detail in the SRI project final report (6), especially appendix B. Meteorologists connected with Project Stormfury believe it highly improbable that seeding will cause any substantial change in the course of the hurricane, and other important consequences of seeding are not foreseen at this time. We wish to stress that our role in the decision analysis of hurricane modification has been to provide the methodology for analyzing a complex decision with uncertain consequences. The specific assumptions have been provided by the hurricane meteorologists associated with Project Stormfury and by other experts in relevant fields. Because of space limitations these assumptions cannot be discussed in detail in this article; the interested reader is assisted to consult the project's final report or communicate directly with the authors. The type of seeding is assumed to be the same as that used in the Hurricane Debbie experiments: massive multiple seeding of the clouds in the outer eyewall region with silver iodide. During September 1971, Project Stormfury conducted seeding experiments of a different type on Hurricane Ginger (R. C. Gentry, internal communication, National Oceanic and Atmospheric Administration, October 1971). The Ginger experiment involved the seeding of clouds in the rain bands well outside the eyewall region. This "rainsector" experiment was selected because Ginger had a large and poorly formed eyewall and was judged not to be a good subject for eyewall-region seeding. Although some changes in cloud structure and wind field occurred at a time when they might have been caused by seeding, these changes were minor compared with the dramatic changes that occurred in Hurricane Debbie after seeding. Because of the difference in type of seeding, the Ginger results do not imply a need for revision of the analysis or data presented in this article.
8. In some hurricanes, such as Diane (1955) and Camille (1969), precipitation-induced inland flooding has also been an important cause of property damage. Seeding might cause some increase in precipitation. In considering the policy decision to permit seeding we ignored these precipitation effects, but they might sometimes be important in the decision to seed a specific hurricane.
9. Throughout the analysis it is assumed that seeding would be authorized and carried out by some agency of the federal government.
10. C. Holliday, *Technical Memorandum WBTM SR-45* (Environmental Science Service Administration, Washington, D.C., 1969).
11. The details of the derivation of this probability distribution are given in appendix B of (6). The indirect approach of using the Holliday relation combined with pressure-change observations was first suggested by R. C. Sheets of the National Hurricane Research Laboratory.
12. S. L. Rosenthal, *Technical Memorandum ERLTM-NHRL 88* (Environmental Science Service Administration, Washington, D.C., 1970). See also *Project Stormfury Annual Report 1970* (National Hurricane Research Laboratory, Miami, 1971).
13. A probability distribution on an uncertain quantity x will be denoted $P(x)$ whether x takes on discrete or continuous values. If x is discrete, $P(x)$ will be the probability mass function; if x is continuous, $P(x)$ will be the probability density function. A probability distribution of the normal or Gaussian family specified by its mean m and standard deviation s will be denoted $f_N(m, s)$.
14. The average effect of seeding and the fluctuation from the average may be regarded as (independent) normal random variables whose sum represents the effect of seeding on a specific hurricane. According to well-known results in probability theory, this sum will be normally distributed with a mean equal to the sum of the two means and a standard deviation equal to the square root of the sum of the squares of the two standard deviations.
15. The effect of seeding and the natural change in the storm are described as independent normal random variables and the total change is their sum. The independence assumption is judged an appropriate summary of present knowledge; sensitivity to this assumption is examined in (6). Important assumptions such as this one were reviewed with Project Stormfury meteorologists. A letter to us from R. C. Gentry (October 1970) stated, "While seeding may affect different hurricanes by different amounts, we are not yet prepared to predict these differences." The assumption of independence does not deny that there may be a relationship between the natural change occurring in a hurricane and the effect of modification. When information about this relationship becomes available, it should be incorporated into the analysis and the independence assumption should be withdrawn.
16. H. Raiffa, *Decision Analysis: Introductory Lectures on Choices Under Uncertainty* (Addison-Wesley, Reading, Mass., 1968); M. Tribus, *Rational Descriptions, Decisions, and Designs* (Pergamon, New York, 1969).
17. D. W. North, *IEEE Trans. Syst. Sci. Cyberm.* 4 (1968), p. 200.
18. The details of the calculation of c_1 are given in (6). Similar relationships between maximum sustained wind speed and property damage have been stated by other investigators [R. L. Hendrick and D. G. Friedman, in *Human Dimensions in Weather Modification*, W. R. Derrick Sewell, Ed. (Univ. of Chicago Press, Chicago, 1966), pp. 227–246]. In November 1971, D. G. Friedman communicated to us some results from analyzing insurance claim data. He finds an exponent of 6.7; this value would lead to much larger reductions in property damage than were assumed in our analysis. Other investigators have suggested an equation of the form $d = c_1(w - w_0)^n$, where c_1 and w_0 are empirical constants (R. C. Gentry, private communication). This equation would give results essentially equivalent to ours.
19. This procedure is an approximation, which depends on the fact that seeding costs are small compared with costs of property damage.
20. It is shown in (6) that the results are not sensitive to the discrete approximation.
21. For example, if an exponential utility function with a risk aversion coefficient of $\gamma = 0.001$ is used, the difference between the certain equivalents for the two alternatives increases from \$21.67 million to \$24.2 million. Because of stochastic dominance, any risk attitude will always leave seeding as the preferred alternative. Further discussion on risk preference may be found in (5) and (17).
22. These issues are discussed in detail in appendices E and F of (6).
23. In answering this question we assume that the government is willing to pay up to \$1 to avoid \$1 of property damage.
24. It is possible for the responsibility costs to be so high that a hurricane would not be seeded even if it were certain that H_1 is true. This amount of responsibility cost implies that the government would prefer an unseeded hurricane to a seeded hurricane that causes only half as much property damage.
25. For these calculations a system of computer programs for evaluating large decision trees, developed by W. Rousseau of Stanford Research Institute, was used.
26. These discrete outcomes correspond to a reduction of 10 percent or more. The discrete approximation simplifies the analysis by restricting the number of possible experimental results. Earlier we considered the revision of probabilities based on the results of the 1959 Hurricane Debbie experiments. There the discrete approximation was not used, but it would have given equivalent results.
27. R. C. Gentry, personal communication. In arriving at this figure it was assumed that military aircraft based in the Pacific could be used in the seeding.
28. *Project Stormfury Annual Report 1968* (National Hurricane Research Laboratory, Miami, 1969).
29. The details of this calculation are given in (6).

30. This article summarizes research performed for the National Oceanic and Atmospheric Administration, U.S. Department of Commerce, contract 0-35172; the project leader is D. W. North. The authors acknowledge the substantial contribution of Dr. Dean W. Boyd. The authors also wish to acknowledge Professor Gary Widman of Hastings College of the Law, University of California, San Francisco, for legal research supporting the project and Dr. Cecil Gentry, Dr. Robert Simpson, Dr. Jeanne Simpson, and many others who have been associated with Project Stormfury for their assistance and cooperation. The findings and conclusions presented are the sole responsibility of the authors and do not necessarily reflect the views of the U.S. government or any of the individuals mentioned above.

ANNEX III

INFANT AND CHILDHOOD MORTALITY IN LESS DEVELOPED COUNTRIES - AN ANNOTATED BIBLIOGRAPHY

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VIII PERIODICALS

REGIONAL STUDIES

All of the following studies present statistical information concerning infant and childhood mortality and related variables for specific geographical areas. Correlations and causal relationships are measured and discussed.

Adlakha, A. L., A Study of Infant Mortality in Turkey, University of Michigan, PHD, 1970. This study looks out the urban-rural differentiations, demographic variables, socio-economic, educational and environmental characteristics of couples in Turkey who have experienced infant mortality.

Arriaga, Eduardo, Mortality Decline and Its Demographic Effects in Latin America, Population Monograph Series, #6, University of Cal, Berkeley, 1970. This book does not specifically address 0-5 mortality but it is good background material for understanding the impact on age structure and other effects of measures that lower mortality.

Chandrasekhar, S., Infant Mortality, Population Growth and Family Planning in India, The University of North Carolina Press, Chapel Hill, 1972. This is a review of infant mortality trends in the world as well as in India, causes and preventive strategies.

Hamer, J. H., The Cultural Aspects of Infant Mortality in Subsaharan Africa, Northwestern University, PHD, 1962. Statistics and discussion are presented indicating magnitude of infant mortality in this region of Africa, available medical resources, social organization and customs that pertain to infant mortality.

Harrington, Judith, A Comparative Study of Infant and Childhood Survivorship in West Africa, Cornell University, PHD, 1971. This is an excellent detailed analysis of factors that inflence infant and childhood mortality in West Africa. A lucid description of the pattern of mortality in this area and a comprehensive bibliography are included.

Harrington, Judith, Economic Development and Mortality in Infancy and Childhood: Comments from the West African Case, Department of Population Planning & CRED, University of Michigan, 1974. This is an interesting analysis that "supports the idea that economic development can be crucial in lowering the high rates of infant and childhood mortality...but it can also work to increase mortality". This report stresses malnutrition as the most serious factor leading to mortality in this age groups but points out that a synergistic network of forces are at work.

Puffer, Ruth and C. Serrano, Patterns of Mortality in Childhood, Pan American Health Organization, Scientific Publication #262, 1973. This study reviews the underlying and associated causes of death for 35,000 children below the age of five in 13 localities in Latin America and two areas in North America. Socioeconomic, medical resource availability, environmental sanitation and demographic data are presented among many other variables.

Puffer, Ruth, Patterns of Urban Mortality, Pan American Health Organization, Scientific Publication #151, 1967. The study reviews the underlying and associate causes of death in adults by sex, age and other characteristics in eleven cities in Latin America and one in North America.

Vaidyanathan, K. E. ed., Studies on Mortality in India, The Gandhigram Institute of Rural Health and Family Planning, Tamilnadu, Chapts 2 10,11, 1972. These three chapters deal exculsively with infant mortality. Chapter 2 discusses problems of measrufing infant mortality. Chapter 10 takes a look at infant mortality in an urban area, Bombay, and Chapter 11 analyzes factors affecting infant and early childhood mortality in India.

Wallace, Helen, et al., Maternal and Child Health Practices, Problems, Resources, and Methods of Delivery, C.C. Thomas, Publisher, Sptingfield, Ill. 1973. This is probably the newest, most reputable book on the subject. Most of the discussion concerns the USA, but several chapters review international infant and childhood morbidity and mortality problems.

Wyon, John and J. Gordon, The Khanna Study Harvard University Press, Cambridge, Massachusetts, 1971, Chpat 7, "Deaths and Population Pressure". This chapter reviews the rates and causes of infant and childhood mortaltiy in Punjab, India.

In the School of Public Health Library, University of Michigan, there are numerous reports from health ministries of various countries. Many of these reports contain morbidity and mortality statistics for the 0-5 age group.

INFANT AND CHILDHOOD MORTALITY- GENERAL

Babson and Benson, Primer on Prematurity and High Risk Pregnancy, The C. V. Mosby Co. St. Louis, 1966. The book looks at the important complications of pregnancy that lead to premature delivery; current methods of diagnosis and treatment, and care of the newborn when "prevention measures fail to delay untimely births.

Behar, Moises, "Death and Disease in Infants and Toddlers of Preindustrial Countries", American Journal of Public Health, Vol. 54, #7, July 1964. This article provides data revealing age-specific mortality rates from seven days to four years in several LDCs compared with the USA rates.

Butler, Neville, Perinatal Mortality, E. & S. Livingstone, LTD., Edinburgh, 1963. This report presents sociological, clinical and pathological data in a statistical manner concerning the determinants of perinatal mortality in 1958 in Britain. A classic study.

Donabedian, Avedis, "Infant Mortality and Socioeconomic Status in a Metropolitan Community", Public Health Reports, Vol. 80, #12, Dec. 1965. The author considers the socio-economic determinants of infant mortality for the Boston area

and introduces a methodology for calculating relationships.

Dugdale, A. E., "The Built-In Failure Rate of Immunization at Infant Health Clinics", The Lancet, Feb. 22, 1969. There is a need for looking at the failure to immunize more children in LDCs. This article suggests ways in which immunization rates can be improved.

Falkner, Frank, "Key Issues in Infant Mortality", The Journal of Tropical Pediatrics and Environmental Infant Child Health, Vol. 17, #1, 1971. This is a review of current discussion of causes of infant mortality in the USA.

Feldstein, M., "A Binary Variable Multiple Regression Method of Analysing Factors Affecting Perinatal Mortality and Other Outcomes of Pregnancy", Journal of the Royal Statistical Society, Vol. A 129, 1966. Regression analysis is used to determine relationships between perinatal mortality, maternal age, parity and social class in Britain.

Geijerstam, Gunnar, "Low Birth Weight and Perinatal Mortality", Public Health Reports, Vol. 84, # 11, Nov. 1969. This article reports on the large percentage of low birth weight babies among the infant fatalities and compares Swedish and USA data.

Gopalan, C. M. Behar, P. Robinson, et al., "World Wide Experience: Special Problems and preventive Programmes", Journal of Tropical Pediatrics, Dec. 1968. This is a good review of particular health problems of children in India, Latin American and Africa with special reference to preventive programs developed to meet these problems.

Jelliffe, Derrick and C. Williams, Mother and Child Health: Delivering the Services, Oxford Medical Publications, London, 1972. This is a good comprehensive review of issues concerning the health of mother and child, population problems, measurements of health, health services, etc.- geared towards LDCs.

Kessner, D. J. et al., Infant Death: An Analysis by Maternal Risk and Health Care, Washington, D. C.: Institute of Medicine, National Academy of Sciences, 1973. New York City data for approximately 100,000 births are analysed to determine the relationships between infant mortality, maternal risk variables and prenatal care.

Morley, David, "A Medical Service for Children Under Five Years of Age in West Africa" in The Royal Society of Tropical Medicine and Hygiene Transactions, Vol. 57, 1963. Morley describes in great detail a medical service designed to meet the needs of children under five in rural Nigeria. Costs of treatment and personnel as well as organization of services are given.

Morley, David, "Measles in Nigerian Children", Journal of Hygiene, London, 1963, p. 115. In Africa measles are found to be an outstanding cause of death because of all the complications that follow-diarrhea, bronchopneumonia, malnutrition.

Morris, J.N., & J. A. Heady, "Social and Biological Factors in Infant Mortality" in The Lancet, Feb. 12, 19, 26, March 5, 12, 1955. This is a series of articles that has become a classic study of infant mortality in England and Wales during 1949 and 1950. Age of mother, parity, father's occupation among other variables are considered.

Narangwal Project, Punjab, India, Johns Hopkins University, Baltimore, Maryland, International Health Division. Annual reports are issued describing methodology and data from their project, "Integration of Health Services and Family Planning". Data includes infant and childhood mortality rates and introduction of new health services.

Pan American Health Organization, "Perinatal Factors Affecting Human Development", Scientific Publication # 185, Washington, 1969. These are proceedings of a special session that presented papers discussing maternal factors affecting birthweight, mental performance of children; perinatal conditions that affect the new born's development.

"Report of the Committee on Infectious Diseases", Academy of Pediatrics, Evanston, Illinois, 1970. This manual reviews the etiology, epidemiology and diagnostic tests and treatment of those infectious diseases most prevalent among children.

Russell, Louise, Determinants of Infant and Child Mortality: Report of the Feasibility Study, Part I, National Planning Association, AID Contract No. AID/CM/otr-C-73-212, 1974. This report reviews the literature that discusses various determinants of infant mortality- maternal nutrition, medical care, maternal age, etc.. It also describes the statistical procedures that will be used for developing a causal-effect model that will explain relationships leading to infant mortality.

Shapiro, Sam, E. Schlesinger, R. Nesbitt, Infant, Perinatal, Maternal and Childhood Mortality in the United States, Harvard University Press, Cambridge, 1968. An excellent review of infant and perinatal trends, determinants of mortality in the USA and international comparisons among the more developed countries is presented.

Sloan, Frank, Survival of Progeny in Developing Countries: An Analysis of Evidence from Costa Rica, Mexico, East Pakistan and Puerto Rico, Rand Corporation, R-773-AID, 1971. This study identifies regional differences and potential determinants of infant and childhood mortality in several LDCs. Nutrition and female literacy reveal themselves to be important variables.

Weeman, Myron, "Annual Summary of Vital Statistics, 1972 with Observations on China", Pediatrics, Vol. 52, #6, Dec. 1973. This is a brief summary of infant and childhood mortality trends in the USA and the rest of the world.

World Health Organization, "Human Development and Public Health", Technical Report Series, #485, Geneva, 1972. This is an interesting article that discusses the many variables-environmental, genetic, perinatal, nutritional,etc.- which affect human development.

World Health Organization, "The Organization and Administration of Maternal and Child Health Services", Technical Report Series, #428, 1969. This report presents reasons for providing comprehensive maternal and child health services and th logistics of organization and administrative tasks.

World Health Organization, "The Prevention of Perinatal Morbidity and Mortality", Public Health Paper 42, Geneva, 1972. This is a report of a seminar held in Tours April 22-26, 1969. It presents statistics on perinatal mortality, specific medical problems, suggestions for organization of care and strategies for reducing morbidity and mortality.

World Health Organization, "The Prevention of Perinatal Mortaltiy and Morbidity", Technical Report Series, #457, Geneva, 1970. This report discusses factors influencing the outcome of pregnancy, long term sequelae, standards of care and educational needs.

World Health Organization, "Trends in the Study of Morbidity and Mortaltiy" Public Health Papers, #27, Geneva, 1965. This report reviews problems of notification of infectious diseases, national health surveys and research on mortality and morbidity trends.

INFANT AND CHILDHOOD MORTALITY AND NUTRITION

Aykrod, W.,"Nutrition and Mortality in Infancy and Early Childhood: Past and Present Relationships", American Journal of Clinical Nutrition, Vol. 24. April 1971. This is a comparison of infant mortality and nutritional deficiencies of children in LDCs compared with these same problems in England in the early 1900's.

Baert, J., et al., "Diet Supplementation for Entire Communities, Growth and Mortality of Infants and Children", American Journal of Clinical Nutrition", Vol. 23, #6, June 1970. This article discusses a controlled experiment in Northern Peru, measuring the effects of food supplements with different levels of protein on the health status of four villages. One control group included 6-30 month old children.

Bengoa, Jose, "Nutrition Rehabilitation Centres", The Journal of Tropical Pediatrics Dec. 1967. This article describes the equipment, personnel and organization of a nutrition rehabilitation centre. Bengoa presents cost estimations of treament for malnutrition in hospitals, rehab centres and preventive measures.

Berg, Alan and Robert Muscat, "Nutrition and Development: The View of the Planner", American Journal of Clinical Nutrition, Vol. 25, Feb. 1972. The first section of this article reviews data and literature on the magnitude and pattern of childhood mortality in LDCs.

Berg, Alan, The Nutrition Factor, Its Role in National Development, The Brookings Institute, Washington, D. C., 1973. This is a very interesting book dealing with problems of nutrition in LDCs with implications for development policy

making. Berg discusses strategies for alleviating malnutrition and tries to develop a "practical, systematic approach to program formation."

Cantrelle, P. and H. Leridon, "Breastfeeding, Mortality in Childhood and Fertility in a Rural Zone of Senegal" For specific reference speak to J. Harrington, Population Planning Dept., University of Michigan. The purpose of this study is to examine the relationship between weaning, infant mortality and fertility. Data from the Senegal area is presented and analyzed, looking at childhood mortality by age, sex, birth order, seasonal variation, etc..

Cook, R., "The Financial Cost of Malnutrition", Journal of Tropical Pediatrics, June 1968. This article estimates the costs of malnutrition in children-- treatment expenses and "child life wasteage".

Harfouche, Jamal, "The Importance of Breastfeeding", The Journal of Tropical Pediatrics, Vol. 16, #3, Sept. 1970, Monograph 10. This article reviews the advantages of breastfeeding, the biological processes of lactating, and the critical importance of optimum weaning procedures.

Jelliffe, Derrick, Child Nutrition in Developing Countries, A Handbook for Fieldworkers, Washington, D. C., AID, 1969. This is a good review of problems of childhood nutrition in the tropics. Intervention strategies for alleviating theseproblems are presented.

Jelliffe, Derrick, Culture, "Social Change, and Infant Feeding, Current Trends in Tropical Regions", American Journal of Clinical Nutrition, Vol. 10. Jan. 1962. This is an interesting view of the importance of traditional customs and the influences of modernization on infant feeding habits and the ecology of protein-calory malnutrition.

Knodel, John, "Breastfeeding, Fertility and Infant Mortality, An Analysis of some Early German Data", Population Studies, Vol. 21, # 2, Sept. 1967. An interesting work relating length of breastfeeding to fertility and infant mortality is introduced.

Knutsson, Karl, "Breastfeeding Habits and Cultural Context", Journal of Tropical Pediatrics, Vol. 15, #2, June 1969. This is a study of breast feeding behavior in three Ethiopian communities.

Koncazcki, Zbigniew A., "Infant Malnutrition in Sub-Sahara Africa: A Problem of Socio-Economic Development ", Canadian Journal of African Studies, Vol. 6, #3, 1972. This article discusses the cultural, economic, and ecological factors affecting malnutrition and the magnitude of the problem in Sub-Saharan Africa. Also discussed are the implications of malnutrition for socio-economic development.

Jelliffe, Derrick, Infant Nutrition in the Subtropics and Tropics, World Health Organization, Geneva, 1968, Monograph Series #29. This text is a practical guide to the understanding of the multiple factors that lead to infant malnutrition. Emphasis is on infant feeding and programs that will improve quality of food fed to the child.

Mata, L., J. Urrutia, C. Abertuzzi, "Influence of Recurrent Infections on Nutrition and Growth of Children in Guatemala", American Journal of Clinical Nutrition, Vol. 25, Nov. 1972. A study in Guatemala conducted from 1964 to 1970 reveals data concerning the influences of infection on the nutritional status of children at certain stages of growth.

Morley, David, "Factors Influencing the Growth and Nutritional Status of Infants and Young Children in a Nigerian Village", Trans Royal Society of Tropical Medicine and Hygiene, Vol. 62, #2, 1968. In Africa the second six months of life are critical. Immunity to endemic disease acquired before birth is waning, supply of breast milk is diminishing, and improper supplemental foods are being added to the diet.

Morley, David, "The Management of the Child with Dehydration in a West African Village", The West African Medical Journal, Feb., 1965. A detailed description of the operation, medicine and staff for the rehydration of children in rural areas.

"The Bulanda Project", The Journal of Tropical Pediatrics, Sept. 1966. This article reviews the results of various food preparations given to severely malnourished children as part of a comprehensive treatment program.

The National Academy of Sciences, "Maternal Nutrition and the Course of Pregnancy: Summary Report", Committee on Maternal Nutrition, Food and Health, National Research Council, Washington, D.C., 1970. This document reviews findings concerning the relationship between the nutritional status of a pregnant woman and incidence of toxemia, maternal anemia, and fetal development.

"Nutrition in Maternal and Child Health", The Journal of Tropical Pediatrics, Vol. 14, #3, 1968, Monograph # 5. This article includes a guide to treatment of malnourished children in hospitals and health centres and recipes for infants, toddlers and school children- using indigenous foods.

"Nutrition Issue", The Journal of Tropical Pediatrics, Vol. 15, #3, Sept. 1969. This issue includes articles on protein-calory malnutrition, socio-cultural factors leading to malnutrition, studies of births and deaths in a defined area in Africa.

Plank, S. and M. Milanesi, "Infant Feeding and Infant Mortality in Rural Chile", Bulletin World Health Organization, #48, 1973. Data is presented from Chile showing the relationships between infant feeding practices, medical care, socio-cultural factors, parity and infant mortality.

Primrose, T. and A. Higgins, "A Study in Human Antepartum Nutrition", The Journal of Reproductive Medicine, # 6, Dec. 1971. 1500 pregnant women from Montreal were given dietary supplements and it was found that those women receiving supplements for a longer period had less complications of pregnancy and their children were born at higher birth weights.

"A Proposal to Conduct Community Experiments in the Reduction of Malnourishment in Colombia", Fundacion Para La Educacion Superior, Cali, Colombia, Aug, 1973. This proposal describes the nutritional status of a village population and presents a systems approach for selecting strategies to reduce diarrhea, disease and malnutrition.

Robson, John, Malnutrition, Its Causation and Control, Vol. I and II, Gordon and Breach, N. Y., 1972. An excellent two volume text book that explores the ecology of malnutrition with most examples from LDCs.is this one written by two University of Michigan faculty, both eminent in their field.

Rulison, Michael, Report on Topical Investigation and Analysis of Nutritional Supplements in Family Planning Programs in India and Pakistan, North Carolina, Research Triangle Institute, 1970. This report discusses the relationship between nutrition, infant mortality and fertility. Rulison presents a model simulating the relationship of mortality and fertility.

St. George, John, et al., "Factors Influencing Birthweight in Normal Pregnancy", The Journal of Tropical Pediatrics, Vol. 16, # 3, Sept. 1970. Several factors, genetic and environmental influence the development of the foetus and its weight at birth.

Salamon, J. B. et.al., "Malnutrition and the Common Communicable Diseases in Rural Guatemala", American Journal of Public Health, Vol. 58,#3, March 1968. This article not only discusses the interactions of infectious diseases such as measles, whooping cough, mumps with nutritionalstatus but also describes the syndrome that arises from these interactions and becomes the fatal mechanism of death.

Scrimshaw, N. S., et al., "Nutrition and Infection Field Study in Guatemalan Villages, 1959-1964" Archives of Environmental Health:I "Study Plan and Experimental Design", 14: 657-662, May 1967;II "Field Reconnaissance, Administrative and Technical, Study Area; Population Characteristics; and Organization for Field Activies", 14: 787-801, June 1967; III Field Procedures, Collection of Data and Methods of Measurements", 15:6-15, July 1967; IV "Deaths of Infants and Preschool Children", 15:439-449, Oct. 1967; V "Disease Incidence Among Preschool Children Under Natural Village Conditions With Improved Diet and with Medical and Public Health Services", 16: 223-234; VI "Acute Diarrheal Disease and Nutritional Disorders in General Disease Incidence, 16:424-437, March 1968; VII "Physical Growth and Development of Preschool Children, 17:107-118, July 1968; VIII "An Epidemiological Appraisal of Its Wisdom and Errors, 17:814-827, Nov. 1968. These articles give a complete account of the experimental design and results of the famous Guatemalan field study. Article V and VII in particular presents data on the health status of the children.

Scrimshaw, N. S. and C. Taylor, J. Gordon, Interactions of Nutrition and Infection, World Health Organization Monograph Series # 57, Genova 1968. This well documented study describes the relationship between vitamin deficiencies protein and calory malnutrition and the various diseases inciting or resulting from poor nutritional status.

Wohl and Goodhart, ed. Modern Nutrition in Health and Disease, Lea and Febiger, Phila., 1964. This book includes several articles that discuss the effects of maternal nutrition on prematurity, infant birth weight, toxemia, etc., and the requirement and effects of nutrients on the health status of infants and children. See Hillman and Holt's articles in particular.

World Health Organization, "Nutrition in Pregnancy and Lactation, Technical Report Series #302, Geneva, 1965. This document discusses the effects of diet on the physiological states of lactation and pregnancy and the relationship of these states to the health of the foetus and the newborn child.

INFANT AND CHILDHOOD MORTALITY AND THEIR RELATIONSHIP TO FERTILITY

David, A. S. Infant and Childhood Mortality and Fertility Behavior Conference, Research Triange Institute, North Carolina, Feb. 17, 1971. This includes the proceedings of a conference which review the current issues concerning the relationships of childhood mortality, fertility and health services and nutrition.

"Health and Family Planning" in World Health, Jan. 1974. This issue is devoted to mother and child health benefits received from family planning. Also discussed are the relationships between morbidity and mortality and family size, parity, birth interval, etc.

Kennedy, Frederick, Report on Topical Investigation and Analysis of Promoting Family Planning Through Health Services, Research Triange Institute, North Carolina, 1970. This is an interesting report for AID linking relationships between infant and childhood mortality and fertility. A model is developed looking at the impact of health services on childhood mortality.

McDermott, Walsh, "Modern Medicine and the Demographic Disease Pattern of Overly Traditional Societies: A Technological Misfit", The Journal of Medical Education (Special Edition of Manpower for World Health), Vol. 41, # 9, Part II, Sept. 1966. This a classic and insightful article on the relationship of population growth, environmental conditions, infant mortality and medical technology.

Omran, Abdel, Health Benefits of Family Planning, Maternity-Centered Family Planning Program Paper, Geneva, Oct. 1971, WHO, MCH, 1971. This paper reviews the relationship between family size, spacing, unwanted pregnancies and perinatal, infant and child mortality. It also discusses the preventative aspects of family planning programs for reduction of childhood mortality.

Pradervand, Pierre, Family Planning Programs in Africa, Development Centre of the Organization for Economic Cooperation and Development, Paris, 1970 Pradervand asserts that high infant mortality is one of the main obstacles to family planning acceptance in West Africa.

Sukin, Hope, "A Perspective on the Mortality-Fertility Relationships in Less Developed Countries with Implication for Policy Making", 1974. This paper reviews the literature that describes this relationship on both a macro and

micro level. Also discussed are the effects of health services on infant and childhood mortality.

Wishik, Samuel, "Nutrition, Family Planning and Fertility", presented at the 21st Meeting of the Protein Advisory Group, U.N. in Paris, June 21, 1972, (a mimeo). This article talks about the effects of nutrition on fertility and health status of the newborn child;it then discusses the effects of fertility on the nutritional status of mother and child.

World Health Organization, "Health Aspects of Population Trends and Prospects", Working Paper # 8 for the World Population Conference, 1974. It is an excellent review of literature and analyses of the effects of fertility and population trends on infant, and childhood mortality. Also discussed is the influence of preschool mortality on fertility.

Wray, Joe D. and Roy E. Brown, "Family Planning, Nutrition and Public Health Services"presented at the
This paper both describes the maternal depletion syndrome which contributes to low birth weight infants, poor performance in lactation and in LDCs is often seen among women and discusses infant mortality and its relation to this cycle.

Wray, Joe D., "Will Better Nutrition Decrease Fertility", presented at a Symposium on Nutrition, Fertility and Reproduction, IX International Congress of Nutrition, Mexico City, Sept. 1972. This paper discusses infant mortality in relation to nutrition and the effects of fertility on infant and childhood mortality and nutritional status of mother and child.

MISCELLANEOUS

Benenson, Abram, Control of Communicable Diseases in Man , American Public Health Association, Washington, D. C. 1970. Another classic reference on epidemiology of communicable diseases and preventive and curative measures.

Bryant, John, Health and the Developing World, Cornell University Press, London, 1969. A descriptive approach to health problems in LDCs with some data to put things in perspective.

Buck, Alfred, et al., Health and Disease in Chad, Epidemeology, Culture and Environment in Five Villages, The Johns Hopkins Press, Baltimore, 1970. This is a very complete assessment of the community, social organization, economics, medical services, environmental conditions and epidemiological features of disease in Central Africa.

Felsenfeld, Ambhan, The Epidemiology of Tropical Diseases, Charles C. Thomas, Publishers, 1966. The text reviews the epidemiology of bacterial, mycot ic, parasitic and viral diseases as well as malnutrition and mental disorders in the tropics.

King, Maurice, Medical Care in Developing Countries, Oxford University Press, Nairobi, 1966 Some interesting chapters on the organization of health services, pediatrics, protein calory malnutrition, under-five clinics, immunization of the under fives, specific treatments for certain are included.

Paul, Hugh, The Control of Diseases, E and S Liningstone, LTD, London, 1964. A classic text book on diseases, social and communicable.

Pollack, T. M., Trials of Prophylactic Agents for the Control of Communicable Diseases, WHO, Geneva, 1966. This is a guide to the organization and evaluation of control tests.

Scott, David, Epidemic Disease in Ghana, 1901-1960, London, Oxford University Press, 1965. An interesting study about the major epidemic diseases- plague, yellow fever, smallpox, trypanosomiasis, influenza- trends and control measures in Ghana.

Sector Analysis Division, Bureau for Latin American, AID. This division is working on a series of health models, access to medical care, nutrition and agriculatural development, and an overall health sector, disease oriented model.

Wegman, Myron, "Community Aspects of Child Health", reprint from Brennemann's Practice of Pediatrics, Vol. I, Chapt. 7, 1972. This article discusses trends in infant mortality and organization to promote better medical care.

ADDITIONAL STATISTICAL REFERENCES

Food and Agriculatural Organization Production Yearbook, United Nations, Rome, Annual publication. This publication includes food productivity, livestock development, import and export figures, and processing statistics from most countries belonging to the U.N..

Keyfitz, Nathan, et al., Causes of Death, Life Tables for National Population, Siminar Press, N. Y., 1972. A good source of leading causes of death in countries listed. It includes LDCs but data is limited for many.

World Health Organization Annual Epidemiological and Vital Statistics, Annual publication. This is an excellent reference source and should be available at most major libraries. It includes both mortality and morbidity statistics for a large selection of countries throughout the world.

BIBLIOGRAPHIES

Annotated Bibliography of Vital+Health Statistics, U.S. Dept. of HEW, Public Health Service, HSMHA, 1970.

"Delivery of Health Care Services in Less Developed Countries- A Literature Search", AID/csd-3423 performed for American Public Health Association by the Biological Sciences Communications Project, Washington, D. C., 1973.

Harrington, Judith, A Comparative Study of Infant and Childhood Survivorship in West Africa, Cornell University, PHD, 1971. A good bibliography is included.

Health and Development-An Annotated Indexed Bibliography, The Johns Hopkins University, Dept. of International Health, Baltimore, Maryland, 1972. An excellent and all-inclusive bibliography.

Chandrasekhar, S., Infant Mortality, Population Growth and Family Planning In India, The University of North Carolina Press, Chapel Hill, 1972. A good bibliography is included.

Jelliffe, Derrick, Infant Nutrition in the Subtropics and Tropics, World Health Organization, Geneva, 1968, Monograph Series #29. Good footnotes and references.

Russel, Louise, Determinants of Infant and Child Mortality: Report of the Feasibility Study, Part I, National Planning Association, AID Contract # AID/CM//otr-C-73-212, 1974. An annotated bibliography is presented.

Scrimshaw, N. S. et al., Interactions of Nutrition and Infection, World Health Organization Monograph Series #57, Geneva, 1968. A complete technical and not-so-technical bibliography(fantastic in scope) has been put together.

World Health Organization Publications; Check any reference catalogue. Public Health Papers and The Technical Series Reports are usually listed by topic.

PERIODICALS

All of the following periodicals frequently carry articles concerning various aspects of infant and childhood mortality particularly in Less Developed Countries.

Ecology of Food and Nutrition

International Journal of Health Services

Journal of International Health

Journal of Tropical Medicine and Hygiene

Journal of Tropical Pediatrics

Pediatrics

World Health Organization Bulletin

World Health Organization Chronicle

Efficiency of Health Measures
- Contractor to be selected

Marjorie Belcher, DAA/TA, clarified the background of this project as containing a significant research component for which the RAC review and advice was sought, although the proposal has been developed as a General Technical Service project.

Dr. Linder, Chairman of the Subcommittee consisting of Drs. Carter, Montgomery, and Heady, reported as follows:

This presentation appears to be a preliminary formulation in that there is no formal indication of the institution or the principal investigators proposed. Subsequently, there is reference to the fact that Drs. Peter Heller and Robin Barlow of the University of Michigan had been instrumental in drafting the concept and plan of work. This needs to be clarified in providing a more firm basis for project appraisal. In contrast, Dr. Heady has indicated that he likes the idea of presenting the research concept to RAC for review as a possible means of developing a better proposal. In reviewing the four phases of the proposed study, Dr. Linder noted with interest the prediction of likely outcome to be a shift in responsibility for the delivery of health services from professionals to paraprofessionals. He cited the general principle that one should not insist on statistical precision beyond the level required for the conclusions and actions sought.

This is a well drafted proposal. The scientific honesty concerning the reliability of the data collected in months 15-20 of the workplan is commendable. However, the subcommittee members are skeptical for

various reasons. Dr. Carter believes that the work can't be done as outlined, and he recommends disapproval. The proposal is too diffuse and vague. The reference to a prior project on alternative approaches suggests the need to have a progress report. Dr. Montgomery suggests that the methods proposed can work, although the data are questionable. He questions the appropriateness of the Delphic approach except in the first phase. Dr. Heady likes the presentation, and considers this to be a worthwhile project. While linear programming models are possible in this area, he has reservations about the design, and needs to see the specifications. Hence, there is no adequate basis for evaluation. Dr. Linder summarized that while there is not enough specificity to give advice, he favors the approach to confront health planners with a new emphasis on the judgments of operations analysis. Health planners must move away from policy based on compassionate judgments. This appears to be the wave of the future. Further, this is not a matter of right or wrong decisions, and any incremental improvements have tremendous practical significance.

Since no RAC action is requested, Dr. Linder suggested additional work with emphasis on phases 1 and 2 for later RAC review. Clearly, this is a research oriented project.

Dr. Montgomery commented on the Delphic approach as being appropriate to socio-economic conditions regressed on health status rather than to predictions about the future impact. This application needs to be thought through in more detail. There is considerable literature and experience on this approach which supports the application to judgments rather than to predictions.

Dr. Heady stated that the proposal was well summarized. He would like to see a formal proposal for RAC consideration.

Dr. Long urged further discussion on the optimization of practices and the appropriate degree of refinement of data for practical use. Dr. Swanson pointed out the problem of treating diseases in holistic terms in a probabilistic model, and suggested the advisability of limiting the study to a single disease or some sub-set of diseases. There is not enough information for more evaluative statements. Dr. D. Peterson asked how is it possible to develop a simulation model when the values of the outputs are uncertain. Dr. Long asked how the RAC might work with AID staff in further review of the basic idea.

Dr. Joe Davis, TA/H, agreed that the RAC input was useful. An Experimental Advisory Group which TA/H is attempting to establish has received acceptances from only about half of those approached. The concept for this project has grown out of experiences in the assessment of health sectors. The collection of practitioners views represents a possible short-cut to the more elaborate collection and analysis of basic data. This is a proposal to test the usefulness of this approach. Colombia and Ghana are possible countries with an interest in participation. Even though the data may lack some precision, it will be more valuable that the present basis for many health intervention decisions. A status report of the Colombia project mentioned by Dr. Carter is due at the next RAC meeting and may indicate that it is to be closed out. The gaming approach used at Michigan State is considered to be useful for training objectives, but not as a tool to develop decisions for the field. The lack of specification in this project is recognized and is

a function of lack of staff; a contractor is needed to develop such detail.

Dr. Smuckler commented that while it would be inappropriate for the RAC subcommittee to assist in this effort, RAC members might be able to contribute to a sharpening of the proposal. Dr. Long suggested specific involvement of two or three RAC members in revision of the proposal. RAC cannot review it before the October meeting and consultation he said is needed now. Those members who might be available were requested to indicate their interest. No RAC action was taken.

(Note: Dr. Heady has agreed to assist in this matter).