STATISTICAL ANALYSIS OF THE D. C. COOK PREOPERATIONAL ENVIRONMENTAL MONITORING PROGRAM

Ishwar P. Murarka

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DIVISION OF ENVIRONMENTAL IMPACT STUDIES
ARGONNE NATIONAL LABORATORY
ARGONNE, ILLINOIS

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STATISTICAL ANALYSIS OF THE D. C. COOK PREOPERATIONAL ENVIRONMENTAL MONITORING PROGRAM

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Abstract

This report summarizes the major findings of an evaluation of the statistical adequacy of the preoperational environmental monitoring program at the Donald C. Cook Nuclear Power Plant. As a result of this study we found that variance components analysis methods are adequate to determine large magnitude changes in the environment. When an interaction effect between years and inner-outer factors (reference-stress) exists for the preoperation period, estimating and testing for the plant operation effect becomes difficult. This was illustrated by the benthic data analysis. It was further found that for the determination of impact hypothesis, several-factor-mixed-effects models are not needed. Simplifications, as shown by us, in the collapsed model by us, can provide the answer quite easily. Advanced methods, such as time-series analysis and biomathematical modeling, should be studied for use in the impact analysis. The limited analyses with these techniques showed promising results.

INTRODUCTION

With the support of the Reactor Licensing Division, U. S. Nuclear Regulatory Commission (NRC), Argonne National Laboratory conducted an evaluation of the statistical adequacy of the preoperational environmental program at the Donald C. Cook nuclear power plant. This report summarizes the major findings of this study. Deficiencies in the program, particularly its statistical design and analysis, are discussed.

On the basis of available information regarding the plant and site-specific problems, a purely quantitative approach to this critique was neither warranted nor justified. Therefore, the report progresses through a combination of statistical data analysis, qualitative evaluation, and theoretical rationale.

The report is divided into three sections. The first presents background information on the D. C. Cook monitoring program currently in use. The second pertains to the analysis conducted by consultants to the utility and the additional analyses performed by Argonne. Because many problems of environmental monitoring arise from a poor theoretical basis for the monitoring design, the third section is devoted to a discussion of a theory for the design and analysis of nonradiological environmental monitoring programs.

1. DESCRIPTION OF THE SITE AND EXISTING MONITORING PROGRAM

1.1 THE PLANT SITE

The Donald C. Cook Nuclear Power Plant is located on a 650-acre site in Lake Township, Berrien County, about two miles northeast of Bridgman, Michigan. The station lies on the eastern shore of Lake Michigan at about equal distance from the site boundaries. The facility consists of two units, each of which employs a pressurized-water reactor with an output capacity of 3250 MWt, or approximately 1054 MWe. Unit 1 has been in operation since 1975; Unit 2 startup is proposed for 1978. About 15 billion kWh/yr electrical energy will be generated at full plant operation.

Condenser and service cooling water for the two reactors is drawn from and returned to Lake Michigan by a once-through cooling system. The water enters the plant through three intake cribs located approximately 2250 feet offshore in 24 feet of water. It is discharged by two pipes--one 16 feet in diameter (Unit 1) and the other 18 feet in diameter (Unit 2)--submerged in the lake 200 feet offshore and buried about 300 feet apart under at least 2 feet of sand in approximately 18 feet of water. The total heat-rejection rate for the two reactors at full operating power is calculated to be $15.5 \cdot 10^9$ Btu/hr, and the condenser cooling water flow rate will be 1.645×10^6 gallons per minute (3650 cfs).

Operational monitoring of the effects on aquatic biota of the thermal discharge and cooling water system is required by as specified in the plant's Final Environmental Statement[1] and Environmental Technical Specifications.[2] In addition to thermal effluent as a source of stress to lake biota, four principal chemical waste discharge sources require monitoring: (1) the chlorine added to the condenser cooling and surface water for purification, (2) the steam generator blowdown, (3) the chemical waste solutions from regeneration of makeup water demineralizers, and (4) treated sewage effluent.

In making the environmental assessment and evaluations for the purpose of licensing the plant, the NRC staff anticipated that thermal stresses, chemical additives, and the mechanical injury due to the cooling system components would constitute the principal environmental impacts resulting from its operation. Accordingly, monitoring of the physical, chemical, and biological characteristics of the environment is required in the Environmental Technical Specifications (ETS).[2]

1.2 EXISTING MONITORING PROGRAMS

For the past several years, a monitoring program has been conducted at the plant that is aimed at satisfying the environmental interests of the utility itself and AEC/NRC requirements. To a large extent, the current program was prescribed by the AEC/NRC. The ETS defined plant variables, design features, monitoring requirements, and administrative controls necessary to assure minimizing the impact of the plant on the surroundings, as determined by the environmental review conducted in accordance with the National Environmental Policy Act.

The objectives of the ecological surveillance program are given in the ETS as: (1) to determine the relationship between the plant's thermal discharge and the physical and biological characteristics of the lake water masses in the vicinity of the plant site; (2) to determine the aquatic ecology of this portion of the lake (southeastern corner of Lake Michigan from the St. Joseph River to Trail Creek in Michigan City, Indiana); (3) to determine the effects of plant operation on the physical, chemical, and biological variables of this portion of Lake Michigan and the plant site, including the beach; and (4) to minimize adverse impacts on terrestrial and aquatic biota within and adjacent to transmission rights of way. The evaluation of the surveillance program discussed in this report will also extend to biological monitoring requirements in and around the vicinity of the Cook Plant.

Aquatic ecological studies have been underway at the D. C. Cook plant since 1966, and a comprehensive preoperational general ecological survey, covering about 98 square miles of southeastern Lake Michigan, has been in progress since 1972. It is anticipated that, when compared with the operational conditions, these studies will enable determination of the plant's influence on the biological systems examined. The organisms involved include phytoplankton, periphyton, zooplankton, benthic invertebrates, and fish. The statistical significance of any observed changes in natural populations after plant startup will be tested using analysis of variance.[2]

A summary of methods and sampling stations used for the general ecological survey are given in Table 1. Table 2 provides a descriptive summary of the stations chosen for sampling of the biological communities. Figures 1-4, showing the layout of the sampling locations used in the monitoring program, are incorporated in this report for the convenience of the reader.

Table 1. Stations and Schedule Used for General Ecological Survey (see Table 2 for transect locations and distances from shore)[a]

ZOOPLANKTON

(1) 1973

(a) Short surveys: 5 months (May, June, August, September, November)
10 stations (as shown below)

DC-1	DC-2	DC-3	DC-4	DC-5	DC-6
NDC-.5-2	NDC-7-5	SDC-.5-2	SDC-7-5		

(b) Major surveys: 3 months (April, July, October)
28 stations (as shown below)

DC-1	DC-2	DC-3	DC-4	DC-5	DC-6
NDC-.5-2	SDC-.5-2	NDC-1-1	NDC-1-2	SDC-1-1	SDC-1-2
NDC-2-1	NDC-2-3	SDC-2-1	SDC-2-3	NDC-4-1	NDC-4-3
NDC-4-4	SDC-4-1	SDC-4-3	SDC-4-4	NDC-7-1	NDC-7-3
NDC-7-5	SDC-7-1	SDC-7-3	SDC-7-5		

(2) Years With Concurrent Entrainment and Impingement Studies (1974 onward)

(a) Short Surveys: 5 months (May, June, August, September, November)
10 stations (as shown below)

DC-1	DC-2	DC-3	DC-4	DC-5	DC-6
NDC-.5-1	SDC-.5-1	NDC-7-1	SDC-7-1		

(b) Major surveys: 3 months (April, July, October)
28 stations (as shown below)

DC-1	DC-2	DC-3	DC-4	DC-5	DC-6
NDC-.5-1	SDC-.5-1	NDC-1-2	SDC-1-1	SDC-1-2	NDC-2-1
NDC-2-3	SDC-2-1	SDC-2-3	NDC-4-1	NDC-4-3	NDC-4-4
SDC-4-1	SDC-4-3	SDC-4-4	NDC-7-1	NDC-7-3	NDC-7-5
SDC-7-1	SDC-7-3	SDC-7-5			

(3) Years Without Concurrent Entrainment and Impingement Studies

(a) Short surveys: Same as for (2)

(b) Major surveys: Same as for (2)

PHYTOPLANKTON

(1) 1973

(a) Short surveys: 5 months (May, June, August, September, November)
11 stations (as shown below)

DC-0	DC-1	DC-2	DC-3	DC-4	DC-5
DC-6	NDC-.5.2	SDC-.5-2	NDC-7-5	SDC-7-5	

Table 1. (Continued)

(b) Major surveys: 3 months (April, July, October)
36 stations (as shown below)

DC-0	DC-1	DC-2	DC-3	DC-4	DC-5
DC-6	NDC-.5-0	NDC-.5-2	SDC-5.-0	SDC-.5-2	NDC-1-0
NDC-1-1	NDC-1-2	SDC-1-0	SDC-1-1	SDC-1-2	NDC-2-0
NDC-2-1	NDC-2-3	SDC-2-0	SDC-2-1	SDC-2-3	NDC-4-0
NDC-4-1	NDC-4-1	NDC-4-3	SDC-4-0	SDC-4-1	SDC-4-3
NDC-4-4	SDC-4-4	NDC-7-1	NDC-7-3	NDC-7-5	SDC-7-3
SDC-7-5					

(2) Year Without Concurrent Entrainment and Impingement Studies (1974 onward)

(a) Short surveys: 5 months (May, June, August, September, November)
11 stations (as shown below)

DC-0	DC-1	DC-2	DC-3	DC-4	DC-5
DC-6	NDC-.5-1	NDC-7-1	SDC-.5-1	SDC-7-1	

(b) Major surveys: 3 months (April, July, October)
36 stations (as shown below)

DC-0	DC-1	DC-2	DC-3	DC-4	DC-5
DC-6	NDC-.5-0	NDC-.5-1	SDC-.5-0	SDC-.5-1	
NDC-1-0	NDC-1-1	NDC-1-2	SDC-1-0	SDC-1-1	SDC-1-2
NDC-2-0	NDC-2-1	NDC-2-3	SDC-2-0	SDC-2-1	SDC-2-3
NDC-4-0	NDC-4-1	NDC-4-3	SDC-4-0	SDC-4-1	SDC-4-3
NDC-4-4	SDC-4-4	NDC-7-1	NDC-7-3	NDC-7-5	SDC-7-1
SDC-7-3	SDC-7-5				

(3) Years Without Concurrent Entrainment and Impingement Studies

(a) Short surveys: Same as for (2)

(b) Major surveys: Same as for (2)

BENTHOS

Benthos stations for 1973 were described elsewhere.[a] Beginning in July 1974 benthos were collected from the following stations of the regular grid. Each sample will be the contents of chamber #1 of a tripiex ponar grab. In zone 0, four casts will be made at each station. In zones 1 and 2, two casts will be made at each station. The sampling months will be April, July, and October.

(a) Short surveys: None

(b) Major surveys: 3 months (April, July, October)
30 stations (as shown below)

[a] *"Benton Harbor Power Plant Limnological Studies. Part XIII. Cook Plant Preoperational Studies, 1972," pp. 214-218, March 1973.*

Table 1. (Continued)

	Zone		
	0	1	2
Inner	SDC-1-1 SDC-.5-1 DC-1 NDC-.5-1 NDC-1-1	SDC-1-2 SDC-.25-1 DC-2 NDC-.25-1 NDC-1-2	SDC-1-3 SDC.5-3 DC-3 DC-4 NDC-.5-3
Outer	SDC-7-1 SDC-4-1 SDC-2-1 NDC-4-1 NDC-7-1	SDC-7-3 SDC-7-2 SDC-2-3 NDC-2-3 NDC-7-3	SDC-7-5 SDC-7-4 SDC-4-3 NDC-4-3 NDC-7-5

PERIPHYTON

Months: 7 (May, June, July, August, September, October, November)

Periphyton stations are located along the north and south range poles 1/4 mile north and south of the plant in water depths of 15 and 30 feet.

FISH

Months: 8 (April through November)

Eleven permanent stations were established in the area of the Cook Plant and Warren Dunes State Park (control site). Two seining stations (A and B) north and south of the plant and three gillnetting, trawling, and fish larvae stations (C and D) south of the plant and I north of the plant in 20 and 30 feet of water were established. A gillnetting station is located at station J north of the plant (30 ft of water). A fish larvae station (E) in 70 feet of water was also established for the months of April through August.

At Warren Dunes State Park (control location) one seining station (F); two stations (G and H) in waste depths of 20 and 30 feet for gillnetting, trawling, and fish larvae; and one station (M) fished during April through August at 70 foot of water depth for fish larvae were established. Fish larvae tows shall be conducted at ten stations.

Table 2. The DC, NDC, and SDC Stations: Transects and Distances from Shore[1]

This table includes 54 stations, 18 of which are no longer used for major surveys. The stations used for zooplankton, phytoplankton, and benthos in 1974 are among those listed here. Periphyton and fish are collected at specialized stations that are not included here. Stations whose names end in 0, like NDC-1-0, are in the surf. They are used only for phytoplankton collections.

Entries in the 'Transect' columns are interpreted as follows. Stations in the row marked '0.00' are on the DC transect, which leaves shore right at the plant (41° 58.5' N, 86° 34.0' E) and runs in a west-northwesterly direction with bearing 290°. The other transects are parallel to this one; their distances from it are indicated in the 'Transect' columns in both miles and kilometers. Positive distances refer to transects north of the plant; negative distances refer to transects south of the plant. The distance of each station from shore is measured along the transect and is given here in both miles and kilometers. Metric distances have been rounded to the nearest multiple of 0.40 km.

Transect		Distance of each station from shore (km and miles)							
		0.00	0.40	0.80	1.20	2.00	3.60	6.40	11.20 (km)
km	miles	0.00	0.25	0.50	0.75	1.25	2.25	4.00	7.00 (mi)
-11.20	-7.00		SDC-7-1	SDC-7-2*		SDC-7-3	SDC-7-4*	SDC-7-5	
- 6.40	-4.00	SDC-4-0	SDC-4-1	SDC-4-2*			SDC-4-3		SDC-4-4
- 3.20	-2.00	SDC-2-0	SDC-2-1	SDC-2-2*		SDC-2-3		SDC-2-4*	
- 1.60	-1.00	SDC-1-0	SDC-1-1		SDC-1-2		SDC-1-3*		
- 0.80	-0.50	SDC-.5-0	SDC-.5.1*	SDC-.5-2		SDC-.5-3*			
- 0.40	-0.25				SDC-25-1*				
0.00	0.00		DC-1		DC-2	DC-3	DC-4	DC-5	DC-6
0.40	0.25				NDC-.25-1*				
0.80	0.50	NDC-.5-0	NDC-.5-1*	NDC-.5-2		NDC-.5-3*			
1.60	1.00	NDC-1-0	NDC-1-1		NDC-1-2		NDC-1-3*		
3.20	2.00	NDC-2-0	NDC-2-1	NDC-2-2*		NDC-2-3		NDC-2-4*	
6.40	4.00	NDC-4-0	NDC-4-1	NDC-4-2*			NDC-4-3		NDC-4-4
11.20	7.00		NDC-7-1	NDC-7-2*		NDC-7-3	NDC-7-4*	NDC-7-5	

**Stations marked with an asterisk have not been used in major surveys since May 1, 1972.*

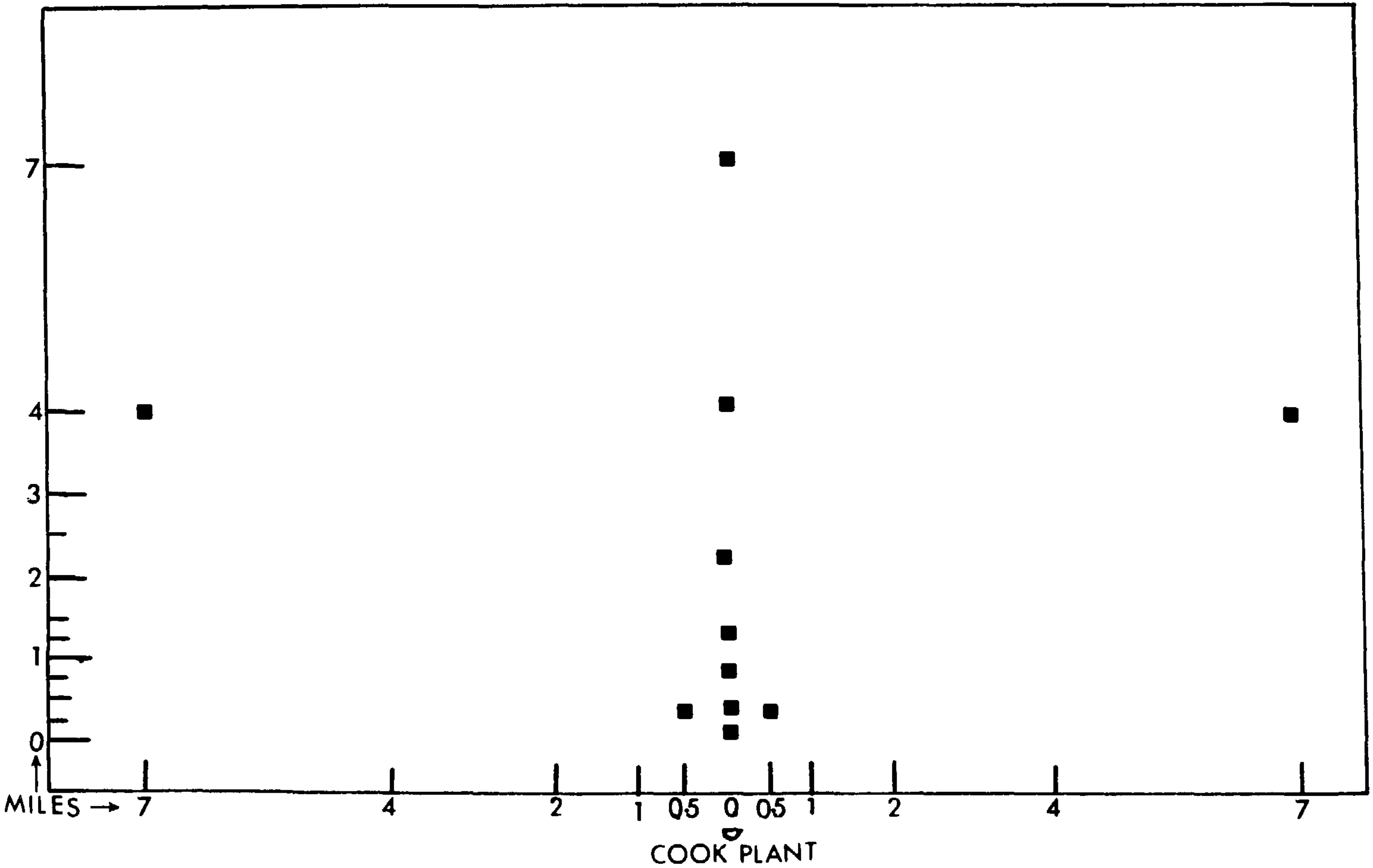

Fig. 1. Station Grid for Short or Monthly Surveys. (NDC-7-5 and SDC-7-5 were added in 1973.)[1]

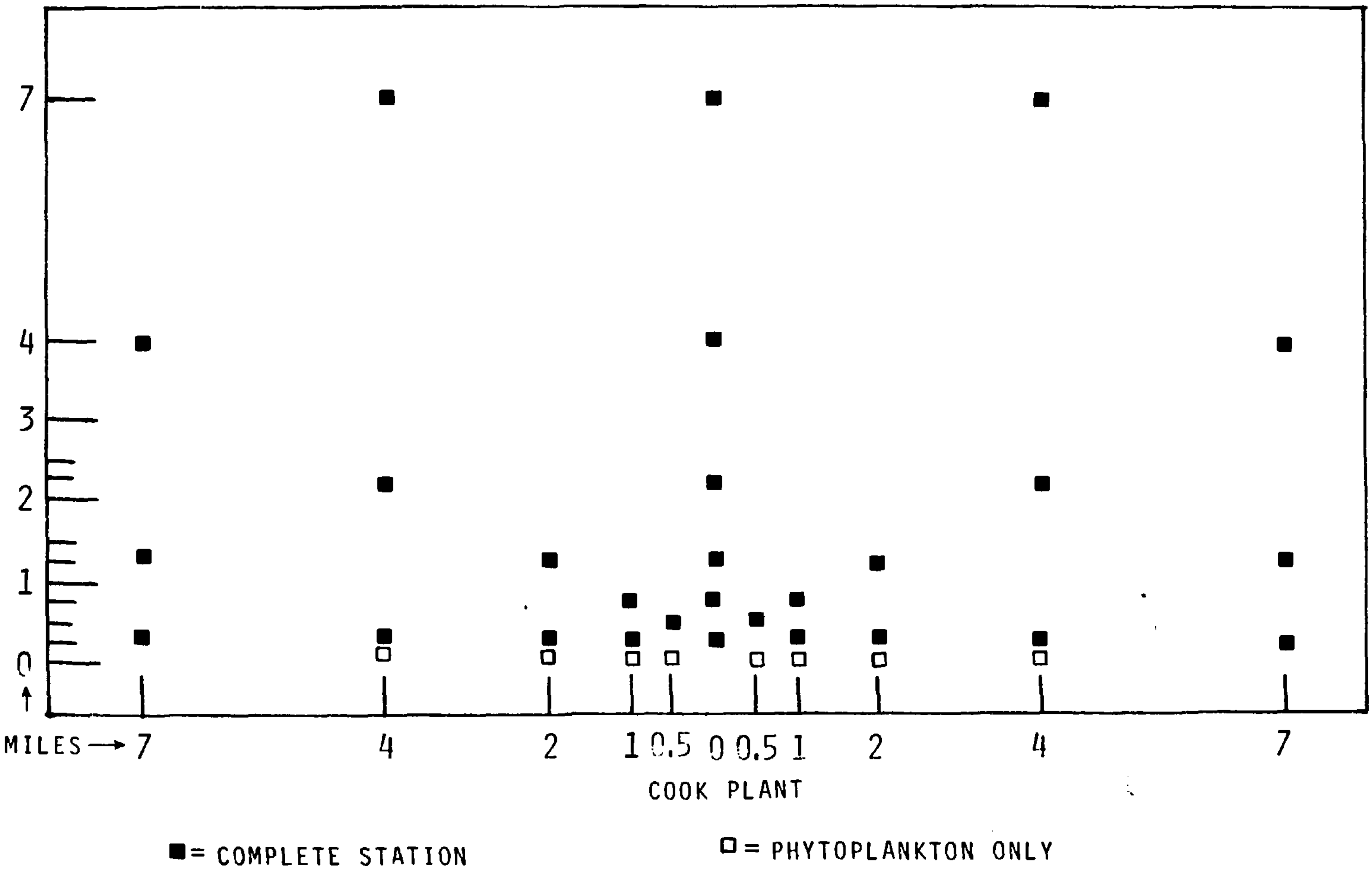

Fig. 2. Station Grid for Major or Seasonal Survey.[1]

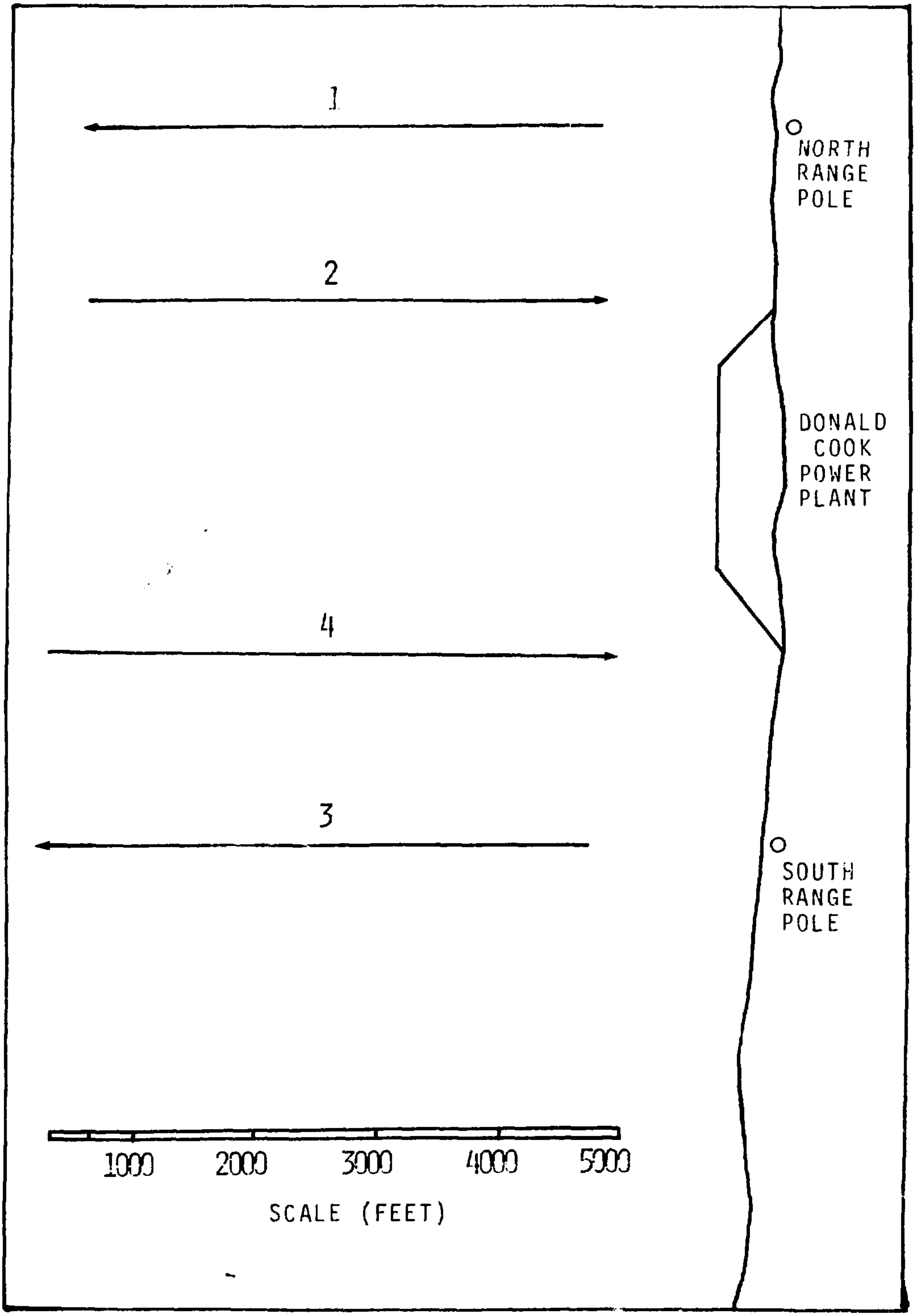

Fig. 3. Location of Transects for Macrophyte Survey.[1]

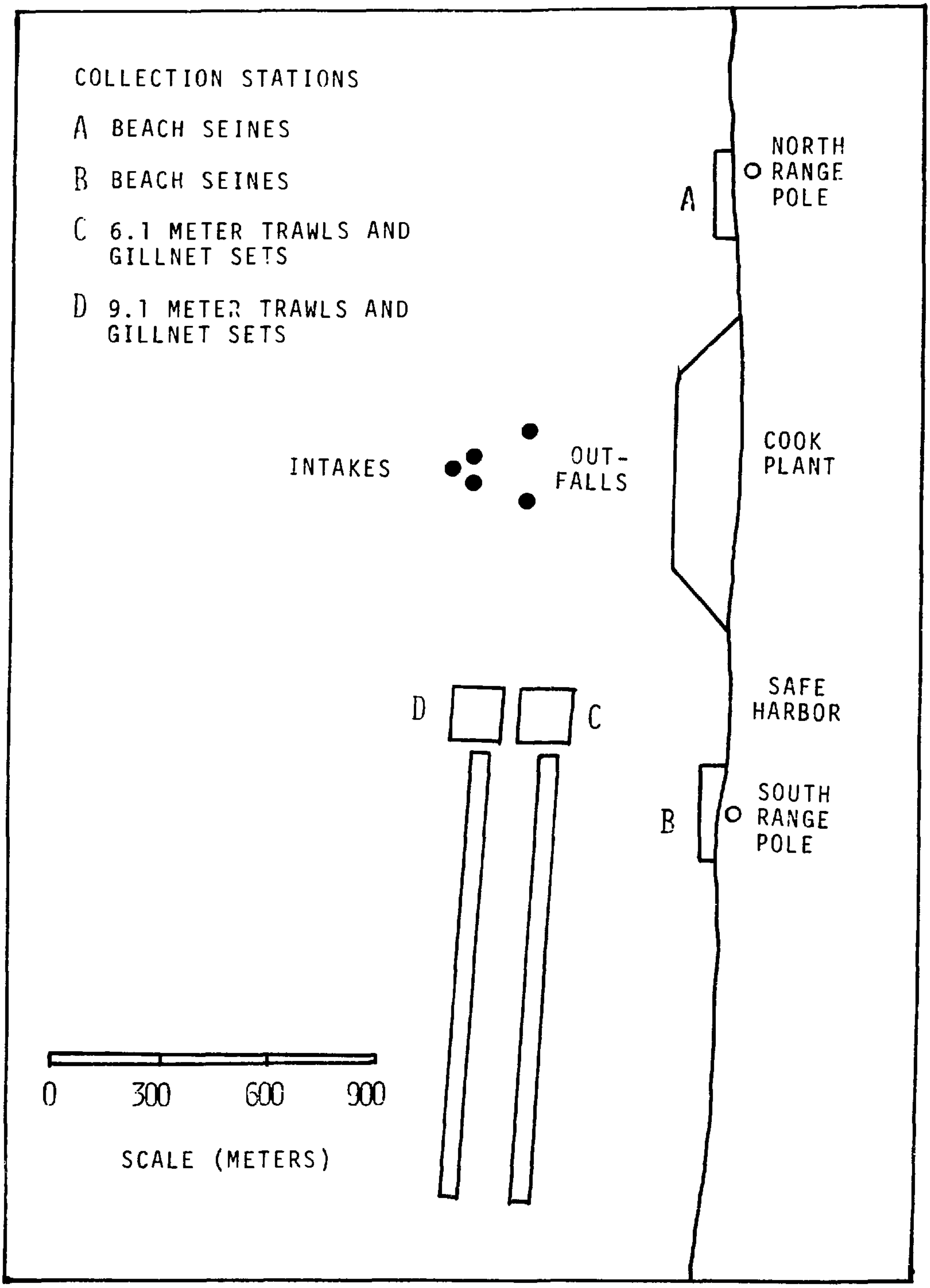

Fig. 4. Collection Areas Located Near Intake and Discharge Structures.[1]

2. STATISTICAL ANALYSIS OF PREOPERATIONAL DATA

2.1 ANALYSIS BY THE UTILITY'S CONSULTANTS

A series of ecological monitoring reports produced by the University of Michigan (consultants) contains the results of biological sampling of the environment near the plant.[3] Some of the early reports in this series represented proposed methods of analysis. A five-way analysis of variance (ANOVA) that would use four years of preoperational and four years of operational data was proposed by Johnston[4] in part XVIII of the report. Subsequently, part XX[5] of the report series examined the statistical power of this method for detecting the effect of waste heat on the benthic population.

2.1.1 Benthos Statistical Analysis Model

The linear model for the five-factor partially nested analysis of variance (used by Johnston)[5] is shown in Equation 1. Table 3 gives the symbols used, the number of levels in each factor, and the type of effects for each factor. The table also shows the ANOVA and the expected mean squares.

$$X_{ijkmpq} = \mu + \alpha_i + \beta_{j(i)} + \gamma_k + \alpha\gamma_{ik} + \beta\gamma_{j(i)k} + \delta_m + \zeta_p + \varepsilon_{q(ijkmp)} \qquad (1)$$

Johnston used the linear model in Equation 1 and carried out the ANOVA on preoperational benthic data (1970–1973). The data collection dates analyzed in the report were:

Year				
1970		July	September	November
1971	April	July	September	November
1972	April	July*		October*†
1973	April*			

**The starred dates had random surveys; the others had grid surveys.*

†Grouped with the November surveys for purposes of analysis of variance.

Based on the results of the ANOVA, Johnston[5] calculated the smallest before-after effect detectable (using the eight-year design) with a 5% significance level and 95% power. These results showed that benthos at the inner stations must undergo a true 5.5-fold increase or decrease relative to the outer stations in order to be detected by the eight-year study.

Table 3. Expected Mean Squares for the Linear Model Shown in Equation 1, a Partially Nested Analysis of Variance[a,b,c]

Factor	Greek Symbol	Name	No. of Levels	Type
C	α_i	Construction time	2 (before, after)	Fixed
Y	$\beta_{j(i)}$	Year	4	Random (nested within C)
D	γ_k	Outfall distance	2 (inner, outer)	Fixed
S	δ_m	Season	3	Fixed
Z	ζ_p	Depth zone	3	Fixed
E	$\varepsilon_{q(ijkmp)}$	Error	3 (no. of replicates)	

Source of Variation	Degree of Freedom	Expected Mean Square
C	1	$\sigma^2_\varepsilon + 216\ \theta^2_\alpha + 54\ \sigma^2_\beta$
Y	6	$\sigma^2_\varepsilon + 54\ \sigma^2_\beta$
D	1	$\sigma^2_\varepsilon + 216\ \theta^2_\gamma + 27\ \sigma^2_{\beta\gamma}$
S	2	$\sigma^2_\varepsilon + 144\ \theta^2_\delta$
Z	2	$\sigma^2_\varepsilon + 144\ \theta^2_\zeta$
CD	1	$\sigma^2_\varepsilon + 108\ \theta^2_{\alpha\gamma} + 27\ \sigma^2_{\beta\gamma}$
YD	6	$\sigma^2_\varepsilon + 27\ \sigma^2_{\beta\gamma}$
Error	412	σ^2_ε
Total	431	

[a] The notation $\beta_{j(i)}$ indicates that the factor indexed by j is nested within the factor indexed by i.

[b] Note that for depth zone and season only main effects are included. Their interactions are neglected. To allow for this the error degrees of freedom have been increased by the appropriate amount.

[c] where $\theta^2_\alpha = \sum_{i=1}^{2} \alpha_i^2$; $\theta^2_\delta = \sum_{i=1}^{3} \delta_i^2/2$; $\theta^2_\gamma = \sum_{i=1}^{2} \gamma_i^2$; $\theta^2_\zeta = \sum_{i=1}^{3} \zeta_i^2/2$;

and $\theta^2_{\alpha\gamma} = \sum_{i=1}^{2} \sum_{j=1}^{2} (\alpha\gamma_{ij})^2$.

2.1.2 Phytoplankton and Zooplankton Analysis

Data have been collected for the 36 sampling locations designated for studying plankton. Generally, the consultants have calculated simple averages and variances for sampling stations and seasons, and have drawn graphs with "error-bars" about the mean values.

Since the data currently available are preoperational measurements, an exercise (similar to that for benthos) can be carried out to determine the expected least detectable change in plankton densities that may be significant for Type I and Type II error probabilities of 0.05. However, such an analysis has not yet been carried out by the consultants to the utility.

2.1.3 Fish Analysis

In environmental impact considerations, the effects of plant operation on the fisheries in the area around the plant are considered very important. Yet the fish sampling and anlysis program is least emphasized in the monitoring scheme. For the months of April through November, several stations are being sampled for fish and larvae. The available reports have not yet proposed methods by which the fish data will be analyzed for an estimation of impact. Therefore, it is not possible to examine the validity and effectiveness of the statistical techniques which may be used to estimate the impact of the plant operation on the fisheries of the region. It appears that the fish monitoring program is weak and should be given detailed considerations so that such a program can be sensitive to detect impacts due to operation of the plant.

2.2 ARGONNE ANALYSIS AND EVALUATION

2.2.1 Benthic Data

Though the analysis of benthic data has been carried out with care, we focused on the question of determining impacts due to plant operation. Therefore, we carried out a number of additional analyses and further examined the linear model in Equation 1 used in Johnston's analysis.[5] At the time of our analysis, benthos data for 1970-1974 were available and were therefore used.

We used the individual data points to carry out a factorial analysis of variance with unequal cell sizes.[6-9] The statistical analysis was carried out on logarithmically (natural base) transformed data. Other transformations, such as square root, should also be tried. We used the linear model shown in Equation 2.

$$\begin{aligned} X_{jkmpq} = {} & \mu + \beta_j + \gamma_k + \delta_m + \zeta_p + \beta\delta_{jm} + \beta\gamma_{jk} + \beta\zeta_{jp} + \\ & \delta\gamma_{mk} + \delta\zeta_{mp} + \zeta\gamma_{kp} + \beta\delta\gamma_{jkm} + \beta\zeta\gamma_{jkp} + \beta\delta\zeta_{jmp} + \\ & \delta\zeta\gamma_{kpm} + \beta\delta\zeta\gamma_{jmp} + \delta\zeta\gamma_{kmp} + \beta\delta\zeta\gamma_{jkmp} + \varepsilon_{jkmpq} \end{aligned} \qquad (2)$$

The model has 71 coefficients (as linear combinations of factor effects). Table 4 gives the symbols used, the number of levels in each factor, and the type of effects for each factor.

Application of Equation 2 to benthic data from 1970-1974 produced the results shown in Table 5. From this ANOVA, we observe that the depth factor effect is the most significant source of variation in benthic densities. However, the main effects of year and season factors are also statistically significant. Of notable significance is the interaction effect of Y × S. The Y × D and S × D interactions are also significant. To further interpret the statistically significant interactions, the averages of the arithmetic and logarithmic benthic densities were calculated (Table 6). From this table of means, we observe that the inner (near the outfall) and outer zone annual average benthic densities have consistently changed. For example, the average benthic density in the outer zone was lower as compared to the inner zone for the years 1970-1972, whereas this relationship reversed for the 1972-1974 period.

A plot of the inner and outer zone annual mean densities (Figure 5) shows a marked reduction in the differences for 1970-1972 as compared with 1972-1974. It should be remembered that the first two years' data included November sampling as one of the levels for the month factor, whereas the last two years' data included October sampling for the month factor. This would indicate that the interaction between month and inner-outer factors is a non-zero quantity. This is supported by the statistically significant F-test value obtained in the ANOVA (Table 5).

Additional interpretational problems arise due to a change made in the sampling device between 1972 and 1973. The first two years' data were collected by using two "full" ponar grabs combined and converted to numbers/m^2, whereas the last two years' data were collected by using three 1/3rd-grabs combined and converted to numbers/m^2. If a correction for this sampling-device change could be made, it is possible that a declining time-trend in the yearly average differences would still be found between the inner and outer benthic densities.

Table 4. Expected Mean Squares for the Linear Model Shown in Equation 2, a Complete Factorial ANOVA with Unequal Cell Size

Factor	Greek Symbol	Name	No. of Levels	Type
Y	β_j	Year	4	Fixed
D	γ_k	Outfall distance	2 (inner, outer)	Fixed
S	δ_m	Month	3	Fixed
Z	ζ_p	Depth zone	3	Fixed
E	ϵ_{jkmpq}	Error	3 or 2	Random

Table 5. D. C. Cook Benthic Analysis, 1970-1974, Used for a Complete Factorial Design

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT					
Source	DF	Sum of Squares	Mean Square	F Value	R-Square
Regression	71	666.9006	9.3929	4.2019	0.7342
Y	*3*	*57.0172*	*19.0059*	*8.5022*	
S	*2*	*50.4692*	*25.2346*	*11.2887*	
D	*1*	*2.3960*	*2.3960*	*1.0718*	
Z	*2*	*422.6966*	*211.3483*	*94.5467*	
Y × *S*	*6*	*38.1212*	*6.3535*	*2.8422*	
Y × *D*	*3*	*11.1535*	*3.7178*	*1.6632*	
Y × *Z*	*6*	*5.6777*	*0.9463*	*0.4233*	
S × *D*	*2*	*9.9985*	*4.9993*	*2.2364*	
S × *Z*	*4*	*16.0242*	*4.0060*	*1.7921*	
Z × *D*	*2*	*1.2870*	*0.6435*	*0.2879*	
Y × *S* × *D*	*6*	*5.1728*	*0.8621*	*0.3856*	
Y × *Z* × *D*	*6*	*19.4921*	*3.2487*	*1.4533*	
Y × *S* × *Z*	*12*	*17.0565*	*1.4211*	*0.6359*	
S × *Z* × *D*	*4*	*0.7490*	*0.1872*	*0.0837*	
Y × *S* × *Z* × *D*	*12*	*9.5882*	*0.7990*	*0.3574*	
Error	108	241.4214	2.2353		
Corrected total	179	908.3220			

Table 6. Annual Means of Benthic Data

Year	No. of Obs.	Inner Zone		Outer Zone		Diff. Inner-Outer
		Density	Log-density	Density	Log-density	
1970-71	18	3209.5	6.9505	2627.72	6.5237	0.4268
1970-72	18	3201.6	7.0079	3108.6	6.6860	0.3219
1972-73	27	5967.9	7.5805	10460.4	8.1485	-0.5680
1973-74	27	11135.9	7.6523	11733.4	8.3527	-0.7004

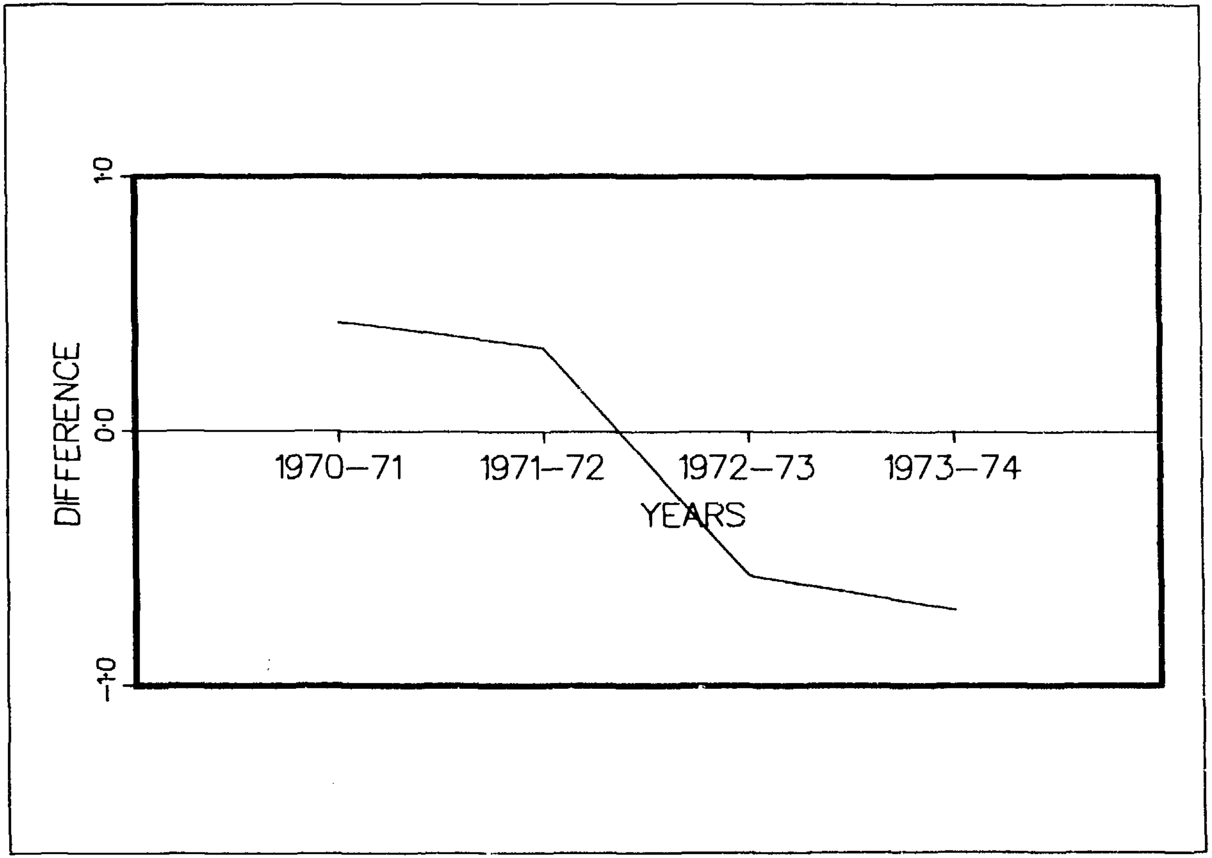

Fig. 5. Plot Showing Differences in Inner- and Outer-Zone Means for Logarithmically Transformed Benthic Densities at the Plant.

To take into account explicitly the effect of gear change, we changed the linear model to a nested-effects ANOVA. The gear types (survey methods) were used as the main factor in which the years were nested. This nested analysis showed that the differences between yearly means between gear types were statistically significant. The main effect due to the depth factor was found to be the dominant source in accounting for the variability in the benthic density. These results are given in Table 7.

Because the interaction effects involving year factors were significant, separate ANOVA's for each year, assuming a complete factorial design within each year, were carried out. These results are given in Tables 8 through 11. The individual-year data analysis showed that the depth, month, and inner-outer factor differences were statistically significant. The interaction between month and inner-outer factors had a tendency of showing significance in all four years.

Table 7. D. C. Cook Benthic Analysis, 1970-1974, for a Split-Plot Design

Source	DF	Sum of Squares	Mean Square
Y (survey)	3	57.0172	9.0057
S × D × Z	17	503.6209	29.6247
Y × S × D × Z (survey)	51	106.2623	2.0835
Residual	108	241.4214	2.2353
Corrected total	179	908.3220	5.0744

Table 8. Factorial ANOVA for 1970-1971 Benthic Data

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT

Source	DF	Sum of Squares	Mean Square	F Value	R-Square
Regression	17	124.8004	7.3412	7.0917	0.8700
S	*2*	*7.3645*	*3.6822*	*3.5572*	
D	*1*	*1.6395*	*1.6395*	*1.5838*	
Z	*2*	*103.4876*	*51.7438*	*49.9858*	
S × D	*2*	*1.0849*	*0.5424*	*0.5240*	
S × Z	*4*	*1.0307*	*0.2577*	*0.2489*	
D × Z	*2*	*5.5652*	*2.7826*	*2.6881*	
S × D × Z	*4*	*4.6277*	*1.1569*	*1.1176*	
Error	18	18.6330	1.0351		
Corrected total	35	143.4335			

Table 9. Factorial ANOVA for 1971-1972 Benthic Data

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT

Source	DF	Sum of Squares	Mean Square	F Value	R-Square
Regression	17	104.1370	6.1257	3.3279	0.7586
S	*2*	*8.5690*	*4.2845*	*2.3276*	
D	*1*	*0.9328*	*0.9328*	*0.5068*	
Z	*2*	*71.5941*	*35.7970*	*19.4474*	
S × *D*	*2*	*8.3119*	*4.1559*	*2.2578*	
S × *Z*	*4*	*8.2959*	*2.0710*	*1.1267*	
D × *Z*	*2*	*2.8672*	*1.4336*	*0.7788*	
S × *D* × *Z*	*4*	*3.5658*	*0.8915*	*0.4843*	
Error	18	33.1328	1.8407		
Corrected total	35	137.2698			

Table 10. Factorial ANOVA for 1972-1973 Benthic Data

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT

Source	DF	Sum of Squares	Mean Square	F Value	R-Square
Regression	17	140.9948	8.2938	3.1585	0.5986
S	*2*	*2.4402*	*1.2201*	*0.4646*	
D	*1*	*4.3546*	*4.3546*	*1.6584*	
Z	*2*	*114.5272*	*57.2636*	*21.8077*	
S × *D*	*2*	*5.4534*	*2.7267*	*1.0384*	
S × *Z*	*4*	*13.0455*	*3.2614*	*1.2420*	
D × *Z*	*2*	*0.1766*	*0.0883*	*0.0336*	
S × *D* × *Z*	*4*	*0.9971*	*0.2493*	*0.0949*	
Error	36	94.5302	2.6258		
Corrected total	53	235.5251			

Table 11. Factorial ANOVA for 1973-1974 Benthic Data

ANALYSIS OF VARIANCE TABLE, REGRESSION COEFFICIENTS, AND STATISTICS OF FIT					
Source	DF	Sum of Squares	Mean Square	F Value	R-Square
Regression	17	239.9509	14.1147	5.3417	0.7161
S	*2*	*70.2166*	*35.1083*	*13.2866*	
D	*1*	*6.6225*	*6.6225*	*2.5062*	
Z	*2*	*138.7653*	*69.3826*	*26.2577*	
$S \times D$	*2*	*0.3210*	*0.1605*	*0.0607*	
$S \times Z$	*4*	*10.7087*	*2.6772*	*1.0132*	
$D \times Z$	*2*	*12.1701*	*6.0850*	*2.3029*	
$S \times D \times Z$	*4*	*1.1465*	*0.2866*	*0.1085*	
Error	36	95.1253	2.6423		
Corrected total	53	335.0762			

2.2.2 Reduction of Linear Model

The motivation for carrying out an ANOVA is the desire to estimate and infer what the environmental impacts due to plant operation will be. The choice of preoperational reference-stress area measurements provides a basis for estimating and testing the power plant effects when operational period data on the environment are obtained. The statistical notion behind this approach is to examine the changes in the reference-stress (inner-outer) density differences exhibited during the preoperational years that may significantly change during the operational years. Narrowing queries to specific questions would result in large reductions of the linear models used for analyzing the data. We find that the multifactor models used by Johnston[5] and by us are not needed for estimating and testing the main effect of the C (before-after) factor and the interaction effect of the C × D factors. Appendix A shows the reduced model's equivalence to the large model when considering the testing of interaction and main effects. However, the reduction of the linear model would not remove the time trend.

The Equation 1 model can be reduced by summing both sides over the subscripts *m, p, and q. Because*

$$\sum_m \delta_m = 0 \text{ and } \sum_p \zeta_p = 0,$$

and if we make the assumption that the years represent "random" observations for the preoperational and operational periods, the reduced model is obtained as shown in Equation 3 below:

$$\sum_m \sum_p \sum_q X_{ijkmpq} = MPQ\mu + MPQ\alpha_i + MPQ\gamma_k + MPQ\alpha\gamma_{ik} + \sum_m \sum_p \sum_q \varepsilon_{qijkmp} \qquad (3)$$

Dividing both sides by MPQ and defining $\frac{\sum\sum\sum_{mpq} X_{ijkmpq}}{MPQ} = y_{ijk}$

and $\frac{\sum\sum\sum_{mpq} \varepsilon_{qijkmp}}{MPQ} = u_{ijk}$,

the model is rewritten as

$$y_{ijk} = \mu + \alpha_i + \gamma_k + (\alpha\gamma)_{ik} + u_{ijk} \ . \tag{4}$$

Appendix A contains the results on mathematical equivalence of the terms in the reduced model as a function of terms in the full model. The ANOVA created by this model is given in Table 12.

Under this reduced model, the data-analysis problem collapses to determining the statistical significance of the interaction effect. At present, only preoperational benthic data are available; therefore, a two-sample means comparison was carried out (following the reduced linear model) to determine if there is an inherent significant difference between the outer- and the inner-zone benthic densities. The comparison resulted in a t-value (-0.36) too small to lead to a conclusion that there are significant differences in the inner and outer zone benthic densities during the preoperational period. Therefore, from the preoperational characterization, no statistically significant difference in the expected benthic densities in the two zones has been demonstrated. However, this assumption does not include the effect of time-trend in the benthic densities, a topic developed in Section 2.2.3.

Table 12. Expected Mean Squares and ANOVA for the Linear Model in Equation 4

Source	d.f.	MS	E(MS)
Construction (α_i)	1	MSC	$\sigma_u^2 + 8 \sum_{i=1}^{2} \alpha_i^2$
Outfall (γ_k)	1	MSC	$\sigma_u^2 + 4 \sum_{k=1}^{2} \gamma_k^2$
Interaction ($\alpha\gamma_{ik}$)	1	MSC	$\sigma_u^2 + 4 \sum_{i=1}^{2} \sum_{k=1}^{2} (\alpha\gamma_{ik})^2$
Error	12	MSE	σ_u^2

2.2.3 Time-Series Analysis of Benthic Data

To further explore the data, a graphical analysis followed by a limited quantitative time-series analysis were carried out for information on the preoperational characteristics of the benthic organisms. The time series on benthic densities for inner and outer zones were obtained by taking simple averages of the data for all depths and stations sampled during a particular month (Table 13). Anticipating a differential effect of plant operation on the organisms residing at various depths, we generated another time-series set which averaged only data for the zones and for depths within zones (Table 14).

To carry out the graphical analysis comparing inner- and outer-zone time series, we prepared time-versus-benthic densities plots, shown in Figures 6 and 7. The two series show similar seasonal oscillatory behavior and have an overall upward time-trend. Although the two series show some dissimilarities, their time-dependent behavior is parallel.

Table 14 data were used in considering the differential effects of power plant operation on the benthic organisms at the various depths. Figures 8 through 13 represent time series plots of average benthic densities, by inner or outer zones, for each of the three depths sampled. Although there is a distinct time-trend, the patterns shown in the Figures 8-13 are irregular. These inconsistencies of the pattern indicate that the use of ANOVA in a linear model framework for such data may not be appropriate.

Table 13. Means of Benthic Data

		Zone	
Year	Month	Inner	Outer
1970	7	4031.7	2333.7
1970	11	4392.7	3003.8
1971	4	1204.2	2545.7
1971	7	2784.3	4403.8
1971	11	4981.8	1690.7
1972	4	1838.5	3231.2
1972	7	6487.1	8222.2
1972	10	6419.3	6762.2
1973	4	4997.4	16396.7
1973	7	15842.4	19453.2
1973	10	14120.1	12337.0
1974	4	3445.1	3410.11

Table 14. Means of Benthic Data by Zone and Depth

			Zone	
Year	Month	Depth	Inner	Outer
1970	7	1	182.5	111.5
		2	3993.0	1363.0
		3	7919.0	5526.5
	11	1	471.5	42.5
		2	1923.0	1619.5
		3	10783.5	7349.5
1971	4	1	171.0	18.0
		2	2047.5	777.5
		3	1394.0	6841.5
	7	1	534.0	479.5
		2	5518.5	1158.5
		3	2300.5	11573.5
	11	1	102.0	72.0
		2	1801.5	470.0
		3	13042.0	4530.0
1972	4	1	597.5	335.0
		2	1874.5	677.5
		3	3043.5	8681.0
	7	1	2305.0	904.3
		2	6686.3	8336.3
		3	10470.0	15426.0
	10	1	2155.7	550.7
		2	2740.3	2391.0
		3	14362.0	17345.0
1973	4	1	2454.7	972.3
		2	3016.3	24152.7
		3	9521.3	24065.0
	7	1	3108.3	5758.3
		2	19620.0	34111.3
		3	24799.0	18490.0
	10	1	1354.3	2340.7
		2	19809.7	12180.3
		3	21196.3	22490.0
1974	4	1	34.0	628.0
		2	2720.0	1588.7
		3	7581.3	8013.7

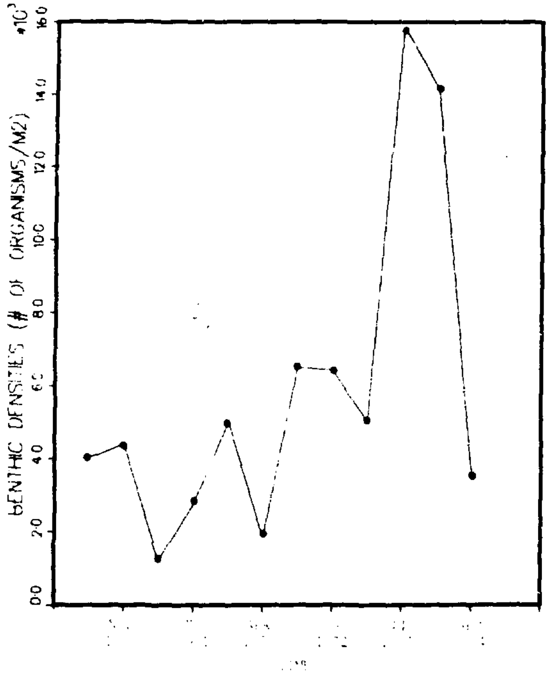

Fig. 6. Time-Series Plot of Average Benthic Densities for Inner Zone.

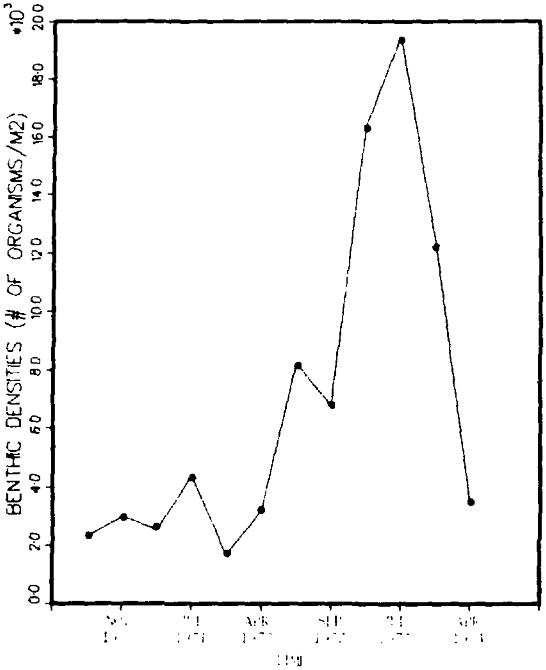

Fig. 7. Time-Series Plot of Average Benthic Densities for Outer Zone

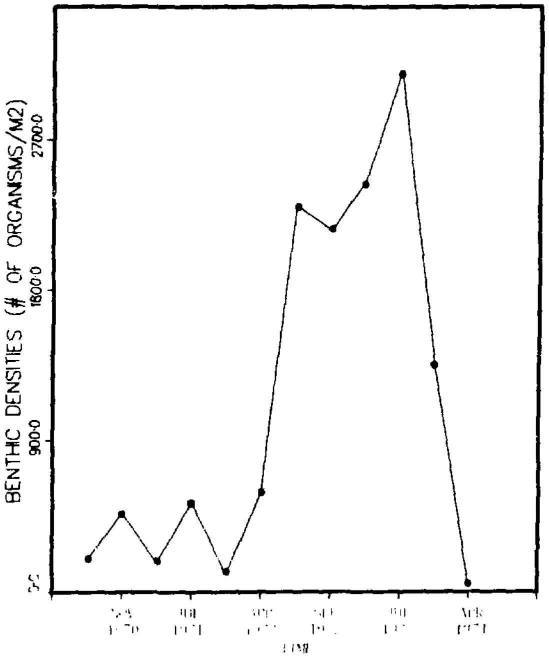

Fig. 8. Time-Series Plot of Average Benthic Densities for Inner Zone Depth 1.

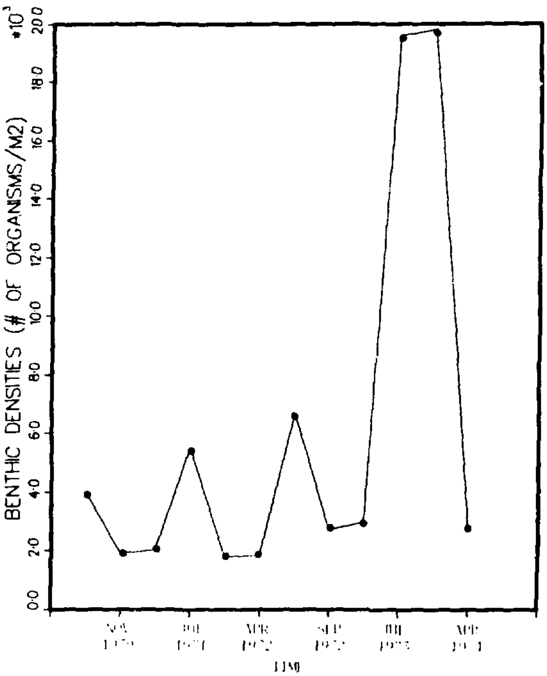

Fig. 9. Time-Series Plot of Average Benthic Densities for Inner Zone Depth 2.

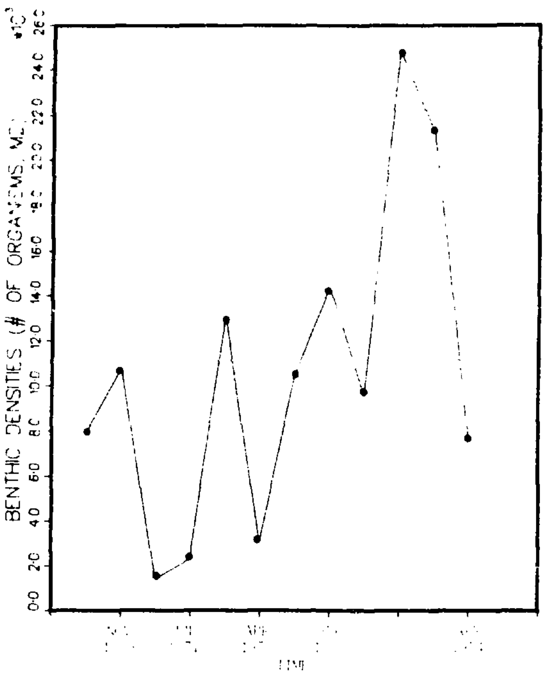

Fig. 10. Time-Series Plot of Average Benthic Densities for Inner Zone Depth 3.

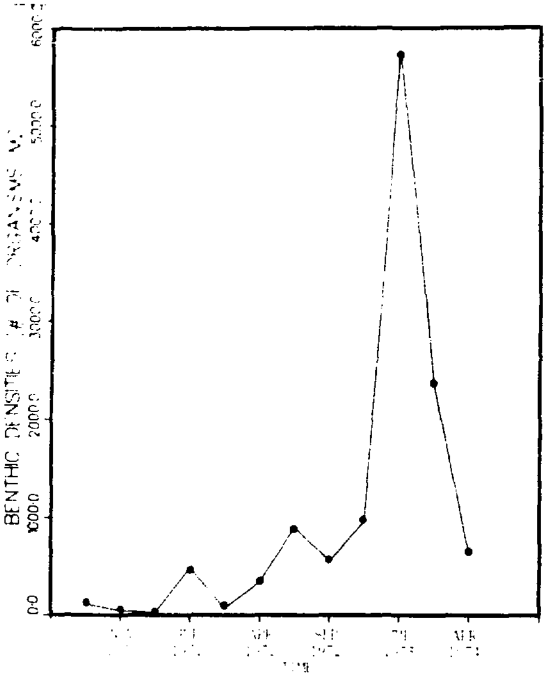

Fig. 11. Time-Series Plot of Average Benthic Densities for Outer Zone Depth 1.

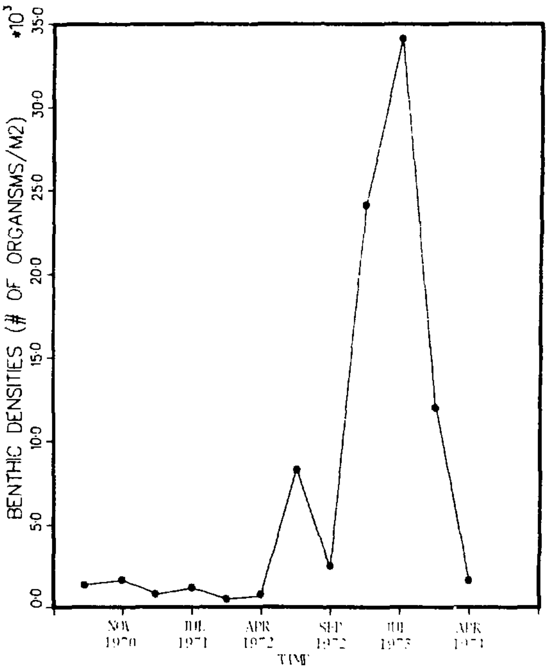

Fig. 12. Time-Series Plot of Average Benthic Densities for Outer Zone Depth 2.

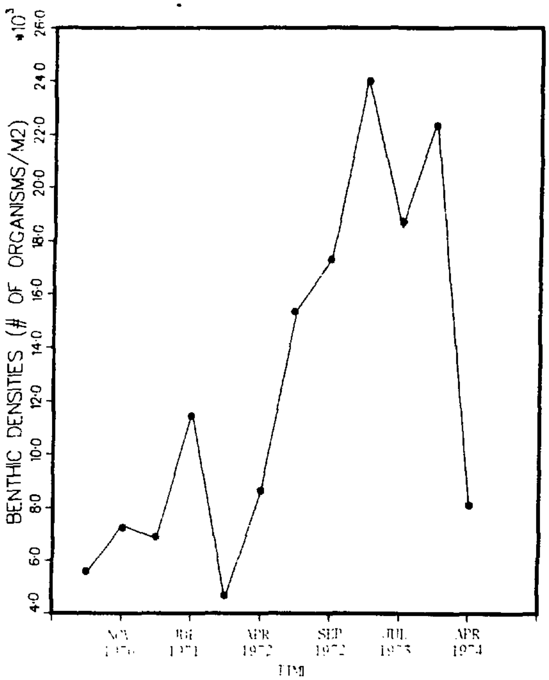

Fig. 13. Time-Series Plot of Average Benthic Densities for Outer Zone Depth 3.

Because of the differences in sampling methods and the number of grab-samples obtained, we averaged the replicated observations for each of the stations sampled to carry out a regression analysis (as an approximation to a complicated time-series analysis) relating reference (outer zone) observations to stressed observations (inner zone). The model in Equation 5 was used to represent the relationship investigated:

$$Y_{ij} = \theta + \phi X_{ij} + U_{ij} , \qquad (5)$$

where Y_{ij} is the mean benthic densities for the i^{th} station in the stress area (inner zone) sampled at the j^{th} point in time, X_{ij} is the mean benthic densities for the i^{th} station in the reference area (outer zone) sampled at the j^{th} point in time, and U_{ij} is a random error for the ij^{th} observation. Because the depth factor has the most significant effect on the benthic densities, we decided that data for various depths would not be combined.

As a first step in ascertaining that the linear-model relationship would be satisfactory, the correlation matrix was computed. Results are given in Table 15. Models resulting from some of the simple and multiple linear regressions performed using the benthic data are shown in Table 16. We observe that there is a considerable degree of success in the use of such an approach. Because of the sampling errors present in both the predictor and predicted variables, further testing and verification must be accomplished before such an approach is adapted as a possible procedure for use in impact evaluations.

Assuming that an acceptable predictor model has been obtained through this regression analysis, we can then calculate expected Y values by use of the observed X values from the plant operation period (Equation 6).

$$\hat{Y}_{ij'} = \hat{\theta} + \hat{\phi} X_{ij'} , \qquad (6)$$

The subscript j' indicates a specific time point in the operational period. The estimate of plant-related impact is then calculated by using the expression given in Equation 7.

Table 15. Correlation Matrix for Zone and Depth Mean Benthic Data

	Inner Depth 1	Inner Depth 2	Inner Depth 3	Outer Depth 1	Outer Depth 2	Outer Depth 3
Inner Depth 1	1.0	0.531	0.622	0.689	0.820	0.839
Inner Depth 2		1.0	0.784	0.870	0.676	0.595
Inner Depth 3			1.0	0.780	0.664	0.555
Outer Depth 1				1.0	0.862	0.559
Outer Depth 2					1.0	0.735
Outer Depth 3						1.0

Table 16. Modified Linear Models for the Determination of Operational Impacts

	Estimated (parameterized) Model	Amount of Explained Variation due to the Model
1)	$\hat{y}_{1j} = \underset{(288.2)}{647.7} + \underset{(0.1550)}{0.4666}X_{1j}$	0.6894
2)	$\hat{y}_{1j} = \underset{(246.1)}{517.3} - \underset{(0.2544)}{0.0459}X_{1j} + \underset{(0.0377)}{0.0881}X_{2j}$	0.8206
3)	$\hat{y}_{1j} = \underset{(415.8)}{-272.5} + \underset{(0.2186)}{0.0574}X_{1j} + \underset{(0.0396)}{0.0360}X_{2j} + \underset{(0.0391)}{0.0854}X_{3j}$	0.8920
4)	$\hat{y}_{1j} = \underset{(423.7)}{-515.1} + \underset{(0.3828)}{0.5687}X_{1j} - \underset{(0.0447)}{0.0096}X_{2j} + \underset{(0.0440)}{0.1264}X_{3j} - \underset{(0.0648)}{0.1266}y_{2j} + \underset{(0.0385)}{0.0266}y_{3j}$	0.9344

Quantities in parentheses are the standard errors of the coefficients.

Definitions

Description	Variable Symbol
Inner Depth 1	y_1
Inner Depth 2	y_2
Inner Depth 3	y_3
Outer Depth 1	X_1
Outer Depth 2	X_2
Outer Depth 3	X_3

$$\hat{Q}_{ij'} = (Y_{ij'} - \hat{Y}_{ij'}) \tag{7}$$

Use of simple t-test (Equation 8) can be conducted to determine the significance of the estimated impact.

$$t = \frac{\hat{Q}_{ij'}}{\sqrt{\text{Variance } (\hat{Q}_{ij'})}} \tag{8}$$

where the estimate of Variance $(\hat{Q}_{ij'}) = s^2 \left[1 + \frac{1}{n} + \frac{(X_{ij'} - \bar{X}_{i.})^2}{\sum_{j=1}^{n} (X_{ij} - \bar{X}_{i.})^2} \right]$.

2.2.4 Calculations of the Least Detectable Change

Johnston[5] calculated the smallest true change in benthic densities that can be declared significant for the Type I and Type II error probabilities of 0.05. He concluded that a 5.5-fold increase or decrease relative to the outer zone must occur for the inner zone to be shown to have significant change in benthic densities.

Following the reduced model given in Equation 4, we calculated the sample coefficient of variation (CV) to be about 62%. Using this value as the population parameter, we calculated that a moderate change (one- to two-fold) can be detected with high confidence (Type I error probability (α) of less than 5%) and high power of the test (Type II error probability (β) of less than 5%). Based on this CV, we calculated the sample size[10,11] (as number of years in each of the preoperational and operational periods) needed to detect the chosen values of differences in the benthic densities for different Type I and Type II error probabilities. Results are given in Table 17.

Table 17. Sample Size (number of years) Calculated for the Benthic Data for the D. C. Cook Station

% Difference	Sample Size for Given α and β Values $\alpha = 0.05$ $\beta = 0.05$	$\alpha = 0.10$ $\beta = 0.10$	$\alpha = 0.20$ $\beta = 0.20$
0.50	19	12	6
0.75	10	6	3
1.00	6	4	2
1.50	4	3	2
2.00	3	2	2

3. THEORETICAL AND PRACTICAL ASPECTS OF ENVIRONMENTAL MONITORING

To be effective, a monitoring program should be designed to provide early warnings of the development of conditions likely to be deleterious to some component of the environment--early enough to permit corrective action to be taken before irreversible impact occurs. Monitoring data are of little value unless they can be properly analyzed, and no effective analysis can be made unless the data are properly collected. To allow confidence in the results, sampling schemes, analytical procedures, and evaluation systems must be designed in accordance with the requirements of probability theory.

Monitoring is usually envisioned as field work: direct study of the ecosystems of concern. Direct investigation is the most common and usually the best method of determining environmental impacts; at times, however, it is impractical or too costly. An investigator may then resort to controlled experiments. Alternatively, he may choose to apply a mathematical model if one of proven reliability on the subject in question is available. In both cases the results from experiments and models--removed as they are from reality--must somehow be checked against actual conditions in the course of determining the worth of such results.

For any particular aspect of environmental investigation the immediate basic tasks are: (1) to define clearly and precisely the objectives of the investigation; (2) to decide upon the type, amount, and precision of the needed estimates; and (3) to establish a means for analyzing the data so that an effective basis for decision making is defined.

3.1 PLANNING FOR DATA COLLECTION

In all data gathering, there are nonrandom effects as well as random errors, each contributing to the degree of uncertainty associated with individual data points and with the data set as a whole. Uses of mathematical formulations to represent the nonrandom behavior of the environmental component of interest and to separate out the random component are necessary for the effective use of monitoring programs as means of providing decision-making criteria.

Depending on the specified objectives of an environmental monitoring program, it is generally assumed that the selected environmental conditions prior to plant operation be understood in such a manner that a periodic evaluation of plant operation and its effect on the environment can be determined by comparison. Further, it is implied that the data gathered throughout the course of the preoperational and operational programs are adequate for a proper impact assessment--i.e., sufficiently comprehensive and precise for statistical operations to be performed so that effective decisions can be made concerning surveillance and operational matters.

Several steps are necessary in planning an adequate data-collection program. These are:

1. Define, determine and limit the environmental characteristics to be surveyed. This must be done with as much foresight of potential changes as possible, which usually involves checking the regulations, reviewing the experiences of similar operation facilities, and investigating any special characteristics of and special interest in particular components of the local environment.

2. Prepare a sampling scheme. This often involves assumptions regarding the data base (existing biotic populations, etc.), and may require pilot investigations to verify or modify such assumptions. Depending upon the nature and extent of the queries, there are trade-offs to be considered in designing a sampling program. These trade-offs involve replications at the same location, number of stations, number of seasons, and number of years. As one obtains more and more years of data, the more precise the results--and the more expensive the programs become. However, we can gain the most on the precision and ability to detect impacts by increasing the number of years.

3. Prepare an operational plan for obtaining the samples, analyzing them, and evaluating the data. This must include adequate data-handling systems and a means for informing decision makers of all results and conclusions meriting their attention.

3.2 STATISTICAL ASPECTS IN DESIGN AND ANALYSIS

Most environmental components, particularly biotic elements, present an ever-changing situation, and they are sampled to determine the course of such changes. Once-only core samplings may suffice for determining bedrock conditions for the life of a plant, but continual sampling for many years is necessary to follow, for example, fish population variation. Classical statistical procedures,[7,9,11,12] such as the t-test, are used to determine the change in the mean value of two or more sample results. Ordinarily, such tests are based upon assumptions of a normal probability density and of independent and homogeneous variance.[6] Time-series data from sequential samplings do not always conform to these assumptions.[13-16] Nonstationary elements, including strong seasonal components, are present, and the data are serially correlated in most instances.[16]

Time-series observations are actually jointly distributed random variables. Mathematical functions representing this type of behavior combine past history with elements of discrete response. A presumed joint distribution function may be written as

$$f_{1\ldots t}(y_1 \ldots, y_t; \underline{\theta}) .$$

The subscript, 1...t, indicates that the parameters, and even the joint distribution function itself, may depend upon particular points in time. So the sampling and data-collection scheme must incorporate the probability sampling required by the stochastic process and by the stochastic dynamic models to be used for analyzing the data. It may be necessary to try several models before one is chosen. It is of utmost importance that the model be chosen as early as possible.[16] Too often, samples are taken and analyzed before any thought is given to the model to be used for analyzing the data.

3.2.1 The Nature of Impacts

We postulate probability laws for the measured changes and variations of an indicator characteristic (response variable) in an undisturbed environment. Assumptions concerning probability models have led to estimates and inferences of the parameters of these distributions. When disturbances resulting from perturbations caused by operating reactors are introduced in the ecosystem, it is common to expect changes in the response variables and their probability distributions. The magnitude and extent of the changes are generally unknown *a priori*. Thus, to estimate these changes one must be able to measure responses to the pertubations caused by the operating reactors. It is appropriate to consider the types of disturbances that may affect a response variable.

For simplicity, let us assume a time-variable phenomenon in which a pulse of some magnitude is added to an otherwise constant response function (see Fig. 14). The effect of this pulse disturbance may be (a) an exponential decay, with total recovery to the original condition; (b) no lasting change in response, i.e., an immediate and complete recovery; (c) a more subtle change in response, in which the effect of the pulse undergoes a very gradual and slow recovery; or (d) no recovery at all. Less likely cases include the situation where the effect may be an intensification resulting in a long-term increasing impact (e), or an exponential approach to a new steady-state value (f).

The task of measuring such responses becomes more complicated when we consider continuous pollution. The responses to a steadily added pollution may be: a cumulative long-term impact (e), a short-term adjustment to a new level of behavior (f), a long-term slow recovery (c), a short-term fast recovery (b), or a long-term slow destruction with no recovery at all (d). Of course, there are a number of possibilities for mixed responses.

3.2.2 Methods for a Statistical Approach

Two classes of statistical methods seem logically attractive for use in environmental impact analysis: (1) general linear-model analysis[6-12,18-20] and (2) time-series analysis.[13-17] Although there is considerable overlap in their use of a final estimation method (i.e., least squares analysis), the basic model considerations and accompanying assumptions are somewhat different.

In the general linear-model approach (i.e., regression, variance-components etc.), variations in the response variable measured over time and space are decomposed into assignable sources of such variations and are assumed to be additive. In a formal case, the residual error part is assumed to be an independently, identically, and normally distributed random variable. However, these assumptions are not so critical and the F-tests are quite robust to departures from these assumptions.

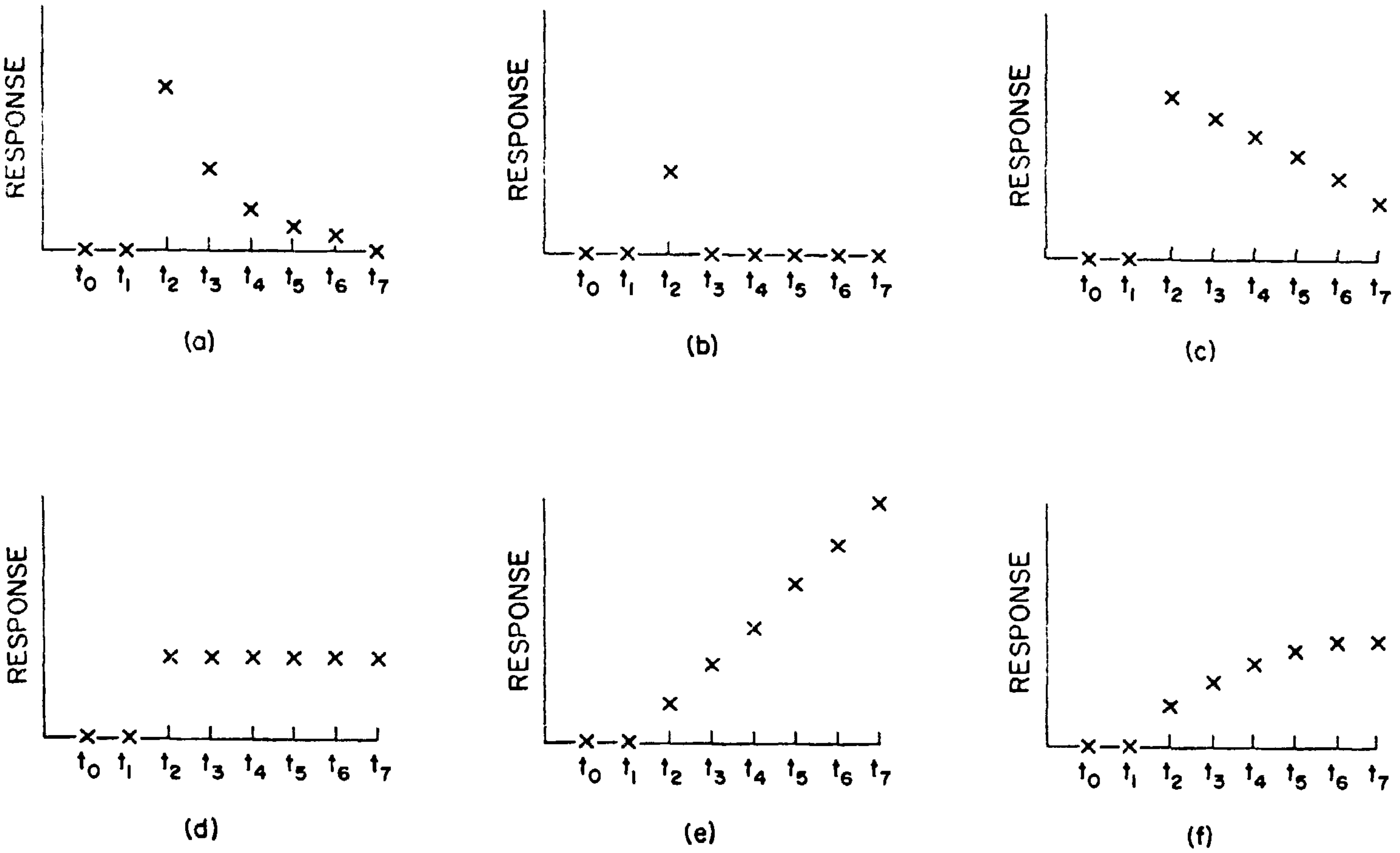

Fig. 14. Possible Responses to Pulse Disturbance in a Stable Time Series.
(Time is represented on the abscissa.)

In using the linear models approach, one is led to formulate the hypotheses or linear contrasts for carrying out the statistical tests. Among these contrasts are the tests for main effects due to the C factor and the interaction effect due to the C × D factors. Such a formulation restricts the statistical comparisons to those that postulate a constant magnitude change in main or interaction effects.

In the time-series analysis approach, the response variable correlation to past observations is taken into consideration in the formulation of a model. The effects of power plant operation are postulated as functions (which may be linear or nonlinear) that can vary in time and space. The residuals might be correlated in time and may have an unknown variance-covarianc structure. The two classes of methods are discussed in the following two sections.

3.2.2.1 Time-Series Analysis

Throughout the period in which environmental statements have been required diligent efforts have been made to obtain monitoring data for each plant seeking a license or licensed. Typically, an environmental monitoring program (similar to the D. C. Cook program) is designed and initiated to obtain biotic and abiotic data from several collection stations and at several points in time. Inherently, these observations have a time-series dependence; seasonal, annual, and spatial observations are likely to be correlated in time and space. The sampling designs and the statistical analysis of the data, therefore, need to address the time-series character of the realizations from the environmental studies.

Under this approach, the basic model consists of the following:

$$y_t = S_j + A_i + \text{Lagged Terms} + \text{Plant Operational Effects Function} + \text{Error Term}, \tag{9}$$

where S_j is the seasonal effect,

A_i is a deterministic factor independent of season,

lagged terms model the autoregressive behavior of the time series,

plant operational effects function is a postulated linear or non-linear representation, and

error term is a stochastic element which may be a NID (o, σ^2) variable or can be modeled by a moving-average process.

Box and Jenkins,[16] Nelson,[14] Anderson,[13] and Brillinger[15] have all treated statistical time-series analysis, and the reader is referred to their books for further mathematical treatment of time-series methodology.

If systematic sampling is used to obtain an observation set which consists of data points spaced at equal time intervals, we can use the methods of model building, estimation, and inference given by Box and Jenkins.[16] Inexperienced users should not use methods for evenly spaced time-series analysis when dealing with unevenly spaced data.

In a recent paper, Box and Tiao[17] have advanced a time-series analysis method called "Intervention Analysis." This method may be appropriate for use in environmental studies carried out at power plants. Specifically, the technique considers the "prior" or "natural" process and then builds up mathematical models to estimate an "effects" function due to disturbances such as operation of the power plant. The technique models a dynamic system for its stochastic behavior and then modifes the model by introducing appropriate "perturbation response function." In Box and Tiao's terminology, the basic model could be an Auto Regressive Integrated Moving Average (ARIMA) process or a Transfer Function process.

To make use of such a technique, data should be gathered frequently and sampling times should be evenly spaced. Because of seasonal components, which may be multiplicative, additive, or a mixture of both, some adjustments must be incorporated into the basic ARIMA model (Box and Jenkins).[16] A term or function representing an expected response to the operation of the nuclear power plant must be added to the model. Simultaneous estimation of the parameters in the nonlinear time-series model gives an estimate of the behavior of the changes of the response variable.

This method cannot be used with data from the D. C. Cook plant because the time-series measurements are very few and no operational data are as yet available. A problem may arise if the series is nonstationary in the variance. A nonstationary condition of the mean can be easily handled by differencing, but the nonstationary variance problem may be difficult to solve.

A modification of the "Intervention Analysis" method is suitable for cur work, so that systematic, evenly spaced data are not required. In this procedure the data are examined in the frequency domain rather than in the time domain. For example, if the response values are adequately modeled by "k" harmonics, then

$$y_t = \delta + \sum_{j=1}^{k} (A_j \sin \alpha_j t + B_j \cos \alpha_j t) + f(t) + u_t , \qquad (10)$$

where δ, A_j, and B_j are regression coefficients, and u_t is a random error assumed to be normally distributed with mean zero and unknown variance σ_u^2.

The function of interest for environmental impact determination is f(t). If f(t) is a linear or intrinsically linear function, then an ordinary least squares analysis will provide values for all the coefficients in the model. Depending on the shape and the values of the coefficients, inferences about the nature and extent of the impacts can be drawn.

All these time-series approaches can be used if the data collected sample the stochastic process fairly intensively. However, further work is necessary to examine the time-series analysis methods for adaptation to environmental impact analysis.

3.2.2.2 General Linear Models Analysis

The general statistical approach taken under this class of methods, as applied to environmental data analysis, is to consider the spatial and temporal distributions of the biotic groups as a sum of responses due to assignable sources of factor levels. Time, space, and sampling locations, together with replicates, are taken to form a factorial experimental design. Generally, natural logarithmic transformation (and several other types, e.g., square root) is used to achieve equality of variances, to make the model additive, and to attain normality of the distribution. Reduction in variance is also attained as a result of the transformation.

Because biological and physical-chemical data are expected to be correlated, we can take advantage of this relationship in detecting an impact by carrying out multivariate ANOVA and covariance analysis. However, because of unavailability of simultaneous covariable measurements, we restricted our analysis (given in Section 2.2) of D. C. Cook data to a univariate variance components form. Quantitative estimates of the magnitudes of impacts induced by nuclear power plant operation are very difficult to make unless the data-collection scheme is designed very carefully. Surveys of a general nature, under a host of unspecified assumptions, are not condusive to a meaningful analysis of the impacts on biological systems.

For many environmental monitoring programs, most objectives of the program are very broadly defined, and no specific impact hypotheses are posed before a program is designed to confirm or disprove a postulated impact. Adequate sample size, serial correlations, and the confounding effects of other simultaneous changes in the environment are given very little attention when a post-hoc analysis, through a general linear model, is carried out. Some of the difficulties can be remedied by the time-series analysis methods while additional effort may be needed to develop additional satisfactory methods.

When pre-operational studies are carried out during the construction period, the construction activities create their own environmental stresses. Even the installation and testing of monitoring equipment can produce disturbances that will be reflected in the data collected. Ideally, data-collection schemes should be designed to either circumvent the contamination or to take it into account, but in practice one is never certain that he has done so.

In conducting the benthic studies at D. C. Cook, the utility's consultants exercised extreme caution and care in carrying out a multi-factor analysis of variance. However, it is apparent that data gathered are being put into an ANOVA framework rather than this experimental design being postulated before that data were collected. The fact that a number of data points were excluded from the analysis to gain a "balanced" experimental design feature indicates an afterthought. It is not readily apparent that the data excluded from the analysis are of no value in assessing the impacts. If so, why were they collected?

In the analysis by Johnston,[5] data from the grid and random surveys were combined to carry out an ANOVA on the means of four full grabs or nine one-third grabs. This ignored the difference in the variance between these means due to the difference in precision. Of greater importance is the introduction of bias due to the gear change. This bias will be reflected in the changed average densities. In fact, we have seen such an occurrence as indicated by the benthic data. As such, substantial masking of the test on the impact hypothesis could be occurring. It is natural to try to improve the data-collection methodology. The assumptions necessitated by mixing various data sets (as a result of changed gear, etc.) lead to increased uncertainties in the detection of plant-related environmental impacts.

An important factor in the designing and analysis of data is that one must consider the appropriate variance component. In our case, the variance quantity of interest is that of environmental variation. That is, if the geographical limits that define an ecological area are likely to be altered by a facility's operation, we must estimate the inherent variability in the area by taking random observations that will give a reasonably precise estimate of the statistical parameters of the distribution for the geographical area. Simply taking repeated samples several times at essentially the same location (commonly but erroneously referred to as "replicates") does not provide a true estimate of the environmental variability. Generally, such repeated measurements underestimate the environmental variance. They do provide a "measure" of how good the sampling gear is, which is important in selecting and ascertaining the performance of a sampling device. But in environmental monitoring or surveillance, such data do not contribute to the estimation of environmental variation and therefore do not properly test an environmental impact hypothesis.

3.2.3 Some Sampling Schemes

Currently, monitoring programs are based on before-and-after comparisons. Data collected in this manner at some frequency (weekly, monthly, or quarterly) will be sufficient to detect some environmental impacts caused by the operation of a power-generating facility, but only gross changes would be noticeable with such a sampling design. Because of temporal effects, seasonal fluctuations, differences in site species, and long-term trends, it is unlikely that smaller impacts will be observed. Depending on the choice of functional relationships that describe the observations, it is likely that irregular and random-like variations in these time-series data could not be separated. This would result in biases of substantial consequence: the impacts are generally confounded and therefore undetectable.

Another system used is to compare reference stations to stressed stations. The assumption is that the paired observations are different only to the extent that one location is affected by the disturbance and the other behaves naturally or less affected. Because biotic systems in close proximity are interconnected, it is erroneous to assume that a reference location will not change over the long term in a manner similar to the stressed station. Therefore, a reference-stressed stations approach must be used with caution.

3.2.3.1 Layout of a Nested Experimental Design

For a nested experimental design one or two biologically most active seasons are selected as a time frame and a number of reference-stressed pairs representing time before plant operation and during plant operation are generated. The statistical experimental (sampling) design will then be in the form shown in Table 18. The table also shows the associated analysis of variance for data obtained from the sampling design.

3.2.3.2 Generalized Sampling Design as a Replicate Complete Factorial

The basic experimental design for the determination of environmental changes is the one shown in Table 19. This is essentially the reduced model given by Equation 4. In a 2 x 2 table framework, the ANOVA will appear as shown in Table 20. The three linear (single degree of freedom and orthogonal) comparisons are as follows:

	Before		After			
Comparison	Reference	Stressed	Reference	Stressed	Divisor	Sum of Square
1	+1	-1	+1	-1	4N	S_1
2	+1	+1	-1	-1	4N	S_2
3	+1	-1	-1	+1	4N	S_3

The impact hypothesis of interest is to test comparison 3 for significance. The question is whether the interaction (equivalent to testing comparison 3) is significant. This analysis assumes that if there is a natural interaction effect (i.e., over the years' differences or if ratios between reference and stressed areas do not remain constant) it will not be separated out from the plant-induced effect. Perhaps, a significant main effect in the before-after comparison and a significant interaction effect could be taken as an interpretation that the environmental impact is present. To facilitate proper interpretation, one should make use of graphs showing the time-series for the reference and stressed location means. Then the statistical significance could be properly identified with changes in the environmental measurements due to the plant operation.

This 2 x 2 table experimental design can be reduced to a 1 x 2 design, if the multiple "reference" stations are paired with the multiple "stressed" stations. Paired ratios or differences or any other needed transformations will generate near replicated observations for the preoperational and operational periods of the plant. Keeping symmetry in the data points will result in simple, two-sample test statistics. This is shown in Table 21.

Again, this simplification is a very appropriate analytical and testing procedure if we assume that the before-and-after period means (in the appropriate variables) are different only because of plant-induced changes and that the "N" observations are uncorrelated both in time and space. Because of the nature of the environmental impact studies, we should use several of these methods in order to arrive at a meaningful inference. No one method should be considered adequate for the analysis of these data.

For a fixed-effects model, the unequal variances and correlation of errors merely reduce efficiency without introducing bias or causing the robustness of the test to be greatly affected.[6,10-11] However, in the random effects model or mixed effects model, the expectations of the mean squares are unaffected

Table 18. Layout of a Nested Experimental (sampling) Design for Environmental Data Collection and Analysis

Year	Before Operation		During Operation	
1	Reference 1	Stressed 1		
	2	2		
	3	3		
	4	4		
2	Reference 1	Stressed 1		
	2	2		
	3	3		
	4	4		
3	Reference 1	Stressed 1		
	2	2		
	3	3		
	4	4		
4	Reference 1	Stressed 1		
	2	2		
	3	3		
	4	4		
5	Reference 1	Stressed 1		
	2	2		
	3	3		
	4	4		
6			Reference 1	Stressed 1
			2	2
			3	3
			4	4
7			Reference 1	Stressed 1
			2	2
			3	3
			4	4
8			Reference 1	Stressed 1
			2	2
			3	3
			4	4
9			Reference 1	Stressed 1
			2	2
			3	3
			4	4
10			Reference 1	Stressed 1
			2	2
			3	3
			4	4

Nested Analysis of Variance for Table 18

Model

$$y_{ijk} = \mu + \alpha_i + \beta_{i(j)} + \varepsilon_{i(j)k}$$

where y_{ijk} is the kth observation in the jth year of the ith plant operating state, μ is a general mean, α_i is the effect due to the ith operating state ($i=1,2$), $\beta_{i(j)}$ is the effect due to the jth year in the ith plant operating state ($j=1, \ldots, L$), and $\varepsilon_{i(j)k}$ is the random error term ($k=1, \ldots, N$).

Source	d·f.	SS	MS	E(MS)
Before-During (α_i)	1	SS_1	MS_1	$\sigma^2_\varepsilon + N\sigma^2_\beta + LN\sigma^2_\alpha$
Years (before-during)(β)	2(L-1)	SS_2	MS_2	$\sigma^2_\varepsilon + N\sigma^2_\beta$
Residual	2L(N-1)	SS_3	MS_3	σ^2_ε

Hypotheses of Interests

(1) $H_o : \alpha_1 + \sum_{j=1}^{L} \beta_{1j}/L = \alpha_2 + \sum_{j=1}^{I} \beta_{2j}/L$

(2) $H_o : \beta_{ij} = \beta_{ij'}$, for $j \neq j'$ within each i .

F test

(1) $\frac{MS_1}{MSE}$ (2) $\frac{MS_2}{MSE}$

Table 19. A 2 × 2 Factorial Design with Replications

		Column 1 Reference	Column 2 Stressed	Row Means
Row 1	Before	M_{11}	M_{12}	$M_{1.}$
Row 2	After	M_{21}	M_{22}	$M_{2.}$
	Column Means	$M_{.1}$	$M_{.2}$	

Table 20. Analysis of Variance Table for the Experimental Design in Table 19

Source	d.f.	SS	MS
Before-after	1	SS_1	MS_1
Reference-stressed	1	SS_2	MS_2
Interaction	1	SS_3	MS_3
Error	(4)(N-1)[a]	SS_4	MS_4
Statistical tests of interest:	$F = \frac{MS_3}{MS_4}$		
	$F = \frac{MS_1}{MS_3}$		

[a] *N is the number of observations in each of the four cells.*

Table 21. Experimental Design and Analysis for a One-Way Layout

	Before	After
	M_1	M_2
Statistical test of interest:	$t = \frac{M_1 - M_2}{S.D.\ (M_1-M_2)}$ with 2 (N-1) d.f.	

N is the number of paired stations in preoperational or operational periods.

but the variances of the estimators are radically changed and the tests and interval estimates will not be robust.[6,10-11] The estimators and tests are similarly affected when non-normality exists.[6,10-11] By use of transformations, the normality requirements may be easily satisfied: however, in the presence of extreme values (or outliers) such transformations are not necessarily completely successful.[21]

Transformations commonly applied when analyzing biological data involve the use of logarithmatic values, square roots, or Box-Cox[21] transformations. These transformations are aimed at variance stabilization.

CONCLUSIONS AND RECOMMENDATIONS

As a result of this study of the D. C. Cook monitoring program, we have learned a number of important things. They are summarized here so that this experience will provide valuable guidance in the formulation of environmental monitoring programs for future reactor sites.

1. It is recommended that no change be made in the data-gathering methods that would greatly interrupt similarities between data points. If a change of collection gear or sampling locations appears to be needed, then an extended overlapping period (for comparison) must be provided. Otherwise, the bias introduced and the changes in the variance structure will mask the results of the impact.

2. Variance components analysis methods are only grossly approximate for the determination of "major" changes in time. These methods should not be relied upon for the determination of statistically significant environmental changes of modest magnitude.

3. Multifactor mixed models for the ANOVA are not needed. Reduced models, such as the one given in Equation 4, can be used and impact estimates can be easily obtained. It is necessary to examine the main effects and the interactions which provide linear contrasts for impact determination. The presence of significant interaction during the preoperational period points toward the interpretational problems with impact estimates.

4. Time-series analysis methods should be used to analyze environmental monitoring data. Specific results and computer software to carry out such analyses should be prepared, and the needed additional research should be carried out.

5. For a time-series analysis, it would be preferable to obtain an equally spaced series of observations. However, such a constraint on data collection is not necessary to carry out time-series analysis. For instance, sampling can be done during the same season each year. Because of fluctuations in the natural environment, the more frequent the observations, the higher the power and more precise the analysis. At least two years of preoperational data must be obtained.

6. The observation system must contain multiple reference locations and multiple potentially affected locations, which must be paired for geographical similarity. The number of such locations to be included will depend on the precision desired. The sampling scheme, then, should call for a systematic sampling procedure in time and space.

7. Covariables for environmental conditions at sampling locations should be measured so that the inherent variability conditions can be corrected in analyzing the data.

8. The fisheries (including ichthyoplankton) monitoring program should not be taken as a model for monitoring schemes at the new plants.

REFERENCES

1. "Final Environmental Statement related to operation of Donald C. Cook Nuclear Plant Units 1 and 2, Docket Nos. 50-315 and 50-316," U. S. Atomic Energy Commission, Directorate of Licensing, August 1973.

2. U. S. Atomic Energy Commission, Appendix B of the D. C. Cook Nuclear Power Plant, Operating License, "Environmental Technical Specifications."

3. "Benton Harbor Power Plant Limnological Studies," Special Report No. 44 of the Great Lakes Research Division, the University of Michigan, Ann Arbor, under contract with American Electric Power Service Corp. and Indiana & Michigan Electric Co., 1973-1974.

4. E. M. Johnston, "Benton Harbor Power Plant Limnological Studies, Part XVIII. Effect of a Thermal Discharge on Benthos Populations: Statistical Methods for Assessing the Impact of the Cook Nuclear Plant," Special Report No. 44, Great Lakes Research Division, University of Michigan, December 1973.

5. E. M. Johnston, "Benton Harbor Power Plant Limnological Studies. Part XX. Statistical Power of a Proposed Method for Detecting the Effect of Waste Heat on Benthos Populations," Special Report No. 44, Great Lakes Research Division, University of Michigan, December 1974.

6. H. Scheffe, "Analysis of Variance," New York, John Wiley & Sons, Inc., 1959.

7. O. Kempthorne, "The Design and Analysis of Experiments," New York, Robert E. Krieger Publishing Co., 1975.

8. D. R. Cox, "Planning of Experiments," New York, John Wiley & Sons, Inc., 1958.

9. B. J. Winer, "Statistical Principles in Experimental Design," New York, McGraw-Hill Book Co., 1971.

10. H. D. Brunk, "An Introduction to Mathematical Statistics," Lexington, Mass., Xerox College Publishing, 1975.

11. M. G. Kendall and A. Stuart, "The Advanced Theory of Statistics," Vols. I (1969), II (1973), III (1968), New York, Hafner Press.

12. R. G. Petersen, "Experimental Designs for Agricultural Research in Developing Areas," Oregon State University Book Stores, Inc., Corvallis, Oregon, 1976.

13. T. W. Anderson, "The Statistical Analysis of Time Series," New York, John Wiley & Sons, Inc., 1971.

14. C. R. Nelson, "Applied Time Series Analysis for Managerial Forecasting," San Francisco, Holden-Day, Inc., 1973.

15. D. Brillinger, "Time Series: Data Analysis and Theory," New York, Holt, Riehart & Winston, Inc., 1975.

16. G. E. P. Box and G. M. Jenkins, "Time Series Analysis, Forecasting and Control," San Francisco, Holden Day, Inc., 1970.

17. G. E. P. Box and G. C. Tiao, "Intervention Analysis with Applications to Economic and Environmental Problems," Amer. Statistical Assn., 70:70-79, 1975.

18. V. L. Anderson and R. A. McLean, "Design of Experiments," New York, Marcel Dekker, Inc., 1974.

19. C. R. Rao, "Linear Statistical Inference and Its Applications," New York, John Wiley & Sons, 1972.

20. S. Searle, "Linear Models," New York, John Wiley & Sons, 1970.

21. G. E. P. Box and D. R. Cox, "An Analysis of Transformations," Royal Statistical Society, Series B 26:211-252, 1964.

APPENDIX A

On the basis of the linear model in Equation 1, the ANOVA and the expected mean squares were obtained. The results were given in Table 3 in the text. The two F-statistics which are of interest for hypothesis testing are the following:

$$F_{1,6} = \frac{MSC}{MSY} = \frac{\sigma_\varepsilon^2 + 216\sum_{i=1}^{2}\alpha_i^2 + 54\sigma_\beta^2}{\sigma_\varepsilon^2 + 54\sigma_\beta^2}\,, \tag{11}$$

and

$$F_{1,6} = \frac{MSCD}{MSYD} = \frac{\sigma_\varepsilon^2 + 108\sum_{i=1}^{2}\sum_{k=1}^{2}\left(\alpha\gamma_{ik}\right)^2 + 27\sigma_{\beta\gamma}^2}{\sigma_\varepsilon^2 + 27\sigma_{\beta\gamma}^2}\,. \tag{12}$$

When we used the reduced model given in Equation 4, we obtained the ANOVA and expected mean squares that are given in Table 12. The two F-statistics which are of interest for hypotheses testing are the following:

$$F_{1,12} = \frac{MSC}{MSE} = \frac{8\sum_{i=1}^{2}\alpha_i^2 + \sigma_u^2}{\sigma_u^2}\,, \tag{13}$$

and

$$F_{1,12} = \frac{MSI}{MSE} = \frac{4\sum_{i=1}^{2}\sum_{k-1}^{2}\left(\alpha\gamma_{ik}\right)^2 + \sigma_u^2}{\sigma_u^2}\,. \tag{14}$$

In order to compare the equivalence of the test under the same hypotheses for the two models, we examined the F-statistics pairs in Equations 11, 13, and 12, 14. We assumed that the years represent random observation when the model in Equation 1 was reduced to that in Equation 4. However, we defined

$$u_{ijk} = \frac{\sum_m \sum_p \sum_q \varepsilon_{qijkmp}}{MPQ}\,.$$

Therefore, we get

$$\sigma_u^2 = \frac{\sigma_\varepsilon^2}{27} .$$

Substituting for the σ_u^2 in Equations 13 and 14, we get:

$$F_{1,12} = \frac{MSC}{MSE} = \frac{\sigma_\varepsilon^2 + 216\sum_{i=1}^{2}\alpha_i^2}{\sigma_\varepsilon^2} \tag{15}$$

and

$$\Gamma_{1,12} = \frac{MSI}{MSE} = \frac{\sigma_\varepsilon^2 + 108\sum_{i=1}^{2}\sum_{k=1}^{2}\left(\alpha\gamma_{ik}\right)^2}{\sigma_\varepsilon^2} \tag{16}$$

Equation 15 is very much like Equation 11 and Equation 16 is very much like Equation 12. The differences in the degrees of freedom for the F-statistics are due to treating the years as random values. The model was also modified from a partially nested model to an un-nested model when the reduction was made.

The equivalence of the two results, except for changes due to modifications in the linear model, shows that a multifactor complex linear model is not needed in order to test the hypotheses regarding environmental impacts.