NAVAL RESEARCH

REVIEWS

MAY 1972

PROFILES IN SCIENCE

Dr. Isabella Karle

Dr. Isabella Karle has been associated with the Naval Research Laboratory since 1946. Her predominant interest has been the structure of molecules both in the gaseous and solid states. She has made landmark contributions to the elucidation of crystal and molecular structure by x-ray and electron diffraction techniques. Dr. Karle played a primary role in the development of the symbolic addition procedure which marked a turning point in structure determination by providing a simple, direct way for solving the structures of crystalline substances. The power of the method makes possible the simultaneous establishment of both the chemical formula and the molecular geometry of unknown compounds. The method extends the applicability of diffraction analysis to many organic and inorganic compounds not amenable to solution by any previous methods. As a consequence, the structures of hundreds of materials falling into this category have been determined during the past few years in laboratories throughout the world. Isabella Karle has received the Hillebrand Award of the Chemical Society of Washington, the Annual Achievement Award of the Society of Women Engineers, the Applied Science Award of RESA, and a Superior Civilian Service Award.

Analytical Models for Manpower Decisions

A. Charnes, W. W. Cooper, and R. J. Niehaus*

In the area of manpower planning, three overlapping, but different types of decision making are generally occurring simultaneously. First, there are the economic or task decisions to determine what work has to be done. From this flows skill requirements planning. Then, individual assignments are made to place individuals into jobs or assignments. This must be done considering the individuals on board, new recruits, and losses to the system. It must also be done in the context of the motives and aspirations of the decision maker determining both the assignments and the people who are being assigned. One quickly comes to the conclusion that the process is not neat and orderly, and inconsistencies are going to occur. This leads to the need for models and information systems to orchestrate the overall process. In the past few years, there has been a significant amount of research on manpower models; thus, some of the needed techniques are being developed. This is particularly true of the economic and skill requirements planning areas. The purpose of this paper is to discuss the analytical models under development in the Office of Civilian Manpower Management (OCMM), Department of the Navy.

The OCMM modelling effort illustrates a way in which the Office of Naval Research has contributed to fundamental research in an operational environment. For the past five years, OCMM has collaborated with two ONR-sponsored research projects, the Management Sciences Research Group at Carnegie Mellon University and the Center for Cybernetics Studies at the University of Texas. The result has produced a strategy of basic research, in an on-site immediate applications context, which has proved fruitful in several ways. It has yielded new models and new mathematics for improved applications.† It has also yielded insights on further opportunities for basic research in

*For a discussion of several of these models including their probabilistic extensions see A. Charnes, W. W. Cooper, R. J. Niehaus, and D. Sholtz "Multi-Level Models for Career Management and Resource Planning" presented at NATO Conference "Manpower Planning Models" at Cambridge, England, Sep 6-10, 1971.

†Dr. Charnes is Professor in the Department of Mathematics at the University of Texas and has written many papers on management science and operations research. Dr. Cooper is Professor of Economics and Industrial Administration at Carnegie-Mellon University. He has served as consultant to many firms and government agencies. Mr. Niehaus is Assistant for Computer Sciences for the Office of Civilian Manpower Management, Department of the Navy. He has written many articles on manpower modeling.

response to potential applications. These opportunities extend from (a) dynamic organization design to (b) new ways of treating data for manpower planning to (c) new methods for integrating previously separated disciplines and management practices.

The OCMM models are built around the use of goal programming* to achieve a given set of management requirements (e.g., manpower requirements). The idea is to try to minimize the discrepancies from these managerial goals by requiring that a penalty be paid in the model objective for moving away from the goals. In this way, inconsistencies which are bound to occur in the manpower planning process can be explicitly calculated and thus controlled. These goal requirements are then subjected to various constraints to reflect such factors as attrition and internal transfers. This use of goal programming made it possible to extend the original models to accommodate budgetary (financial) planning along with manpower planning as twin aspects of a simultaneous decision process.

Data availability formed a very important consideration in the construction of the later versions of the models. In fact, the models bring together several large scale decision systems and the data necessarily had to come from existing or planned information systems. This pointed to such information systems as the Personnel Automated Data System (PADS) for the manpower data and the Navy Cost Information System (NCIS) for financial data. It can be expected that, as additional manpower data becomes available in automated form, they too will be used to support the models.

An extensive computer-driven data system has been developed to test the model designs at the aggregate and career planning levels of decision making. It is named the Five Year Navy Civilian Manpower Plan (FYNCIMP) system. Approximately 60 operational manpower problems have been supported, including such areas as projections of expected retirements, average grade policy testing, and projections of recruiting requirements for scientists and engineers.

Research supported by ONR is also underway to investigate the conversational use of the models by means of remote computer terminals. The purpose of this research is to explore and test a variety of ways in which managers can be led to perceptions that will enable them to take advantage of the OCMM models and the computer arrangements they provide. Furthermore, the fact that two-way or, more generally, multiple-direction levels of communications are involved will need to be considered in this aspect of the research.

*In technical terms, the initial models involved a joining of "Markov processes" together with "goal programming." More precisely, the manpower transition rates were embedded into a goal programming model along with a number of other constraints. The resultant nonlinear and stochastic models are reduced to a linear equivalent for optimization.

Career Management Model

An example of the OCMM models is the one designed to assist the career manager. It is a good example to begin a detailed discussion of the models as it can stand alone, or be linked to a more general planning system or be used to control more detailed dynamic assignment models. A verbal description of the career management model is given in Figure 1.

The objective of this career management model is to minimize a set of priority weights on the discrepancies from the manpower requirements, and on new hires and excess personnel. In most applications these weights are set such that: (a) it is more desirable to miss the individual manpower goals than to fire (or reduce in force (RIF)), personnel, (b) it is more desirable to meet the manpower goals than to have manpower vacancies, and (c) on-board manpower will be considered before any hiring takes place. These weights are used on the assumption that it is more costly to hire or RIF manpower than to maintain manpower already on-board. Future model designs will include the possibilities of shifting excess manpower to those categories where hiring must take place.

The model objective is subjected to a number of constraints. First, the number on board in each job category at the start is set equal to a constant. This ensures that the base period population will be completely accounted for in the model solution. The base period population is than submitted to a matrix of movement or transition rates which distinguishes, probabilistically, between those staying in a particular

OCMM Career Management Model

Objective: (a) Minimize Discrepancies from Civilian Manpower Requirements by Job Category (b) Favor On-board Manpower and New Hires over Reductions-in-Force (RIF's)

Subject to:

	Number on board in Each Job Category in Each Period	-	Possible Amount Over	+	Possible Amount Under	=	Manpower Requirements by Job Category
	Number on board in Each Job Category at Base Period					=	Initial Population
	Number Remaining in Each Job Category		Number on Board in Each Job Category at Present Period	-	New + RIF's Hires	=	0
	Sum of	Number on Board in Each Job Category	x	Salary of Job Category		≤	Total Salary Budget
	Sum of	Number on board in Each Job Category				≤	Total Manpower Available

Figure 1

manpower category, those being promoted, and those leaving the Navy. Given the indicated goals and weights, a certain number of new hires are selected by the models to minimize discrepancies from all goals. The number remaining from those initially on board at the end of the projection period including the effects of promotions plus the new hires, minus any excess personnel, will exactly equal the on-board manpower at the end of the projection periods which extend, as required, for any multiple number of planning periods. Additional constraints include manpower ceilings and the total salary budgets. However, in most of the data studies in which the model has been used, only the manpower ceiling constraints were included.

This model can be (and has been) applied in various ways. Currently, for instance, a variant is being used to assist in the evaluation of policies to control average General Schedule grade. This was in response to an Office of Management and Budget (OMB) directive requiring a lowering of average grade throughout the Federal establishment. The career management model was modified by making the number desired in each of the GS grade categories the manpower goals. The current on-board and the most recent manpower transition rates available from the FYNCIMP system were also used.

The average grade constraint is included in the model by requiring that the sum of the number in each grade times the grade must be less than or equal to the required average grade multiplied by the total projected population on board. This constraint is made to hold for a given population by inserting an additional constraint which requires that the sum of the number in each grade must exactly equal the projected total on board. Additional constraints of upper and lower bounds on the number in each grade are also set. These ensure aginst the naive solution of firing large numbers of high grade personnel and replacing them with large numbers of low grade personnel.

Within two weeks after the issuance of the OMB directive, the above model was developed and it has been used to evaluate a large number of alternative grade distributions and hiring and promotion policies for the Navy. Presently, it is being updated quarterly as new transition rates become available.

A large number of prototype tests using earlier versions of the model have been developed to study the reaction of the model structures to operational data. The largest of these involved a five-year projection of 350 job categories Navy-wide. This resulted in a model containing 3,200 constraints and 5,200 variables. It was solved in sixteen minutes on a CDC 6600 computer by the University of Texas. The large number of constraints and variables results from the fact that an explicit accounting must be made for each job category for each time period. Separate variables for each job category in each time period must also be included for both the positive and negative discrepancies from the goals and for the possibility of hiring or firing. These test results were the first projections for this level of detail for the total Navy civilian white collar population. They indicate that it is practical to consider the implementation of such large-scale manpower planning models.

Multi-Level Model

The preceding section illustrated one kind of extension toward an integrated systems approach in career management and manpower planning. This does not, however, exhaust further possibilities afforded by contact with other modelling efforts. A case in point is the OCMM multi-level model which was developed to bring the career management models into contact with the program planning and budgeting or PPB systems in being or under development within the Navy. One aspect of the importance of this work may be brought into immediate prominence by observing that such planning actually drives the manpower allocation and career management process.

The development of PPB systems beyond the methodology of allocating civilian manpower is not the direct responsibility of OCMM. However, there are strong relationships between aggregate civilian manpower allocations and total force planning. This led to an OCMM investigation of current and proposed PPB methodologies in the General Planning and Programming Division of the Chief of Naval Operations. As a result, it was felt useful to consider the input-out models under development in the Center for Naval Analyses.* As developed at CNA, these models have proved to be of value for examining costs not only for mission and support categories, but also for the program elements of the Five Year Defense Program (FYDP).

A first result from this juncture with the CNA models produced a new multi-level model which integrates the resource allocation features of the CNA models with a career management model. Although the two are considered simultaneously, the model has been arranged so that resource allocation is accorded greater weight in the objective than career management. Goal programming features, which are retained, make it possible to handle inconsistencies in resource availabilities and other requirements. The result, in any event, is a model which is multi-level in the sense that two different levels of decision making are included in the same model.

A description of the multi-level model is given in Figure 2. In this model the input-output transfer rates provide an ability to examine simultaneoulsy relationships between resource producers (e.g., the naval shore establishment) and final resource users (e.g., the fleet).

*See J. H. Augusta, R. A. Jenner, and G. W. Ryhanych "Interim Input-Output Resource Allocation Model" Center for Naval Analyses Research Contribution No. 134, 2 March 1970.

DYNAMIC MANPOWER AND RESOURCE PLANNING MODEL

OBJECTIVE: MINIMIZE DISCREPANCIES FROM OPERATING FORCE SUPPORT REQUIREMENTS AND INCLUDE EFFECTS OF ATTRITION AND RECRUITING ON MANPOWER DECISIONS.

SUBJECT TO CONSTRAINTS OF:

- PROPORTION OF SERVICES EACH SUPPORT ELEMENT PROVIDES TO THE FLEET
- SUPPORT ELEMENT CIVILIAN MANPOWER REQUIREMENTS
- BUDGETARY LIMITS OF EACH SUPPORT ELEMENT
- MANPOWER ATTRITION
- INTERNAL MANPOWER TRANSFERS

Figure 2

This model also uses manpower transition rates to account for interactions between manpower inventories and manpower requirements. The latter are formulated as constraints which join the resource allocation portion of the model to the manpower requirements by means of a series of "coupling conditions." This ensures that imbalances in the manpower planning system will be reflected in the resource allocation system and vice versa. The goal programming aspects of this model also supply flexibility for examing the effects on final user demands of changes in resource inputs as well as manpower requirements.

Still in the testing stage, the model has been submitted to small numerical examples using historical input-output and transition rates extracted and formulated from existing OCMM and CNA sources. These have now been successfully tested on a UNIVAC 1108 computer. The importance of these results are that they show that it is computationally possible, with existing data sources, to use the multi-level cost model. The next step is to formulate and test the model with a small operational problem.

Preparatory Extensions

Another aspect of this work deals with what might be called preparatory formulations and exploitations. Consistent with the philosophy (or strategy) of joining basic research to applied efforts, this aspect of the work is rooted in existing practices and problems. It also extends toward possible future patterns of development and application for which preparatory research is required.

A case in point is the aspect of this research which deals with dynamic assignment models.* This represents an attempt to improve on current and extensive uses of linear programming in so-called assignment model form. It also looks toward future possibilities of dynamic organization designs which responds and interact with differing and developing mixes of personnel, tasks, and organization arrangements.

The current operational assignment models can be characterized as being limited in at least the following ways: they are (1) static and (2) restricted to the use of single index summaries to match individual persons with individual jobs. This means that the models do not explicitly relate a next assignment to past and future assignments. Also, they use a single measure such as a score on a test in order to make the assignments.

This does not mean that the static models are unimportant or impractical. They have been used extensively, for example, to assist in the assignment of military personnel. But these "one-shot" uses are not exhaustive. An example of possible new assignment model uses might evolve from making them dynamic and using multiple alterable characteristics to make the assignments. Multiple alterable characteristics might involve such things as test scores, employment history, job characteristics, aspirations, etc. Such models have been proposed in the course of this research via theoretical mathematical formulations designed to highlight pertinent issues.

The new assignment models are aimed at the problem of making multiple assignments for a variety of tasks at different points in time. They allow for possible carryover of skills and learning as personnel are moved from one assignment to another. This leads to the need for research into a system for forecasting future, as well as present potential in any assignment that might be considered. It also implies a multiple rating of each job including an evaluation of each job's "teaching potential" for improved performance of (possibly different) persons in future jobs as well as the skills the persons must exhibit in performing present jobs. The linking of assignment models with task and skill requirements should evolve very naturally from such considerations and thereby point the way toward extending these separate one-at-a-time assignments into a coherent organizational design woven around the jobs to be performed and the personnel to be assigned.

Dynamic Organization Design

A tie-in between job-related and personnel-related characteristics might also be considered in future research in ways that will lead to new

*See A. Charnes, W. W. Cooper, R. J. Niehaus, and D. Sholtz "An Algorithm for Multi-Attribute Assignment Models and Spectral Analyses for Dyanmic Organization Design." Presented at 41st National Meeting of the Operations Research Society of America, New Orleans, La., April 27, 1972.

approaches to dynamic organization design. This then is likely to transcend the limits permitted by classical managerial devices such as organization charts and (static) manuals for controlling organization structure and individual behavior. The foregoing results open new possibilities for research investigation. How should personnel tests and assignments be evaluated for dynamically varying organization and personnel components? What devices (computerized or otherwise) should we employ in lieu of classical organization charts and manuals to identify and control where we are now and where we are going? Also, what kinds of mathematics will we need to deal with the incommensurable and noncomparable dimensions of such persons and organizations over time?

Summary and Conclusions

The preceding discussion points toward some of the further developments which will be needed, even at very basic levels, before the full fruits of their application potentials can be secured. These research activities should range, it would seem, from systems extensions of behavioral science constructs to new developments in, e.g., non-metric mathematics. The research might also include identification of new types of data as well as developments in computer hardware and software.

We have here tried to indicate some of the many possibilities that this combined basic-applied research has opened in a very important area of human endeavors. We have necessarily omitted many details including the recent extensions this has produced even in modelling mathematics (*e.g.*, chance constrained programming), *etc*. At this point, it seems useful to conclude with the following summary of the potential management uses of the OCMM models:

1. The provision of a systematic basis for assessing and evaluating future plans for the utilization of civilian manpower in light of current and projected trends in the Navy and in the private economy,
2. The testing of various policies to assist in the control of average grade,
3. The evaluation of the impact on manpower and other shore resource requirements of the additions to, or deletions from naval operating forces,
4. Systematically supplied ways for evaluating inconsistencies between manpower and budgetary allocation decisions,
5. Systematic ways for evaluating the effect of inflation or other such changes in operating force support requirements and manpower requirements,
6. Determination and depiction of the effects of attrition and internal manpower transfers on both short and long run decisions.

7. The integration of career management, training, recruitment, and advancement planning with budgetary and strategic decisions.

Finally, in the more distant future, we suggest the possibility of dynamic organization designs of a more flexible (changing) variety than those admitted by static organization charts.

Instrument to Measure Radiation

Two Naval Research Laboratory scientists have applied for a patent on an invention which can measure the energy deposited (called the "dose") in silicon by intense bursts of x-rays.

The NRL instrument, called an adiabatic calorimeter, is absolute in that it does not require comparison with a known field of x-rays. Its operation is based on the accurate measurement of the instantaneous temperature rise in a pure metal such as silicon, for which the heat capacity is well known.

Dr. Kenneth M. Murray and Frank H. Attix of the NRL Nuclear Sciences Division, who developed the device, said it has proven to be accurate, reliable, and much simpler to use than calorimetric dosimeters of earlier types. It provides a convenient method for calibrating other non-absolute radiation instruments, such as thermoluminescent dosimeters.

The Aurora Facility near Washington, which is operated and maintained for the Defense Nuclear Agency by the Harry Diamond Laboratories, is already using the first calorimeter of this type, built at NRL, as their primary dosimetry standard for measuring x-ray output in radiation damage studies.

The calorimeter is designed in a spherical shape to provide equal radiation response regardless of the direction from which x-rays strike it. The temperature rise is measured in the center of a pea-sized ball of silicon by a thermistor, which changes its electrical resistance with change of temperature. The silicon ball is surrounded by a shell of the same material to provide thermal and radiation equilibrium, and an outer shell of aluminum to prevent radio-frequency interference. The entire device is insulated from surrounding air by enclosing it in a ball of styrofoam.

Although the present design was tailored to the measurement of x-ray dose in silicon, other pure materials such as graphite or copper could be substituted for measuring dose in those materials. Moreover the device is easily adapted to the measurement of intense electron beams such as those generated by linear accelerators ("Linacs"), in place of x-rays.

It is expected that the simplicity of this instrument will clear the way for wider applicability of the calorimetric method in the measurement of intense radiation fields.

Prevention and Cure of Cavitation Erosion

A. Thiruvengadam*
School of Engineering and Architecture
The Catholic University of America

Cavitation erosion is one of the major engineering problems confronting the designers of modern high-speed naval hydrodynamic systems. It is caused by the collapse of bubbles at or near the solid boundaries guiding high speed flow. Figures 1 and 2 show typical cases of cavitation of super cavitating propellers and strut-pod intersections.

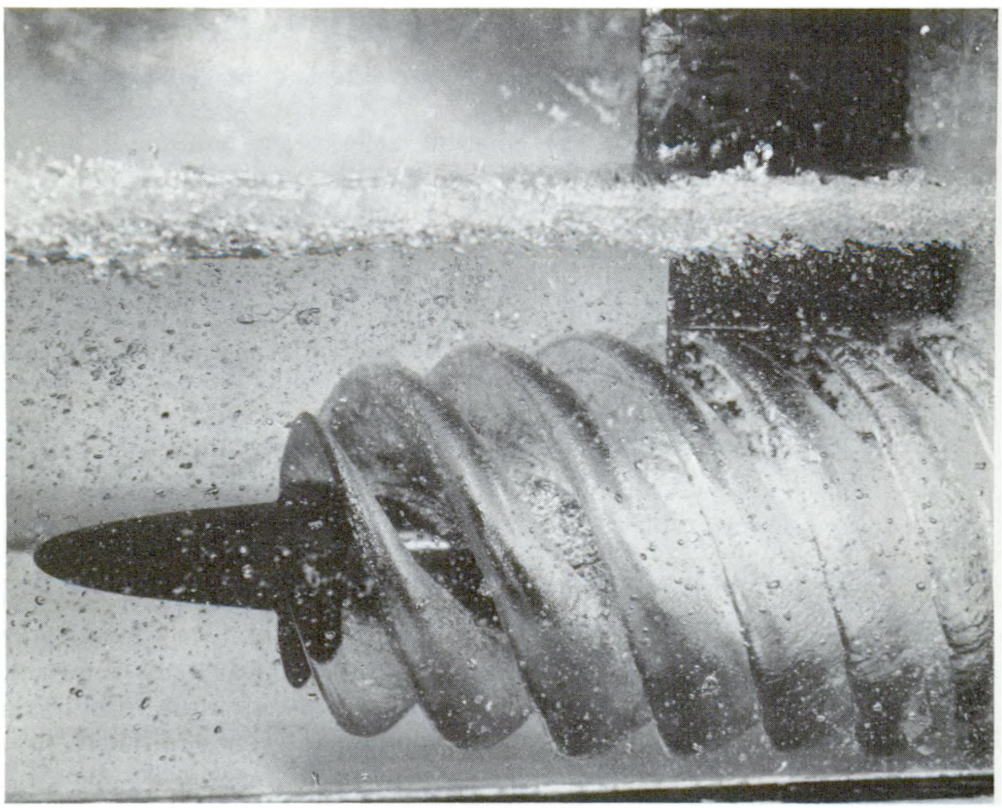

Figure 1 — Vortex cavity behind a super cavitating propeller is shown in this photograph. The invention of super cavitating propeller is one of most significant technological achievements during last decade in the field of high speed hydrodynamics. In spite of its many distinct advantages, the material problems and cavitation erosion are still limiting its widespread use.

---

*Dr. Thiruvengadam is Professor in the Department of Civil and Mechanical Engineering at The Catholic University of America. His contributions to the understanding of the phenomena of cavitation damage and impact erosion are internationally known.

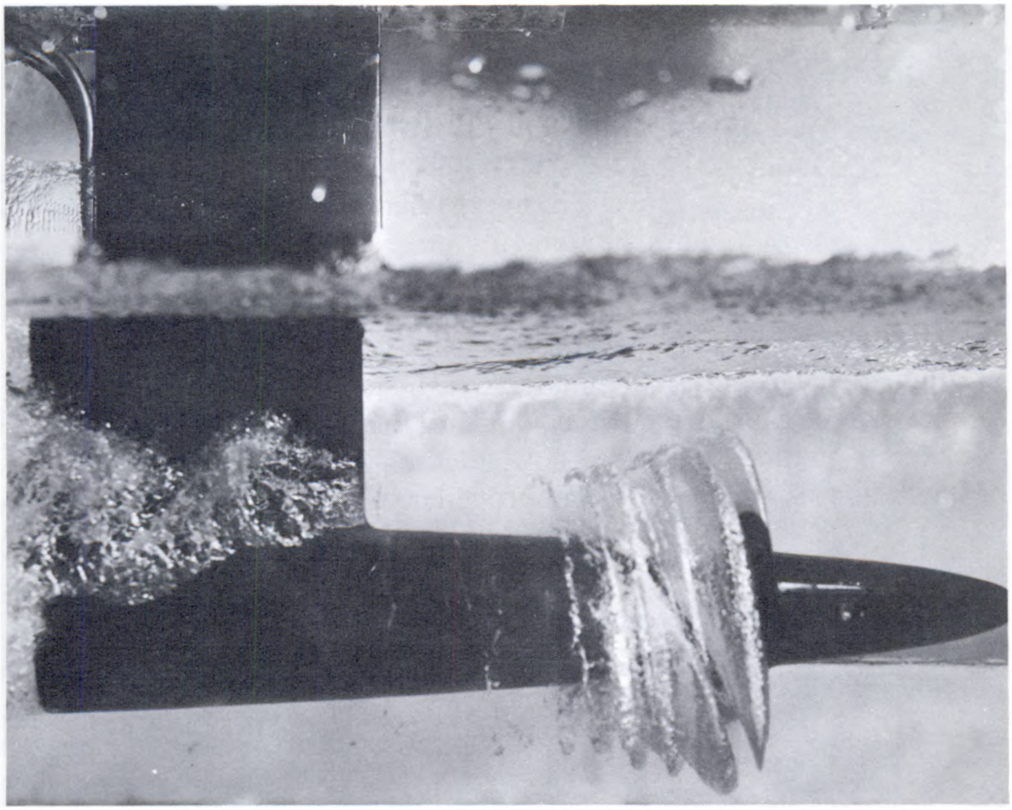

Figure 2 — Cavitation erosion of various ship appendages is also a major problem. This photograph shows the cavitation at the strut pod intersection. Serious erosion of the order of 1/4 inch in half hour operation on HY-80 steel in service trials has been produced by this type of cavitation.

It is a serious problem in hydrofoils (Figure 3), rudders, marine propellers (Figure 4), sonars, bearings, engine liners, pumps, valves, control systems, torque converters and aircraft engines, to mention only a few.

With increasing requirements of higher speeds, smaller sizes, and better reliability and service life for this hardware, the modern designer is concerned with several engineering aspects as shown in Figure 5. The design and material selection process draws information from basic research, screening of materials, and available experience on protection techniques. Basic research on bubble growth and collapse, material erosion and environmental interaction has generated much needed fundamental knowledge. The relative resistance of many materials has also been catalogued using one of several screening tests. These tests include: (1) the vibratory test, (2) the rotating disk test, (3) the Venturi test, and (4) the jet impact test. Basic research combined with screening tests has led to several useful protection techniques which include the use of more resistant materials (inlays, overlays and elastomeric coatings), and the cathodic protection and air injection methods. These protection techniques are successful in some instances but not so useful

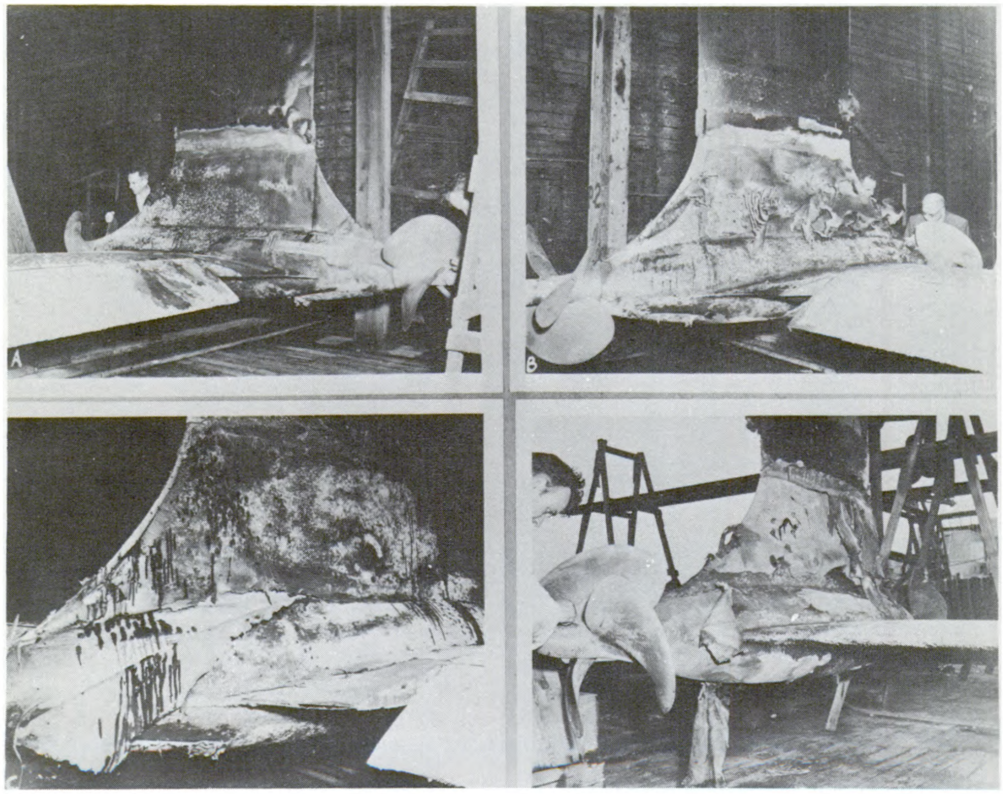

Figure 3 — Cavitation erosion is a serious problem in hydrofoil boats. Proper design and operating procedures have produced encouraging results.

in other cases. If erosion is serious at the designed operating conditions, operational requirements such as capacity, power, and speed might be reduced. However, if the design is hopeless in terms of erosion rates, then redesign is generally recommended.

During redesign, one would correct obvious mistakes, avoid cavitation if at all possible, and provide air vents at problem areas. It would be highly desirable to verify the redesign (or a preliminary design) with the help of a model test before costly manufacture is initiated. Such model tests would lead to the necessary modifications of design so that the erosion intensity levels are within the capability of the candidate material. Attempts to develop such modeling techniques are currently underway. The objective of this paper is to describe these developments, which are the result of ONR support, for the general use of designers and operators.

Definition of the Intensity of Erosion

The task of coordinating basic research with field experience was first initiated by Knapp (Ref. 1) in the early fifties. This task seemed

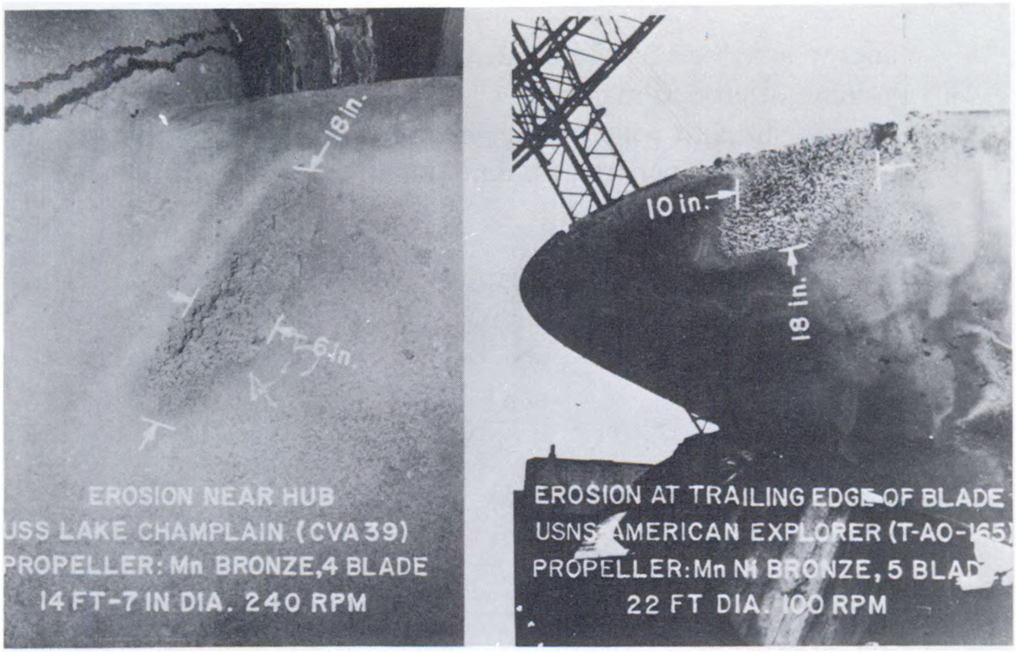

Figure 4 — Cavitation erosion of ship propellers generally occurs at a rate of approximately an 1/8 inch per year. However some propellers are known to erode at a rate of one inch in 20 hours at certain critical operating conditions.

formidable to him at that time, as is evident from the following remark (Ref. 2):

> "However, at this point, the investigator finds himself on brink of an abyss gazing out over completely unknown territory since no satisfactory method has been developed for measuring the absolute intensity of cavitation, either in the laboratory or in the field. Future work on the relative resistance of materials to damage should be correlated with studies of mechanics of damage. An important step would be the development of a definition of intensity of cavitation and some rational measure of it which could be used both in hydraulic machines and structures and in equipment employed for determining relative resistance."

Although several investigators including Knapp attempted to develop such a definition for the intensity of erosion, it is only recently, that this task has been accomplished. During the process of erosion, a certain volume of material is removed from the surface as a result of the work done by the erosive forces. The energy absorbed by the eroded material is given by

$$E = \Delta V \cdot S \qquad [1]$$

where:

E = energy absorbed by the eroded material
ΔV = volume of eroded material
S = erosion strength which represents the energy absorbing capacity of the material per unit volume under the action of the erosive forces.

The intensity of erosion is then defined as the power absorbed by the material per unit eroded area (Ref. 3) and is given by

$$I = \frac{\Delta V \ S}{A \ \Delta t}$$

$$= \frac{\Delta y}{\Delta t} S \qquad [2]$$

where:

A = area of erosion

Δy = mean depth of erosion $= \dfrac{\Delta V}{A}$

Δt = exposure time

This is the output intensity of erosion as seen by the material; similarly one can derive an expression for the bubble collapse intensity which is the input to the erosion process (Ref. 4).
Then

$$\frac{\Delta y}{\Delta t} \cdot S \qquad \propto P_i \ R \ n \qquad [3]$$

where:

P_i = impact pressure
R = size of the bubble or jet
n = number of impacts per unit time.

These ideas have been incorporated into a master chart for cavitation erosion as shown in Figure 6. In this chart, the intensity of erosion is plotted against the rate of mean depth of erosion for various materials ranging from soft lead to very highly resistant stellites. The range of intensities typical of practical machines varies from 10^3-10^4 in.-lb/year-in.^{2}. (The screening tests such as the vibratory test and rotating disk test operate at intensity levels on the order of 10^5 in.-lb/year-in.^{2} (1 watt/m^2)). The depth of erosion is generally in the range of a fraction of an inch per year. Chemical corrosion rates on steels are in the range of

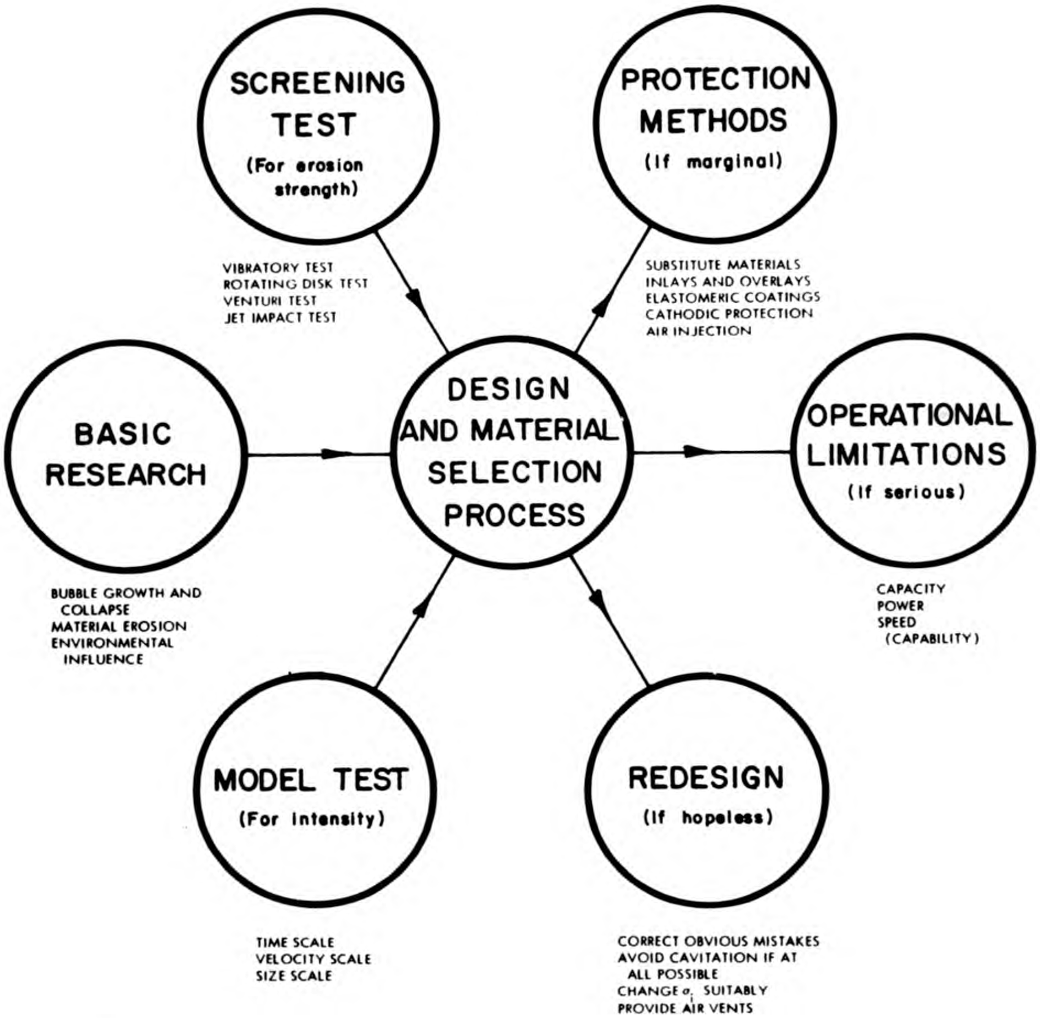

Figure 5 — Engineering aspects of cavitation erosion

10^{-3}-10^{-2} in. per year (ipy). Erosion rates on the order of 1 ipy represent serious erosion which may warrant operational limitation or redesign.

The level of threshold intensities for various metals are on the order of 10^{-1} w/m² at the most. Elimination of cavitation damage by substituting one metal for another is possible only up to this level of intensity. For this reason, the usefulness of cathodic protection also seems to be limited at this level. If one is prepared to tolerate some erosion and periodic maintenance, then the materials selection coupled with cathodic protection can possibly extend the allowable intensity levels up to 1 w/m². However, if the intensity levels are higher than these values, then the foregoing protection methods may not work. In such cases, hydrodynamic redesign, air injection, and specifying limits for operation are the alternate remedial possibilities. These considerations are pictorially represented in Figure 7. Further field and laboratory investigations are needed to confirm these ideas.

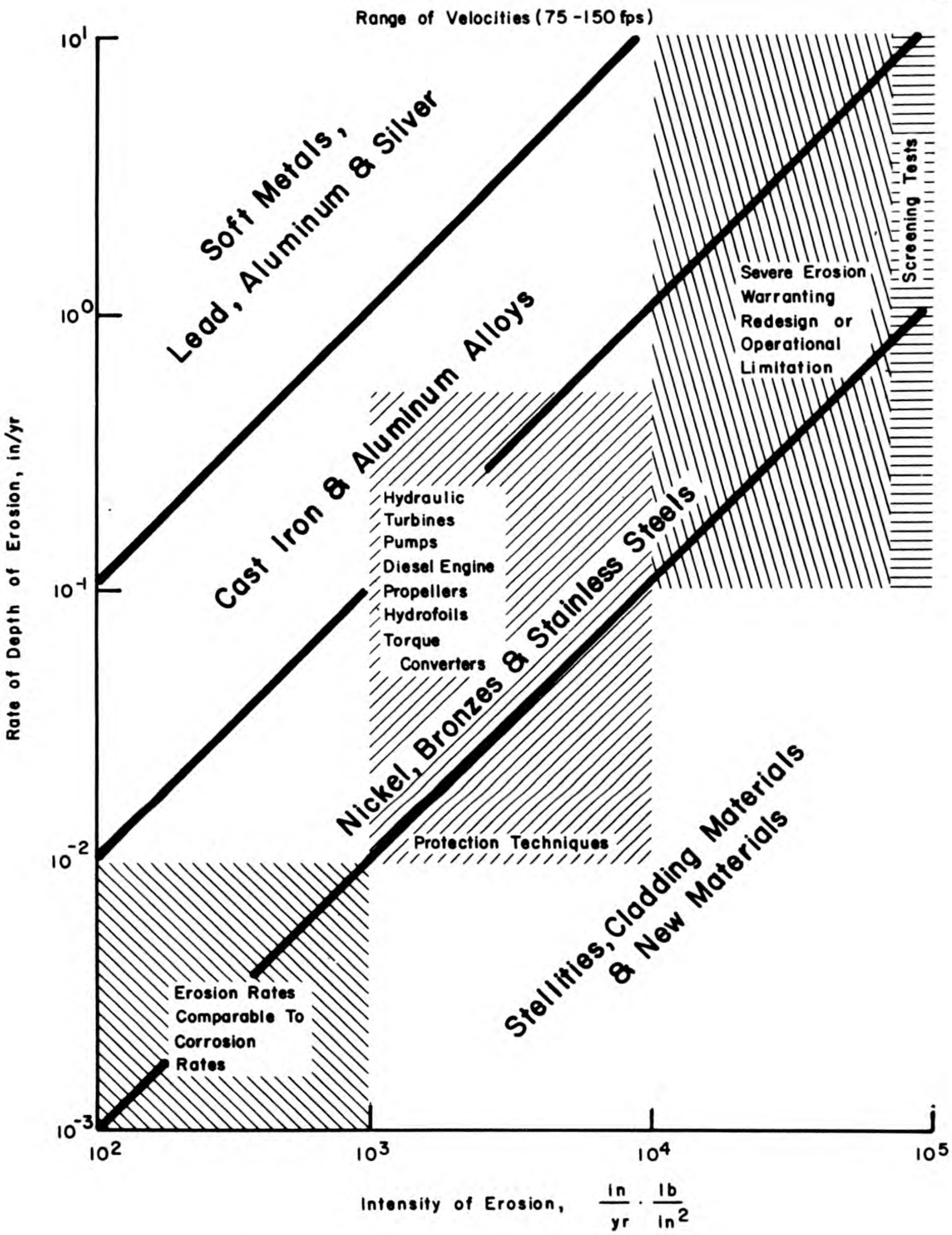

Figure 6 – Master chart for cavitation erosion

Another tool for the benefit of designers and operators is a multipurpose nomogram (Figure 8) called erosion estimator. It provides a visual idea of the range of intensities encountered in actual practice within the range of the depth of erosion, material used and time of operation. It also provides a quick and easy method of estimating the intensity of erosion for a given field installation. Lastly, the selection of better materials, if available is easily made.

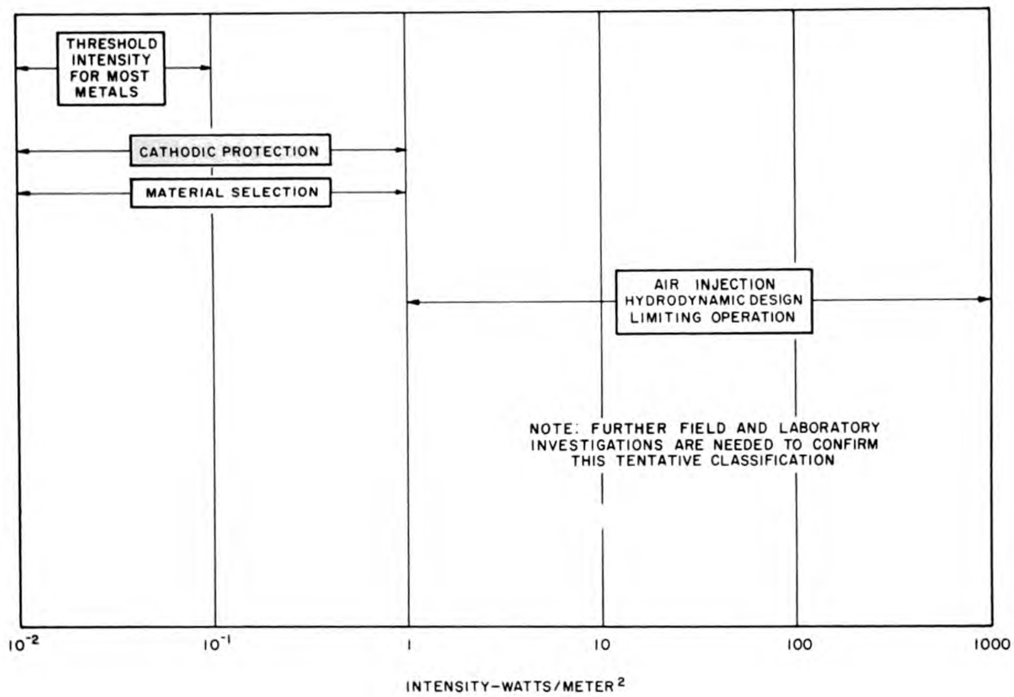

Figure 7 – Range of intensities for the possible application of known protection methods

The procedure in using this estimator is as follows:

1. To determine the intensity of erosion, if the depth of erosion, the erosion strength of the material eroded and the duration of erosion are available, draw a straight line connecting the depth of erosion and the erosion strength of the material eroded. This line will intersect the pivot line (the second line from the left without any scale). Join this point of intersection with the duration of erosion by means of another straight line which will intersect the intensity scale, thus giving the intensity of erosion for this case.

2. To determine the depth of erosion after a given operating time on a given metal, if the intensity of the system is known, proceed as follows: draw a straight line connecting the duration of operation and the intensity so as to intersect the pivot line. A straight line joining this point of intersection and the erosion strength of the material would intersect depth of erosion scale, indicating the depth of erosion for these conditions.

3. To determine the erosion strength of the material required to give a certain depth of erosion after a given duration of operation in a system of given intensity. In this case, a straight line joining the intensity and the time of operation would intersect the pivot line. Another straight line connecting this point of intersection and the depth of erosion would cut the erosion strength scale at the required value.

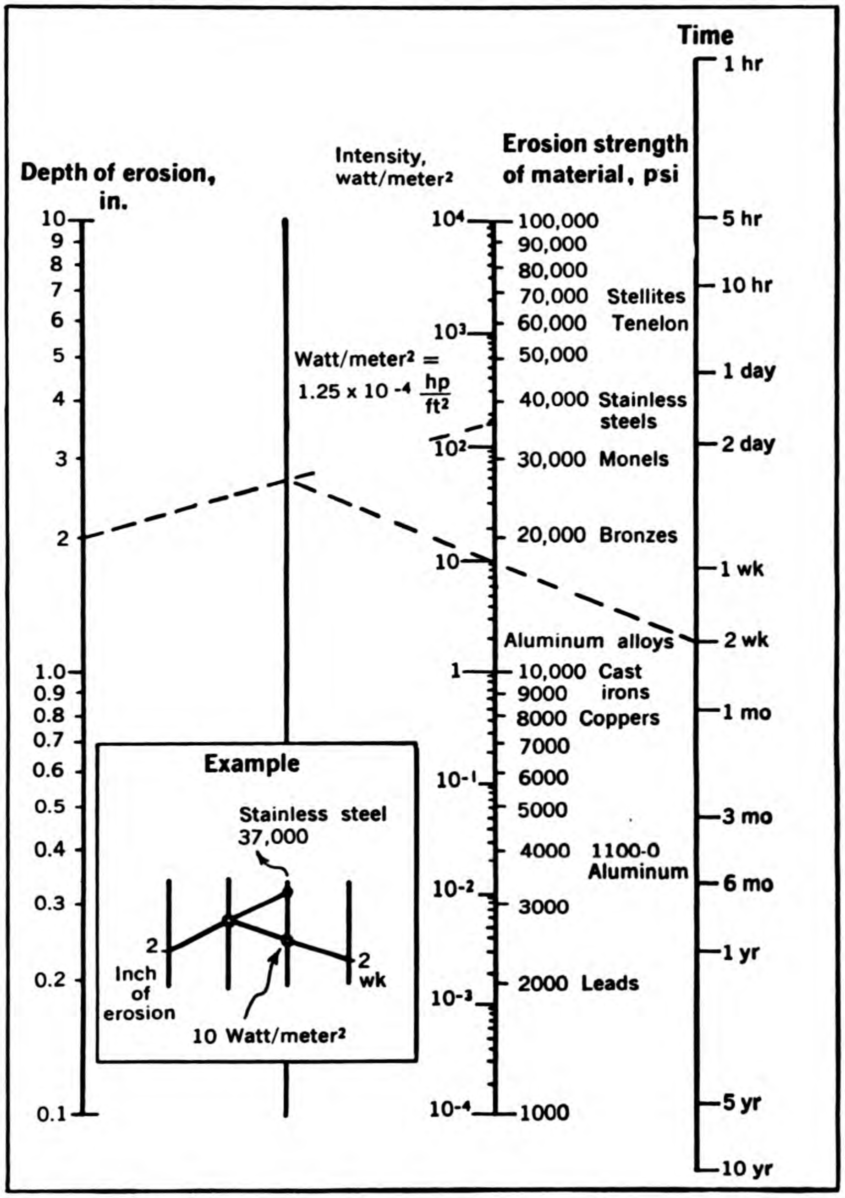

Figure 8 – Erosion intensity estimator

4. Similarly one can find the duration of operation for a given system of known intensity, fabricated from a given material, if a criterion for the allowable depth of erosion is set.

The estimator should be a convenient design tool for engineers. The usage of the proper units as shown in the nomogram for each parameter will yield the intensity in watts per square meter.

Exposure Time

One of the basic parameters involved in cavitation erosion is the exposure period. It is now well established that the rate of erosion is very much dependent on the exposure time (Ref. 5,6). This dependency makes the comparison of the performance of different candidate materials difficult; for example, a prototype operates over a long period as compared to the short exposure periods in a screening test.

The rate of erosion increases from negligible values, reaches a maximum, then decreases and levels off, in some cases to a steady value. A typical curve is shown in Figure 9. Such relations for a spectrum of materials are shown in Figure 10. The erosion time for these materials varies over a time scale from a few minutes to a few days.

An elementary theory of erosion has been formulated making use of some of the recent ideas such as the erosion strength, intensity of erosion and fatigue failure probability. The following differential equation may be derived making use of these ideas.

$$\frac{dI}{dt} + \frac{kI^{5/2}}{1/\eta^2} - \frac{I}{\eta}\frac{d\eta}{dt} = 0 \qquad [4]$$

$$k = \frac{-2}{S\sqrt{AI_c}}$$

where

I = intensity of erosion
k = a constant with length as dimension
η = the efficiency of erosion
t = time of erosion.

Equation (4) can be normalized with respect to the time at which the intensity is a maximum. The resulting normalized differential equation is

$$\frac{d\bar{I}}{d\tau} + \frac{\bar{k}\bar{I}^{5/2}}{1/\bar{\eta}^2} - \frac{\bar{I}}{\bar{\eta}}\frac{d\bar{\eta}}{d\tau} = 0 \qquad [5]$$

where

$\tau = t/t_1$

$\bar{I} = \dfrac{I}{I_{max}}$

$\bar{\eta} = \eta/\eta_1$

$\bar{k} = \left.\dfrac{d\bar{\eta}}{d\tau}\right|_{\tau = 1}$

(Subscript 1 corresponds to the maximum intensity of erosion I_{max})

The general solution of the normalized equation of erosion is given by

$$\bar{I} = \frac{\overline{\eta}}{\left[1 + \frac{3}{2}\,\bar{k}\int_{1}^{\tau} \eta\, d\tau\right]^{2/3}} \qquad [6]$$

This theory predicts the relative rate of erosion (the ratio between the rate of erosion and the peak rate of erosion) and the relative exposure time (the ratio between the exposure time and the time corresponding to the peak erosion rate). This prediction and the experimental data for various materials are compared in Figure 11. This approach offers the possibility of using a weaker material to learn about the erosion potential of the prototype material at comparable intensities of erosion in a shorter time (Ref. 7). The selection of materials for the model will be governed by several requirements such as structural strength, environmental effects, reproducibility of results and techniques employed in the manufacture of the models, in addition to the considerations involving test duration. The influence of corrosion on model-prototype correlations is currently being studied.

Scaling Laws

Recent experiences with full scale systems show that, in some cases, even the most resistant material was severely eroded in short operational periods (Ref. 8). In such cases, redesign is generally recommended.

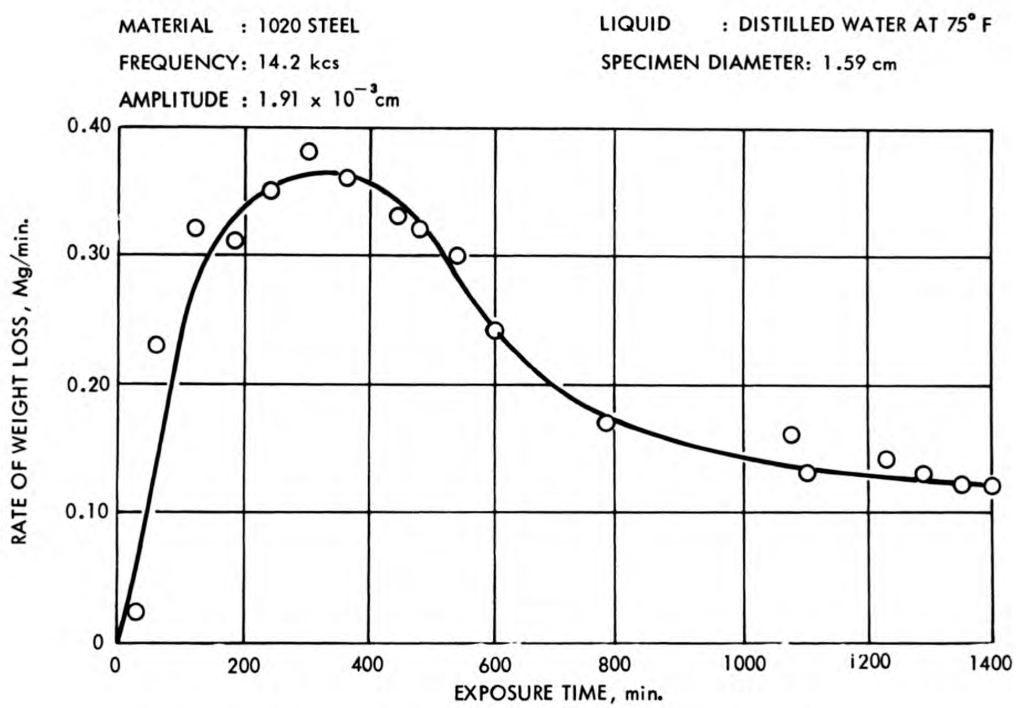

Figure 9 – Relation between exposure time and cavitation erosion rate of SAE 1020 steel

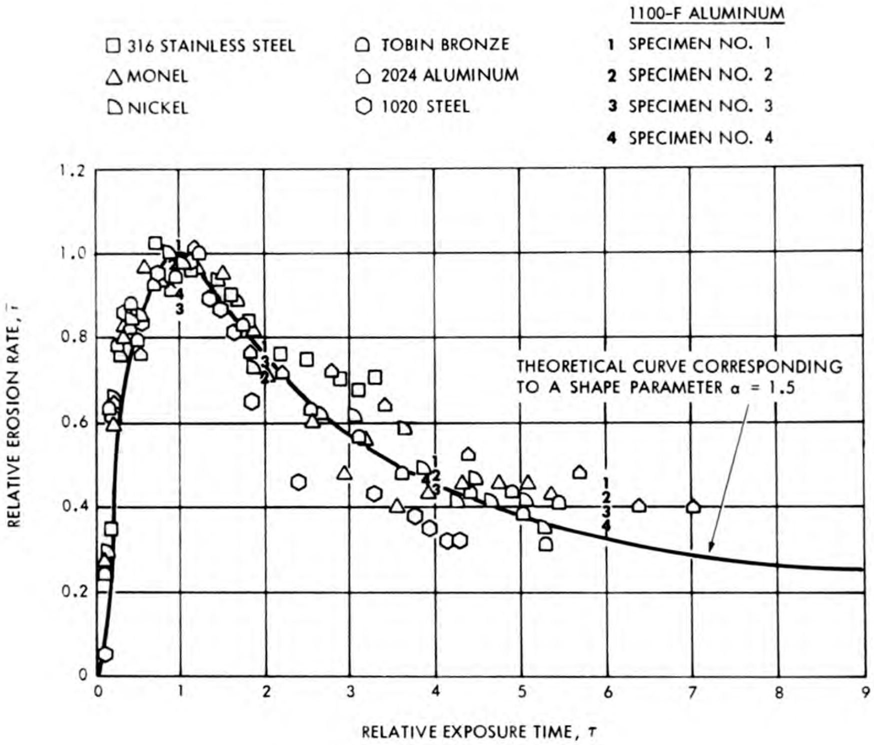

Figure 10 — Erosion rate and exposure time relations for seven materials

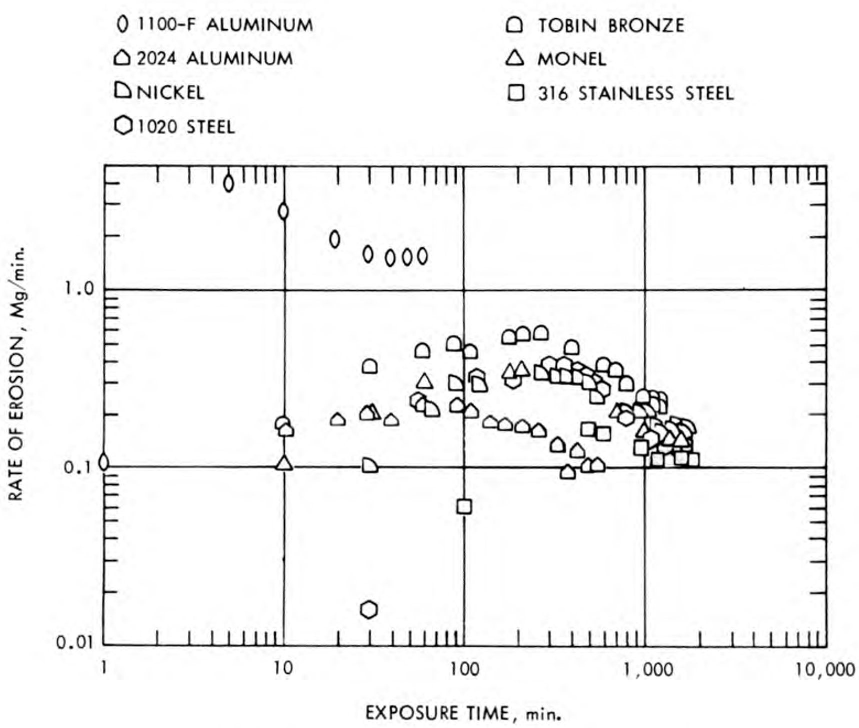

Figure 11 — Relative erosion rate as a function of relative exposure time for the seven materials

It would be highly desirable to verify the design (or a preliminary design) with the help of a model test before costly manufacture is initiated. Such model tests might lead to necessary modifications of a design so that the erosion intensity levels are within the capability of the candidate material.

However, the feasibility of model testing depends upon the ability to scale exposure time, speed and size of the system. The problems involved in scaling exposure period has been discussed in the previous section. Now let us consider the velocity and size scales. The intensity of bubble collapse depends upon three parameters, namely, the impact pressure, the size of the bubble and the frequency of impact. Using this approach, one can show (Ref. 4) that

$$\phi = \frac{\sigma}{d}\,(\Delta\sigma)^{1/2}\,\exp\left[-\frac{2.67}{W(\Delta\sigma)}\right] \qquad [7]$$

is an expression for the erosion number, ϕ, for the jet impact case; where

$\phi = \dfrac{I}{(1/2)\,\rho V o^3}$ -Erosion number

$\delta = \dfrac{\overline{d}}{\ell}$ -Relative nuclei size

$W = \dfrac{(1/2)\,\rho V o^2\,\overline{d}}{\gamma}$ -Weber number

$\sigma = \dfrac{Po - Pv}{(1/2)\,\rho V o^2}$ -Cavitation number

$\sigma_i = \dfrac{Pi - Pv}{(1/2)\,\rho V o^2}$ -Cavitation inception number

$\Delta\sigma = (\sigma_i - \sigma)$ -Degree of cavitation

ρ = density of liquid
Vo = free stream velocity
Po = free stream pressure
Pi = free stream pressure at inception
γ = surface tension of the liquid
$\overline{d}$ = mean diameter of nuclei
ℓ = characteristic linear dimension
and Pv = vapor pressure of liquid.

The analysis leading to the above relationships takes into account the influences, of nuclei-size-distribution, surface tension, vapor pressure, density, pressure, velocity, size of the model, the bubble growth and collapse, the frequency of collapse and the mode of collapse (such as spherical collapse (Ref. 9) or jet impact (Ref. 10)). In essence, these nondimensional parameters form the preliminary scaling laws governing the phenomenon of cavitation erosion. These scaling laws indicate that it is possible to model erosion in the laboratory and to predict the prototype performance. In addition, they explain many currently available experimental observations. For example, Knapp's sixth power law, reported contradictions to this law, influence of cavitation number and the effect of size of the model can all be explained reasonably well with these scaling parameters.

Although model tests would enable the designer to minimize the intensity of cavitation erosion in a given design, it would be advisable for him to select a suitable protection technique as a back-up safety measure.

Protective Coatings

Protection against cavitation erosion may be considered from several points of view: (a) elimination of the problem at the source by hydrodynamic design; model tests are important in this case; (b) use of highly resistant materials in zones of expected cavitation attack; (c) use of artificial means such as cathodic protection and air injection. In the past, several repair procedures and protection methods have been highly successful in some cases, while the same methods were not so successful in other situations. An important example is the use of elastomeric coatings to protect marine systems against corrosion as well as cavitation erosion.

The superior erosion resistance of elastomeric coatings is illustrated in Figures 12 and 13. In a rotating disk screening test, common propeller materials such as manganese bronze, manganese nickel bronze and nickel aluminum bronze erode at a rate of about 1/16 inch in 72 hours at a speed of 150 fps (Figure 12). This corresponds to an erosion rate of 8 ipy. At the same intensity of erosion of the rotating disk screening test, elastomeric coatings such as neoprene offer remarkable erosion resistance as shown in Figure 13. This figure shows the performance of neoprene coating at 150 fps after 72 hours of exposure in the rotating disk apparatus (Ref. 11).

Although elastomeric coatings offer excellent resistance to erosion in a laboratory screening test, their success in service applications is rather limited. Some coating systems behaved extremely well in the screening test at relatively higher velocities, whereas the same coating system failed miserably in field applications at much lower velocities (Figure 14). Adhesion failure of these coatings in service is still a mysterious problem. Considerable effort has been spent in screening elastomeric coatings for hydrofoil applications (Ref. 11); however further

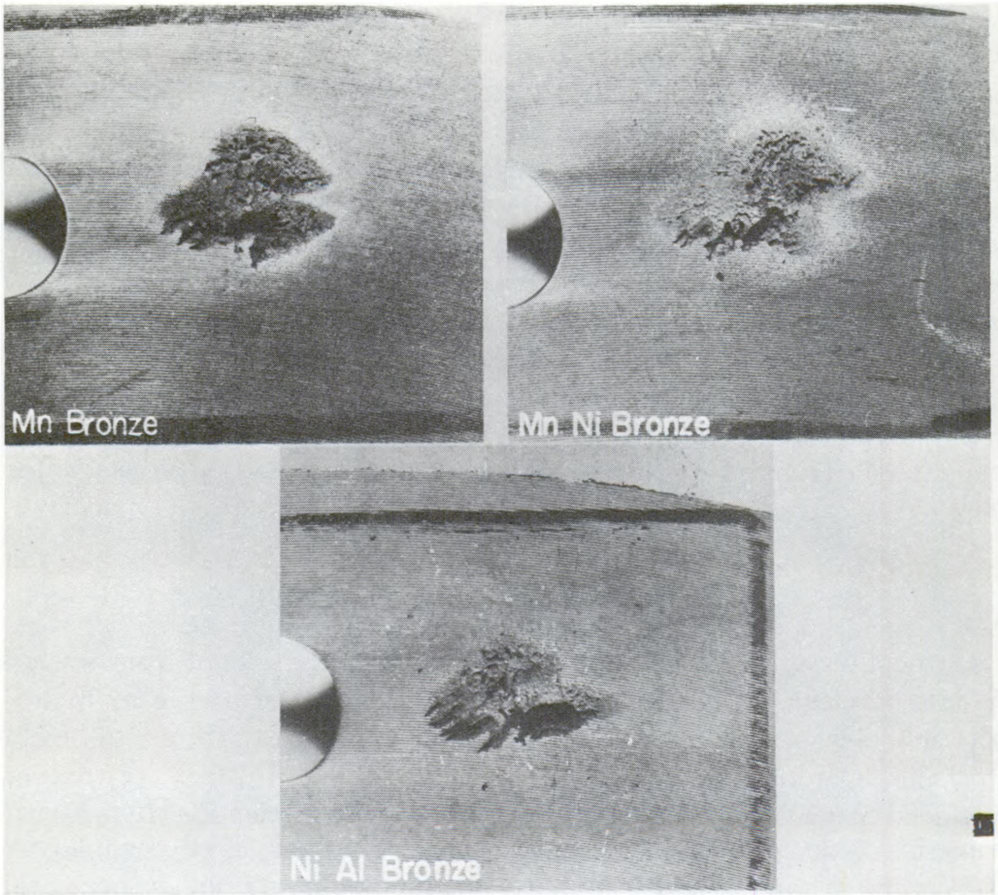

Figure 12 — In a rotating disk screening test, common propeller materials such as manganese bronze, manganese nickel bronze and nickel aluminum bronze erode at a rate of 1/16 inch in 72 hours at 150 fps. This corresponds to 8 inches per year rate of erosion.

basic research is necessary to understand how these coatings respond to the dynamic pressures created by the cavitation bubble collapse and how they fail to adhere to the substrate. Understanding of the mechanism of adhesion failures and the development of coating systems with adequate adhesion strength will eventually enhance the operating life of hydrodynamic systems to a great extent.

Concluding Remarks

Although many controversies still persist (Ref. 12), considerable strides toward a basic understanding of the phenomenon of cavitation erosion have been made during the last decade. The design and material selection process is being helped greatly through this understanding. Development of modeling techniques would be very valuable to designers. Further research on the mechanism of resistance and adhesion failures of elastomeric coatings is needed. Research on the metallurgical

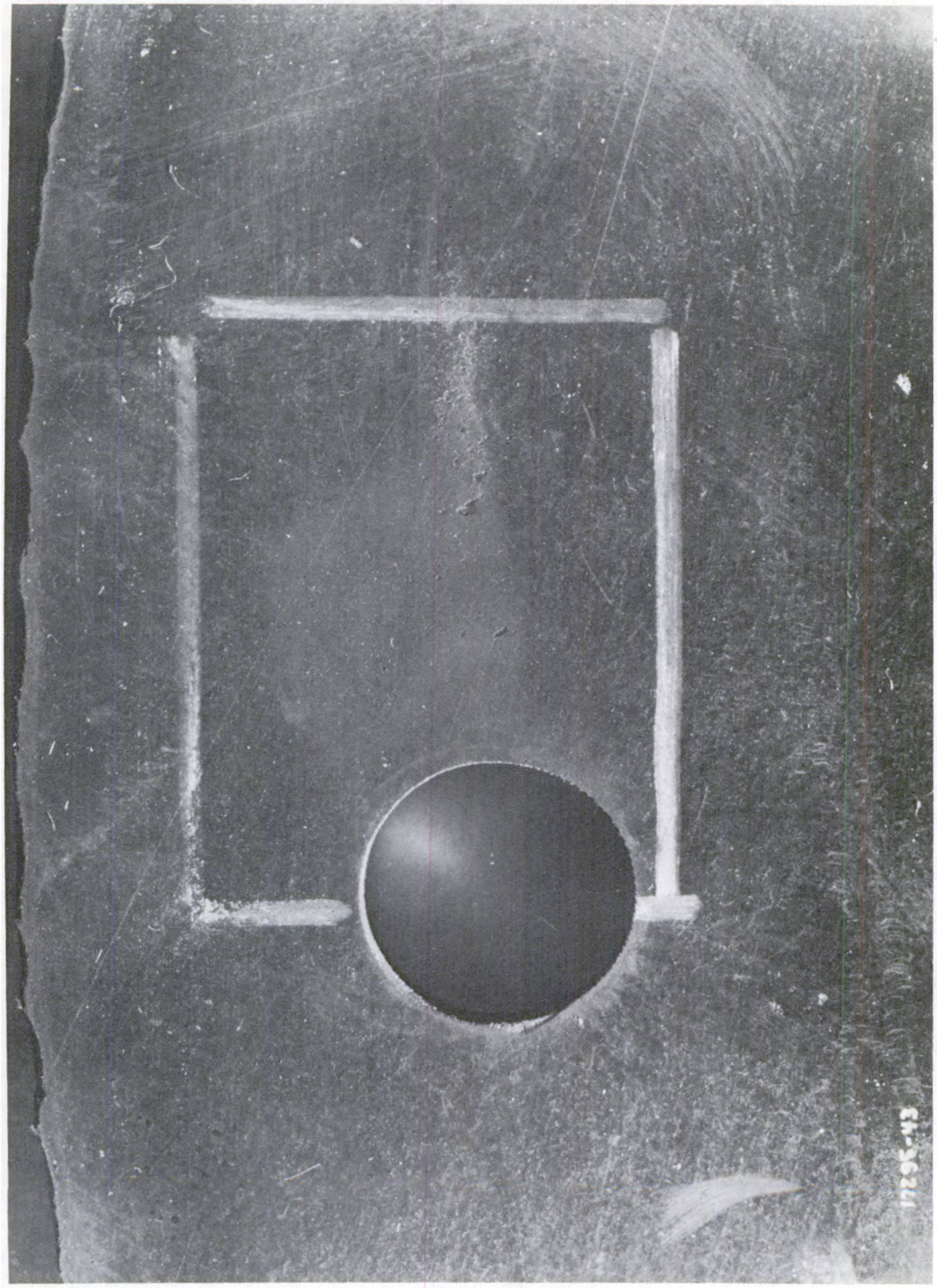

Figure 13 — Elastomeric coatings such as neoprene and polyurethane offer remarkable erosion resistance. This figure shows the performance of neoprene coating at 150 fps after 72 hours exposure in the rotating disk apparatus.

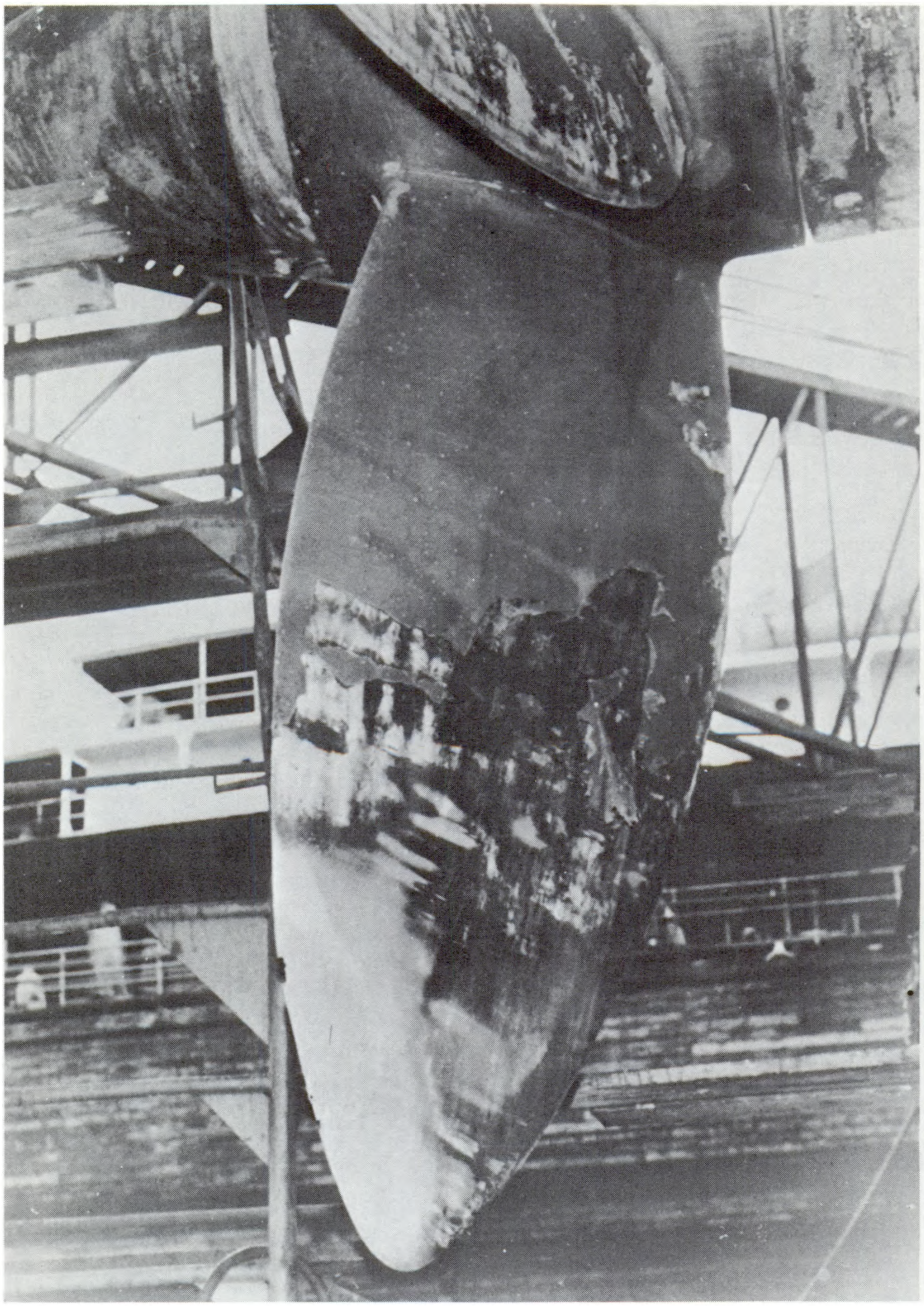

Figure 14 – Although elastomeric coatings offer excellent resistance to erosion, adhesion failure of these coatings in service is still a mysterious problem. Understanding of the mechanism of adhesion failures and the development of coating systems with adequate adhesion strength will eventually enhance the operating life of naval propellers to a great extent.

aspects of resistance to erosion may lead to more resistant metallic overlay or inlay materials. Auxiliary protection techniques such as air injection and cathodic protection need further study. The interaction of corrosion on erosion, particularly at lower intensity ranges, is of current interest. Quantitative field observations through carefully planned service trials and evaluation of the performance of protection methods will eventually lead to the development of better and new protection methods. Attempts are being made to harness the destructive forces of cavitation erosion in mining, tunnelling, drilling and cleaning applications; they require further research at higher erosion intensity ranges.

References

1. Knapp, R.T., "Accelerated Field Test of Cavitation Intensity," *Trans. ASME 80*, 91-102, 1958.
2. Knapp, R.T., "Present Status of Cavitation Research," *Mechanical Engineering* 76, 731-734, 1954; AMR 8 (1955), Rev. 430.
3. Thiruvengadam, A., "A Comparative Evaluation of Cavitation Damage Test Devices," *ASME Symp. on Cavitation Research Facilities and Techniques*, 157-164, 1964.
4. Thiruvengadam, A., "Scaling Laws for Cavitation Erosion," *Proc. of the Symp. on Flow of Water at High Speeds, Leningrad, U.S.S.R. International Union of Theoretical and Applied Mechanics*, June 22-26, 1971.
5. Heymann, F.J., "On the Time Dependence of the Rate of Erosion Due to Impingement or Cavitation," *ASTM STP* 408, 70-110, 1967.
6. Plesset, M.S. and R.E. Devine, Effect of Exposure Time on Cavitation Damage," *Trans. ASME, Journ. Basic Engr.*, Vol. 88, No. 4, Series D, December 1966, pp 691-705.
7. Thiruvengadam, A., "On the Selection of Modeling Materials to Scale Long Term Erosion Behavior of Prototype Systems," *Proc. of the Third International Conference on Rain Erosion and Allied Phenomena, Royal Aircraft Establishment*, Farnborough, England, 1970.
8. Morgan, William B., and Lichtman, J.Z., "Cavitation Effects on Marine Devices," *ASME Symp. on Cavitation State of Knowledge*, 195-241, 1969.
9. Mitchell, T.M. and Hammitt, F.G., "Collapse of a Spherical Bubble in a Pressure Gradient," *ASME Cavitation Forum*, May 1970.
10. Plesset, M.S., and Chapman, R.B., "Collapse of an Initially Spherical Vapor Cavity in the Neighborhood of a Solid Boundary," Rep. 85-49, Cal. Inst. of Tech., Div. of Engr. and Appl. Science, June 1970.
11. Kallas, D.H., and Lichtman, J.Z., "Cavitation Erosion," *Environmental Effects on Polymeric Materials*, Vol. 1, Chapter 2, Interscience, New York, 1968.
12. Eisenberg, P., "Cavitation and Impact Erosion Concepts, Correlations, Controversies," *ASTM STP* 474, 3-38, 1970.

On the Naval Research Reserve

The Research Reserve program is composed of 66 companies throughout the United States. The Naval Reserve Officers are qualified in the conduct and/or administration of scientific research, or in patent, trade mark, and copyright matters. These officers are available in the event of national emergency to meet the needs of the Office of Naval Research and the Naval Establishment. Through the year the companies report on their activities and training programs.

Active Duty for Training in a Contributory Role

For the past couple of years the Research Reserve Program has encouraged members of the Program to perform their active duty for training in a contributory role at naval activities. Two members of Naval Reserve Research Company 3-4, Rochester, New York, contributed to the regular Navy while on their annual training duty.

LCDR Byron W. Buell, USNR, was assigned to the Ocean Technology Division of the Naval Research Laboratory, where he worked on the Light Behind the Camera (LIBEC) program. LCDR Buell experimentally verified the theoretical design concept for a light source reflector to provide uniform bottom illumination under sea water. The experiment was successfully completed.

CDR E. Schickler, USNR, was assigned to the Destroyer Development Group, Newport, Rhode Island. One potential problem area which he was able to spot was the influence of wave motion on the flotation characteristics of the system which was believed essential to maintain an effective antenna platform. He then investigated the application of an "elastic" hydrophone cable for this purpose and devised a simple method of testing the effectiveness of such cables by simulating wave motion alongside the DESDEVGRU pier. With the assistance from their staff personnel, several designs were tested. The project was concluded successfully with a preliminary design recommendation including a means of packaging the elastic cable within the existing space allocation.

Officers of NRRC 3-9 Serve as Science Fair Judges

The New York School Science Fair is co-sponsored as a community service by the New York Academy of Sciences and the New York News. The Fair is conducted by the American Institute of New York City in cooperation with the Board of Education.

National Laboratories serving as Navy Award judges offered to arrange a one day tour of the scientifically elaborate Brookhaven National Laboratory Complex. Captain George H. Klaus, USNR of 3-9 also contracted Mr. W. T. Schwendler, Chairman of the Executive Committee of the Grumman Corporation, who is extremely active in promoting scholarships and programs for the young talented scientists and engineers of Long Island. An immediate response was obtained and will result in the award of five Grumman Lunar Module models of significant value.

Radioisotope for Heart Research

At the Naval Research Laboratory's cyclotron facility, scientists have solved a number of problems associated with adequate production of ^{129}Cesium, a radioisotope being evaluated as a diagnostic agent in certain heart defects.

With the support of the National Heart and Lung Institute (NHLI), Myocardial Infraction Branch, the Cardiac Research Laboratory and the Radioisotope Laboratory of the University of Cincinnati College of Medicine are now conducting heart studies on canine test subjects using ^{129}Cesium produced by the NRL-prescribed technique.

The ^{129}Cesium is injected into the bloodstream of a test subject, is traced through the normal heart muscle, and leaves an absence of take-up in a myocardial infarct (the area of the heart muscle which is dying because of lack of blood supply.)

Cincinnati Medical College heart specialists say test results have enabled them to establish a dose which gives a high quality heart image. They say they can identify the presence, location and size of an experimentally induced infarct in the subject by repeated scans over 24 hours following a single intravenous injection of ^{129}Cesium.

In a letter of appreciation to NRL, Dr. Robert J. Adolph, Director of the Cincinnati Medical College Cardiac Research Laboratory said, "The practical application of this diagnostic technique to man is most promising, and the potential rewards in patient care are staggering.

"More than 500,000 deaths are attributable to myocardial infarction each year in the U.S. Of those who reach the hospital, the majority of deaths result from shock, which in turn is related to the size of the infarct.

He continued, "It is hoped that ^{129}Cesium, given intravenously and routinely to all hospitalized patients, will predict which patients have large infarcts and are likely to develop shock, so that early definitive therapy can be initiated."

Research Notes

Man's First Space Observatory From the Moon

Man's first moon-based space observatory was on board Apollo 16.

For the first time, space explorers were able to study and record planetary and astronomical phenomena from the moon with a special gold-plated camera, based on concepts developed by Dr. George Carruthers of the Naval Research Laboratory, who is Principal Investigator for this experiment. Dr. Thornton Page, presently stationed at the Manned Spacecraft Center, is Co-investigator. The Program Manager responsible for adapting the camera for the lunar mission is William Conway of NRL's Space Science Division.

Officially called the Lunar Surface Ultraviolet Camera/Spectrograph, its mission will be to record ultraviolet emissions from the earth's upper atmosphere, the earth's geocorona and megnetosphere, and their interaction with the solar wind. It also will study interplanetary and interstellar gas, nebulae, and external galaxies, and will search for traces of a lunar atmosphere and/or volcanic gas emissions.

Soon after Apollo 16 landed on the moon, the 50-pound portable unit (it weighs 8.3 pounds on the moon), which is mounted to a pallet on the lunar module (LM) with its tripod legs folded upward, was removed from its plastic protective casing and set up in the shadow of the LM to protect it and its film from direct sunlight during operational periods.

Its battery box was deployed in the sunlight at the edge of the LM shadow since it must be kept warm to supply its rated power output. The battery box is connected to the camera by a flexible cable.

Except for the battery pack, the instrument is gold-plated to protect it from the extreme cold temperatures in the moon's dark regions. Gold absorbs more heat than it emits, thus required temperatures can be maintained to keep the camera operational.

The basic component of the unit is an f/1.0 Schmidt camera of 3-inch aperture, which uses electronographic rather than photographic recording. Incoming light passes through the corrector plate aperture to the spherical primary mirror, and is then imaged onto the focal surface. This surface is coated with a thin layer of potassium bromide, which emits electrons when exposed to ultraviolet light of wavelength less than about 1600 A.

The main advantage of this electronographic technique is that the 25-kilovolt electrons are recorded with almost 100 percent efficiency on the electron-sensitive film. The electronographic camera is a factor of 10 to 20 times faster than a similar one using conventional photography.

After the device is set up on the lunar surface and directed toward its target, it is ready for operation. The astronaut initiates a programmed imagery and spectrographic sequence by pressing a START button. The sequence automatically repeats itself until the astronaut shuts it off, changes the target and starts the sequence again.

The instrument can be rotated 360 degrees and tilted upward a maximum of 87 degrees. Earth is the only planned target directly visible to the astronauts.

The other planned targets are pointed at with the aid of setting circles. The accuracy of pointing is better than three degrees.

When the recording mission is completed, the film transport (containing the exposed film) is removed from the rear of the unit and carried on board the LM for return to Houston, where the film will be carefully processed.

NRL scientists say now that a space observatory operating from the moon will be available, new and valuable information never before made possible will be recorded about earth, its solar system, and galactic and extragalactic neighbors.

Establishment of the AIDJEX Main Camp

The main camp for the 1972 Arctic Ice Dynamics Joint Experiment (AIDJEX) has been established on a large Arctic ice floe approximately 300 miles northeast of ONR's Naval Arctic Research Laboratory (NARL), Barrow, Alaska. The main camp includes thirty prefabricated buildings which were constructed at NARL and assembled at the AIDJEX site by NARL personnel. The main camp is designed to house up to ninety scientists, technicians and support personnel.

The establishment of the main camp was preceded by site selection. On February 25, a Twin Otter landed on the ice to verify that a long, straight refrozen lead adjacent to the candidate ice floe was thick enough and smooth enough to permit landing heavy cargo planes, in particular, C-130's. The ice was 5-1/2 feet thick over approximately 3600 feet. Later on February 25, the first C-130 in history to land on wheels on unprepared sea-ice touched down with its cargo of 38,890 pounds. The C-130, operated by Interior Airlines, was under NARL charter. By March 1, the primary cargo, totalling 442,133 pounds had been delivered to the site, mostly by C-130, supplemented by NARL's R4D's and the Twin Otters.

Even as the C-130's were being unloaded, buildings were being erected, and by 28 February, four buildings, including a large mess hall, were completed. By 7 March, all thirty buildings, electrical wiring, etc. were completed and several scientific experiments were being run. The Naval Arctic Research Laboratory's establishment of as large an ice floe camp as that of AIDJEX in such a short time, and with high efficiency, is considered a major accomplishment.

AIDJEX is a cooperative research effort which is vital to the goal of forecasting ice motion and deformation on all spatial and temporal scales. It involves Canada and Japan, as well as the United States, many participating institutions, and several funding agencies. Principal U.S. agencies providing support are ONR and the National Science Foundation, (NSF). The AIDJEX coordinating office at the University of Washington, which is supported by NSF, provides central planning and coordination. NARL, which is supported by ONR, provides the bulk of the logistical support. Both ONR and NSF support individual projects in the research program, as do other agencies and governments. The 1972 AIDJEX includes a main camp, established at 75°22.9′N, 147°41.6′W, two satellite manned camps, which were established approximately 60 miles away from each other and from the main camp, and five unmanned meteorological stations well outside the triangle formed by the manned camps. The camps were disestablished in late May. The number of personnel at the main station exceeded that of any previous non-Soviet drifting station by a factor of two.

Technique for Measuring Pollutants with X-Rays

At the Naval Research Laboratory scientists, working under an Environmental Protection Agency contract, have developed a simple, fast, and inexpensive technique for monitoring and measuring pollution samples, from either the air or water, through an advance in x-ray spectrometry.

L. S. Birks and J. V. Gilrich of NRL's X-Ray Optics Branch who are principal investigators in the research and Dr. J. Wagman, project officer at EPA's National Environmental Research Center in North Carolina, reported that particulate or precipitate samples filtered from air or water require no specimen preparation and can be placed immediately in the x-ray equipment for measurement of harmful elements.

The NRL improvement has increased the detectability of pollutants by more than 10 times thus making it easier to investigate violations of the pollution regulations.

Advances made by NRL in the past year make it likely that x-ray spectrometry may become the workhorse for analysis of particulate pollutants throughout the nation. Because the x-ray method is nondestructive, he noted, the samples can be retained as evidence for legal prosecution of pollution cases.

In a recent general review to be published by the American Chemical Society, Mr. Birks suggested that the technique as it now stands should be a significant improvement over other methods for analyzing particulate pollutants.

NRL scientists expect to recommend to the EPA that the x-ray technique be used nationwide for the measurement of particulate pollution.

New Water/Oil Resistant Coating

Scientists at NRL are developing a new class of water/oil resistant polymer which can be applied as easily as a conventional epoxy or polyurethane in coating form, and which will provide protection for metallic substrates from water.

NRL investigators say the new coating not only holds promise for use in the marine environment, but also for application to artifical human organs where a hydrophobic quality may be needed against penetrating water and body fluids.

Because other hydrophobic polymers composed only of fluorocarbon have not proved practical for application as continuous films, they have received slight attention for use in a marine environment.

U. S. GOVERNMENT PRINTING OFFICE : 1972 O - 469-992

Inflatable Vacuum Seal for Eccentric Tubes

A Naval Research Laboratory scientist has developed a simple vacuum seal for the ends of large quartz or glass plasma containment tubes that has proven to be important in NRL's plasma research concerning fusion.

The invention by Marvin P. Young, an electrical engineer with NRL's Plasma Physics Division is an inflatable seal which includes a flexible O-ring surface that creates a uniform pressure for compression of an O-ring against the tube's outer periphery.

A vacuum housing of this type was used in NRL's PHAROS experiment (a two-megajoules THETA-PINCH experiment with an axial current conductor passing through the plasma). Costs were much less because it allowed use of quartz tubes with large outer diameter eccentricities and eliminated the requirement for accurately grinding the ends.

In explaining the method, Mr. Young said a molded polyurethane housing was designed to fit loosely on the end of the tube, with enough flexibility to conform to its eccentricity. After the housing and O-ring are in place, the chamber behind the O-ring surface is pressurized. The subsequent constriction of this surface causes uniform O-ring compression on the outer periphery of the tube.

In addition, he said, the O-ring seal may be made to the outer surface or the inner surface of the plasma tube and may be made of an insulating material.

NAVAL RESEARCH REVIEWS publishes highlights of research conducted by Navy laboratories and contractors and describes important naval experimental facilities. Manuscripts submitted for publication, correspondence concerning prospective articles, and changes of address, should be directed to Code 109, Office of Naval Research, Arlington, Va. 22217. Requests for subscriptions should be directed to the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402. Subscription price: $1.75 per year in the U.S. and Canada; $2.25 per year, foreign; $0.20 per individual copy. The issuance of this periodical approved in accordance with Dept. of the Navy publications and printing regulations.

Editor: WILLIAM J. LESCURE

NAVSO P-510

Associate Editors:

A. R. LAUFER, ONR PASADENA

A. R. DAWE, ONR CHICAGO

A. L. POWELL, ONR BOSTON

D. A. PATTERSON, NAVAL RESEARCH LABORATORY

IN THIS ISSUE

VOL. XXV, NO. 5

ONR is supporting research to develop analytical models which will eliminate overlapping work and wasted time in personnel matters such as what jobs are necessary, who can best do them, and economic requirements.

Cavitation erosion is one of the major engineering problems confronting the designers of naval hydrodynamic systems. Modeling techniques are being developed to avoid cavitation.

Scientists drilling a diving hole at the AIDJEX camp. *See page 31.*

DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
ARLINGTON, VA. 22217

OFFICIAL BUSINESS

PENALTY FOR PRIVATE USE, $300

POSTAGE AND FEES PAID
DEPARTMENT OF THE NAVY

U.S.MAIL

DoD-316