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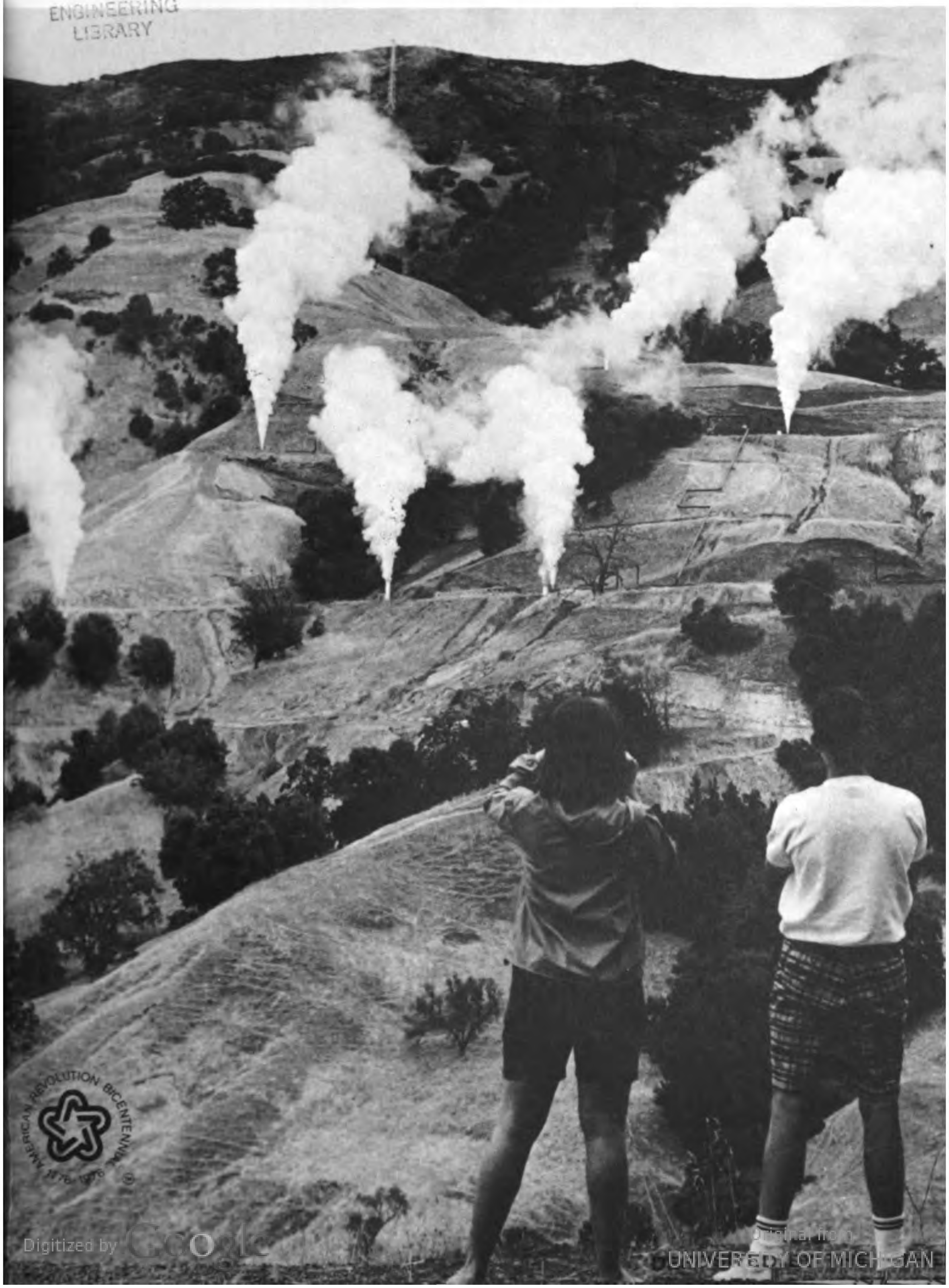

PROFILES IN SCIENCE

Dr. Villard

Dr. Villard is Professor of Electrical Engineering at Stanford University, and a Senior Scientific Advisor at the Stanford Research Institute. A contractor of ONR's for more than 25 years, Dr. Villard has always been interested in a combination of basic and applied research. His studies of the ionosphere contributed to meteor burst communication; upper atmospheric wind determination; improved HF propagation prediction, and various forms of ionospheric 'radar' for detection of nuclear explosions, rocket launches, and aircraft. He and his students contributed more than any other single group to an Air Force over-the-horizon system for detecting mass ICBM launches. A member of the Naval Research Advisory Committee since 1967, he served as its chairman from 1973 to 1975. Winner of the IEEE Morris Liebmann Memorial Prize in 1957, he is a member of both the National Academy of Engineering and the National Academy of Science.

Approaches to Pattern Recognition System Design

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I. Introduction

Several years ago the Sunday *New York Times* asked this question: "Will a full week of shorter trading hours bring happiness to brokerage firms whose back offices are jammed with paper work?" and reported the following item: "A professor of psychology at Harvard University warned that by the year 2000 the limit of man's mind to absorb information may be reached. 'We may already be nearing some kind of limit for many of the less gifted among us,' he said, 'and those still able to handle the present level of complexity are in ever-increasing demand.'" Certainly the daily press has little doubt that information is exploding.

In recent years our very complex and technologically oriented society has created a situation in which more people and organizations have become concerned with handling information and fewer with handling materials. The need for improved information systems has become more conspicuous, since information is an essential element in decision making, and the world is generating increasing amounts of information in various forms with different degrees of complexity. The advent of the digital computer has created numerous areas of research and applications not known just a few years ago. Many of these areas are direct outgrowths of the need for better techniques for information processing.† One of the major problems in the design of modern information systems is automatic pattern recognition, which forms the theme of this article.

Information is a valuable resource. It is not difficult to visualize the countless savings of monetary and manpower resources which could be realized in this country alone by the availability of information on a large-scale basis and by improved information

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†Tou, J. T., and Gonzalez, R. C., *Pattern Recognition Principles*, Addison-Wesley Publishing Co., Reading, Mass., 1974, p. 1.

processing techniques. Better, more complete information systems would, for example, help eliminate many of the costly duplications of effort which are often the result of inadequate knowledge about a problem or of reported previous and current efforts toward its solution.

Raw information is, of course, of limited use. Anyone who has had to do an in-depth literature survey of a popular topic is well acquainted with the difficulties of assimilating large quantities of data in a reasonable time. Man's physical and intellectual limitations have lead in recent years to investigations related to the utilization of machines for carrying out "intelligent" tasks normally associated with human behavior. The general area which deals with machine intelligence is usually referred to as *artificial intelligence* (AI). The goal of work in this field is to integrate in an AI system the full capabilities of both man and machine. Although we are still a considerable distance away from this goal, very significant results have been obtained in the few years that this area has been in formal existence.

Basically, an AI system can be structured in two forms: man-controlled and autonomous. A man-controlled system serves as an extension of its user's capabilities, while an autonomous system is able to interact with its environment without the aid of human intervention. The latter system is what we often call a robot. As indicated in Figure 1, the basic functions of an AI system are *perception* and *analysis*. Perception deals with the problem of inputing into the system relevant information about its environment, while the analysis function is concerned with interpreting this information to produce meaningful responses.

Pattern recognition is a sub-area of artificial intelligence which deals with data classification. Pattern recognition methods are usually employed in the early stages of an AI system in order to identify relevant information in the system's environment for further processing by the analysis stage. Often, the principal function of an

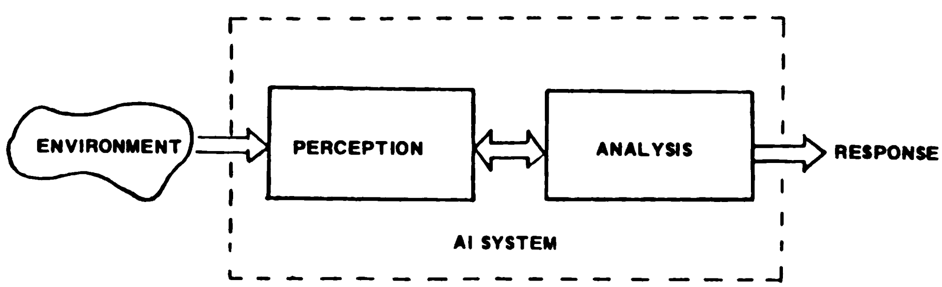


Figure 1 – Elements of an artificial intelligence system

AI system is simply data classification. In this case, the desired response is the identification of various classes of inputs. An AI system designed to perform this task is usually simply called a pattern recognition system. Some examples of the functions performed by these systems are target recognition, character recognition, speech recognition, electrocardiogram screening, chromosome classification, X-ray screening, and fingerprint recognition. In all these tasks, the desired system output is information related to the nature of the input. For example, in electrocardiogram screening we are interested in identifying normal vs. abnormal EKG's, while in speech recognition the problem is usually one of identifying individual words.

The Office of Naval Research's interest in pattern recognition stems from a realization of the potential tactical advantages of autonomous systems in such areas as target detection and identification and unmanned vehicle control. This paper is a general review of the principal approaches to pattern recognition system design.

II. Patterns and Pattern Classes

As used in this article, a *pattern* is a quantitative or qualitative description of an object, while a *pattern class* is a set of patterns that share some common properties. The subject matter of pattern recognition deals with techniques for assigning patterns to their respective classes–automatically and with as little human intervention as possible. For example, in the alphanumeric character recognition problem there are normally thirty-seven classes, one for each of the twenty-six letters and ten numerals, and a rejection class containing all unacceptable characters. The function of a character recognition machine is to identify and assign each input pattern into one of the available pattern classes.

Before a pattern can be processed by a machine it is necessary to convert it into a description acceptable by the processor. Figure 2(a) shows an example of a grid measuring scheme suitable for converting certain types of patterns into a binary representation. If we assume that the grid has n elements, the measurements can be arranged in the form of a *measurement* or *pattern vector*:

$$\underline{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \tag{1}$$

where each element x_i is, for example, assigned the value 1 if the *i*th cell contains a portion of the pattern, and is assigned the value 0 otherwise. It is common terminology to refer to pattern vectors simply as patterns. The term *feature vectors* is also used by some authors.

Another example is shown in Figure 2(b). In this case, the objects of interest are continuous functions (such as acoustic signals) of a variable t. If these functions are sampled at discrete points $t_1, t_2, \cdots, t_n$, a pattern vector may be formed by letting $x_1 = f(t_1), x_2 = f(t_2), \cdots, x_n = f(t_n)$. It is evident that in this particular representation the components of x are real quantities in the range of the functions, unlike the binary values obtained from the representation shown in Figure 2(a).

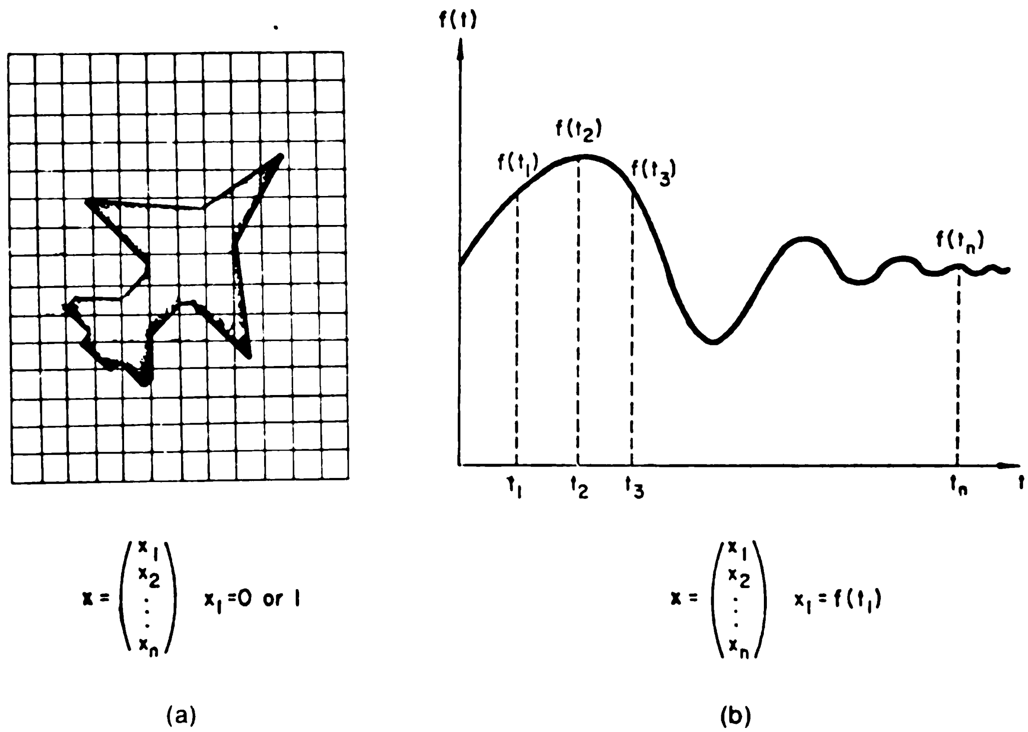


Figure 2 — Two simple schemes for the generation of pattern vectors

Another practical example of automatic pattern classification is found in optical character recognition devices such as the machines that read the code characters on ordinary bank checks. The stylized character set found on most U.S. checks today is the familiar American Bankers Association E-13B font character set. As shown in Figure 3, this set consists of 14 characters which have been purposely designed on a 9 X 7 zone grid in order to facilitate their reading. The

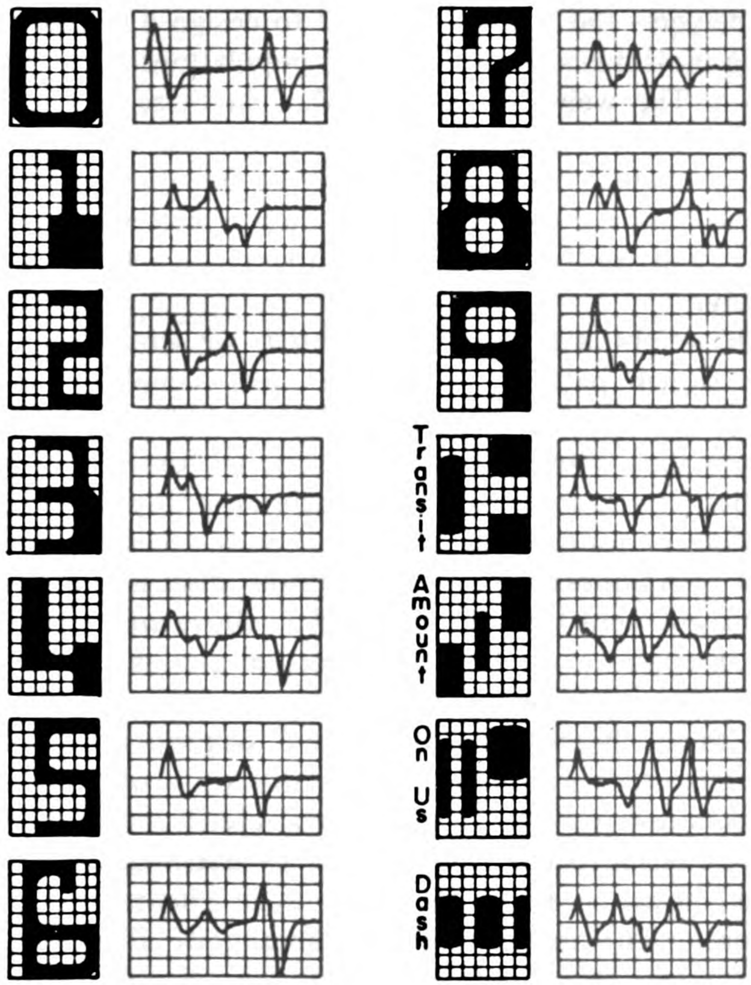


Figure 3 — American Bankers Association E-13B font character set and corresponding waveforms

characters are usually printed in ink which contains very finely ground magnetic material. If the character is being read by a magnetic device, the ink is magnetized before the reading operation in order to accentuate the presence of the characters and thus facilitate the reading process.*

The techniques discussed above for the generation of pattern vectors yield pattern classes which are characterized by numerical information. Clearly, the relative value of this information is strongly influenced by the types of measurements used to generate the pattern vectors. As an illustration of these concepts, consider the following simple, hypothetical pattern recognition problem. Suppose that we have two classes of professional athletes—jockeys and

*Tou, J. T., and Gonzalez, R. C., *Pattern Recognition Principles*, Addison-Wesley Publishing Co., Reading, Mass., 1974, pp. 21-22.

football players—and that it is desired to design a system capable of classifying individuals from these two populations according to their occupation. The weight of an individual in these two categories is certainly the most revealing feature. Weight measurements performed on these individuals would yield a set of one-dimensional patterns such as the ones shown in Figure 4(a), where patterns corresponding to jockeys and football players are shown as black and white dots, respectively.

If both weight and height were used, we would then obtain a two-dimensional pattern vector for each sample member. The resulting pattern classes might look like those shown in Figure 4(b). When more than three measurements are performed our powers of visualization are no longer effective in interpreting the properties of the resulting pattern classes and it becomes necessary to resort to analytical techniques, such as the methods discussed in Section IV.

The measurement techniques described above are useful in pattern recognition applications where the pattern classes can be meaningfully characterized by numerical information. There are situations, however, where the information required for proper recognition is of such a nature that a numerical representation is of little use, either because it is not practical or simply because it does not adequately describe the essential characteristics of a pattern class. An example of this is shown in Figure 5 which is an illustration of a human chromosome. The measurement technique of Figure 2(a) could

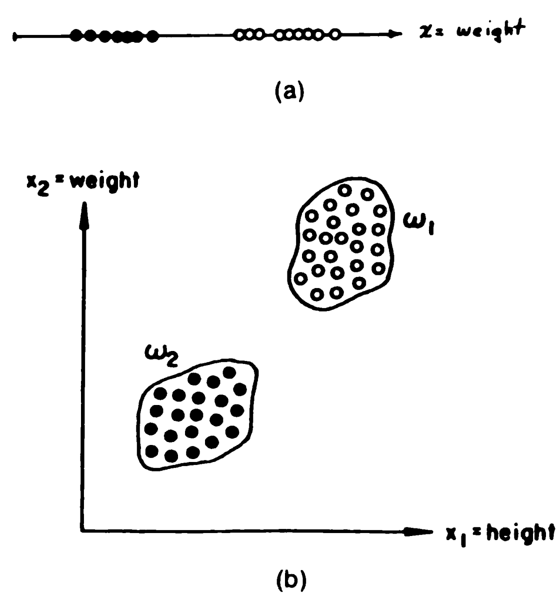


Figure 4 — (a) Pattern classes resulting from weight measurements. (b) Classes resulting from measurements of weight and height

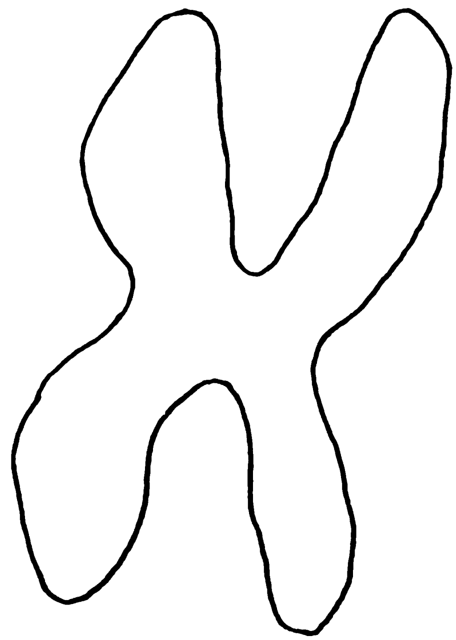
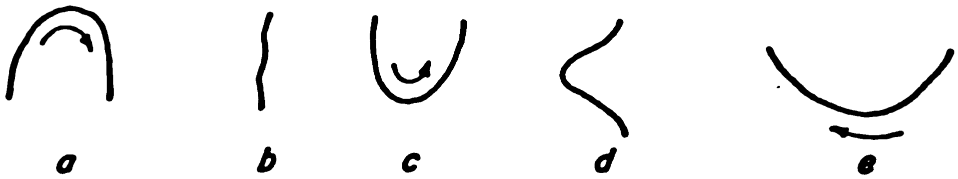


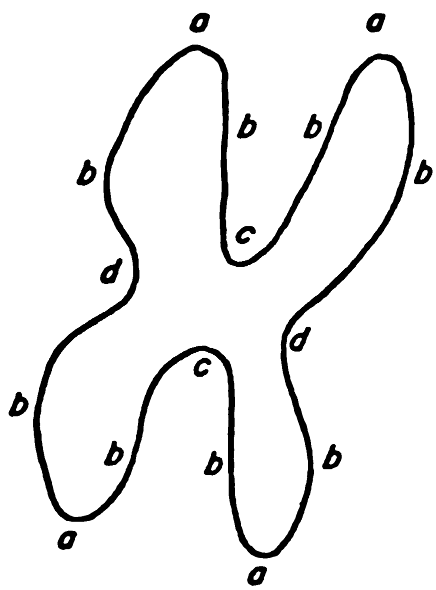
Figure 5 — Illustration of a typical chromosome

certainly be used in this case to represent chromosomes in the form of binary pattern vectors. However, the proper formulation of a chromosome recognition system requires the utilization of pattern structure such as the number and length of chromosome arms. These features are best extracted by a measurement scheme such as the one illustrated in Figure 6. Figure 6(a) shows what may be called *primitive structures*. By tracking a chromosome boundary in a clockwise direction it is possible to detect and encode these primitives in the form of a string of qualifiers, as shown in Figure 6(b). Thus, this particular chromosome is described by the string *abcbabdbabcbabdb*. It is interesting to note that the string representation would require considerably less machine storage than a binary representation which uses a sufficiently fine grid in the measurement process.

String representations are adequate to describe patterns whose structure is based on relatively simple connectivity of primitives. A more powerful approach for many applications is realized through the use of tree representations. Basically, any hierarchical ordering scheme leads to a tree structure. Two examples of this are shown in Figure 7. The tree representation of the pattern shown in Figure 7(a) is obtained by successive applications of the relationship "inside." Thus, denoting the root of the tree by the symbol γ, we see from Figure 7(a) that the first level of complexity involves a and c inside γ. This produces the first two branches emanating from the root. The next level involves b inside a and d and e inside c, which completes the tree description of the pattern. The example shown in Figure



(a)



abcbabdbabcbabdb

(b)

Figure 6 — String reprsentation of patterns. (a) Primitive structures.
(b) Coded chromosome

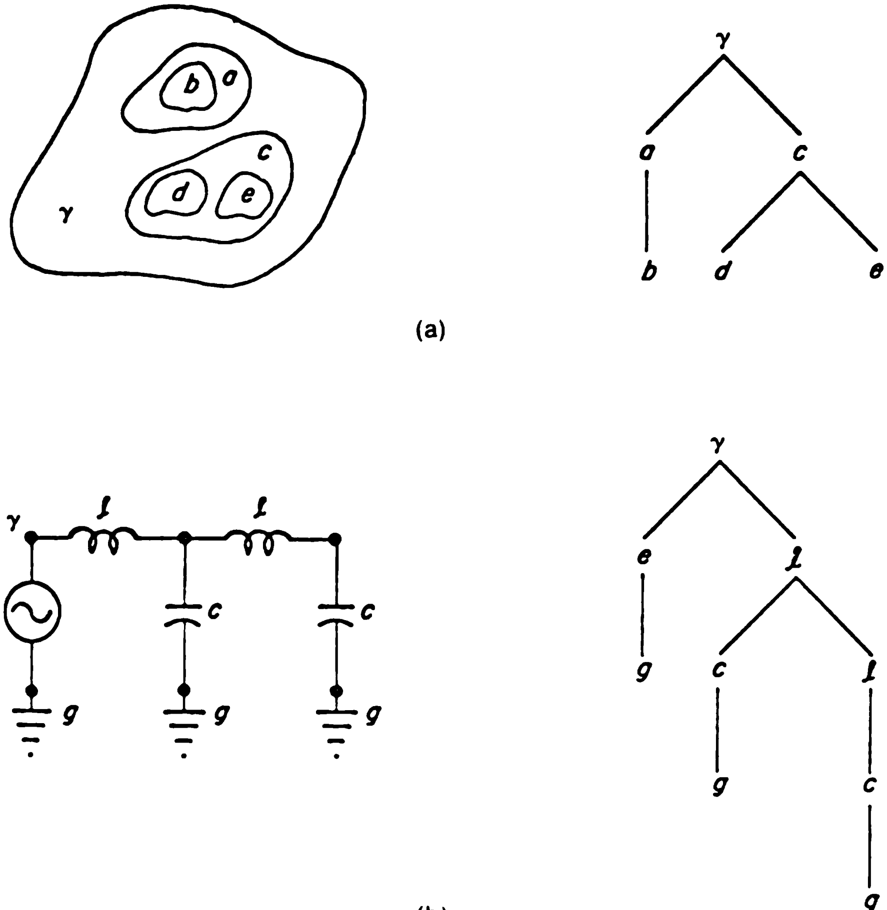


Figure 7 — Tree representation of patterns

7(b) can be represented by a tree by using the relationship "connected to." Choosing the root of the tree as the leftmost upper node in the pattern yields the tree shown.

A string is a special case of a tree where the root is the first symbol of the string and each successive node has a single branch. Similarly, a tree is a special case of a class of more general representations called *graphs*. The use of graphs for pattern description is illustrated in Figure 8. Figure 8(a) shows a pattern and Figure 8(b) shows a rough approximation of this pattern by polygons. The interconnection of the polygons at appropriate vertices yields the graph representation shown in Figure 8(c).

The pattern classes which result from the last three measurement schemes discussed above are sets of strings, trees, or graphs. The properties of these pattern classes are best exploited by the syntactic pattern recognition methods introduced in Section IV and discussed in more detail in the books by Tou and Gonzalez and by Gonzalez and Thomason listed in the bibliography.

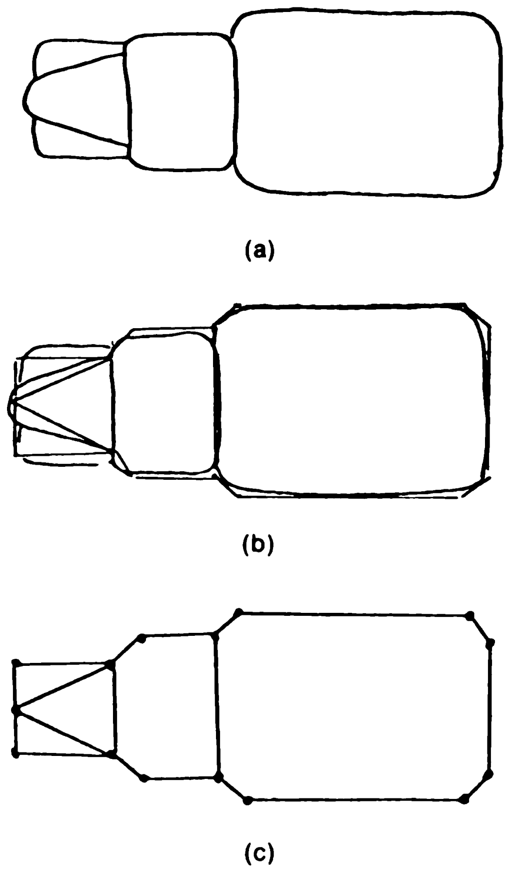


Figure 8 — Graph representation of patterns. (a) Pattern. (b) Approximation by polygons. (c) Resulting graph.

III. Components of a Pattern Recognition System

The principal function of a pattern recognition system is to arrive at decisions concerning the class membership of the patterns with which it is confronted. Several major information transition processes take place between the time a pattern is input and a decision is made by the system. These processes, which are summarized in block diagram form in Figure 9, extract from the input data the discriminatory information required for classification. The functions of the blocks shown in Figure 9 are briefly discussed as follows.

The sensor is simply the measurement device which transforms the input patterns into a form suitable for machine manipulation. Although some simple pattern recognition systems operate on the input data directly from the sensor, it is common practice to follow the sensor with a preprocessor and feature extractor. The preprocessor removes unnecessary or corrupting elements from the measured data, while the feature extractor extracts from the preprocessed data the features required for classification. The chromosome measurement problem discussed in Section II is a good example of these three functions. Suppose, for example, that a

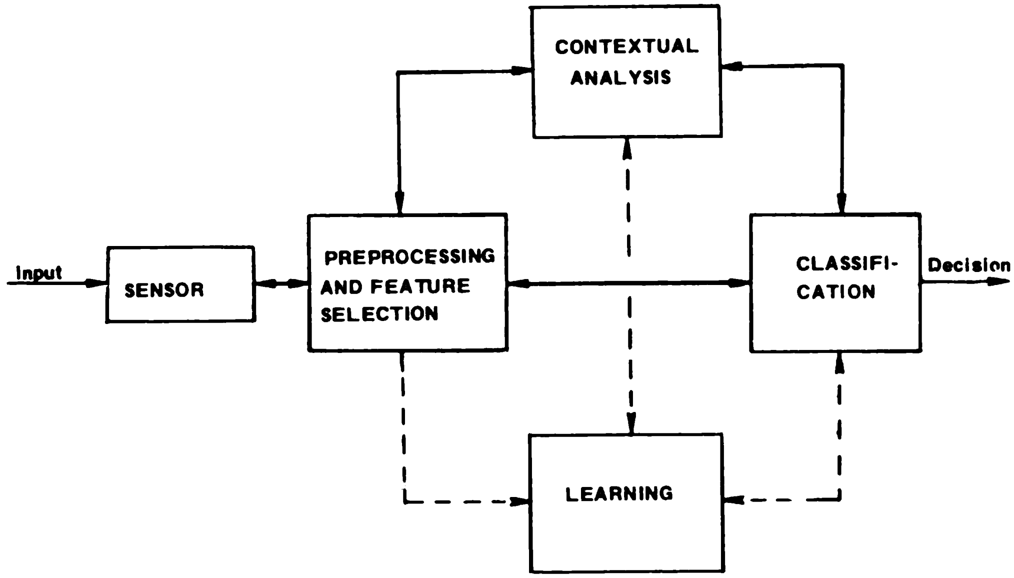


Figure 9 — Components of a pattern recognition system

chromosome is digitized by a sensor which uses a grid scheme such as the one shown in Figure 2(a). The preprocessor would consist in this case of a set of procedures for determining the outer boundary of each input pattern, while the feature extractor would extract from the boundary the primitives (features) shown in Figure 6(a).

The feature extraction process is often followed by contextual analysis in order to enhance the information content present in a pattern. In the above example, contextual analysis could be used to detect the occurrence of a certain sequence of important features. In more complex situations, such as the recognition of spoken words, it is essential to take into account the context in which the pattern (i.e., word) to be classified is being used. The results of the contextual analysis process are finally fed into the classification stage whose function is to combine all the information extracted from the input pattern and then arrive at a decision concerning the class membership of that pattern.

In the above discussion it has been implicitly assumed that the system "knows" the information processing operations that must be performed on an input pattern in order to arrive at a decision. Although the general form of these operations is specified by the system designer, each specific operation is in most cases characterized by variable parameters which must be adapted to a given pattern recognition problem. The adjustment of these parameters is usually carried out by utilizing sample patterns in what is called a *learning* or *training* process.

Machine learning techniques may be subdivided into two principal categories: (1) *supervised* and (2) *unsupervised*. In a supervised learning situation, the system parameters are estimated by algorithms which utilize training sample patterns whose class membership is specified externally by the system designer. In this manner, the unknown parameters are adjusted to fit a situation where the pattern classes are specified and characterized by representative samples. Clearly, the ultimate success of this approach is dictated by the quality of the sample set used to train the pattern recognition system.

The unsupervised learning approach is used when there is little or no *a priori* knowledge about the pattern classes of a given problem. In essence, this approach attempts to extract the pattern classes present in a set of data in which the classification of the available sample patterns is not completely known.

The learning process described above is shown as a dotted stage in Figure 9. This representation is adopted to indicate that learning may, but need not, be an integral part of the normal routine operation of a pattern recognition system. For example, a system that has been designed using a reasonably complete set of representative samples needs to be subjected to further learning only for updating purposes. On the other hand, a system that operates in a dynamic environment where the nature of the pattern classes changes rapidly may require continuous learning in order to perform satisfactorily.

IV. Approaches to Pattern Recognition

Approaches to pattern recognition system design may be divided into three principal categories: (1) the heuristic approach, (2) the decision-theoretic approach, and (3) the syntactic approach.

Heuristic Approach

This approach deals with the development of models which attempt to duplicate in some sense the recognition processes employed by humans or other "intelligent" organisms. Since these processes are far from being fully understood, heuristic approaches to pattern recognition generally consist of a set of *ad-hoc* procedures designed to perform specific recognition tasks. Consider, for example, the design of a pattern recognition system for classifying handwritten characters. The decision-performing logic of such a system can be based on the number, position, and spatial relationships of the strokes composing each character. This logic is clearly of a heuristic nature since the system designer must specify, based on intuition and experience, how the components of a character are evaluated to arrive at a decision.

Another example of the heuristic approach is found in many automatic electrocardiogram interpretation systems. In this case the problem is one of developing a system which arrives at decisions by following as closely as possible the process employed by a physician in interpreting an EKG. Thus, the performance of such a system is almost entirely dependent on how well it can imitate the physician's capability to detect and interpret significant events in an EKG record.

It is evident from the above discussion that the heuristic approach to pattern recognition consists of procedures which are tailored to the needs of each specific application. There is, therefore, little that can be said in general concerning this approach. For this reason, a foundation to pattern recognition techniques is best acquired by approaching the subject matter from the decision-theoretic and syntactic points of view. In addition to the fact that they encompass a unified body of basic results, a thorough understanding of these approaches is essential background for the development of pattern recognition systems based on heuristic concepts.

Decision-Theoretic Approach

The decision-theoretic approach is based on the utilization of decision functions for pattern classification. As a way of introduction to this concept consider Figure 10 where two pattern classes are

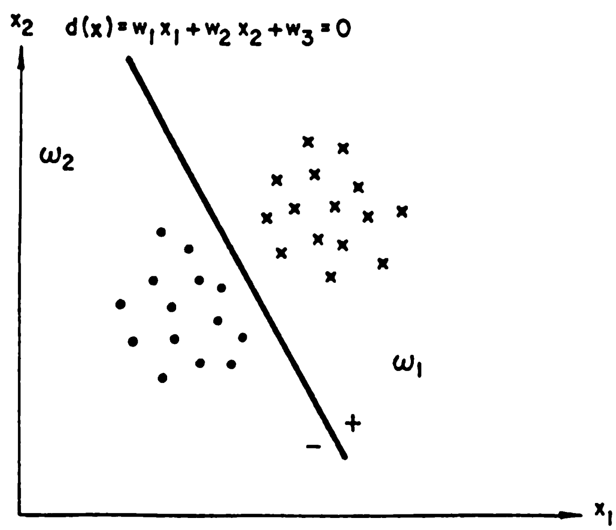


Figure 10 — A simple decision function for two pattern classes

shown. It is seen in this figure that the two pattern populations can be separated by a line.

Let $d(\underline{x}) = w_1 x_1 + w_2 x_2 + w_3 = 0$ be the equation of a separating line where the w's are parameters and x_1, x_2 are the general pattern coordinate variables. It is clear from the figure that any pattern $\underline{x}$ belonging to class ω_1 will yield a positive quantity when substituted into $d(\underline{x})$. Similarly, $d(\underline{x})$ becomes negative upon substitution of any pattern from class ω_2. Therefore, $d(\underline{x})$ can be used as a *decision* (or *discriminant*) *function* since, given a pattern $\underline{x}$ of unknown classification, we may say that $\underline{x}$ belong to class ω_1 if $d(\underline{x}) > 0$, or to ω_2 if $d(\underline{x}) < 0$. If the pattern lies in the separating boundary, we obtain the indeterminate condition $d(\underline{x}) = 0$.

When there are more than two classes, one of the most-often-used approaches is to establish M decision functions $d_1(\underline{x}), d_2(\underline{x}), \ldots, d_M(\underline{x})$ with the property that if a pattern $\underline{x}$ belongs to class ω_i, then

$$d_i(\underline{x}) > d_j(\underline{x}) \qquad j = 1, 2, \ldots, \mathrm{M}; j \neq i \tag{2}$$

where M is the number of classes. Equation (2) specifies a decision rule in which each pattern to be classified is substituted into all decision functions. The pattern is then assigned to the class whose decision function yields the largest numerical value. Ties are resolved arbitrarily. It is noted that the simple example introduced above is a special case of Equation (2). Thus, if $M = 2$, we have that for all patterns of class ω_1, $d_1(\underline{x}) > d_2(\underline{x})$ and, conversely, for all patterns of class ω_2, $d_1(\underline{x}) < d_2(\underline{x})$. Defining $d(\underline{x}) = d_1(\underline{x}) - d_2(\underline{x})$ leads to the condition $d(\underline{x}) > 0$ for $\underline{x}$ in ω_1 and $d(\underline{x}) < 0$ for $\underline{x}$ in ω_2. In general, the equation of the decision boundary separating classes ω_i and ω_j is given by

$$d_i(\underline{x}) - d_j(\underline{x}) = 0 \tag{3}$$

The above concepts need not be restricted to two-dimensional patterns and linear decision boundaries. In the n-dimensional case the decision functions of Equation (2) may be expressed in the general form

$$d_k(\underline{x}) = \sum_{\ell=1}^{K} w_{k\ell}\phi_\ell(\underline{x}) \qquad k = 1, 2, \ldots, \mathrm{M} \tag{4}$$

where the $\{\phi_\ell(\underline{x})\}$ are real, single-valued functions of the pattern $\underline{x}$, and $\{w_{k\ell}\}$ are the coefficients of the decision function corresponding to class ω_k. Equation (4) is quite general in the sense that it can represent a variety of very complex decision functions in n-dimensional space.

The usual approach in employing Equation (4) is to first specify the functions $\{\phi_\ell(\underline{x})\}$. The problem then becomes one of determining the coefficients $\{w_{k\ell}\}$ for each class so that relation (2) will hold for as many patterns as possible. The decision-theoretic approach to pattern recognition deals with algorithms for estimating these parameters using sample patterns in a training process. Thus, if the pattern recognition system performs well during training with a well-chosen set of representative patterns, it may be expected to perform satisfactorily when confronted with "field" data during normal operation.

There exist numerous adaptive algorithms which can be used for training a pattern recognition system. These algorithms can be divided into (1) deterministic, and (2) statistical procedures. As evidenced by this breakdown, deterministic algorithms deal with the estimation of the decision function coefficients directly from the patterns without resorting to statistical considerations, while statistical algorithms are based on the statistical properties of the various pattern populations under consideration.

Although a study of these algorithms is outside our present scope, it is important to bear in mind that the decision-theoretic approach to pattern recognition plays a very significant role in applied as well as theoretical work in this field. The interested reader can consult the book listed in the bibliography by Tou and Gonzalez for further study on this subject.

Syntactic Approach

The decision-theoretic approach discussed in the previous section is ideally suited for applications where patterns can be meaningfully represented in the form of numerical quantities, such as the examples shown in Figure 2. There are applications, however, where the structure of a pattern plays a very important role in the classification process. In these situations the decision theoretic approach suffers from serious drawbacks because it lacks a suitable formalism for handling pattern structures and their relationships. Scene analysis is a good example where the decision-theoretic approach finds few applications since in this case the structure and relationships of the various components of a scene are of fundamental importance in establishing a meaningful recognition scheme.

The syntactic* approach to pattern recognition has been receiving increased attention during the past few years because it possesses the

*The terms *linguistic*, *structural*, and *grammatical* pattern recognition are also often used in the literature to denote the syntactic approach.

structure-handling capability lacked by the decision-theoretic approach. Syntactic pattern recognition is based on concepts from formal language theory, whose origin may be traced to the middle 1950's with the development by Noam Chomsky of mathematical models of grammars related to his work in natural languages. One of the original goals of the work of linguists working in this area was to develop mathematical models capable of describing natural languages such as English. The hope was that, if this could be done, it would be a relatively simple matter to "teach" computers to interpret natural languages for the purposes of translation and problem solving. Although it is generally agreed that these expectations have been unrealized thus far, spin-offs of research in this area have had a significant impact on other fields such as compiler design, computer languages, automata theory and, more recently, pattern recognition.

Basic to the syntactic pattern recognition approach is the decomposition of patterns into subpatterns or primitives. Figure 11 shows such a decomposition where the patterns shown are expressed in terms of the primitives discussed in Section II to yield the string *abcbabdbabcbabdb* for the submedian chromosome and the string *ebabcbab* for the telocentric chromosome.

Suppose that we interpret each primitive as being a *word* permissible in some grammar, where a *grammar* is simply a set of rules of syntax for the generation of *sentences* from the given words. These sentences certainly could consist of strings of words such as

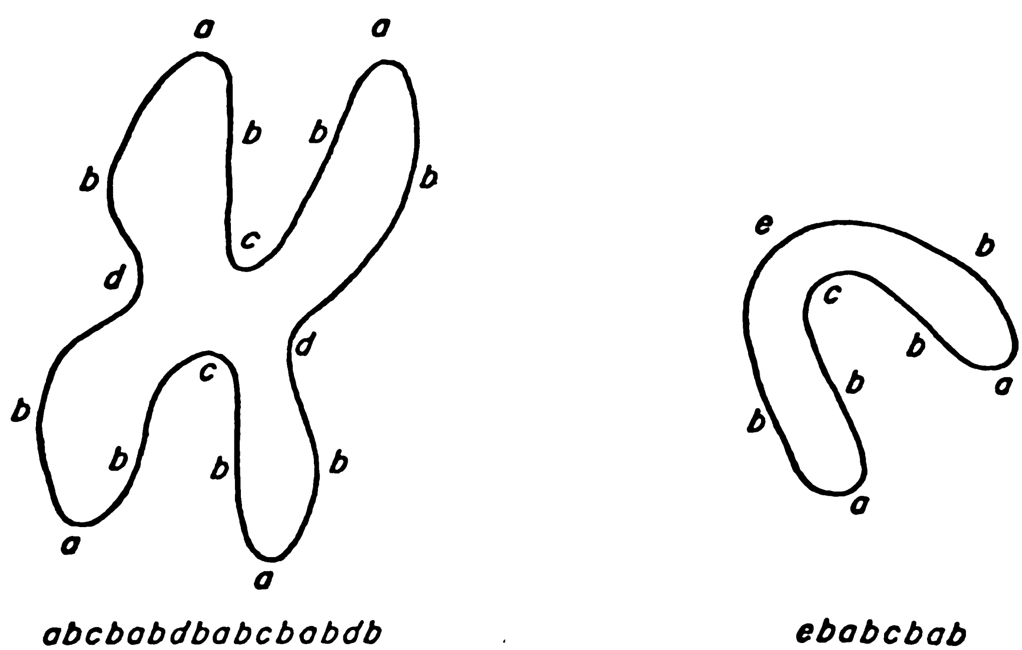


Figure 11 — Submedian and telocentric chromosomes coded using the primitives shown in Figure 5

the ones associated with the chromosome structures described above. It is further possible to envision two grammars G_1 and G_2 whose rules allow the generation of sentences which correspond to submedian and telocentric chromosomes, respectively. Thus, the language $L(G_1)$ generated by G_1 would consist of sentences representing submedian chromosomes and the language $L(G_2)$ generated by G_2 of sentences representing telocentric chromosomes.

Once the two grammars G_1 and G_2 have been established, the syntactic pattern recognition process is in principle quite simple. Given a sentence representing an input pattern, the problem is one of deciding over which language the input sentence represents a valid sentence. Thus, if the sentence belongs to $L(G_1)$, we say that the input is a submedian chromosome. If it belongs to $L(G_2)$ we say that it is a telocentric chromosome. A unique decision cannot be made if the sentence belongs to both languages. If the sentence is found to be invalid over both $L(G_1)$ and $L(G_2)$, the input pattern is assigned to a rejection class consisting of all invalid patterns.

In the M-class case, the syntactic classification approach is the same as that described above, with the exception that there are M grammars involved in the process. In this case, a pattern is uniquely assigned to the ith class if it is a sentence of only $L(G_i)$ and no other language. A unique decision cannot be made if the sentence belongs to more than one language. And, as above, if a pattern is not a sentence of any of the languages under consideration, it is assigned to a rejection class.

V. Summary

In this article we have briefly reviewed some of the principal analytical approaches to the design of pattern recognition systems. This area of research has been receiving increased attention not only from the military, but also from many other government, industrial, and private sectors.

Of the approaches discussed in Section IV, syntactic methods offer the advantage of providing a formalism for handling pattern structures and their relationships. The relative merits of this approach and its potential use in the development of an autonomous system for target detection and identification are presently being investigated by ONR.

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Mini-Computerized Radar Reader

A team of engineers at the Naval Research Laboratory (NRL) has developed a digital mini-computer-based facility for collecting, processing, and displaying synthetic aperture radar (SAR) data and imagery.

The new system includes an airborne wideband digital tape recorder for collecting raw SAR data and a dual-mode digitizing photometer/densitometer for digitizing film-recorded data. Raw radar data may be processed into imagery in either an optical correlator or a digital computer. Image manipulation is under interactive computer control. Final image output is on a pseudo-color TV display.

In 1971, NRL's radar experts were assigned the problem of determining how effective a synthetic aperture radar would be for target classification. The use of a variable-focus static optical correlator technique makes it possible to classify many targets; but the operation is lengthy and requires highly trained operators.

To alleviate some of the major shortcomings of the optical systems, the scientists decided to "go digital." However, existing SAR digital correlators and software were of little use. A digital correlator was needed that would only be required to process small scenes instead of normal mapping requirements; and, with great processing flexibility, would be initially controllable by an operator, but could later be made automatic.

The facility devised has two main functional subsystems, one to collect digital SAR phase histories and one for digital processing of the phase histories. Both produce computer-compatible tapes for further processing. The processing subsystem uses a mini-computer with special software to perform correlations and output the images on a color TV display.

Energy for Naval Operations: A Critical R&D Problem

P. R. Gillette*
Stanford Research Institute

Introduction

Although estimates of remaining U.S. and world stocks of fossil fuels vary somewhat, it is becoming increasingly clear that:

- The earth's supply of gaseous and liquid fossil fuels will be exhausted within the next few decades, and its supply of solid fossil fuels will be exhausted within the next few centuries.
- The U.S. supply of solid fossil fuels is being exhausted at about the world-wide rate, but its supply of gaseous and liquid fossil fuels is being exhausted at about twice the world-wide rate.

The importance of energy to the Navy's world-wide operations, both afloat and ashore, has made it the second-largest energy user and the largest user of foreign-origin energy among U.S. military services. The Navy is therefore particularly vulnerable to the threats of energy supply cutoffs and cost increases posed by the rapidly-approaching exhaustion of fossil fuel supplies in the U.S. and the rest of the world.

The Navy must plan to counter these threats of energy supply cutoffs and cost increases (which may be politically, as well as economically, motivated) by

- Developing, for the near future, sufficient properly-located energy storage facilities and stored reserves to permit operation of all essential forces and facilities for long periods without energy resupply from any sources that are either controlled by or subject to interdiction by non-U.S. agencies;
- Developing, for the mid-range future, a capability for operation of all essential forces and facilities on electrical power or liquid fuels derived from available (though exhaustible) supplies of naturally-occurring fissionable nuclear fuels and/or solid fossil fuels;

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- Developing, for the long-range future, a capability for operation on electrical power or liquid fuel derived from artificially-bred fissionable fuels or from solar, wind, hydro, sea-thermal or geothermal energy.

As an essential step in the development and implementation of such plans, the Chief of Naval Research and the Chief of Naval Development have been collaborating in the direction, support, and monitoring of a number of studies (including one by Stanford Research Institute's Naval Warfare Research Center) to assess the general situation, to delineate available alternatives, and to determine what R&D efforts are necessary for evaluating those alternatives and implementing the most appropriate ones. Some of the results obtained by the Naval Warfare Research Center, including the results of an initial analysis of the energy supply problems of remote Naval information-handling activities, are summarized in this review.

Feasible Energy System Concepts

The basic configuration of a system for satisfying the totality of energy needs of a Naval operating force or shore facility will encompass means for acquiring energy (from the environment or other outside source), means for storing it (necessitated by mismatches between rates of acquisition and rates of utilization), and means for converting it from the forms in which it is acquired to those in which it is stored and subsequently to those in which it is utilized. The system to be used by a given force or facility will be one of three variants of this basic configuration, or some combination of those variants, depending upon the form or forms in which energy is available to the force or facility.

The first of these variants (Figure 1) utilizes a storable liquid mixture of hydrocarbons as energy source and storage medium. It converts the chemical energy of this fuel into mechanical energy by means of an external-combustion or internal-combustion heat engine, into electrical energy by utilizing such a heat engine to drive an electrical generator, and into thermal energy for space heating by utilizing heat-engine exhaust heat or by burning the fuel separately. This is of course the kind of system that is currently in most general use, both afloat and ashore, and it will continue in general use as long as storable liquid hydrocarbon mixtures are readily obtainable from available supplies of gaseous, liquid or solid fossil fuels. It may be noted in passing that the use of gas turbines as the heat engines would make for flexibility in the choice of fuels as well as for reliability and maintainability; it is true that the conversion efficiency of

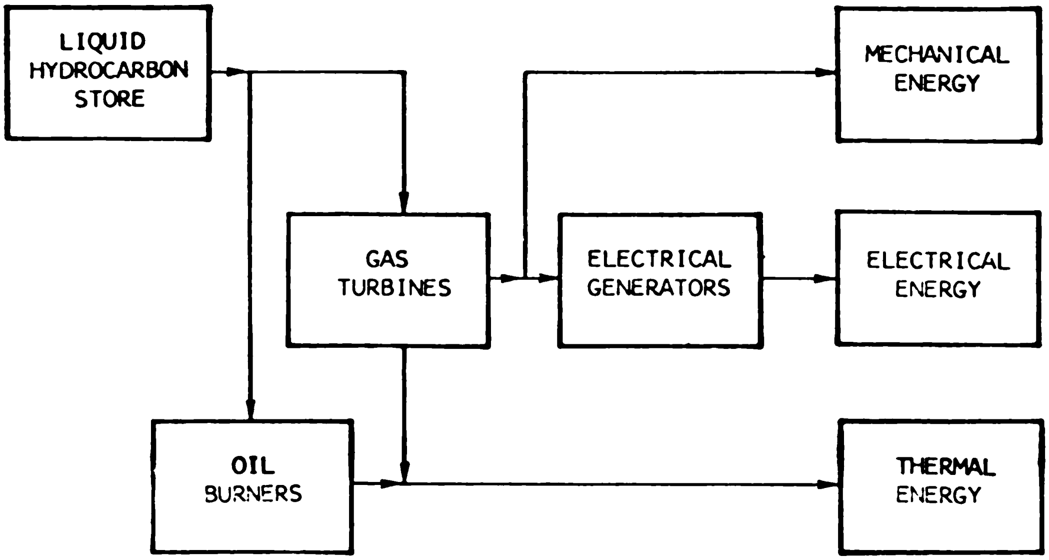

Figure 1 — This system utilizes a storable liquid mixture of hydrocarbons as the energy source. This system is now the most generally used by the Navy.

gas turbines is relatively low, but where the exhaust heat can be utilized for space heating or cooling this might not be a disadvantage.

The second variant of the basic system configuration (Figure 2) utilizes a geothermal water/steam mixture, a stream of flowing water, or wind. It converts the energy from one of these sources into electrical energy by means of a turbine-generator combination, and then converts electrical energy into chemical energy for storage, either by charging electrolytic storage batteries or by electrolytically producing hydrogen from water. The chemical energy of hydrogen can be converted to mechanical energy by a gas turbine, to electrical energy by fuel cells or a turbine-generator combination, and to thermal energy by a burner. Electrical energy can of course be converted to mechanical energy by electric motors and to thermal energy by heat pumps or resistive heaters. This kind of system shows promise for locations ashore where geothermal energy, water flow, or wind velocity is sufficient to provide an economically useful source of energy. Where the energy source is an elevated reservoir of water, the reservoir itself can be the energy storage means, and, if the activity's vehicles can be powered by storage batteries, hydrogen production and storage may be inappropriate. A geothermal hot water well is an essentially constant energy source, and wind is a highly variable one; hence storage means are necessary to match these sources to variable loads.

The third variant of the basic configuration (Figure 3) utilizes nuclear, sea thermal, or solar energy. It converts the energy from one of these sources into electrical energy by means of a combination of

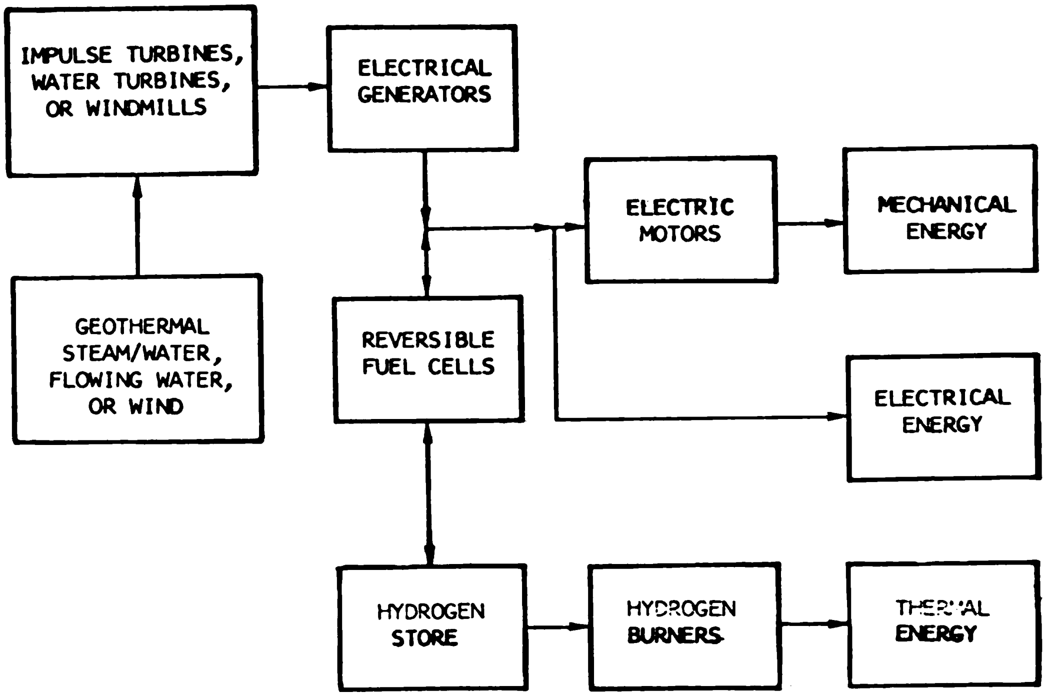

Figure 2 — This energy system utilizes a geothermal water/steam mixture, a stream of flowing water, or wind as the energy source.

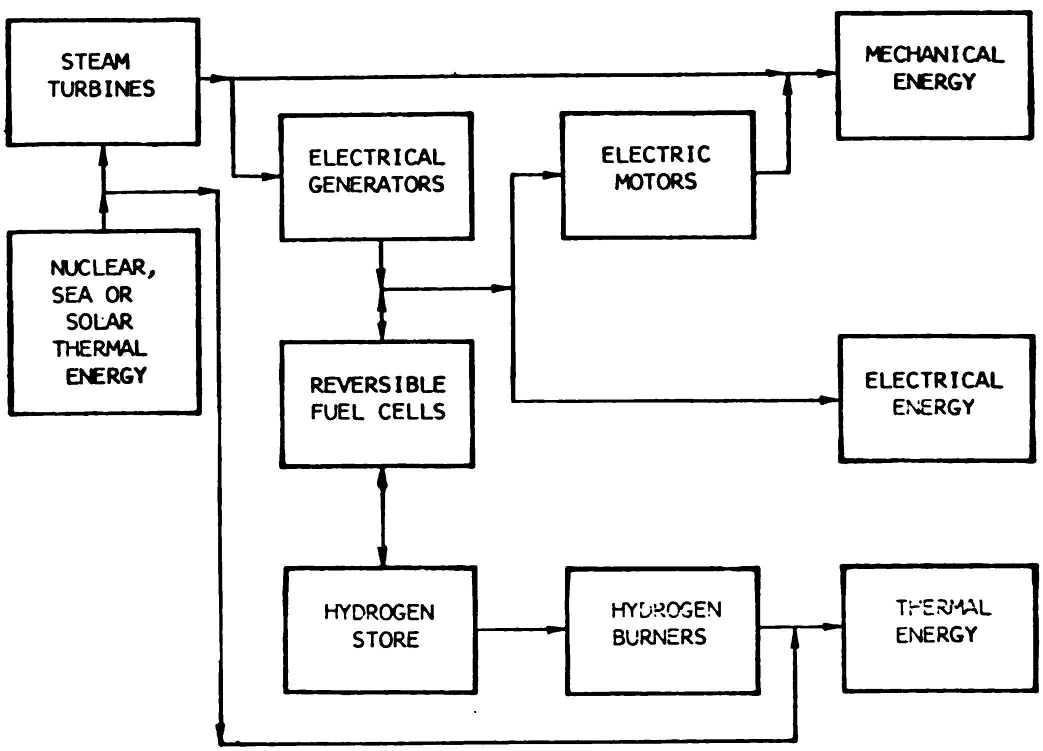

Figure 3 — This system uses nuclear, sea thermal, or solar energy. It converts the energy from one of these sources into electrical energy by means of combination of a heat engine and an electrical generator.

a heat engine and an electrical generator; beyond that point this variant is the same as the second one. This kind of system shows promise for coastal locations near the equator and near deep seas (where the temperature difference between sea surface and bottom is sufficient to be economically exploitable) or locations ashore where atmospheric conditions provide high average insolation levels. A sea thermal energy acquisition device must be so large a structure that (for economic reasons) it should be treated as a constant energy source, and solar radiation at ground level is a highly variable one; hence storage means are necessary to match these sources to variable loads. High-power nuclear energy sources are sufficiently compact to be useful for submarines, surface ships and large shore stations, and their output is sufficiently controllable to permit conversion directly into mechanical energy for submarine or ship propulsion. However, aircraft carriers and large shore stations may be required to supply fuel for aircraft, surface craft, and large ground vehicles; if those vehicles can be designed to use hydrogen (or some simple and locally producible hydrogen compound) as fuel, the energy systems of the carriers and shore stations should include means for producing and storing such fuel. A store of hydrogen may also be useful for handling peak electrical and thermal loads, and even peak propulsion loads.

In order to satisfy all of the energy requirements of a Naval complex (whether it be a task force at sea or a station ashore) in the most effective and economical manner, the facilities for satisfying those requirements must be designed and operated as an integrated total energy system. If energy is available in more than one form, a hybrid of the variant configurations described above may be appropriate. It may also be appropriate to use available liquid and solid wastes as sources of thermal energy. All such combinations should be considered with due regard for the desirability of minimizing system complexity.

A comparison of complete life-cycle costs must be a primary criterion for selecting among possible alternatives throughout the system planning and design process. However, the significant strategic and tactical advantages to be gained by making Naval complexes, whether ashore or afloat, self-sufficient with respect to energy must also be given full consideration in the selection of energy system configurations.

Analysis of Remote Naval Shore Activities

In order to obtain a general idea of the relative attractiveness of the above-described alternate energy system concepts for remote

Naval information-handling activities, the cost of satisfying the energy requirements of activities at seven representative locations with systems of these types has been estimated. The physical environments of the locations range from arctic to equatorial, and Naval Communications and Radio Stations, Naval Facilities, and Naval Security Group Activities are all represented. The seven locations are:

Adak Island, Alaska (NAVCOMSTA, NAVFAC, NAVSECGRUACT)
Centerville Beach, Calif. (NAVFAC)
Cutler, Maine (NAVRADSTA)
Diego Garcia, Br. Indian Ocean Terr. (NAVCOMSTA)
Edzell, Scotland (NAVSECGRUACT)
Northwest Cape, Exmouth, W. Australia (NAVCOMSTA)
Sidi Yahia, Morocco (NAVCOMSTA)

Rough estimates of total ten-year (1985-1995) costs have been made for hydrocarbon-fueled systems and nuclear, geothermal, sea thermal, solar and wind energy systems for these locations. Study resources did not permit collection of detailed and accurate information on energy availability and requirements at these locations, or of detailed and accurate information on costs for the various types of systems considered. Hence neither capacity requirements nor unit costs could be estimated to better than a factor of about two. The validity of the cost estimate for any given location and system type is of course affected by both of these uncertainties. However, the validity of estimates of relative costs of different system types for any given location depends primarily on the accuracy of unit cost data, and such estimates should therefore be good to within a factor of two. The costs of nuclear, geothermal, sea thermal, solar and wind systems are compared with the costs of equivalent hydrocarbon-fueled systems in the following paragraphs.

Nuclear fission power appears to be much more attractive for supplying Adak's combination of a NAVFAC, NAVSECGRUACT, and NAVCOMSTA than for supplying Centerville Beach's NAVFAC, because of the rate at which cost per unit of power output goes up as output capacity goes down for nuclear systems. The ratio of the cost of a nuclear system to that of a hydrocarbon-fueled one would be roughly four for Adak, sixteen for Centerville Beach, and eight for each of the other locations.

Of the seven locations considered, only Adak in the Aleutian chain has ready access to geothermal energy, and only Diego Garcia in the Indian Ocean has ready access to sea thermal energy. The limited cost data on critical elements of these two types of systems suggest that costs for a geothermal system at Adak and a sea thermal system at Diego Garcia would be about the same as those for hydrocarbon-fueled systems to serve those sites.

Variations in length of day and amount of cloud cover with latitude and season combine to make annual total amounts of available solar energy greatest for those locations near the equator and least for those near the arctic circle. (It may also be noted that seasonal variations at a given location usually outweigh all shorter-term variations in the determination of energy storage capacity requirements.) A solar total energy system would cost four or five times as much as a hydrocarbon-fueled one at Diego Garcia or Northwest Cape, twenty-five or thirty times as much at Adak, and eight or nine times as much at the other more temperate locations.

Annual total amounts of available wind energy tend to be greatest at those locations where the available solar energy is least. (Also, at any given location the monthly total amounts of available wind energy tend to be greatest at those seasons when the available solar energy is least; this means that a hybrid solar-wind system would require less energy storage capacity than either a solar system or a wind system alone.) A wind energy system would cost one-third as much as a solar energy system at Adak, two-thirds as much at Edzell, nine-tenths as much at Centerville Beach or Cutler, twice as much at Sidi Yahia, and two-and-a-half times as much at Diego Garcia or Northwest Cape.

These comparisons are summarized in Table 1.

TABLE 1

Ratios of 10-year Costs of Alternate Energy Systems to those of Equivalent Hydrocarbon-Fueled Systems

Location	Nuclear Fission System	Geo/Sea Thermal System	Solar Thermal System	Wind Energy System
Adak	4-5	~1 (geo)	25-30	8-10
Edzell	8-9		8-9	5-6
Cutler	8-9		8-9	7-8
Centerville Beach	16-18		8-9	7-8
Sidi Yahia	8-9		8-9	15-18
Northwest Cape	8-9		4-5	10-12
Diego Garcia	8-9	~1 (sea)	4-5	10-12

R&D Program Requirements

Our brief examination of remote Naval information-handling activities and their energy requirements, and of possible alternate energy sources and systems for satisfying those requirements, has revealed needs for extensive research and development efforts in four general areas:

- Essential requirements (as differentiated from current usage) for each necessary form of energy at each activity
- Quantities of energy available from various environmental sources at each activity
- Technical feasibility and efficiency of various techniques for energy acquisition, conversion, transfer, and storage
- Life-cycle costs of implementing various techniques for energy acquisition, conversion, transfer, and storage.

These needs, which apply not merely to remote information-handling activities but to Naval shore activities generally and even to Naval forces afloat, are discussed in the following paragraphs.

Currently available information on energy usage at Naval activities does not provide a clear indication of essential energy requirements; i.e., metering and recording of the consumption of electrical power, heating fuel, and propulsion fuel is not generally done in sufficient detail to provide an adequate basis for the development of valid emergency reallocation, rationing, and load-shedding plans. Such plans should be based on an accurate breakdown of the current energy consumption of each Naval force and facility into five categories: (1) essential for the survival of the force or facility; (2) essential for performance of the primary functions of the force or facility; (3) essential for subsistence of force or facility personnel; (4) required for performance of desirable though not essential operations and subsistence functions; (5) non-essential consumption that could be eliminated through improvements in structures, equipment, or operations. The necessary improvement of metering and recording processes and also the necessary collation, evaluation, and interpretation of the resulting data must be carried out by the individual forces and facilities, with appropriate direction, guidance, and support from cognizant systems commands.

Currently available information on the environment at Naval shore facilities does not provide a clear indication of the amounts of geothermal, hydro, sea thermal, solar, and wind energy that may be available at those locations. Assessment of the availability of geothermal energy requires geophysical exploration which, in those areas that show sufficient promise, must culminate in the drilling and testing of exploratory wells. Assessment of the availability of hydro energy involves identification of existing or possible reservoirs and measurement of water capacities, flow rates, and heads; tidal as well as more conventional types of hydro energy should be considered. Assessment of the availability of sea thermal energy involves determination of the proximity of deep seas and the prevailing bottom and surface water temperatures and ocean currents. Assessment of the availability of solar and wind energy requires continuous measurement of insolation and wind velocity at appropriate sites for solar collectors and windmills. Measurements for assessing the availability of conventional hydro, sea thermal, solar and wind energy must be performed over a period of years to be truly meaningful, and must therefore be performed by personnel stationed at the individual facilities. The assessment of geothermal energy resources may require less time, but will also involve work at the individual sites. This on-site data collection, collation, evaluation, and interpretation should be directed, guided, and supported by the Naval Facilities Engineering Command.

Research and development efforts on geothermal, nuclear, sea thermal, solar, and wind energy systems are now underway and are being monitored by the Navy. However, none of these efforts are far enough along to provide all of the engineering data necessary for the design of operational systems for remote Naval facilities. Experimental systems utilizing all five kinds of energy have been built and operated long enough to demonstrate basic technical feasibility. However, several different system concepts have been proposed for each kind of energy, and further work must be done to provide the data necessary for selection among those alternatives. This work should include construction and test of prototypes (sized appropriately for a remote Naval facility) embodying the more promising concepts for each kind of energy, in order to make valid comparisons.

Similar statements may be made regarding the current status of the various possible techniques for energy conversion and storage. Techniques for the production, storage and utilization of gaseous and liquid hydrogen and various possible metal hydrides, hydrocarbons, alcohols, and carbohydrate materials are being examined; the utilization techniques being investigated include fuel cells, magnetohydrodynamic generators, gas and steam turbines, and gas and steam piston engines of various kinds. Again, much more work must be done, including construction and test of appropriately-sized prototype plants and vehicles, before valid comparisons can be made.

Prototype construction and operation is necessary not only to provide engineering data such as the energy output produced by a given size equipment with a given energy input, but also to provide data on operating and maintenance personnel requirements and life-cycle costs. These data are all necessary for making valid comparisons of competing concepts for utilizing the same kind of energy and of concepts for using the several different kinds of energy that may be available for utilization by any given Naval force or facility.

Coherent Microwave Generator

Scientists at the Naval Research Laboratory have developed a coherent microwave generator which produces intense electromagnetic radiation from the interaction of an intense relativistic electron beam and a spatially modulated magnetic field in combination with a homogeneous magnetic field region.

The device is magnetically tuneable and can produce high-level radiation of narrow or wide bandwidth over an extremely large range of wavelengths.

The generator produces microwave energy of the order of 10^8 to 10^9W in the 3-cm to 1-mm wavelength region with a secondary objective to produce electromagnetic energy of the order of 10^8W at wavelengths shorter than 1 mm.

Simultaneous Two-Wavelength Operation in Infrared Lasers

A laser system which provides simultaneous operation of any two laser transitions occurring in an infrared laser has been developed at the Naval Research Laboratory.

A chemically active element in combination with a germanium flat polarizes and spatially separates the two laser beams so that their polarizations are perpendicular to each other, and directs the laser beams to separate gratings.

Each grating is rotated to select and reflect a laser beam of a particular wavelength back through the system so that two particular beams are directed from the output.

Research Notes

Fog Research

Three unique radars which sense individually by electromagnetic energy, sound and light are giving new information on the occurrence, nature and behavior of marine fog in a study underway at Naval Electronics Laboratory Center, San Diego.

"Fog in a marine environment is a potentially serious problem to naval operations," says Dr. Juergen H. Richter, an electronics engineer who is in charge of the Center's portion of the research project conducted jointly with the University of Nevada.

NELC is one of several institutions engaged in a comprehensive fog research program sponsored by Naval Air Systems Command and Office of Naval Research.

Fog hampers aircraft landings on carriers, poses problems in coastal or harbor navigation and weakens optical and infrared signals used for signaling and communications. A better understanding of the nature of marine fog and improvements in forecasting its formation and dissipation is needed in order to cope with fog problems more effectively.

At NELC the study centers around the use of some of the most advanced remote sensing techniques available. Work is carried out on the ocean side of San Diego's Point Loma area. One sensor is a frequency modulated continuous wave (FM-CW) radar developed by Dr. Richter to sense moisture fluctuations in the atmosphere with extremely high resolution. This provides the most detailed picture of atmospheric microstructure now possible. The second sensor emits bursts of audible acoustic energy (sometimes called sodar for sound detection and ranging) which are scattered by temperature fluctuations in the atmosphere. This gives a picture of the thermal structure of the atmosphere. The third remote sensor, called lidar (for light detection and ranging) senses particulate matter and is used in the fog study to measure cloud height. These three sensors combined provide an accurate picture of the marine layer thickness and structure.

The marine layer is the portion of the atmosphere which extends from the surface up to the temperature inversion commonly found in the San Diego area. This layer structure is monitored in the NELC observational program during fog formation and dissipation periods.

Fog occurrences in the San Diego area may be divided into stratus related fogs mostly found in summer and post Santa Ana fogs prevalent during fall and winter. Stratus fogs are caused by a downward extension of the low stratified clouds (stratus clouds) common during summer months. The type of fog caused by lowering of the stratus cloud base is often associated with a decrease in marine layer height. This decrease in marine layer thickness confines the total moisture content to a small vertical volume which results in increased relative humidity. This in turn is a condition conducive to fog formation. While this kind of fog formation process is related to the depth of the marine layer, our remote sensors have shown that there are other fog events which occur without any apparent changes in marine layer height.

The FM-CW radar—in addition to being able to see small moisture fluctuations—is also a very sensitive detector for rain and light drizzle. It can measure rainfall rates as low as 0.01 millimeter an hour and, most importantly, can sense the drizzle or rain aloft even if it does not reach the ground.

Dr. Richter said that drizzle has been observed during fog occurrences when such fog is not related to changes in marine layer height. Observations give further credence to the conjecture that drizzle which does not necessarily reach the ground may be responsible for a particular kind of fog which forms in the following manner. Radiative cooling at the top of the stratus deck at some distance upwind causes the formation of drizzle within the stratus cloud. The drizzle falls into the drier sub-cloud layer and partially or totally evaporates. This accounts for a downward redistribution of moisture with a subsequent lowering of the cloud base until the base reaches the ground and fog occurs.

Formation of any fog requires condensation of moisture on small particles called aerosols which are suspended in the atmosphere. The stratus related fogs form on the marine aerosols which are often salt particles. During Santa Ana conditions when the wind flows from the land out to sea, another kind of aerosol gets transported over the ocean. These land (or continental) aerosols consist of a variety of particulates such as dust and organic matter. The dense fogs often seen during and toward the break-up of Santa Ana conditions in San Diego are believed to be formed by these continental aerosols which get transported over the water and represent condensation nuclei for the moist marine air.

Condensation may occur over the water and when the Santa Ana condition weakens and the wind direction changes from land to sea the fog may roll in with a spectacular frontal appearance. Sometimes condensation occurs after the continental aerosols move with the moist marine air back over land and radiative cooling reduces the temperature enough to permit condensation and fog formation.

Dr. Richter said that a dropsize spectrometer will soon be added to NELC's fog research program in order to gain more insight into the differences between stratus and Santa Ana fogs. The spectrometer is an instrument which measures particle size and number of particles per volume.

Enhanced Nonlinear Optical Effects Through the Use of Naturally Twinned Crystals

The primary objective of the Office of Naval Research and the Advanced Research Projects Agency Frequency Difference Generation Program at MIT is to produce intense, continuously tunable infrared radiation for use in high-resolution atmospheric absorption spectroscopy. This is accomplished by using nonlinear optical interactions in a crystalline material to extract the frequency difference between fixed frequency ruby laser output and the output from a tunable ruby laser-pumped dye laser. A second objective is to identify and determine the properties of nonlinear frequency-doubling materials which can be used to efficiently convert IR and near IR radiation to the blue and ultraviolet regions of the spectrum. This program is supported by the Office of Naval Research and the Advanced Research Projects Agency.

Early in the program the principal investigator, Professor C. Forbes Dewey, and his collaborators discovered that difference frequency generation capabilities of non-birefringent, highly nonlinear crystalline materials can be greatly enhanced by using crystals with natural twin planes. At each twin plane, the sign of the nonlinear polarization reverses so that, for randomly-spaced planes, the effective coherence length increases as the square root of the number of twin planes, N, while the difference frequency generation capabilities increase linearly with N. In the case of twin planes with uniform, controlled spacings, the observed nonlinear effects are expected to increase as N^2.

The anticipated effects of randomly-spaced twin planes on frequency-difference generation have been observed experimentally using twinned ZnSe as the nonlinear crystal. It was found that the 4 μm infrared difference frequency radiation obtained using this crystal was approximately 250 times as intense as that obtainable using an untwinned ZnSe crystal of comparable length.

During the ZnSe difference frequency generation work, it was discovered that the amount of difference frequency radiation obtained did not increase as rapidly as expected when the intensity of the pump radiation was increased. Through a series of careful quantitative experiments, it has now been determined that the observed results are attributable to absorption of difference frequency radiation by free carriers that are liberated by absorption of pump radiation second harmonics. Since these second harmonics are produced as unavoidable byproducts of the nonlinear process, it is imperative (for high power operation) that the band gap of the nonlinear material used exceed twice the energy of the pump photons. This is a highly significant finding since it applies to all frequency difference generation experiments in which semiconducting doubling crystals are employed.

Because of the anticipated N^2 dependence of radiation yield, it would be highly desirable to grow nonlinear crystals with regularly-spaced twin planes. Prof. Gus Witt of M.I.T. has now been enlisted to grow such crystals, and experimental work is underway. The technique used by Prof. Witt involves a replication process in which a twinned seed is used to initiate crystal growth. The technique will first be tested with InSb and, if successful, will subsequently be extended to produce regularly twinned ZnSe and other crystals. Meaningful experimental results should be forthcoming within two months.

In addition to its use for frequency difference generation, there is every reason to believe that the twin plane technique will allow highly nonlinear, non-birefringent crystals to be used for efficient frequency doubling. Preliminary experimental results that have recently been obtained support this conjecture. Experiments were carried out in which a twinned ZnSe crystal was used to frequency double .8 μ - 1.1 μ radiation derived from a tunable dye laser. Copious quantities of blue-green radiation were obtained throughout the entire wavelength range. It was estimated that the intensity of the blue-green radiation obtained was about one thousand times as great as it would have been if an untwinned ZnSe crystal had been used. Quantitative analysis of the data obtained is currently underway.

Professor Dewey and his co-workers have compiled a list of six potential non-birefringent doubling crystals which, when used in conjunction with the twin-plane nonlinear optical technique, should yield highly efficient frequency doubling into the blue-green spectral region. Of all the crystals listed, ZnSe is predicted to be the poorest contender by at least a factor of ten.

Deepest Simulated Saturation Dive on Nitrogen and Oxygen

BMC (DV) Joseph J. Bikowski, USN, MM1(DV) Richard A. Jackson, USN and HMC(DV) Normand L. R. Tetrault, USN, were confined in the "Genesis" pressure chamber at the Naval Submarine Medical Research Laboratory for two weeks—one week at a simulated depth of 198 feet of sea water and one week being decompressed. This project, was designed to test the operational feasibility and physiological responses to breathing high pressures of nitrogen with an oxygen content only slightly above that present in air at the surface, thus avoiding the dangers of oxygen poisoning that compressed air would produce in long exposures at this depth. More exotic and expensive gas mixtures such as helium and oxygen are usually employed in saturation dives, and this was the longest exposure to nitrogen-oxygen mixtures ever conducted at this great a depth.

Saturation diving is based on the concept that, at a fixed depth, body tissues rapidly become saturated with the breathing gas available. Once saturated, the time required for safe decompression does not increase. Thus, divers or tunnel workers could live in pressurized habitats for long periods without increasing the time required for decompression. For example, in the current series of dives,

First man out: HMC (DV) Normand L. R. Tetrault, USN, is greeted by the Commanding Officer, Naval Submarine Medical Research Laboratory, Cdr. R. L. Sphar, MC, USN and Cdr. C. A. Harvey, MC, USN, Co-ordinator of the Project, when he emerged from the "Genesis" pressure chamber at the Laboratory.

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tissue saturation would be complete within 60 hours, and once past that point, the time required for decompression to the surface would be the same for the remaining 4-1/2 days. Thus, saturation diving technique offers advantages in longer working time compared to time spent in decompression and less danger of decompression sickness (the "bends"), since only one decompression takes place in return for days of productive work.

Dr. Charles F. Gell, Scientific Director of the Laboratory, emphasized that over twenty-five investigators, representing the multitude of scientific disciplines within the Laboratory, compiled extensive biomedical information. Extensive physiological monitoring was conducted in order to verify the health status and the adequacy of the environment for diving. Full evaluation of the experimental data will take several months, but the experiment has shown that divers can adapt to the inert gas narcosis ("rapture of the deep") produced by nitrogen at that depth (equivalent to 247 feet of compressed air) and physiologically tolerate such an exposure. They performed moderately heavy work loads and complex performance tasks successfully, but enough performance decrement remained so that it was felt that nitrogen-oxygen saturation diving projects would be limited to a somewhat shallower depth in the open ocean or in tunnel projects where such techniques would offer financial, safety and technical advantages.

Evaluation of each diver's status will continue for several weeks after the dive to insure that no subtle long-term effects are present, and they will be followed in the Longitudinal Health Study at the Laboratory for many years. The Naval Submarine Medical Research Laboratory will continue to evaluate compressed air and nitrogen-oxygen mixtures as breathing gases for saturation dives as part of the U.S. Navy's continuing contribution to diving and Submarine Medicine. Shallow and intermediate depth saturation dives, employing these techniques, will provide marine biologists, caisson workers, marine geologists, oceanographers, oil companies and U.S. Navy divers access to projects previously considered economically unfeasible.

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 730, 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: $6.50 per year in the U.S. and Canada; $8.15 per year, foreign; $0.55 per individual copy. The issuance of this periodical approved in accordance with Dept. of the Navy publications and printing regulations.

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Cover Caption

Spectacular "blow-out" of eight geothermal steam wells at The Geysers located on the slopes of the canyon near Cobb Mountain, California. *See page 19.*

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