S. Office of Naval Research

407-C

NAVAL RESEARCH

REVIEWS

OCTOBER 1978

Engin

PROFILES IN SCIENCE

Dr. George Carrier

Dr. Carrier is the T. Jefferson Coolidge Professor of Applied Mathematics at Harvard. For many years the Office of Naval Research has supported his important work concerned with phenomena in fluid mechanics, such as ocean current theory, aerospace matters, and rotating fluids. Professor Carrier was one of the authors of the outstanding text, *Functions of a Complex Variable: Theory and Technique.* He is a member of the Naval Studies Board of the National Research Council, the National Academy of Sciences, and the National Academy of Engineering. He has received the Von Karman Medal and most recently the Timoshenko Medal.

In recent years Professor Carrier has worked closely with ONR in organizing and chairing the Workshop on Numerical Hydrodynamics in 1974 and the Twelfth Symposium on Naval Hydrodynamics in 1978. Both conferences were sponsored by ONR and the National Academy of Sciences. Professor Carrier is Chairman of the National Academy of Sciences National Research Council Panel on Mathematical Research Alternatives for the Navy. This Panel is an advisory Committee to the Mathematical and Information Sciences Division of ONR.

Materials and Mankind

Morris Cohen *
Massachusetts Institute of Technology
Cambridge, Massachusetts

This article is based on an ONR 30th Anniversary Lecture given in Boston, Massachusetts at the International Conference on Materials by Professor Morris Cohen. Since its beginning in 1946, ONR has supported Professor Cohen's research. Through supporting research of outstanding material scientists, ONR became a pioneering force in many of the important accomplishments in the material sciences during the last several decades.

Introduction

We shall be concerned here with two broad objectives: (a) to illuminate the partnership between man and his materials as it has developed over the centuries, and (b) to highlight society's intellectual approach to the understanding and utilization of materials through science and engineering.

For present purposes, we need two key definitions (1):

Materials are the portion of matter in the universe that man uses for making things, i.e., structures, machines, devices, and innumerable products.

Materials science and engineering (MSE) involves the generation and application of knowledge relating the composition, structure, and processing of materials to their properties and uses. It is essential to note that MSE is referred to in the singular as a coherent field; it is not properly separable into science on the one hand and engineering on the other. Of course, some parts of this spectrum, when viewed more narrowly, may be regarded as science-dominated whereas other parts are correspondingly engineering-dominated.

Materials in History

Materials have entered into man's existence and development ever since his emergence in the grand evolutionary scheme-of-things. Certainly, the use of wood, stone, shells, bone, hides, and natural fibers

*Dr. Morris Cohen is Institute Professor and Ford Professor of Materials Science and Engineering at MIT. He is a renowned physical metallurgist devoting much of his research to the properties of iron and steel.

had much to do with the ascent of man from animal-ness to human-ness. Primitive man gradually found that such materials, available in nature, could be fashioned into utensils, ornaments, shelter, clothing, even tools and weapons. One can imagine the potential impact on thinking man when he first learned that a soft, formable mud, now known as clay, could be rendered strong and rigid just by heating. It was, in effect, a new type of materials processing, rather analogous to the cooking of food. With that event — the accidental firing of clay — came the dawning of a powerful conception, namely that the materials given by nature can be deliberately changed and improved by man himself for his own purposes. Indeed, a new partnership was thus born between man and his surroundings through materials!

History records many ways in which materials profoundly influenced social change, and so caused society to depend even further on materials. The very earliest trading centers were probably based on the availability of flint in local regions. Here was a material brittle enough to be chipped into knives, handaxes, and spearheads, and yet was sufficiently hard and strong to cut, chop, and pierce other materials. The trading centers provided an environment for human settlement and cultural exchanges, perhaps even contributing to the origin of agriculture.

Obviously, the rise of commerce and, later, of government stimulated the need for record-keeping. The materials at hand affected the form of writing that developed, and thereby the local culture. The Sumerians of the Tigris-Euphrates Valley had abundant clay to serve as their stationary, and the sharp, rigid stylus that then had to be used for inscribing favored the simple wedge-shaped, cuneiform type of characters which emerged. The Egyptians, on the other hand, had flexible fibers in the form of papyrus reeds which could be matted into a writing surface, and on which they could write with brushes and colored fluids derived from nearby vegetation. These circumstances permitted a relatively sophisticated, hieroglyphic form of writing to develop.

In a similar vein, the prevailing differences in available materials also accounted for the contrast between the mud-brick and the cut-stone architectures of the two regions.

To take another example of the interplay between materials and society, the substitution of iron and steel for copper and bronze, starting at about 1200 B.C., brought about far-reaching changes in social institutions. The relative abundance of iron meant that the ruling groups could not control its distrubtion, as was the case with the more-limited copper. In a sense, iron became the "democratic metal," in that it raised the living standards of the common man through its widespread use in tools, household utensils, agricultural implements, and weapons. New craftsmen appeared on the scene who could earn a livelihood and contribute new skills to the advance of society. Chisels became available for stone-cutting, drills for bead-making, dies for coining, and then came an enormous jump in productivity with the construction of machines from iron and steel. Even the dynamics of warfare altered dramatically when all the foot soldiers could be equipped with weapons and shields made from the "democratic metal;" in the Bronze Age only a select few in the armies could have the benefit of metallic weaponry and armor.

Thus, over the ages of civilization, societal dependence on materials inevitably grew more compelling and pervasive — for trade and manufacture, for standards of living, for national security and well-being, and for enhancing the capital wealth of mankind. To some degree or other, this materials-and-mankind connection has been evolving for some hundred thousand years. But during the past few decades, society has begun to regard materials in a sharply different light. This recent change seems almost discontinuous when viewed against the backdrop of history.

Two new system-concepts have arisen in the field of materials. Materials are now recognized as one of the connective tissues of world economies and nations, ranking with such other basic resources as food, energy, living space, information, and manpower itself. That vast materials complex is designated as the global *materials cycle.* It links mankind and governments directly to the substance of nature.

At the same time, there are strong intellectual and social forces at play which are aligning various branches of knowledge into a *science and engineering of materials.* The resulting multidiscipline — MSE — combines the great human adventure of seeking deeper insights into matter, and of marshaling such knowledge for societal advance. In its broadest dimensions, MSE constitutes a system of disciplines that overlays the materials cycle.

Characteristics of the Materials Cycle

Figure 1 is a schematic representation — in highly simplified form — of the materials cycle. *Raw materials* are taken from the earth by mining, drilling, and harvesting (at lower left in Figure 1). These materials (ores and minerals, coal, crude oil and natural gas, rock, sand, timber, crude rubber, etc.) are processed into *bulk materials* (metals, chemicals, cement, lumber, fibers, pulp, rubber, electronic crystals, etc.); they are then refined further around the circuit into *engineering materials* (alloys, ceramics and glass, dielectrics and semiconductors, plastics and elastomers, concrete, building board, paper, composites, etc.). At the right of Figure 1, the engineering materials are fabricated and assembled into structures, machines, devices, and other products for societal use. And after these materials have thus performed in their various applications, they are discarded and become junk, either to enter the circuit again and again by recycling, or to return to earth whence they came. In this perspective, the materials cycle is a closed cradle-to-grave system.

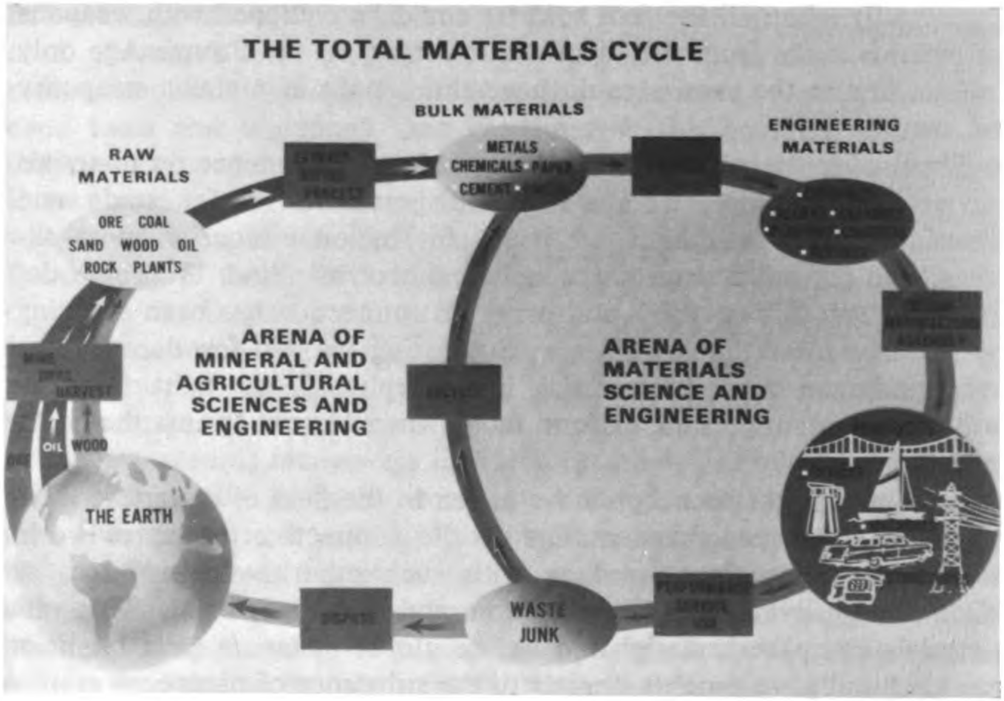

Figure 1 — Schematic representation of the global materials cycle in simplified form, indicating the flow and conversion of materials from the earth to societal use and, eventually, back to earth (1).

The materials cycle is an enormous enterprise. About 15×10^9 tons of raw materials are produced annually in the world, with some 1/3 of it being consumed in the United States. Very roughly, 50-60% of this incredible bulk is in the form of nonfuel materials (metallic materials, nonmetallic inorganic materials, and organic (nonfood) materials) and 50-40% is in the form of fuel materials (petroleum, natural gas, and coal). Not only is the United States a net-importer of raw materials, but (a) such net imports as a percentage of the nation's total materials consumption is rising, and (b) both the population and the per-capita usage of raw materials are climbing more rapidly *outside* the United States than *within.* Clearly, then, the materials cycle plays an interconnecting role in the foreign as well as the domestic affairs of most countries around the world.

The materials cycle is, of course, driven by societal demand (at lower right in Figure 1) which exerts a pull on the circuit. The flow of materials depends on what people and institutions are willing to pay for, and so value increments in the form of labor, energy, cost of capital, etc. are added to the materials as they move around the loop. Table 1 illustrates this build-up in value for the world production of aluminum in 1963 (2). The price (column 2) of the mining product (bauxite at $8/ton) increases by a factor of 125 in moving through the various processing steps to become wrought semifinished shapes and castings

Table 1. Value Added to Aluminum at Various Stages of Processing in the Materials Cycle (1963)

Process	World Aluminum Production			
	Product (Price)	Tons (millions)	Value ($ millions)	Increase In Value ($ millions)
Mining	Bauxite ($8/ton)	30	240	240
Ore Refining	Alumina ($75/ton)	12	900	660
Smelting and Refining	Aluminum Ingot ($450/ton)	6	2700	1800
Fabrication and Casting	Wrought Shapes and Castings ($1000/ton)	6	6000	3300

After Pick (2).

(at $1000/ton). While the weight of product is being reduced to one-fifth (column 3) between these two stages, the total value of product (column 4) is becoming 25 times greater in traversing this section of the materials cycle. Column 5 shows the value-added at each of the intermediate steps.

To indicate another example of the same trend, the total raw materials consumed in the United States per year (1974) amounts to about 5% of the GNP, but processing to the stage of engineering materials and their fabrication increases the overall value by a factor of 4. It has been estimated that approximately 20% of the workforce in this country is engaged in this part of the materials cycle, again giving direct evidence of the penetration of materials into human existence and quality of life.

At virtually every point around the materials cycle, there are strong interactions among materials, energy, and the environment. An illustrative case is shown in Figure 2, which plots the energy required to produce a ton of refined copper as a function of the grade of copper ore (3). As existing mines become depleted, the designated points on the curve will move to the left, with more-and-more energy being consumed to handle larger-and-larger quantities of rock and gangue per unit of valuable product obtained. At the same time, there will be increasing problems in disposing of the rejected matter, thus throwing further burdens on the landscape. Indeed, almost all materials processing affects the environment in one way or another, injecting social costs into the flow of materials around the cycle.

The close interplay between materials and energy is particularly evident in the U.S. economy. About one-third of the energy consumed by

American industry goes into the value added to materials in their production and fabrication. Table 2 shows the twelve largest consumers of energy among the primary materials industries in the United States (4). Aluminum and copper involve electrical processes and are energy-intensive. Materials such as sand, gravel, and stone are of low energy-intensity; relatively little processing is necessary to convert the parent raw materials into engineering materials for final use. Steel is of intermediate energy-intensity, but its large tonnage puts it at the top of the list in Table 2 as a total energy consumer.

On the other side of the coin, materials are crucial for making energy available in the first place. In addition to the obvious indispensibility of fuel materials for producing energy, one finds that essentially all of the advanced energy-conversion technologies are presently materials-limited in terms of efficiency, reliability, safety, and cost-effectiveness; included in this category are gas turbines, nuclear reactors, solar energy, magnetohydrodynamics, coal conversion, high-energy-density batteries, and fuel cells.

The materials cycle also affords an analytical framework for dealing with perturbations in the availability of materials at various points around the cycle, whether with reference to the world, to a country, an industry, a company, or a factory. The flow of materials anywhere in the cycle can be sensitive to economic (e.g., cartels), political (e.g., em-

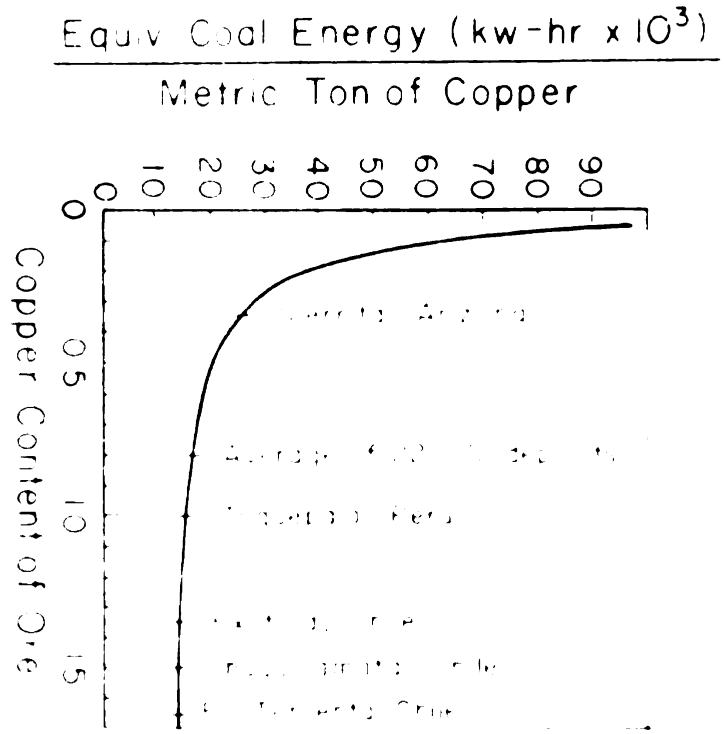

Figure 2 — Energy required to produce refined copper vs. grade of copper sulfide ore (3).

Table 2. Largest Consumers of Energy Among the Primary Materials Industries in the United States (1973)*

Material	Annual Tonnage (10^6 tons)	Unit Energy (10^6 BTU/ton)	Annual Energy (10^{12} BTU)
Steel slabs, grey iron + steel castings	152.	24.9	3800
Primary aluminum (ingot)	4.53	244.	1100
Portland cement	90.5	7.6	688
Ammonia	15.	39.	586
Primary copper (refined)	1.97	112.	221
Glass containers	12.4	17.4	216
Chlorine (gas + liquid)	10.3	19.3	199
Quicklime	21.4	8.5	182
Phosphorus (P and P_2O_5)	6.12	24.	147
Oxygen, nitrogen (gas + liquid)	24.5	4.5	111
Sand, gravel, crushed stone	1860.	0.056	104
Primary zinc	1.42	65.	92
		Total	7446

After Kellogg (4).
*Data are based on total consumption in the United States, including both domestically-produced and imported materials.

bargoes), and social decisions (e.g., environmental constraints) made in other parts of the circuit. Materials shortages, when analyzed in this context, are usually found not to be due to scarcity in the earth, but rather to dislocations in the cycle which interfere with the expected arrival of materials at any given point in the usual amounts and at reasonable prices. For example, shortages may arise, not because the earth is running out of the material in question, but because certain processing or transportation capacity has become inadequate somewhere in the circuit.

Table 3 presents some interesting aspects concerning the availability of nonfuel materials in the world and in the United States (5). The comparison is based, in each case, on the ratio of the expected demand to the exploitable reserves, thus providing an index of the relative scarcity. Curiously enough, the listings of materials most likely to be in short supply on this basis are very different depending on whether the world or the United States is taken as the "materials universe."

Still another view of the world materials picture is portrayed in Figure 3, specifically for metals (6). Here, the annual production of various metals is plotted against their crustal abundance. Without any

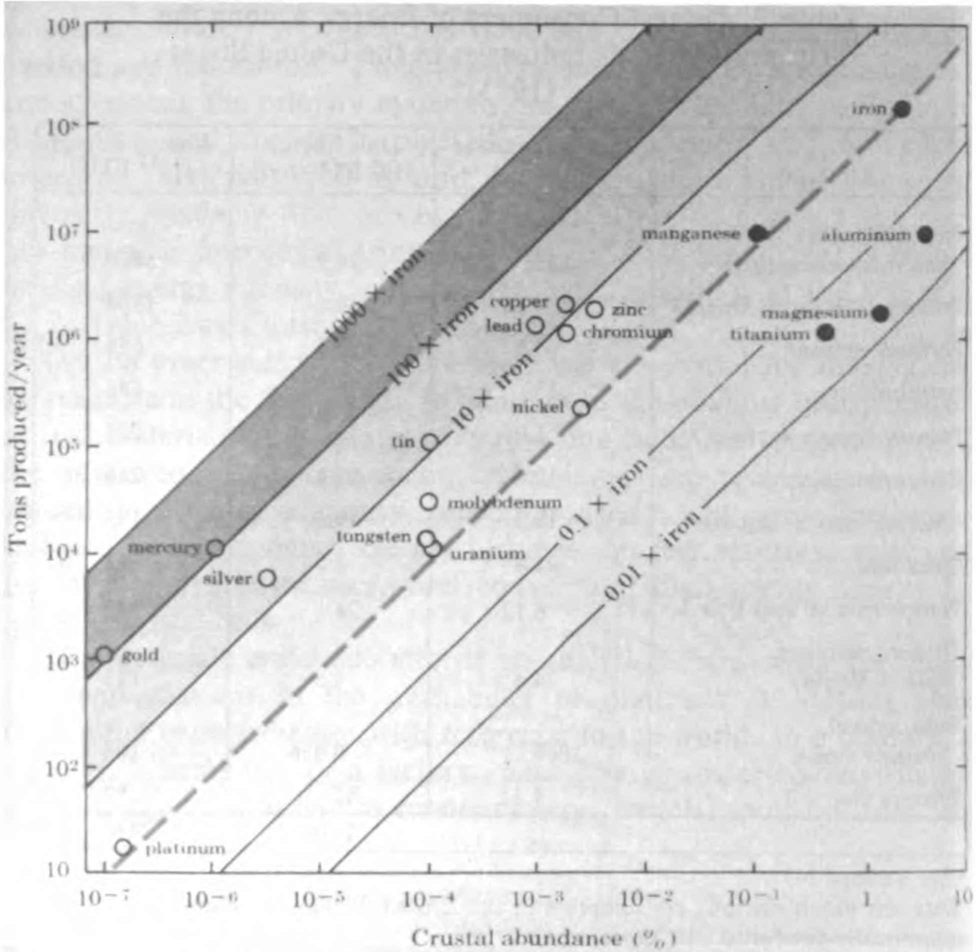

Figure 3 — World production of metals per year vs. their abundance in the earth's crust. Iron is taken as the reference metal here. Metals lying above the iron baseline are being mined more rapidly than iron relative to their crustal abundances; metals falling below the iron baseline are being mined proportionally more slowly than iron (6).

Table 3. Nonfuel Materials in Potential Short Supply

In order of Decreasing Scarcity Factor =

$$\left(\frac{\text{Cumulative Demand (1972 to 2000)}}{\text{Exploitable Reserves}}\right)$$

World		United States	
01. Mica sheet	07. Tin	01. Chromium	07. Niobium
02. Silver	08. Zinc	02. Manganese	08. Antimony
03. Bismuth	09. Asbestos	03. Titanium	09. Cobalt
04. Fluorspar	10. Tantalum	04. Nickel	10. Thorium
05. Mercury	11. Tungsten	05. Palladium	11. Platinum
06. Graphite	12. Cadmium	06. Aluminum	12. Vanadium

After ref. (5).

overall planning or directives, society has tended to produce (and use) more of those metals which are more prevalent in the earth's crust, and vice versa. In the log-log plot of Figure 3, the metals whose points happen to fall along any one of the indicated straight lines are being produced at the very same rate per year in proportion to their respective abundances, even though the absolute tonnages may differ by many orders of magnitude. Hence, if the line through iron is taken as a reference, then the metals whose points lie above this sloping line are being produced faster than iron, relative to their respective crustal abundances; these include mercury, gold, silver, lead, copper, tin, chromium, zinc, and molybdenum. In contrast, magnesium, aluminum, and titanium are being underproduced in the world compared to iron.

Needless to say, all these manifestations of the materials cycle will have direct bearing on the evolution of national materials policies, both in the industrialized and in developing countries, inasmuch as by its very nature, the materials cycle intertwines the supply-and-demand sectors of the materials field. Although the materials-flow around the loop can be drastically and unpredictably distrubed by events lying outside the domain of materials, nevertheless scenarios can be played out within the materials cycle to prepare for appropriate countermeasures.* Some of these possibilities are stockpiling, recycling, and substitutions.

Materials Science and Engineering

We have already defined materials science and engineering (MSE) and, as a body of knowledge and inquiry, its relation to the materials cycle. Figure 4 illustrates the central theme of MSE: (a) to relate the microscale structure of materials to their macroscale properties and then to their eventual performance in service, and (b) to make this spectrum of knowledge relevant to society in connection with materials processing** and manufacture for cost-effective application.

In the sense of Figure 4, MSE can be viewed operationally as a knowledge-generation-and-transmission system which links basic research and fundamental science on the left to human needs and the pull of society on the right. In this way, MSE provides a matrix or connective tissue for those disciplines and subdisciplines which shed light on materials; it does not replace any of these branches of knowledge. Thus, MSE constitutes a multidisciplinary field which promotes interac-

---

* A timely study on "Contingency Plans for Chromium Utilization" has been published recently by the National Research Council (7). It was pointed out that "The rate at which remaining chromium reserves are becoming concentrated in Rhodesia and South Africa makes substantial impact of any chromium cutoff a possibility that cannot be dismissed casually."

** Processing as here defined comprises the operations intended to produce, shape, and control the properties of materials, so that they can perform effectively for societal use.

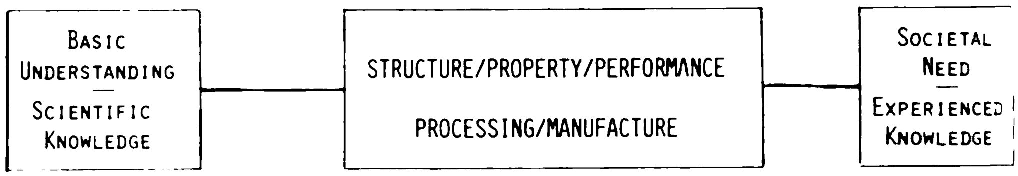

Figure 4 — Materials science and engineering as a knowledge-generation and knowledge-transfer system for materials, connecting basic science to societal need. Scientific knowledge flows to the right, while experienced knowledge flows to the left.

tions among otherwise-separate disciplines; it exposes society — however circuitously — to the opportunities opened up by fundamental knowledge concerning materials, while, reciprocally, basic science is being exposed to the materials-related demands and experience of society. This two-way conduction of scientific and empirical knowledge is an important attribute of MSE that has developed only within the last few decades.

The brief historical perspective given in the previous section has shown that materials technology in one form or another has been practiced and advanced for thousands of years. Among craftsmen, artisans, and artists over the ages, there emerged a fine experience-based appreciation of the property/processing/performance relationships of materials; this was manifested, for example, in the utility of pottery, textiles, tools, and weapons, as well as in the beauty of jewelry, decorations, art, and architecture. Yet, throughout such remarkable achievements in materials technology, even through the Scientific Revolution of the 17th century and the Industrial Revolution of the 18th and 19th centuries, almost nothing was contributed to the understanding of materials by the scholars and intellectuals. Materials were too complicated, too unpredictable, even too dirty, for the philosophers and scientists of the day to deal with. The hands-on workers already knew that materials had functional, even aesthetic, properties which could be brought out by processing to serve the market place or an imperious patron; but explanations were lacking.

It was only during the 20th century — mainly during the past few decades — that thinkers and doers joined forces in the field of materials. What finally forged into place was the scientific link in the chain — the coupling of internal solid-state structure to external properties. Materials were discovered to contain an inner hierarchy of many structural levels, with sufficient complexity to offer a foundation for their outwardly-revealed properties. Microstructure was disclosed by optical microscopy, substructure by electron microscopy, crystal and molecular structure by x-ray diffraction, atomic structure by excitation spectroscopies, and nuclear structure by high-energy bombardment. This internal architecture of materials furnished a new framework in which, at long last, explanation could be added to practice and understanding to empiricism; and so modern MSE could be born.

Waves of scientific knowledge then began to flow from left-to-right in the multidisciplinary conduction band of Figure 4 and, countercurrently, waves of experienced knowledge flowed from right-to-left. The resulting turbulence of ideas and excitement proved to be highly catalytic, and erupted into a diversity of new man-made materials: synthetic fibers, high-strength and high-temperature alloys, new ceramic and dielectric materials, optical glass, nuclear fuels, semiconductors, superconductors, synthetic diamonds and rubies, composite materials, amorphous metals, and a remarkable variety of plastics.

It is worth emphasizing some salient features of this interactive process:

(a) In the COSMAT (Committee on the Survey of Materials Science and Engineering) study (1), several material innovations were examined in considerable detail. It appears that the two-way flow of information in MSE is most productive when the mixing of understanding and need are so closely intermingled that cause and effect are difficult to distinguish one from the other. In the main, however, the *initial* impetus in the MSE system seems to arise more frequently from "societal pull" than from "scientific push."

(b) Another prominent factor in such material advances is the operation of MSE in an *inter*disciplinary mode. Because of the *multi*disciplinary nature of MSE, the field lends itself to specifically-coupled combinations of disciplines which are deliberately brought together to serve a mission-oriented purpose. This interdisciplinarity requires, at least temporarily, that the participants place primary emphasis on the overall group objective rather than on their respective disciplines. And yet, as COSMAT has noted, each such discipline contributes importantly to the total effort by making available its own concepts, viewpoints, techniques, and lore.

(c) The successful linkage of structure, properties, and performance in MSE should not be construed to mean that properties can be predicted from structure, and performance predicted from properties; expectations of this sort lead not only to unknowns but also into the realm of unknowables (8). In general, structures do not "speak up" and tell us the properties they have, and certainly not the properties that make materials useful to mankind. In contrast, we have to approach the structure with prior knowledge about some property gained from curiosity or experience originating outside the structure, and then — with a leap of the mind — try to deduce which level(s) of the internal architecture will "resonate" with the property in question. In the resulting interplay, there is a reciprocity between structure and properties in which each reflects the other, and each contributes in its own way to understanding the other. To all intents and purposes, the structure itself stands mute about properties until it is asked the right questions. A striking case-in-point is the double-helix structure of the DNA molecule. This structure is beautifully complex, but is does not "come alive" until we address it with some independently-known properties of life, e.g., does the DNA structure have the ability to reproduce, and can it encode sufficient genetic information to determine what kind of a cell to grow into?

This unknowability about properties from structure *alone* has its counterpart in the property/performance interrelationships. The performance of materials invariably encompases many more parameters and dimensions than can be contained in the information derived from measured properties alone. Consequently, we must recognize that the successful operation of MSE does not depend on fundamental predictability in going from the more elemental to the more complex, but rather on the symbiotic interplay among structure, properties, and performance, i.e., with knowledge freely flowing back-and-forth among them and each reinforcing the others toward the better understanding and utilization of materials.

Some Examples of Materials Science and Engineering in Its Interdisciplinary Mode

Ten case studies were reported by COMSAT (9) to illustrate how MSE functions as an interdiscipline. Brief summaries are included here (taken from pp. 3-15 to 3-18 of ref. 9) to document the aforementioned characteristics of MSE.

Heatshield Design

This example particularly illustrates the systems approach. The materials development is embedded in a broader design problem, but the overall design is strongly influenced, in fact almost completely determined, by materials capabilities. The development of an adequate heatshield for manned re-entry of space vehicles required the contribution of a wide range of disciplines and utilized contributions from several organizations and many locations. In our language, this program is science-intensive. The program had a clearly defined overall objective and is an example of responsive materials R & D.

Transistors

The transistor story emphasizes the changing nature of a materials R & D program with time. In its early phases, only fundamental understanding of the nature of electrical conduction in semiconductors was involved. The motivation or "application" was stated only in a most general way, but there was a perceived need to replace vacuum tubes in communications circuitry. Although this program substantially increased understanding of the solid state, it necessarily built on much basic work in physics and chemistry which had been completed in earlier decades. As the program succeeded in providing device capabilities, the emphasis naturally shifted from research on phenomena to the engineering aspects of design and manufacture. Movement of personnel from research to development played an important role. This program provides a particularly strong example of close coupling between basic research and engineering. The solid-state industry which has grown out of the original transistor work is the arch-type of a science-intensive industry and creative materials R & D. The transistor story also illustrates the cardinal importance of a proper intellectual and working environment for innovative materials R & D. A sense of direction was provided by the management in a sufficiently general way so that individual creativity and insight were encouraged, and yet was sufficiently definite to arouse the enthusiasm and dedication of the experts involved. Leadership in the research and development program fell naturally on those able to span intellectually and motivationally the full scope of such programs.

Razor Blades

In an industry which might be thought of as experience-based, the internal objective to achieve substantial improvement in shaving performance led to a materials R & D program requiring considerable science and sophisticated techniques. The program was quite interdisciplinary, involving experts in biophysics, physical chemistry, physical metallurgy, and contributions from the life sciences. The use of a new scientific diagnostic instrument, the scanning electron microscope, for the first time provided a way for measuring the performance difference of various razor-blade materials. A key point in the program was the somewhat accidental observation of deposition of thin films of polymers on steel surfaces. The major feature, however, was the organizational climate and the ability of the investigators to recognize the importance of this observation and to properly exploit it for their overall objective. Materials R & D seldom runs a neatly planned course; it requires perception, training, and freedom to capitalize on an unexpected event or observation. The result was a new, hard-alloy coating of the blade covered, in turn, by a thin, tough plastic layer.

Synthetic Fibers

The field of synthetic fibers, spanning several decades in time, is very large in terms of the number of investigators and orginizations involved in R & D as well as in terms of market volume. As in the case of the transistor, the early effort was on basic understanding, but there was also a perceived need to improve on natural fibers. In time, engineering emphasis was added but not at the expense of further scientific investigation so that we now find the general problem of synthetic fibers being attacked across the entire spectrum from basic science to engineering. The major contributions to this important development have been made by chemistry, but inputs were required from other disciplines such as the metallurgical development of appropriate containers for the hot-liquid corrosive melt. To reach the ultimate customer, this materials advance also required innovations in spinning and weaving machinery for the new fibers.

Textured Materials

Textured materials is a description used in this report to refer to polycrystalline microstructures in which a degree of control is exercised on the alignment of neighboring crystals. Examples are permanent magnet alloys, and high-strength phosphor bronze alloys for use as springs in relays and connectors.

The central theme of materials science in the relation between composition, structure, and properties is beautifully illustrated by this program. Here the emphasis is on structure, more particularly control of structure, and its influence on properties. Basic work by a physicist, followed many years later by metallurgists in the laboratory and supported by extensive computation techniques from the mathematicians, has led to a capability for predicting the structure and related physical properties of materials in terms of the processing steps used in its preparation. This program has set a high standard for the direct contributions which science can make to practical programs.

Integrated Circuits

Although this is a logical follow-on to the transistor story, it is included as a separate piece because different aspects of materials R & D are illustrated. In the rapid development of integrated circuits, effective coupling has been achieved principally through cross-licensing of patents among industrial organizations which are highly competitive. Whereas the transistor required important new scientific understanding, the creation of the sophisticated integrated circuits resulted principally from inventiveness and engineering ingenuity, particularly in processing technology. At the same time, the small dimensions and extreme material purity needed for integrated circuits could not be achieved without a wide array of diagnostic tools and instrumentation provided by earlier unrelated scientific programs.

Aluminum Conductors

Copper conductors for electricity come from an experience-based industry, but recent problems in copper availability as reflected in price have injected new science and engineering into the industry. Although aluminum as it existed a few years ago was unsatisfactory for many copper-wire applications, materials R & D has demonstrated that it is possible to modify and control aluminum alloys to meet the necessary properties, such as electrical conductivity, ductility, and corrosion resistance. The objectives of the program were clear, the time scale was relatively short, and the contributions were more of an engineering nature than scientific. This is a clear example of the user in a science-intensive industry demanding new material capabilities and providing leadership to attain that end. It illustrates the ability to develop, through materials R & D, a substitute material to satisfy a specified function.

Polymer-Modified Concrete

Cement and concrete are an experienced-based industry with long traditions, very high volume, and intense pressure on unit cost. An expansion of the polymer field has now touched this long-standing material and is providing new capabilities through polymer latex-modified Portland cement. At the same time, new understanding is being generated concerning the fundamental mechanisms of cementitious attachment. Closer coupling has been accomplished between academic and industrial investigators in this area.

TV Phosphors

The discovery of an important red phosphor illustrates the wide span of scientific knowledge which is sometimes required in materials R & D and the very close linkage which can be obtained between new scientific understanding and very practical application. Scientific studies in support of laser-host materials led to the discovery of a commercially significant red phosphor. A central element of this program was the ability of the investigators to pursue and exploit unpredicted observations.

Ceramic Oxides

Major new materials may result from the application of new understanding in one field applied to a different class of problems. Such was the case in the development of new high-density and, therefore, pore-free ceramics. Insight and stimulation for this work resulted from the earlier contributions of metallurgy and physics.

Although the above summaries cannot do proper justice to the full case studies conducted by COSMAT (pp. 3-60 to 3-97 of ref. 9), nonetheless these glimpses nicely convey the varied scope and modus operandi of MSE.

A General Prospective

In the years ahead, as mankind finds itself under mounting pressure to accommodate to nature, there will be increasing regard for the materials cycle as one of the elemental strands of national and world systems, along with food, energy, information, and the environment. At the same time, society will inevitably structure its growing knowledge-base so that the human mind will be ever stimulated to understand nature more thoroughly, and likewise human purpose will be ever motivated to cooperate with nature more prudently. This is precisely what MSE strives to do in the realm of materials — the very substances by which mankind is inherently bound to nature. Surely, then, the spectrum of knowledge which we now call MSE has a central role to play in human destiny.

References

1. The general viewpoint presented here concerning the field of materials is based largely on the COSMAT Reports entitled "Materials and Man's Needs":

   COSMAT Summary Report, National Academy of Sciences (1974), and

   COSMAT Supplementary Report, National Technical Information Service (1975):
   Volume I. The History, Scope, and Nature of Materials Science and Engineering,
   Volume II. The Needs, Priorities, and Opportunities for Materials Research
   Volume III. The Institutional Framework for Materials Science and Engineering
   Volume IV. Materials Technology Abroad
2. H.J. Pick, "Decisionmaking in Industry and Its Implications for Energy and Other Resources," *Engineering Implications of Chronic Materials Scarcity*, Office of Technology Assessment, U.S. Congress (1977) 37.
3. N.J. Page and S.C. Creasey, "Ore Grade, Metal Production, and Energy," J. Research U.S. Geological Survey **3** (1975) 10.
4. H.H. Kellogg, "Sizing Up the Energy Requirements for Producing Primary Materials," Engineering and Mining J. **178** (1977) 61.
5. E.J. Dyckman, "Review of Government and Industry Studies on Materials Supply and Shortages," *Department of Defense Materials Workshop*, Battelle-Columbus Laboratories, Columbus, Ohio (1975) A22.
6. B.J. Skinner, "A Second Iron Age?," American Scientist **64** (1976) 258.
7. *Contingency Plans for Chromium Utilization*, National Materials Advisory Board, National Research Council, Washington, D.C. (1978).
8. M. Cohen, "Unknowables in the Essence of Materials Science and Engineering," Materials Science and Engineering **25** (1976) 3.
9. COSMAT Supplementary Report, National Technical Information Service (1975) Volume I.

Gradient Channel Field Effect Transistor

The gradient channel field effect transistor (∇FET) has been developed at Texas Instruments under ONR Contract to improve the linearity and reduce intermodulation distortion of microwave power field effect transistors. The basic principle involved is to introduce a nonlinear donor impurity doping profile under the FET gate such that the total charge depleted under the gate is a linear instead of a nonlinear function of applied gate voltage. This not only improves device linearity but has had the serendipitous effect of reducing device noise.

Texas Instruments and Sylvania are now teamed in an effort to build an electronic warfare system for Air Force use which will use the new ∇FET design. In a separate development, Texas Instruments will use the ∇FET in a low noise 17 GHz airborne radar for Air Force and Navy use.

Hana Kai II: A 17-Day Dry Dive at 18.6 ATA Saturation

Suk Ki Hong*
State University of New York
at Buffalo

Both physiological and technical limitations inherent in conventional breath-hold or SCUBA diving led to development of the saturation diving technique about 20 years ago. Since then a number of saturation diving experiments have been conducted throughout the world. As a result, we now know that men can live, at least for a few days, at a depth equivalent of 2,000 ft. We also know that men are able to perform rather strenuous tasks in a helium-oxygen (heliox) environment at a pressure equivalent to a depth of 5,000 ft. These studies are extremely important in defining the ultimate limit of diving depth which is compatible with the survival of man.

Another equally important question concerns the maximal duration of a dive. However, an answer to this question is more difficult to obtain because multi-day exposure at a given depth is involved, and the divers must also be observed for an undefined length of time after a dive to ascertain that there were no major residual effects on physiological and/or psychological functions.

The major objective of the Hana Kai II ("Hana Kai" means "working in the sea" in Hawaiian) dive was to investigate man's response to a 17-day continuous exposure to a dry heliox hyperbaric environment at 18.6 ATA (absolute atmosphere) which is equivalent to 580 feet of sea water (fsw) or 265 pounds per square inch (psi). The following parameters were measured: 1) energy balance, 2) body fluid balance, 3) cardiorespiratory functions, including physical exercise capacity, and 4) psychological functions. The dive was sponsored by the University of Hawaii and was carried out in collaboration with the Japan Marine Science and Technology Center (Yokosuka, Japan), Webb Associates (Yellow Springs, Ohio), Naval Medical Research Institute (Bethesda, Maryland), and Tripler Army Medical Center (Honolulu, Hawaii). More than 20 scientists from the above organizations worked together and 8 comprehensive scientific reports are published elsewhere (1-8).

Five male members of the Department of Physiology of the University of Hawaii served as subjects. They were selected from 8 volunteers based on rigorous physical, physiological and psychological examinations.

*Dr. Hong is currently Professor of Physiology at the State University of New York at Buffalo. Until 1975, he was Professor and Chairman of Physiology and Director of the NOAA-Sea Grant-sponsored "Human Performance in the Sea" program in the University of Hawaii. He directed the Hana Kai II dive.

The dive was carried out in March and April, 1975 at Makapuu Point in Honolulu using an underwater habitat, Aegir. Although "Aegir" could actually be submerged to a depth of 580 ft, Hana Kai II was carried out at the surface. This dive was supported by the Office of Naval Research and Naval Medical Research and Development Command.

All subjects entered the chamber a day before the start of the 3-day predive control period in order to become acquainted with the habitat as well as with all experimental procedures. During the predive control period, all measurements at 1 ATA air were carefully made. The chamber has then compressed to 18.6 ATA over a 14-hr period. At 18.6 ATA, the chamber gas was composed of 5.84% N_2, 1.64 O_2 and 92.28% helium, with a density 3.8 times higher than that of 1 ATA air. The above concentration of O_2 is equivalent to approximately 0.3 ATA of O_2 pressure which is slightly higher than in air (0.2 ATA). The chamber pressure was clamped at 18.6 ATA for 17 days after which decompression began. After completion of decompression (which took approximately 7 days), all subjects were asked to stay in the chamber for 3 additional days (postdive control period) to repeat all measurements to see if all functions recovered to the predive level. The chamber temperature was maintained at thermoneutral level at which subjects feel neither hot nor cold. It is around 26°C (79°F) at 1 ATA air but had to be raised to about 30-31°C (86^88°F) at 18.6 ATA heliox. The relative humidity was maintained at about 50-70%. The level of CO_2 in the chamber was negligible (CO_2 pressure < 2 mm Hg).

The total length of the Hana Kai II experiment was exactly one month. However, all subjects tolerated the hardship remarkably well, which led to a successful completion of the project.

Energy Balance

It was noted that men under saturation diving conditions lose body weight despite adequate-to-high food intake. However, the reasons underlying the above phenomenon are not known. Therefore, we attempted to study this problem.

To determine what causes the weight loss requires a careful accounting of all the elements of the energy balance accompanied by an accounting of fluid balance. For the calculation of energy input, we determined the daily food intake, caloric loss through feces and urine, and changes in body fat content (i.e., energy store). For the calculation of energy output, we measured the daily O_2 consumption and CO_2 production. Whenever there is an imbalance between energy input and output, one would expect a change in body weight.

The body weight decreased continuously at 18.6 ATA. On the average, the body weight decreased by 1.5 kg (about 3 lb) after 17 days at

18.6 ATA. However, such a weight loss was completely reversed during decompression.

The mean daily energy expenditure increased from 2,261 Kcal during the predive control period to 2,535 Kcal at 18.6 ATA (12% increase). On the other hand, the mean daily energy input (corrected for fecal and urinary losses and changes in body fat storage) remained at about 3,250 Kcal during predive control period and at 18.6 ATA. In other words, there was an excess of caloric intake over expenditure, indicating that the observed reduction in body weight at 18.6 ATA is not due to a caloric deficit. According to our best estimate based on the actual measurements of total body water volume during the predive control period and on the 9th day at 18.6 ATA, approximately 40% of the weight loss can be accounted for by reduction of body water and the rest (60%) by a loss of body fat. Such a loss of body fat in the face of more than adequate caloric intake is a big mystery, and we are not able to explain this phenomenon at this time.

Body Fluid Balance

Maintenance of constant body fluid volume and composition is one of the major requirements to support divers' activities during a prolonged saturation dive. However, we noted that the urine output increased significantly in most of the previous saturation dives reported in the literature. Therefore, we asked the following two questions: 1) What is the mechanism for this increase in urine output at high pressure (this phenomenon will be referred to as "hyperbaric diuresis"), and 2) what are the physiological consequences of this diuresis? Could this lead to a serious loss of body water or electrolytes?

In order to answer the above questions, we carefully measured all elements of body fluid and electrolyte balance accompanied by the determination of total body fluid volume, assessment of renal functions, and measurements of various endocrine factors that influence body fluid and electrolyte balance. For the determination of the fluid balance, the daily fluid intake (drinks, water in food, and water of oxidation) and daily fluid output (urine, fecal water, and insensible water loss) were documented. Similar balance studies were made of three major electrolytes: Na, K and Cl.

As expected from the results of many previous saturation dives, the urine output increased significantly at 18.6 ATA. The daily urine output during the predive control period was approximately 1,800 ml, and increased to nearly 3,000 ml during the first 3-4 days at 18.6 ATA. Subsequently, the daily urine output decreased somewhat, but was still maintained at about 2,500 ml during the rest of the hyperbaric period. On the other hand, the daily elimination of water in the feces remained unchanged throughout the dive. Despite such a persistent diuresis at 18.6 ATA, the daily fluid intake virtually unchanged throughout the dive (approximately 3,000 ml). This means that the observed diuresis is not due to the increased fluid intake. Another interesting finding was that the total body fluid volume as measured on the 9th day at 18.6 ATA was not significantly different from that measured either predive or postdive control period, indicating the absence of net fluid loss (i.e., dehydration). In other words, the overall fluid balance appears to be maintained at the midpoint of the dive despite the increased urine output. This is possible only if the third avenue of the fluid loss (i.e., the insensible water loss) is decreased at high pressure. Although the accurate measurement of the insensible water loss was somewhat hampered by the mild movements of the habitat floating on the water, the results indicated the reduction of this component from approximately 1,500 ml per day at 1 ATA to 1,000 ml at 18.6 ATA. It may be noted that the magnitude of the difference in insensible water loss (500 ml per day) between the two pressures is comparable to that of urine output. Based on these findings it is concluded that the hyperbaric diuresis is primarily due to the suppression of the insensible water loss and also that there is no major disturbance in body fluid balance at high pressure.

Additional comments are needed, however. As stated earlier, the degree of diuresis during the early hyperbaric period was greater than that during the subsequent period. Moreover, unlike during the subsequent period at 18.6 ATA, definite signs of dehydration were noted during the early hyperbaric period, indicating that factors other than the suppression of the insensible water loss are also involved in inducing a greater diuresis at the beginning of the dive. These factors are still largely unknown, but we think it may be related to the redistribution of body fluid leading to an increase in the thoracic blood volume.

The pressure-induced reduction in insensible water loss as described above is most likely due to the reduction in the diffusion of water vapor from the body surface into the hyperbaric environment (with a high gas density). For many years, physicists and engineers have been aware of the dependence of gas diffusion rate on the density of the gaseous atmosphere into which a gas diffuses. Since one component of the insensible water loss involves the diffusion of water vapor from the body surface into the ambient gaseous atmosphere, it is not surprising to see a reduction of the insensible water loss at high pressure.

The reduction in the insensible water loss in the face of a constant fluid intake should increase the total body water volume which would be accompanied by a reduction in the osmotic pressure of body fluid. These changes will in turn suppress the release of antidiuretic hormone (ADH), thereby decreasing the free water reabsorption from the renal tubule (and hence increasing the urine output). The daily excretion of ADH indeed decreased from the predive control level of 40 mU to 20 mU after 5 days at 18.6 ATA.

Cardiopulmonary Functions

The divers experienced altered cardiorespiratory function with increased ambient pressure. The two most consistently reported changes are the slowing of the heart beat (this will be referred to as "hyperbaric bradycardia") and increased work of breathing due to increased gas density. Since the heart rate represents one of the two elements that determine the cardiac output (the volume of blood the heart can pump out per unit time), we attempted to study the impact of the bradycardia on the cardiac output. Moreover, altered mechanics of respiration associated with breathing a denser gas mixture have been known to induce redistribution of blood in the body. Since the maximal oxygen uptake (or aerobic work capacity) depends on the efficient delivery of oxygen to working muscle with the help of the cardiorespiratory system, we wondered if the above described alterations of cardiorespiratory functions at high pressure would interfere with the diver's maximal exercise capacity.

With the onset of compression, a well known bradycardia appeared. The magnitude of bradycardia increased with pressure. By the time the compression to 18.6 ATA was completed, the heart rate decreased from the precompression level of 60 beats to 50 beats per minute. However, the heart rate remained low for only the first 2 days at 18.6 ATA and then increased to the predive level on the 3rd day at pressure. Curiously, the heart rate decreased again transiently to 50 beats per min on the 12th day at pressure. In other words, the heart rate seems to fluctuate during a prolonged exposure to high pressure, and the reasons for this phenomenon are not at all clear at present. More importantly, however, these changes in heart rate were generally associated with inverse changes in the stroke volume (the volume of blood pumped out by one heart beat), and thus the cardiac output remained largely unchanged.

The above changes in the stroke volume were measured by using a non-invasive, electrical impedance plethysmography technique which was developed by Dr. Kubicek of the University of Minnesota. From the values of transthoracic electrical impedance (to the nearest 0.1 ohm) in response to a 100-KHz, 4 mA excitation current, one can calculate the stroke volume and the thoracic conductive volume (TCV). The latter volume has been shown to reflect the intrathoracic fluid volume including blood. Since blood is the most mobile component of the intrathoracic fluid, it is generally assumed that the changes in TCV reflect the corresponding changes in intrathoracic blood volume.

We noted that the TCV tended to increase during the early phase of compression to 10.5 ATA (300 fsw) and then fell. The TCV returned to the predive control level by the 2nd day at 18.6 ATA when the peak diuresis was observed. These findings suggest that the increase in TCV during compression may be the cause of the early increase in urine output, which seems to have produced a systemic dehydration as described above.

It has been known that normal subjects react reflexly to the sudden imposition of nonelastic respiratory loads by one of two typical responses: 1) by immediately increasing the tidal volume (V_T, the depth of breathing) and decreasing the frequency of breathing (f); or

2) by increasing the expiratory reserve volume (ERV, the maximal volume of gas that can be expired from the end-expiratory level) with little or no change in V_T and f. The latter mechanism was dominant in Hana Kai II divers. The ERV increased from 2,500 ml at 1 ATA to 3,100 ml at 18.6 ATA. We also observed an increase in negative inspiratory pressure at 18.6 ATA, which may be in part related to the increase in ERV. Such an increase in negative inspiratory pressure would increase the venous return, accounting for the above described increase in TCV.

One of the well documented effects of high pressure is the reduction of maximal voluntary ventilation (MVV, maximal breathing capacity). Earlier studies by other investigators predicted that the MVV should decrease by about 40% at 18.6 ATA heliox. Our measurements indicated a reduction of MVV from 200 liters per minute at 1 ATA air to 120 at 18.6 ATA heliox, a 40% decrease in agreement with the above prediction.

One of the ultimate goals of saturation diving is to engage in underwater work. Therefore, it is most important to define the diver's maximal work capacity in a given hyperbaric environment. One of the most useful tests for this purpose is to determine the maximal oxygen uptake ($\dot{V}O_2$max) during maximal exercise. At 1 ATA air, the average $\dot{V}O_2$max was 3.10 liters per minute and the endurance time of the maximal work load was 4.19 minutes. At 18.6 ATA, the $\dot{V}O_2$max increased to 3.20 liters per minute and the endurance time to 6.22 minutes. We were at first surprised to find these improvements in the maximal work capacity at 18.6 ATA but then realized that there is a difference in oxygen pressure between the two environments (0.3 ATA at 18.6 ATA versus 0.2 ATA at 1 ATA air). In order to see if such a small difference in the level of oxygen pressure could make a difference in a maximal work capacity we repeated the measurements at 18.6 ATA using a gas mixture with oxygen pressure of 0.2 ATA (instead of 0.3 ATA used in the earlier experiment). Both the $\dot{V}O_2$max and the endurance time returned to 1 ATA values. These results indicate that, despite alterations in various cardiorespiratory functions at 18.6 ATA, the delivery of oxygen to the working muscle to support the maximal work load is not affected by this pressure.

Cognitive and Psychomotor Functions

Measurements of spatial orientation, associated memory, general intelligence, arithmetic ability, reaction time, and personal/social perceptions were made on the divers. In general, there was substantial evidence of a reduction in cognitive performance at pressure. Performance was most severely disrupted during early stages of the dive, with recovery over time. General fatigue (as measured by subject reports, physiological and behavioral observations) was high throughout the dive, partly due to excessive research demands placed on the subjects.

Environmental stressors such as fatigue, anxiety, health problems, personal and social adjustment, and aspects of perceptual deprivation were considered to be influential in reducing performance effectiveness.

In another series of experiments, we studied auditory, visual and gustatory (taste) sensation. In general, auditory and visual functions were maintained well at pressure. However, there were some changes in taste sensitivity, with sweet sensitivity increasing over time and sour sensitivity declining over the course of the dive. Divers were more sensitive to bitter stimuli and less sensitive to salt at pressure.

Summary

Various physiological and psychological functions of 5 male divers were studied during a 17-day heliox saturation dive at 18.6 ATA (with oxygen pressure of 0.3 ATA and chamber temperature of 30-31°C). The results may be summarized as follows:

- The body weight decreased continuously at 18.6 ATA, with an average reduction of 1.5 kg after 17 days. The overall energy expenditure increased slightly (by 12%) at 18.6 ATA, but the total energy intake far exceeded the expenditure.
- The urine output increased significantly at 18.6 ATA while the fluid intake remained fairly constant throughout the dive. Except during the first 3-4 days following compresion (when signs of dehydration were observed), the overall body fluid balance was maintained. The hyperbaric diuresis was attributed to the suppression of the insensible water loss from the body surface. However, other factors (such as redistribution of body fluid) also seem to play a role in bringing about a greater diuresis during the early hyperbaric period.
- The heart rate decreased during the first 2 days at 18.6 ATA, after which it increased to the predive level. However, the cardiac output was maintained normal even when the heart rate was lowered. The intrathoracic blood volume (as estimated by changes in the thoracic conductive volume) increased transiently during the early state of compression, which coincided with the onset of diuresis.
- The expiratory reserve volume increased by 600 ml. The negative inspiratory pressure also increased, which may be partly responsible for the increase in thoracic conductive volume.
- The maximal work capacity increased slightly at 18.6 ATA when the oxygen pressure was 0.3 ATA but was comparable to the 1 ATA air level when the oxygen pressure was reduced to 0.2 ATA.
- Cognitive performance was most severely disrupted during the early stages of the dive, with recovery over time. Some changes in taste sensitivity were noted.

References

1. Hong, S.K., Smith, R.M., Webb, P., and Matsuda, M. (1977), "Hana Kai II: A 17-Day Dry Saturation Dive at 18.6 ATA. I. Objectives, Design, and Scope," *Undersea Biomed. Res.* 4(3): 211-220.
2. Webb, P., Troutman, S.J., Jr., Frattali, V., Dressendorfer, R.H., Dwyer, J., Moore, T.O., Morlock, J.F., Smith, R.M., Ohta, Y., and Hong, S.K. (1977), "Hana Kai II: A 17-Day Dry Saturation Dive at 18.6 ATA. II. Energy Balance," *Undersea Biomed. Res.* 4(3): 221-246.
3. Hong, S.K., Claybaugh, J.R., Frattali, V., Johnson, R., Kurata, F., Matsuda, M., McDonough, A.A. Paganelli, C.V., Smith, R.M., and Webb, P. (1977), "Hana Kai II: A 17-Day Dry Saturation Dive at 18.6 ATA. II. Body Fluid Balance," *Undersea Biomed. Res.* 4(3): 247-265.
4. Smith, R.M., Hong, S.K., Dressendorfer, R.H., Dwyer, H.J., Hayashi, E., and Yelverton, C. (1977), "Hana Kai II: A 17-Day Dry Saturation Dive at 18.6 ATA. IV. Cardiopulmonary Functions," *Undersea Biomed. Res.* 4(3): 267-281.
5. Dressendorfer, R.H., Hong, S.K., Morlock, J.F., Pegg, J., Respicio, B., Smith, R.M., and Yelverton, C. (1977), "Hana Kai II: A 17-Day Dry Saturation Dive at 18.6 ATA. V. Maximal Oxygen Uptake," *Undersea Biomed. Res.* 4(3): 283-296.
6. O'Reilly, J.P. (1977), "Hana Kai II: A 17-Day Dry Saturation Dive at 18.6 ATA. VI. Cognitive Performance, Reaction Time, and Personality Changes," *Undersea Biomed. Res.* 4(3): 297-305.
7. O'Reilly, J.P., Respicio, B.L., Kurata, F.K., and Hayashi, E.M. (1977), "Hana Kai II: A 17-Day Dry Saturation Dive at 18.6 ATA. VII. Auditory, Visual, and Gustatory Sensations," *Undersea Biomed. Res.* 4(3): 307-314.
8. Smith, R.M., and Hong, S.K. (1977), "Heart Rate Response to Breath Holding at 18.6 ATA<" *Respir. Physiol.* 30: 69-79.

New Facility to Test Energy Systems and Concepts

In fulfilling its operational obligations, the Navy has a limited budget with which to buy energy. Understandably, it directs as many funds as possible to supply its sea and air forces. In an effort to achieve the greatest energy return for its financial investment, the Navy wants to reduce consumption of natural gas, electricity and fuel oils at shore facilities. The plan is to make Navy bases as energy-independent as possible of commercial sources.

The answer can be found in two approaches: (a) development of alternate power systems such as solar, wind, ocean thermal energy conversion, and geothermal; and (b) energy conservation. To achieve these goals the Navy has built the Advanced Energy Utilization Test Bed (AEUTB) at the Civil Engineering Laboratory (CEL), Naval Construction Battalion Center, Port Hueneme, Calif. The AEUTB is the only site in the country designed and built solely for research and development of energy conservation and alternate energy sources. Its basic purpose is to test specific energy systems and concepts to evaluate integrated systems.

CEL will continue to alter the physical characteristics of the test bed to evaluate a variety of heating, ventilation, air conditioning and energy systems for eventual inclusion into Naval shore facilities. The highly diversified site contains 1,300 square feet of working space. By adjusting Movable walls and ceilings, it can be transformed into office spaces, medical facilities or typical family housing, complete with heating, cooling and sanitary systems. Incidentally, the single family, two-story, three-bedroom residence for enlisted men is the most common structure in the Navy's real property inventory. The test bed now controls seven energy systems during its initial research efforts. Two are alternate power sources, solar and wind. The other five are conservation systems; (1) the shell of the test bed, (2) lighting, (3) heating and cooling, (4) electrical, and (5) equipment for detection and measurement of energy losses.

The AUETB may be common to a variety of building uses but its capabilities are new and unique. For example, utility systems can be switched from conventional energy sources to wind or solar sources by flipping a switch, changing a plug or repositioning a vent. This permits integration of different systems, using solar or wind generated energy to augment or replace conventional sources. Any combination of two, or all three, can be utilized at one time. The test bed's integration capabilites enable engineers to obtain data on system interrelationships: information not presently available anywhere. Only through a testing capability such as the AEUTB can the best combination of energy conservation and alternate energy systems be determined.

Test bed for energy research — The Advanced Energy Utilization Test Bed (AEUTB) at the Navy's Civil Engineering Laboratory, Port Hueneme, Calif. is the only system designed and fabricated solely for research and development of energy conservation and alternate energy sources.

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: $11.00 per year in the U.S. and Canada; $13.75 per year, foreign; $1.00 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:

L. LARMORE, ONR PASADENA
G. SANDOZ, ONR CHICAGO
A.L. POWELL, ONR BOSTON
D.A. PATTERSON, NAVAL RESEARCH LABORATORY

IN THIS ISSUE

VOL. XXXI, NO. 10

This article describes the partnership between man and his materials and society's intellectual approach to the understanding and utilization of materials through science and engineering.

The following parameters were measured: energy balance, body fluid balance, cardiorespiratory functions, including physical exercise capacity, and psychological functions.

Cover Caption

New Navy Ships such as the hydrofoil Pegasus require new and improved materials to meet their projected performance requirements. Another example of man and his material needs. *(See article beginning on page 1.)*

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
DoD-316
CONTROLLED CIRCULATION RATE

U.S.MAIL