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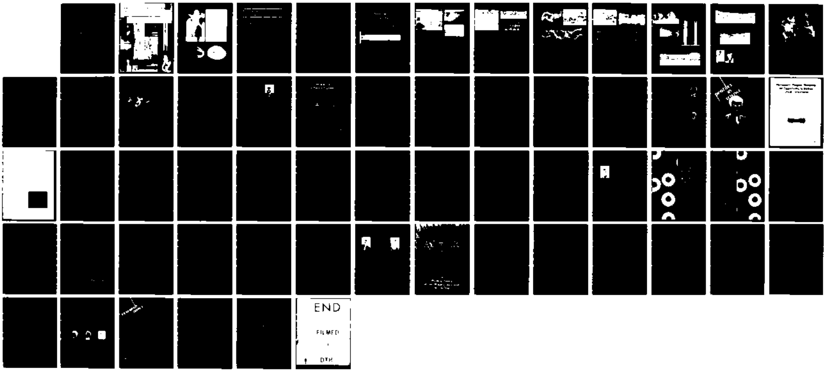

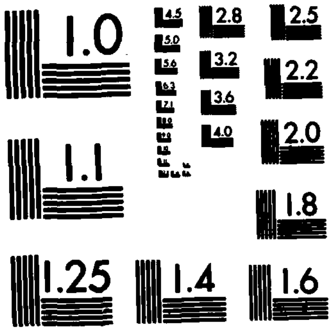

MICROCOPY RESOLUTION TEST CHART
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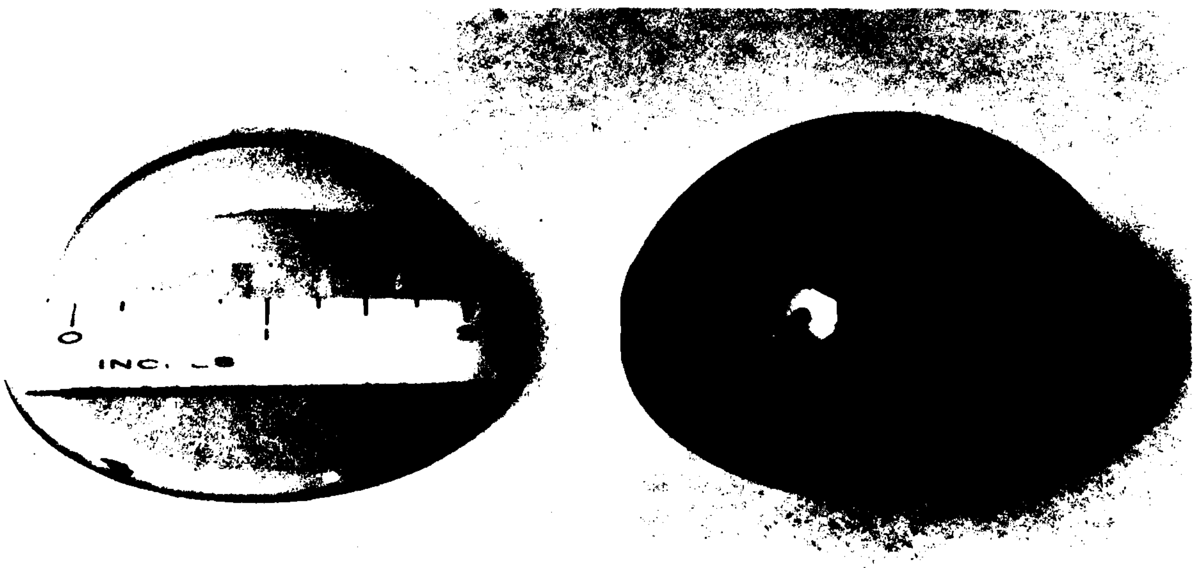
Naval Research Reviews

Office of Naval Research
Four 1982
Vol XXXIV

Engineering Sciences

Office of Naval Research investigators have been discovering new materials for missile domes and providing the scientific bases for improving existing materials since the late 1960's. The dome is at the front of the missile and is essentially a window that protects the imaging system. In some cases the dome properties can limit the missile flight profile.

ONR studied in the early 1970's the fracture behavior of dome materials and developed the fundamental phenomenology of fracture processes. In the mid-1970's, ONR made major contributions to understanding the erosion behavior of domes due to dust and water drop impact. During this period, ONR also contributed to the understanding of the effects of thermal shock on the fracture of domes. In the early 1980's, ONR scientists discovered new materials and new concepts for toughening domes. This on-going research is preparing new materials for the future Navy.



The black dome (right) is hot-pressed magnesium fluoride or IRTRAN-1. Domes of this type have been used for many years. The clear dome (left), developed by the Office of Naval Research, is an advanced replacement for the IRTRAN-1 dome and has much better erosion resistance, hardness and clarity at visible wavelengths than the earlier dome material.

Naval Research Reviews

Office of Naval Research
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Vol XXXIV

ARTICLES

DEPARTMENTS

About Our Cover

Through specialized photography, as shown on the cover of this issue, new phenomena pertaining to the fluid dynamics of simple water jets have been revealed. This research will lead to improved Navy fire-fighting capabilities as a result of better hose-nozzle design.

Naval Research Reviews publishes articles about research conducted by the laboratories and contractors of the Office of Naval Research and describes important naval experimental activities. Manuscripts submitted for publications, correspondence concerning prospective articles, and changes of address, should be directed to Code 732, Office of Naval Research, Arlington, Va. 22217. Requests for subscription should be directed to the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402. For this quarterly publication a yearly domestic subscription is $11.00 and foreign is $13.75. A single domestic copy is $3.75 and foreign is $4.70. *Naval Research Reviews* is published from appropriated funds by authority of the Office of Naval Research in accordance with Navy Publications and Printing Regulation P-35. Controlled circulation postage paid at Washington and additional mailing offices.

The Engineering Sciences Directorate of ONR —"Science makes it known; engineering makes it happen."*

by Aurthur M. Diness

The Engineering Sciences Directorate of ONR includes three Divisions which cover the program areas of mechanics, materials, and the information sciences. The articles published in this issue of *Naval Research Reviews* reflect examples of scientific goals and research challenges of the Engineering Sciences Directorate and provide insights and illustrations of the exciting opportunities for responding to critical and anticipated engineering research needs of the Navy and Marine Corps. These goals and opportunities are a reflection of what the Office of Naval Research has as its deepest concern, the advancement of science and engineering so as to improve the U.S. Navy's operational capabilities.

The recent ONR management initiative that created the Engineering Sciences Directorate integrates several primary engineering disciplines into a single structure. The thrusts of the Directorate can be stated in a succinct way: "Science makes it known; engineering makes it happen." This new structure gives special recognition to the frequent need for interdisciplinary and transdisciplinary research in many areas of research which are of naval interest. Indeed, the important message of these articles, beyond their description of particular project approaches and progress, is the demonstration that cross fertilization of concepts within the young Engineering Sciences Directorate and between the engineering research community and allied disciplines has already begun to develop solutions to basic problems, which span the engineering sciences and which are of great importance to the Navy.

The papers in this issue supply both overview treatment of Division activities and in-depth coverage of selected research topics. The Mechanics Division, spanning the fields of fluids, structures, and propulsion, is represented by a paper on nozzle flows which gives an overview of research performed on the instabilities in free water jets. Unique photographic and flow visualization techniques are used to study fundamental changes in free jet characteristics between water and dilute polymer/water solutions. In the case of the Materials Division, the research story is told in three papers. One article develops an overview of frontier scientific activity aimed at achieving the understanding that will lead to improvement in lasting protection against corrosion of metals through the use of organic coatings. A second article, related to the need for improved sensing capabilities, emphasizes the potential of "composite ceramic materials" to enhance the reliability and stability of advanced optical and electronic devices. The last paper, facing concerns about increased costs and the possible unavailability of cobalt, describes research efforts to discover new materials to substitute for permanent magnets which contain cobalt. The Information Sciences Division is represented by two survey papers treating the broad subjects of software engineering and artificial intelligence. A common interest of these, tied to the urgent goal of both reducing the costs and improving the quality of computer software, is the design of methodologies to provide sophisticated tools to facilitate human programming and, ultimately, to exploit artificial intelligence concepts for the full automation of the total programming process.

Examples of interdisciplinary activity are both explicit and implicit in this set of articles from the Engineering Sciences Directorate. Progress in the development and use of organic coatings is attributed to research approaches that integrate the disciplines of surface chemistry, electrochemistry, metallurgy, and polymer science. A new program in manufacturing science, essential to its objective of realizing dramatic improvements in advanced automation procedures, consciously incorporates the technologies of mechanical engineering, materials science, and artificial intelligence into a single program construct. Further, the necessity of comprehending the potential impact of automation on national societal and economic concerns is the basis for continuing close liaison and joint research efforts between the engineering sciences and psychological sciences research programs. Additional opportunities of this kind exist in programs being planned and implemented in areas such as precision engineering, structure-fluid interactions, materials processing and ramjet propulsion. We intend to have our programs both "make it known" and "make it happen" in the engineering sciences. It is the commitment and dedication of the Engineering Sciences Directorate to forge new and more profound approaches for responding to Navy problems and scientific issues, in many cases through opportunities arising from a continuous exploration of interdisciplinary research opportunities. ■

*An old saw of uncertain origin.

Water-Jet Photography

by

John W. Hoyt
and
John J. Taylor
San Diego State University

Figure 1. Water discharging from a 0.25 inch diameter nozzle with 50 pounds per square inch nozzle pressure.

Through specialized photography, new insights have been opened into the fascinating fluid dynamics of simple water jets. With a goal of improving Navy fire-fighting capability through better hose-nozzle design, the fundamentals of water-jet flow are being explored with the support of the Office of Naval Research. The concept of improving nozzles for fire-fighting was an outgrowth of observations that jets of dilute polymer solutions appeared much more coherent, had far less spray, and seemed to carry further than ordinary water jets. To really begin to understand these differences in water jets, high-speed photography is required.

In order to capture details of the jet flow, high-speed macrophotography was desired. Specialized cameras, adapted to the predominantly axial motion of the water jets, were designed and built by one of the authors, J. J. Taylor. The basic principle of his cameras is to compensate for the axial motion of the image of the jet. This is done by either moving the film, or rotating the image with a rotating mirror, so that at the instant of exposure, the axial motion of the image is stopped on the film. All the jet photos shown here were taken with these specially designed cameras. Lighting techniques are extremely important to bring out detail, and this area required much development also. The final exposure is by one or more electronic flashes, modified to give sharp cutoff exposure times of about 5 μsec.

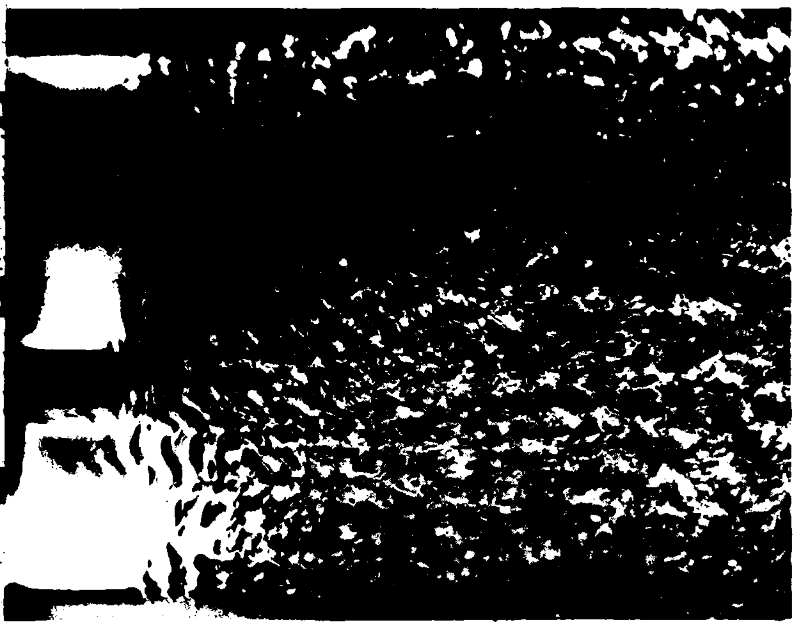

Figure 2. Detail of laminar-turbulent transition waves on surface of water jet.

Figure 3. View of amplification of surface waves with consequent spray detachment.

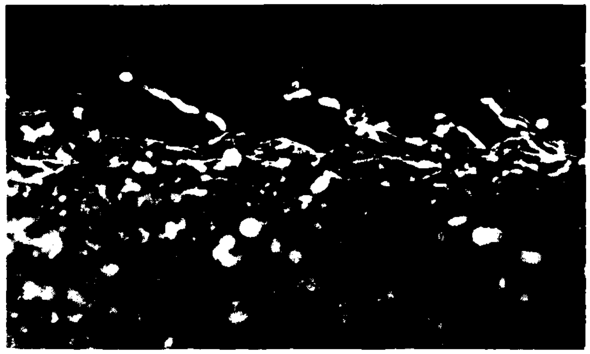

Figure 4. Close-up of spray formation on surface of water jet.

When one looks at a jet of water from a garden hose (and all of these photos were taken at pressures and with nozzle sizes typically found in home garden hoses) the impression is usually that of a very short region of clear water emerging from the nozzle, followed by a cloudy, spray-emitting jet from then on. The fluid mechanics of this common observation are revealed by high-speed photography.

Figure 1 shows the jet from a ¼ inch diameter nozzle at a water pressure of 50 pounds per square inch. The clear zone at emergence is laminar flow, with instability waves on the jet surface finally breaking down into turbulence. Motion perpendicular to the jet axis becomes so violent that water particles become detached and spray appears. The surface of the jet is no longer clear, but becomes an opaque white. How the initially laminar zone is formed from the turbulent flow upstream of the nozzle is another fascinating bit of fluid dynamics, and not well understood, since by any calculation of Reynolds number or other scale for indicating the flow state, the emerging jet should be turbulent. Nevertheless, jets from many types of water nozzle have transition to turbulence on the jet surface after emergence from the nozzle.

The transition begins when surface waves appear (the free-surface analogue of Tollmien-Schlichting waves in the boundary layer). Some details of these waves are shown in Figure 2. Initially the waves are almost axisymmetric, but quickly change to a more irregular pattern. The wave spacing (wave-length) can be predicted from linear stability theory. Smaller waves can occasionally be seen riding on the crests of the major waves. The amplitude of the waves then increases until particles of water are thrown radially outward as shown in Figure 3. The details seen in these photographs provide new insight into the mechanism of jet breakdown. These findings may lead to a consistent theory of jet breakdown.

More detail on the spray formation is given in Figure 4, where it can be seen that water particles, initially ejected vertically, assume a slanted position with respect to the jet axis. This is because immediately upon ejection they are subjected to air resistance and lose some of their axial velocity. Slowing down, they become slanted backwards with respect to the jet. Meanwhile, surface tension is pinching off spherical droplets which become the spray. These droplets form a cloud around the jet.

If the surface tension is reduced, the spray-pro-

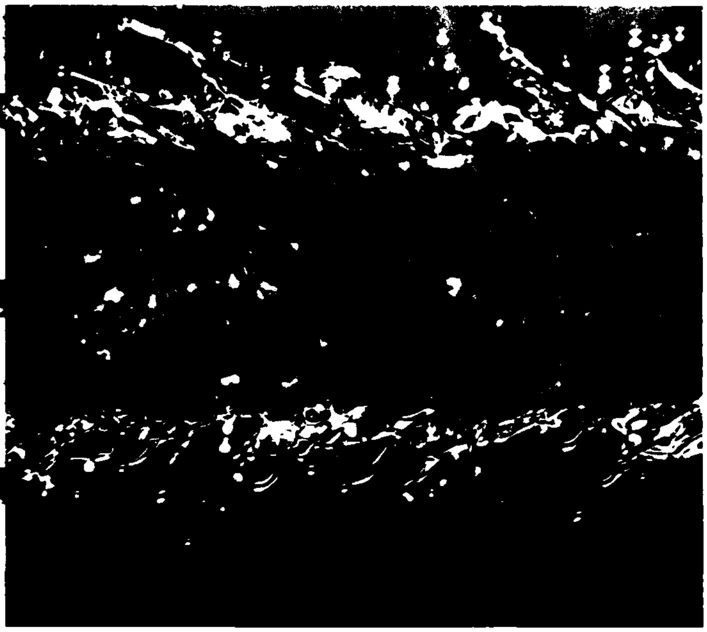

Figure 5. Low surface-tension enhances the spray-production phase of a Kerosene jet.

Figure 6. Water jet surrounded by spray. Helical motion can be detected. (144 nozzle diameters downstream.)

Figure 7. Bubbles of air riding on the surface of a water jet. (Rayon threads have been added to the water to demonstrate that the flow inside the jet is turbulent.)

duction effect is amplified. Figure 5 shows a jet of kerosene with copious spray formation due to its low surface tension. All of this is happening within a few jet diameters of the nozzle exit.

A few more jet diameters (physical length downstream divided by the diameter of the nozzle) downstream, the jet appears to be surrounded by spray (Figure 6) while the surface of the jet itself has changed significantly. Bubbles of air are now riding on the surface of the jet. These air bubbles have been formed by the action of the water particles initially detached from the main surface of the jet. A part of the detached water (that part not pinched off to form spray) returns back into the jet, bringing a bubble of air with it. These bubbles will ride on the jet surface, gradually disappearing until they are nearly all gone by the final jet breakup.

With lighting especially adapted to see through the jet, the bubbles are distinctive, as shown in Figure 7. Occasionally the release of a bubble can be seen in a photo, as in Figure 8, with consequent circular ripples on the surface of the jet.

Jets are unstable to two kinds of disturbances; axial and helical. Theory suggests that the axial instabilities (corresponding to the initial waves on the jet surface) die out after a few nozzle diameters downstream and the helical instabilities, amplified by aerodynamic resistance, cause the final jet breakup. Photographs verify the theory. The rather slight helical motion noticed in Figure 6 is further amplified as shown in Figures 9 and 10 until the entire jet is describing a corkscrew-like motion. Of course, this mode cannot exist very long and aerodynamic forces on the jet cause it to become distorted, as in Figure 10, and finally disintegrate in a cloud of spray as shown in Figure 11.

All of the preceding photos were of jets from a conventional tapered nozzle of the type used in fire-fighting. If the nozzle is designed to optimize laminar-flow production so that the jet remains laminar beyond the usual axial instability region of a few nozzle diameters, the spray-production phase can be largely avoided and the jet surface will remain smooth throughout the length of the jet. Figure 12 shows such a jet leaving the nozzle (a slight internal turbulence developing inside the jet is revealed by the lighting which makes the jet transparent). At the helical instability phase, Figure 13 shows the jet surface to remain smooth. Small particles of rayon thread have been added to the flow in order to assist in the

Figure 8. Air bubbles breaking out of the jet surface leave circular ripples.

Figure 9. Enhancement of the helical phase of water jet flow.

interpretation of the photos.

The addition of high-polymers to the jet causes a very distinct visual effect. Figure 14 shows side-by-side comparisons of a pure water jet and one containing 200 parts per million of poly (ethylene oxide). This polymer is occasionally added to fire-fighting hosestreams since it greatly reduces the turbulent friction thus giving a greater water pressure at the nozzle. Both water and polymer jets are at the same pressure of 50 pounds per square inch in Figure 14, however.

When the polymer jet is photographed and compared with a water jet at the same pressure and using the same nozzle, (Figure 15) part of the reason for its smoother appearance to the eye is immediately apparent. The polymer jet has had transition to turbulence inside the nozzle itself, and thus short-circuits the spray formation phase of the water jet. This observation of earlier transition to turbulence in polymer-solution flows has been verified by other experiments also.

Another attribute of polymer-solution flows is their viscoelastic characteristic. That is, the flowing liquid is not only viscous, but also elastic like a rubbery solid. The net result is that the surface of polymer jets is smooth, since the small-scale axial instabilities are quickly damped. Looking at the jet a few tens of diameters downstream from the nozzle (Figure 16) we see that the surface is smooth and the helical instabilities are discernible. Further downstream (Figure 17), the helical pattern is striking, and the jet appearance resembles a twisted rod of glass.

Finally, at breakup, several hundred nozzle diameters downstream, the thread-forming or "pituitous" character of polymer solutions subjected to elongational stresses becomes evident. Figure 18

Figure 10. The jet has almost disintegrated due to its corkscrew-like motion.

Figure 11. All cohesiveness is lost as the jet breaks up. (288 diameters downstream.)

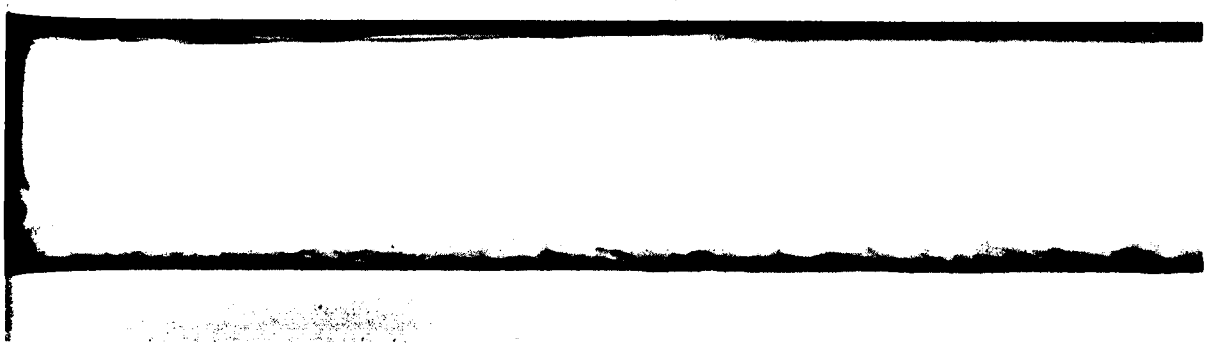

Figure12. Water jet emerging from special design nozzle at left. The laminar flow is seen to contain growing turbulent areas inside the jet.

demonstrates how droplets associated with the jet disintegration are tied together with long threads of polymer. These threads are formed because of the high "elongational" or stretching viscosity of the polymer solutions. Thus the overall jet is much more compact when polymers are used, compared with the spray-like disintegration of pure water jets. This greater coherence may be of value in placing fire-fighting streams in precise locations as is occasionally the requirement in fighting shipboard fires.

Many fluid-dynamic details of water jet flows still remain unexplained. It will be a long time before we can say that we completely understand this complicated flow which we take for granted in our everyday life. Through photography, we have been able to reveal some of the flow processes. We are confident that this new knowledge will be useful in designing better flow nozzles both for fire-fighting and for industrial operations. ■

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Figure 13. The helical phase in a jet designed to avoid axial instabilities.

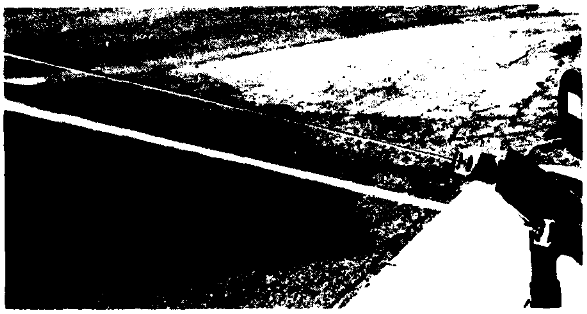


Figure 14. Visual comparison of water jet (foreground) and jet containing 200 ppm poly(ethylene oxide) in background. Both jets are at same pressure and nozzles are identical in design.

Figure 15. The polymer jet (below) is discharging at the same pressure and from the same nozzle as the water jet above. Transition to turbulence occurs inside the nozzle when polymers are used.

Figure 16. Helical instabilities on a 200 ppm poly(ethylene oxide) jet.

Figure 17. The helical phase becomes more exaggerated in a polymer jet, 192 diameters downstream.

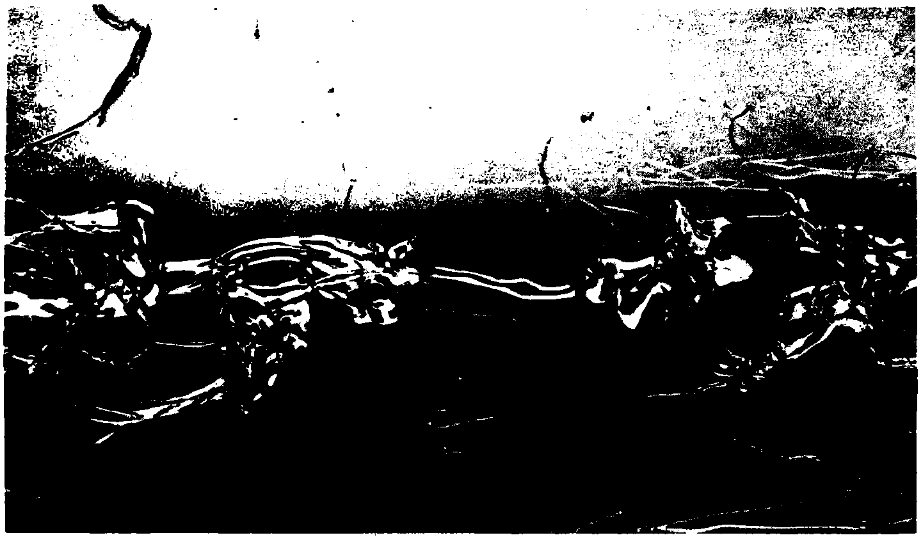
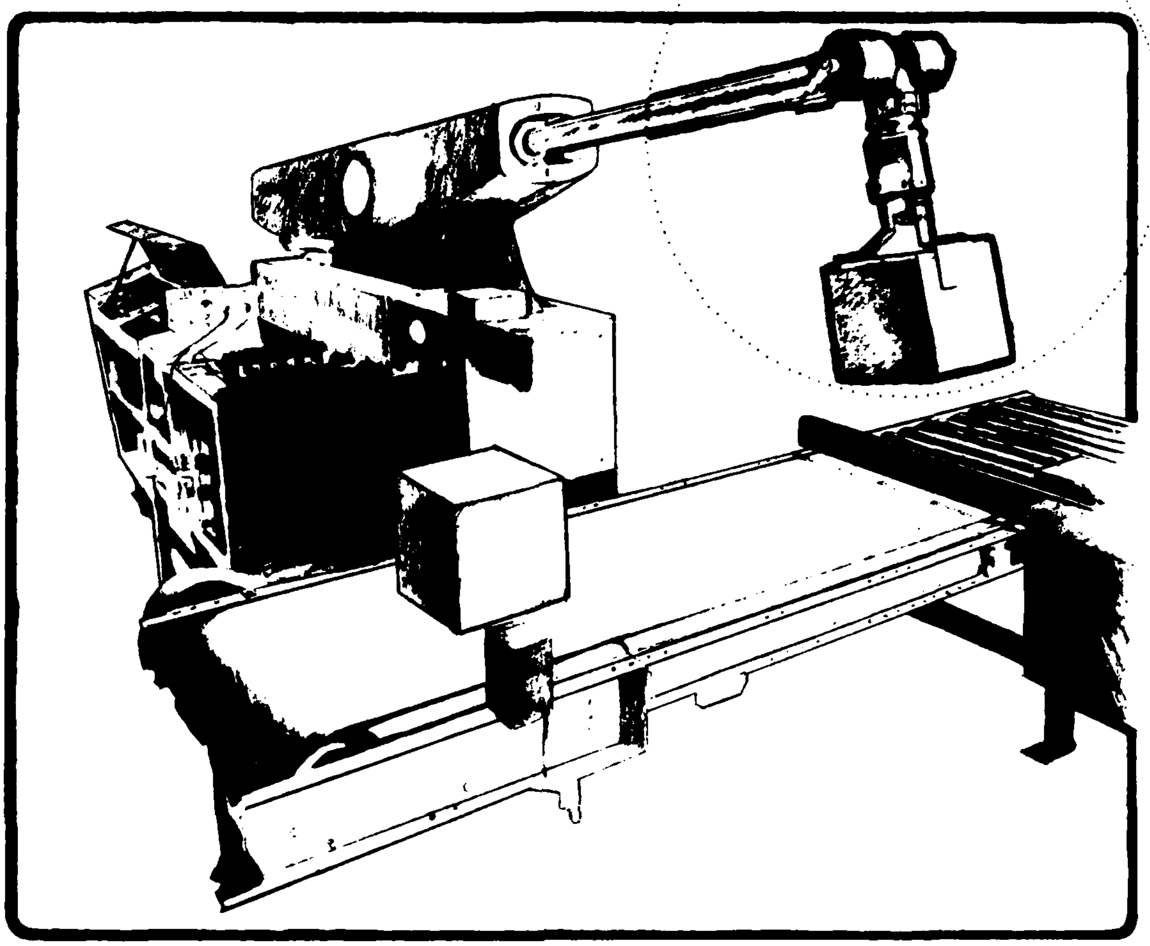


Figure 18. Breakup of polymer jet, 335 diameters downstream.

Authors

Jack Hoyt and John Taylor, shown here working on water jets, have been associated for serveral years in this Office of Naval Research sponsored research. Dr. Hoyt has taught at the Naval Academy, Rutgers, and now at San Diego State since leaving the Naval Ocean Systems Center where he was a research engineer. Mr. Taylor is an independent consultant and was formerly Chief Engineer at the Ohio Brass Co.



Research Directions in Artifical Intelligence

by

Alan L. Meyrowitz
Office of Naval Research

Introduction

The Office of Naval Research (ONR) program in artificial intelligence (A.I.) has two main components, one in automated aids to decision making and the other in robotics. Broadly viewed, research in the first area is intended to automate and extend human intellectual skills, and research in the second area is intended to do the same for human physical skills. There is a strong connection between the two areas, inasmuch as the robots of interest are those which exhibit intelligent behavior in planning and performing their activities. Many of the procedures for problem solving, which are crucial to aids to decision making, will play an important role in the controlling software for intelligent robots.

Designers of A.I. systems do not try to anticipate situations in detail. Instead, they build into their systems a broad knowledge of facts and strategies which will enable the systems to cope with whatever situations may arise. In order to build such systems and endow them with qualities we normally associate with intelligence several basic research areas must be addressed.

These are:

a. Knowledge Acquisition, which studies alternatives for the intelligent system to obtain the information which it needs to do its work.
b. Knowledge Representation, which is concerned with expressing that information, and organizing it so it can be accessed and used efficiently.
c. Automated Reasoning, which is concerned with learning and adaptation, and building procedures to mimic the human capabilities for planning and solving problems.
d. Human-Machine Interface, which studies devices for building a rich environment of two-way communication between people and machines.
e. Psychology, which studies the skills and information which people bring into situations where they would want to use intelligent systems; psychological studies thus help provide for a careful match between the capabilities of people and the capabilities of machines.

ONR contractors are addressing these basic research areas as they build the scientific foundations for a number of applications which are going to be important to the Navy in coming decades; principal among these being expert systems, natural language understanding systems, and crisis alerting systems. Current research directions to develop such systems as aids to decision making, and research directions in the area of robotics, are described below.

Expert Systems

Expert systems[1] are computer systems that provide advice and consultation in specific knowledge areas, such as equipment maintenance, situation assessment, or electronic circuit design. Research to support expert system technology has advanced to the point that a new profession called knowledge engineering has emerged. Typically, the person who is a knowledge engineer will interrogate the person who is a domain or applications expert in order to learn both the data about the expert's knowledge area and the heuristics, or rules of thumb, which the expert routinely uses to solve problems. Such an interrogation can proceed tediously over several months or more, and the information derived is incorporated into the automated system as rules of inference, usually called production rules. The expert system will operate by applying the production rules to information in its knowledge databases and to information provided by the user to describe his current problem. Reasoning is thus a process of automated deductive inference as the user interacts with the system through a computer terminal. On the one hand, therefore, progress has been made on key aspects of building the knowledge bases and production rules to create the expert system, and on the other hand important work has been accomplished to provide a mechanism to allow a person to access and use the system.

The state-of-the-art as briefly described above is not sufficient to build the more advanced, sophisticated systems which the Navy will need, systems in command and control, for instance, or in logistics, where they would serve as aids in the design, manufacture, use, and maintenance of equipment. One severe constraint which must be overcome is that current systems can conveniently present only a single point of view. An expert system for equipment maintenance, on the other hand, ought to present not only the point of view of the blue-collar worker who routinely repairs the equipment, but also the points of view of his supervisor, the manufacturer, and the equipment designer among others. It can be argued that any user should be able to select the point of view appropriate to his needs; the alternative is to somehow merge all points of view into a single authority, an authority sensitive to the needs of the user as an individual and to the demands of the problem being presented. Conceptually, that is a very difficult task.

There is also a need to speed system creation by allowing the human expert to build a system by himself through interactive dialogues with the computer. Ideally, he should be able to say less, with the computer offering enough intelligence to fill in details, make generalizations, and suggest improvements to problem solving strategies. Special languages not now available will be needed to facilitate the specification of objects, relationships between them, and the building of the production rules that are the heart of the system.

The advanced expert system during use should support the dynamic fix, which is to say if the user feels he has a problem solving strategy which is better than one offered by the system, he should be able to annotate the system to make his suggestion available for subsequent evaluation by himself and other users. Eventually, the expert system should be smart enough to substitute one strategy for another based on the system's own assessment of which is superior.

In the area of knowledge representation, it is currently the case that expert systems cannot cope with more than about 1000 production rules, and the complexity of each rule is limited to guarantee a real-time capability of interacting with the user. Research is needed to support systems requiring thousands, even tens of thousands, of production rules, and in this regard we must explore the theoretical limitations on our ability to access, search through, and computationally manipulate those many thousands of rules.

In addition to strengthening our ability to automate deductive inference, sophisticated systems will require us to automate inductive inference, reasoning by analogy, and common sense reasoning. Inductive inference[2] will allow the system to learn from experience as people do; analogical reasoning will enable a system to solve a current problem by reviewing its memory of previous solved problems, and is the key to eventually building systems which can reason across knowledge areas; and common sense reasoning will enable the system to show sound, practical judgement independent of any specialized knowledge which might be built into it.

With ONR support, considerable research is underway to explore the potential of computer interface devices such as touch screens and video disks. The long-term objective of this work is to allow the user the greatest possible flexibility in choosing how he wants to enter information into the system and how he wants to get information out of the system. Techniques to be developed will likely emphasize the use of advanced graphics capabilities integrating text with cartoons, photographs, motion pictures, and sound[3].

The main thrust of pertinent psychological studies is to determine what expert systems, and what designers of expert systems, need to know about people. Human problem solving techniques (and flaws in those techniques) must be studied to guide us in the design of expert systems which can be used for training people in disciplines requiring complex problem solving skills. We also want to know more about how to design expert systems which can explain their behavior in terms the user can best understand. In general, we need to know more about how people reason about complex systems; this to provide clues to the automation of problem solving strategies (although we do not want to limit automated systems to procedures which apparently operate within the human mind).

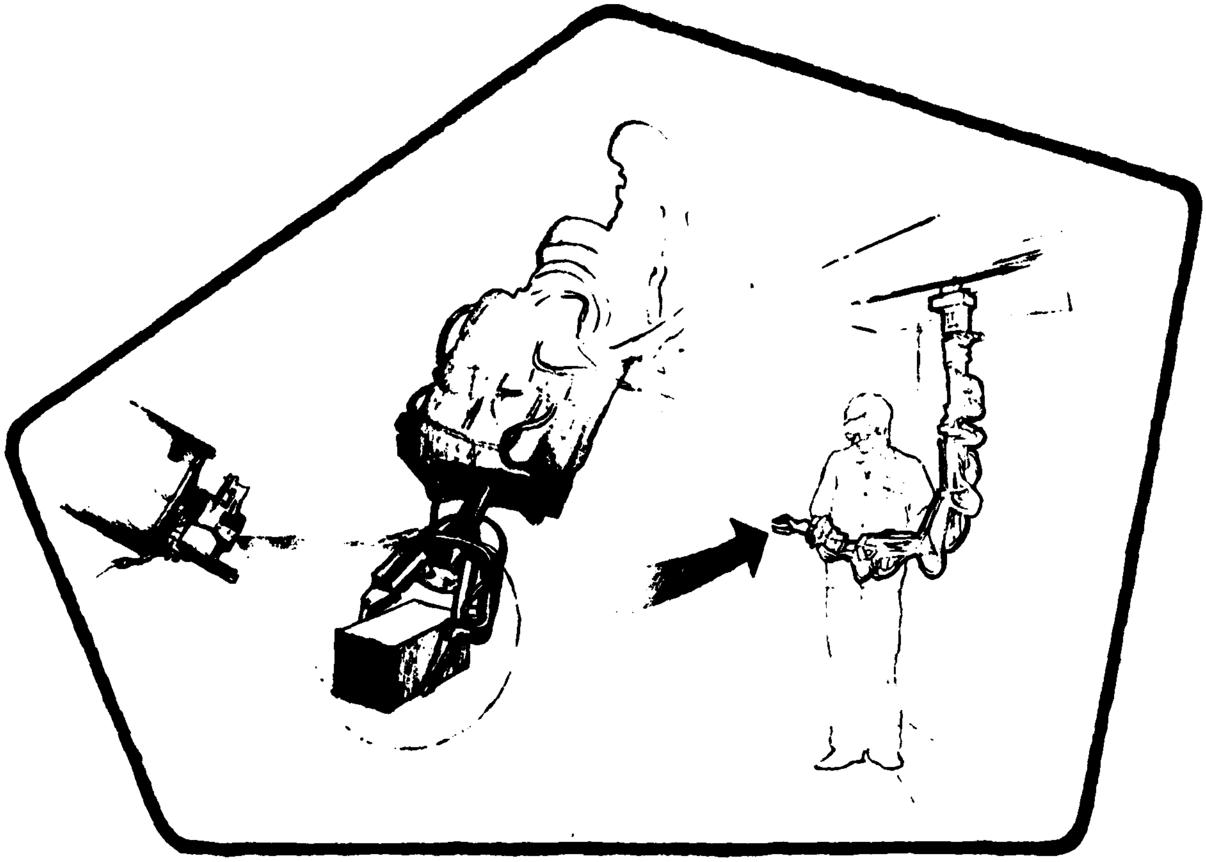
Natural Language Understanding

Research in natural language understanding[4] is to a large extent directed toward the automatic comprehension of the English language in which people habitually think and communicate. A short-term goal likely to be realized in the coming decade is the development of a natural language system with advanced capabilities to serve as the front-end to a database; this would allow a user with virtually no technical training to update a database and obtain information easily. A fragment of a dialogue between a user and a natural language system might appear as follows:

USER:	Which planes have crashed during the past 12 months?
SYSTEM:	Does 'planes' refer to classes of aircraft or to particular aircraft?
USER:	Classes of aircraft.
SYSTEM:	Two planes have crashed during the past 12 months.
USER:	Which ones?
SYSTEM:	(Plane designations)

As the fragment illustrates, the system is capable of recognizing ambiguities and requesting clarification; it also is able to build up an understanding of the context of the questions as the dialogue proceeds, so the user does not have to restate his interests. Such capabilities can be found to a limited extent in a number of existing prototype systems, but in general it is true that a great deal of research must still be done to design systems which can understand questions referencing a very broad context, understand complex grammatical constructions beyond simple nouns and verbs, not be too literal in interpreting questions and statements, understand metaphors, and appreciate the psychological nuances of language. Notwithstanding the great deal of work remaining, tremendous progress has been made and natural language understanding systems are now moving out into the commercial world.

Related work which ONR is supporting has the long-term objective of developing systems which can automatically assimilate information. Such systems could be used, for example, to review the huge volume of information now warehoused by the intelligence agencies and which includes books (in many languages), journals, motion pictures, trip reports by persons who have visited foreign countries and have written about their experiences or perhaps



have only drawn pictures of what they have seen, etc. Systems capable of assisting in this review must be able to index material, construct abstracts, recognize contradictions, inconsistencies, and similarities, organize material by priority, and assign credibility to information.[5]

Crisis Alerting Systems

Crisis alerting systems are systems which take an active role in warning about imminent critical events. The majority of current conventional information systems are batch oriented and produce reports once a month, or once a week, in any case long after a database has been updated. Even when there is a capability for the user to sit at a terminal and interrogate a database in real-time, the situation is still dependent upon the right person asking the right question at the right time. What is needed is a system which can take an active role: once a manager, for instance, has expressed his concerns, the system should automatically monitor the incoming data streams looking for situations that match those concerns. ONR contractors have been very successful in building such capabilities into database management systems, and these systems are now transitioning into other government agencies and the Navy labs. For example, the Naval Ocean Systems Center at San Diego has picked up for further study the recent excellent work in alerting systems which has been accomplished at the University of Pennsylvania, where a database provided by the Federal Aviation Administration was a major catalyst in accelerating the research effort. The FAA database provided a five-year historical file on the planes in question, including detailed flight schedules, manufacturing data, malfunctions and maintenance data. With the aid of an advanced data base management system, the database was explored in a multiplicity of ways to identify distributions and trends in equipment failure, and this provided insights in the experimental setting and monitoring of alerts.

Deep problems remain to be solved in issues related to the setting of thresholds within alerting systems, monitoring those thresholds, and conveying alerts to users once those thresholds have been passed. There is a need, for instance, to provide a capability for post-alert exploration of the database, so that the user can sit at a computer terminal and ask any question about the alert: who set the alert, what the threshold was, what the source of the information was, etc. Source calibration is particularly important in military intelligence, since some sources may routinely overstate or understate, and knowing this is crucial to deciding how we should react to an alert. There is also a need to automatically resolve inconsistent alerts set by various users of the information system, and we would expect the system to be smart enough to realize when two or more people are interested in the same alert even though they may be using different words to express themselves. An alerting system with advanced capabilities must also be able to cope with too many alerts being sounded (the Cry-Wolf Syndrome); it will be necessary to filter out minor alerts so the really important ones can be identified. As a final example of an area to be explored, we need to better define when and how the automated system should take action on its own in response to an alert. In the manufacturing environment, for instance, an alert might sound on the assembly line to indicate an important part is about to be depleted. Rather than have a human being fill out a requisition form, it may be preferable to have the system activate a robot which would go into a warehouse and retrieve the needed parts from a bin.

Robotics

The ONR program in robotics is intended to extend the capabilities of robots and apply robotics to the solution of Navy problems. An evolution is desired to move us from the use of essentially dumb robots to the use of intelligent robots capable of self-correcting behavior to cope with unexpected events. The approach has been to create and maintain centers of excellence in robotics at Carnegie-Mellon University and at the Massachusetts Institute of Technology where a multidisciplinary effort can be applied drawing upon the talents of outstanding researchers in computer science, artificial intelligence, mechanical engineering, mathematics, psychology, and operations research. Research in special topics is also supported at other universities and industrial sites; several projects have the combined participation of academia, industry, and the Navy laboratories.

In building the scientific foundations for advanced robotics, ONR contractors are addressing the following topics:

a. Reasoning, which is vital to the operation of machines which can learn and adapt, plan their activities and solve unexpected problems.
b. Sensing, which includes not only vision but also touch and hearing.
c. Manipulation, which includes the design and demonstration of robotic hands having the same dexterity as the human hand.
d. Mobility, which would allow a robot to walk freely around a room, crawl, climb a ladder, do anything, for example, that might be required to allow movement around a ship.
e. Spatial management, which addresses the need to organize the environment in which robots must work and anticipate constraints imposed by the environment.
f. Multiple robots, which must work cooperatively on complex tasks.
g. Efficient computational algorithms, which are required for the real-time control of intelligent robots.

The accomplishments to date in the robotics program have been numerous, and include new formulations for the differential equations which govern the motion of arms with many joints—formulations which can be applied to allow the real-time control of the arms required for complex activities; the design and bulding of arms and hands actuated by tendons, where tendon control is seen as the basis of a technology allowing truly dexterous devices capable of intricate assembly operations and the manipulation of objects for inspection; new materials and techniques to automate the sense of touch; and vision systems which can recognize shape by using shading and binocular stereo.

Major research activity in the coming decade will include the design of new robotic software incorporating modern mathematical techniques with the classical heuristic approaches of artificial intelligence; procedures to support autonomous underwater robots and vehicles; robotic arms with a high power-to-mass ratio and excellent dynamic response; and new techniques for integrating vision, touch, and hearing within a single robotic system. Potential applications of intelligent robots include underwater assembly and maintenance, mine sweeping, search and recovery, and scientific missions.

Conclusion

Expert systems, natural language understanding systems, crisis alerting systems, and robotics are not disjointed areas of research activity.[6] Quite the contrary, they have a common basis in the fundamental research issues that were listed in the Introduction. Certainly natural language systems which automate the comprehension of books and journals would support knowledge acquisition within an expert system. The devices developed for an efficient interface between the user and an expert system would play an important role in conveying alerts, through clever use of color, for instance, in a graphics display, or sound to accompany and emphasize what is presented on a screen. Advances in our ability to represent knowledge within the intelligent robot would likely benefit as well the state-of-the-art in intelligent aids to decision making. So basic research projects supported by ONR have implications which transcend particular systems, and it is an on-going responsibility of management to try to identify and capitalize on the complementary aspects of the projects.■

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Perspective on Software Engineering

by

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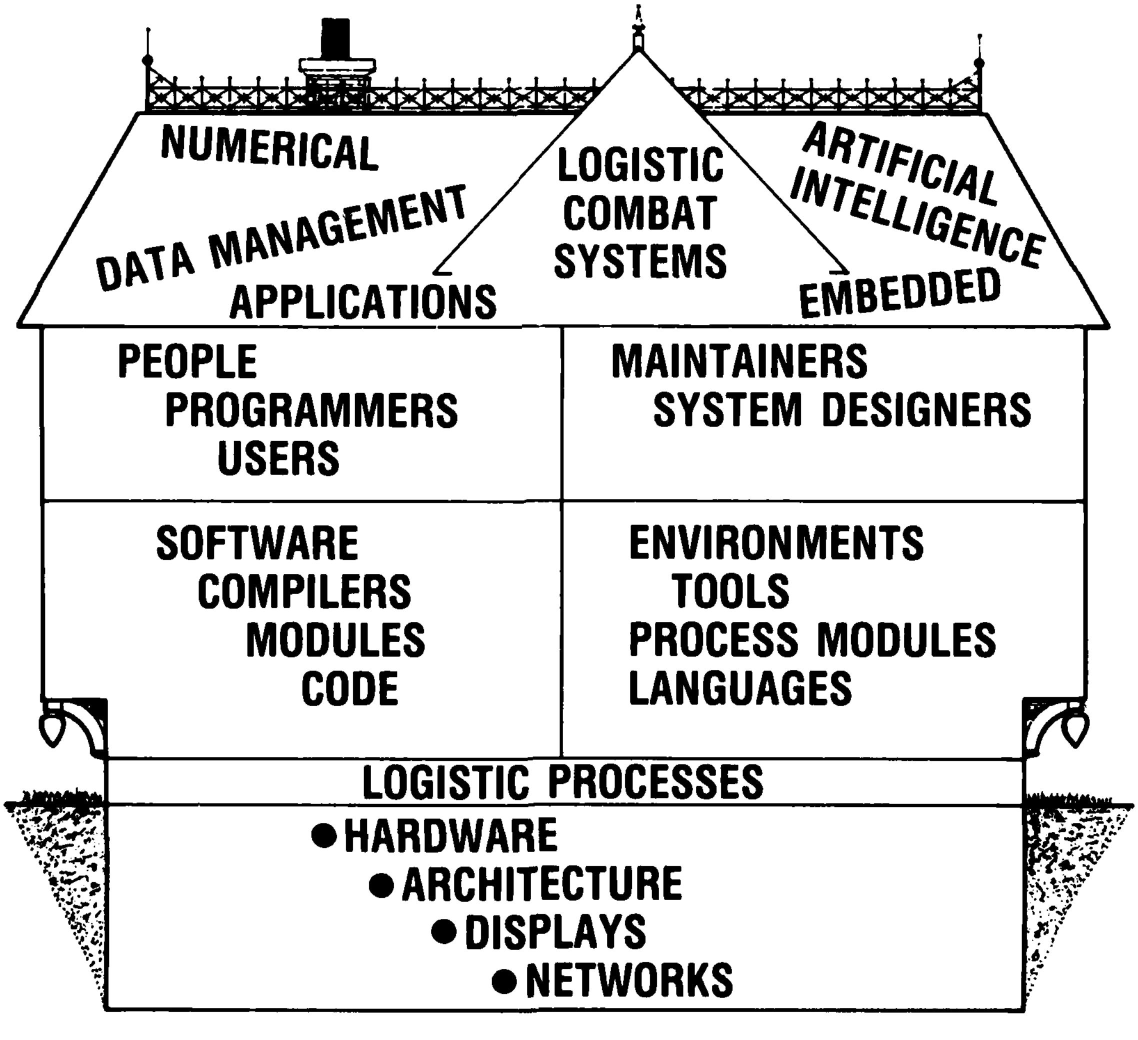

Figure 1.

Introduction

Software rather than hardware has become the principal bottleneck in effective computer utilization. We indicate the reasons for the software crisis, discuss the distribution of costs over the software life cycle, and examine how programming languages and software tools can support the construction of cheaper and more reliable software. Currently two types of computer systems are being developed which will have a considerable impact an software technology in the next two decades. Soon to be available are high resolution, graphics based computers whose low cost will make them widely available. Within two decades, knowledge based, intelligent problem solving systems may become available. Research in software engineering to meet the needs of future computer systems is discussed. We conclude that modernization of software technology will require changes in priorities from hardware-intensive to software-intensive research and development. and that software modernization is critical in maintaining industrial and military competitiveness in an information age.

The Software Problem

During the period 1950-1980 the cost of computer hardware has decreased by a factor of two every two to three years. The cost of a computer which executes a million instructions per second and has a million bytes of main memory has decreased from several million dollars in the 1960's to a few thousand dollars in the 1980's. During this same period the complexity of computer applications has increased by several orders of magnitude. The decreasing cost of hardware combined with the increasing complexity of applications has caused software rather than hardware to become the principal bottleneck in effective computer utilization. The cost of software as a proportion of total computer expenditures has increased from under 20 percent in 1960 to over 80 percent in 1980.

The first computers were developed in the 1940's primarily for the purpose of solving numercial problems arising in physics and engineering. In the 1950's banks and airlines began using computers for payroll and data management applications. Numerical computation involves the execution of algorithms that generate transient data structures that are used as stepping stones in computing a numerical result but may be discarded once the result has been computed. In contrast, data management deals with non-transient data structures that may represent the state of an evolving system or organization, and are subject to both automatic updating as a result of computation and human updating to reflect unforeseen structural changes in the system being modelled.

In the 1960's computers were increasingly used as control mechanisms to drive equipment on aircraft and ships and in chemical plants. Computer applications which control the operation of a larger system whose purpose is not primarily computational are called embedded computer applications. A study of military computer expenditures in 1973 indicated that over 50 percent of the total software cost of 3 billion dollars was devoted to embedded computer applications. Embedded applications may involve both data management and real-time requirements and require careful consideration of the interface between the computer and the host system in which it is embedded. They must be designed for evolution to meet changing requirements in the host environment. Embedded computer systems are becoming increasingly important as computers become indispensable components of military equipment. The development of techniques for building and managing embedded computer systems is a primary goal of software technology.

Programming techniques developed for numercial problems with several hundred lines of code are inadequate for large embedded applications with hundreds of thousands of lines of code. Large software projects in the 1960's and 1970's frequently failed to meet schedules, were subject to enormous cost over-runs, and sometimes had to be abandoned because their complexity became unmanageable.

In the late 1960's it was realized that there was software crisis and that progress in software technology required the development of systematic techniques for managing the complexity of large software systems. The discipline of software engineering was born with the aim of providing a technological foundation for the development of software products analogous to that provided by conventional engineering for the development of physical products.

Figure 1 illustrates that computer application technology rests on the foundations provided by hardware and software technology as well as people who use, program and maintain the application systems. Application areas are continuing to expand, embracing numerical calculations in the 1950's, data management in the 1960's, embedded computer applications and very large systems such as contract and logistics systems in the 1970's and 1980's. Future applications will no doubt include expert systems which allow the user to communicate with the computer in a very high level language and allow the computer to make intelligent decisions based on knowledge about the application area.

Software engineering, like other branches of engineering, is concerned with the development of a technology for the cost-effective production of an economically valuable product. It differs from other branches of engineering because of the unique nature of software products. Physical products like cars or television sets have a non-negligible unit production cost requiring both labor and raw materials. In contrast, software costs are concentrated entirely in producing the initial prototype, with negligible costs in producing additional copies. Software does not wear out, although it may become obsolete. Reliability is determined by logical features such as correctness and robustness rather than by the physical endurance of raw materials.

Software is a logical rather than a physical product. Constructing software is in many respects more like constructing a mathematical proof than like building a house or a television set, since we are concerned with logical properties of the program rather than with physical constraints of materials. Software can be viewed as a solution to a problem. In fact software products are judged by their usefulness in problem-solving rather than by an abstract correctness criterion. This requires engineering as well as mathematical standards to be applied in their construction. Further discussion of the nature of the software problem and of research directions in software engineering can be found in references 1 and 2.

The Software Life Cycle

A framework for understanding the process of software production is provided by the software life cycle. The software life cycle may, as a first approximation, be defined in terms of the following phases:

Requirements Analysis
Design Specification
Implementation
Testing and Integration
Maintenance and Enhancement
Replacement or Retirement

Studies of the distribution of costs over the software life cycle have resulted in some surprising discoveries.[2] It was found that the costs of maintenance and enhancement dominate the costs of other phases of the life cycle, typically being over 80 percent of the total cost of a software project. The cost per line of debugged code in the maintenance phase was found to be between ten and one hundred times greater than in the program development.

Large embedded computer applications typically have a lifetime of over fifteen years during which the operational characteristics of the system in which they are embedded may undergo changes that require substantial changes in the program. Embedded computer applications frequently require modification of more than 10 percent of the operational code per year and frequently grow at a rate of over 10 percent per year to provide new operational capabilities for the host system.

Application programs cannot be designed as black boxes that need never be opened once they have been developed. They must be designed so that they can be maintained and enhanced by persons other than their originators. Programs should be carefully structured into modules each of which performs a well-defined and carefully documented subcomputation. Modularity and understandability are important in reducing the costs of maintenance and enhancement of application programs.

Examination of the distribution of costs over the software life cycle suggests that reduction of the costs of maintenance and enhancement should be an overriding concern in software design. Greater investment in requirements and design can result in a better-structured program that reduces the costs of subsequent maintenance and enhancement. It can also reduce the number of costly errors propagated to later phases of the life cycle. An analysis of the distribution of errors over the software life cycle revealed that two-thirds of those found during the maintenance and enhancement phase were errors in requirements and design and only one-third were coding errors. Moreover, it was found that the cost of fixing errors was much lower when they were found early in the life cycle. These data also suggest that greater investment early in the software life cycle can result in reduced overall costs and in greater reliability of the software product.

Programming Languages

Programming languages are important in enhancing the productivity of the programmer. The introduction of Fortran helped to increase programmer productivity for numerical problems by an order of magnitude. Cobol has increased programmer productivity in data processing applications. But these languages are no longer adequate for the increasingly sophisticated data management and embedded computer applications of the 1980's and 1990's. In response to this need, the language Ada was developed at the initiative of the Department of Defense to support large embedded computer applications with many hundreds of modules and real-time requirements. It represents an evolution of earlier programming languages such as Fortran, Algol, Pascal, PL/I and Simula. It eliminates some design deficiencies of earlier languages and incorporates some new features that support not only program development but also the design and the maintenance phases of the software life cycle. Ada is still under development, and its practical effects will not be felt for several years. Indeed ways to measure and assess the effectiveness of Ada are still research issues. However, Ada does have many innovative features that support the construction of cheaper and more reliable software. For example, Ada supports both program design and coding as part of the same higher-level language, and encourages modular program construction. Modular program construction in turn facilitate maintenance and enhancement by localizing the effect of program changes at the module level. There is vigorous activity surrounding Ada and its development should be rapid.

It is difficult to predict the future course of language development. However, the one significant need that has been addressed and that future programming languages must address is: programmer productivity. Over the past decade, no new language has proved to be the vehicle for a dramatic increase in productivity. Two new approaches are on the horizon and may prove useful in a decade or two. Languages which permit programmers to express their ideas in a graphical or two dimensional way, rather than in the traditional serial way should be decidedly helpful in the programming of large, distributed systems such as those for logistics or combat, or for complex chip designs. All of these are characterized by many processors connected by communication links and acting in concert to do a task. Graphical languages should help the programmer visualize designs for these systems, thereby resulting in clean, well understood designs. A second form that programming languages might take is akin to English. This will permit non expert users to more readily program and interact with systems, such as expert systems mentioned earlier.

Software Environments

The construction of software is not done in a factory as are material goods. It is built by a programmer, or a team of programmers, using a software production environment. The notion of an environment is relatively new, as the production of software is just emerging from the age of the artisan crafting software by hand. The environment contains aids in the form of special software programs that are needed to assist programmers and maintainers at every phase of the life cycle. These special programs are called "tools," because they help software engineers to build systems in the same way that conventional tools help engineers build physical and electronic structures. Software technology started with relatively few tools in the 1950's and is becoming more tool-intensive as it matures. But we are in the midst of a period of rapid technological change. One of the objectives of software engineering is to develop software tools that will enhance the productivity and amplify the mental abilities of the programmer.

The concept of a programming environment is still new, but it is not difficult to describe characteristics that future environments must have. They must be designed so as to be responsive to the dynamics of a large software system over its lifetime, probably decades. The software will be designed and built in the environment, and will come back to it for modification and changes. Thus environments must keep a knowledge base about the software in such a form that a novice user can quickly learn about the system and be aided in understanding the effects of changes. Environments must have facilities for rapidly producing prototype systems which can be tested and evaluated against specification. (The question of rapid prototyping is a large research subject in itself). New tools will certainly be produced in the course of time and the environment must have the facility to incorporate and integrate new items into the tool kit. Finally, the environment must be "user friendly" because numerous people with a great variance of skills will work with it over many decades. This too is a serious research area.

Advanced Computer Systems

The 1980's will bring developments in hardware technology that will have a great impact on software technology. One such development is networks of powerful personal computers with high-resolution bit-map displays, multiple windows to keep track of multiple activities, large memories (at least one megabyte), and unlimited disk memories. Such (fourth generation) computers will be commonplace by 1985, costing under 10,000 dollars. Fourth generation computers will fundamentally change the nature of man-machine communication.

Fourth generation computer systems provide a high-level man-machine interface that can display new and interesting representations of structures residing in computers. They can display the dynamic transformation of structures during a computation, and can simultaneously display several structures in multiple windows of the screen. Such displays provide information about intermediate states of a computation that is useful in increasing our dynamic understanding of the process. This user interaction at intermediate states will allow the user to exercise greater control over the course of a computation.

As graphical interfaces become commonplace we will increasingly think in terms of two-dimensional graphical images rather than one-dimensional textual strings, and the development of information representations that support geometrical intuitions will become important. The new display technology will open up new vistas in computer-based education. These computers will become more effective as tools for simulated training and as tools for retraining of computer science personnel in new programming languages, and in modern software methodology and application programming techniques.

Computations involving a high degree of man-machine interaction may be contrasted with computations which aim to substitute computer intelligence for human intelligence in controlling the course of a computation. Artificial intelligence is concerned with replacing human decision by computer decisions over as broad a domain as possible. This objective differs from the fourth generation objective of providing the user with information and control over the course of a computation. Knowledge-based systems that aim to substitute computer intelligence for human intelligence emphasize the internal representation of knowledge in a form that facilitates computer intelligence rather than displays that enhance human insight and human intelligence.

By the 1990's our understanding of the techniques of knowledge representation and artificial intelligence may have increased to the point where computers will exhibit some degree of natural language understanding and expert systems with natural language input will become feasible as driving mechanisms for embedded computer applications.

The Japanese have undertaken an ambitious research project on "Fifth-Generation Computers" whose objective is to develop an intelligent man-machine computer interface suited to the hardware and software technology of the 1990's. This project is regarded by some U.S. researchers as overambitious. But it represents a unified approach to the development of an integrated intelligent man-machine interface by a syndicate of industries and universities that has no parallel in the United States. In view of past Japanese technological successes and their current domination of the market for semiconductor production, the Japanese attempt to develop an edge in software technology in the 1990's must be respected. Even if the stated goals of the project are not achieved, this project could result in a less ambitious integrated software-hardware technology that could encroach on U.S. domination of the computer field in the same way that Japanese automobiles have displayed U.S. automobiles.

Research Needs

It is the intent here to describe briefly several promising areas of research that will contribute both to the scientific foundations of software engineering and to radical changes in the way software is produced and maintained. These will, hopefully, lead to an order of magnitude improvement in programmer productivity.

For some time programmer productivity—no matter how it is measured—has not increased at a rate sufficient to meet the demand. Moreover, there is little on the horizon to indicate significant improvements in the near future. There are some research directions that show promise here. Many powerful, inexpensive, fourth-generation computers could be linked together in a network with a common database of information so that a team of programmers, each with his/her own computer, can work together to produce large software systems. There are deep research questions associated with this notion. These include the organization of information, sharing of it among workstations, and notations for program families. Indeed, the interaction among these issues creates problems that do not exist when each is considered alone. This is also a research question.

It is likely that very great increases in programmer productivity can be achieved by combining a system which allows one to compose new programs that make use of previously written code with previously accumulated programmer experience. Researchers speak of their intent to develop a "software library," but what they have in mind is hardly analogous to a conventional library. The analogy breaks down in two ways. First, no one knows how to classify software so that users know clearly what it does, what resources it consumes, etc. Second, no one knows how to hook together software library pieces so as to achieve an efficient, effective result. The need is for a system in which a user would get help in building or modifying programs, including help with finding appropriate elements in the library. This implies that powerful reference, cataloguing and retrieval services should be provided. In order to make effective use of these library elements, it will also be necessary to provide help instantiating, enriching, restricting, and combining them appropriately. This will require powerful techniques for program composition from library elements, as well as methodological guidelines for their proper use. Parameterized (also called "generic") modules will be one of the most important of these. There is a need for enforcing consistency of data representation and control flow in combining programs. Clearly there are many research issues here.

The notion of reusable software, described above, leads one to consider the rather longer term goal of fully automating software production. Many research issues arise here. One is the question of automatically translating high-level specifications into correct operating code. The area is difficult and progress is slow. Systems which have been developed are rather limited in scope. A research direction in this area is for expert systems, which are based on artificial intelligence techniques, and incorporate knowledge of programming. Advances here are thwarted by two problems. The science of expert systems is still in its infancy. Much is still to be learned about fundamental principles, construction and operation of expert systems. Also, it is going to be difficult to identify and understand thoroughly the basic software development knowledge which would reside in such an expert system. Clearly the problems of automatic programming require a long term research effort for solution.

Software engineering is less than fifteen years old, and consequently does not have a solid base of science from which to draw principles for design and operation. In contrast, traditional engineering disciplines have the scientific results of two hundred years (or more) as a foundation. One result of this discrepancy is a lack of precise and well understood parameters of measurement in software engineering. This discipline needs metrics.[1] These will not be derived from physical sciences, but will, like software itself, come from human ingenuity. Computer science does not suffer from a lack of proposed metrics, but many are being used out of necessity without the benefit of a deep understanding. Time is not on the side of orderly software metrics development. The demand is high, thereby inhibiting a detailed examination, gradual acceptance, and eventual standardization.

Perhaps software engineering as a discipline has more in common with economics, psychology, and political science than with the physical sciences. These disciplines deal with human activities and they are also struggling with problems of measurement. Whether or not software and computer science can benefit from the experiences of these fields is at best debatable. However, one lesson stands out clearly; where there is no confirmed scientific theory, there is need for a high quality experimental paradigm, accepted by the scientific community, so that hypotheses can be tested, confirmed, and evaluated. This need is abundantly clear in software engineering. To show that metrics are critical throughout software engineering, it suffices to list areas of need: measurements of software development, design of experiments, software project forecasting, life cycle parameters, prediction of resources for large scale software projects, comparison of high level languages, data collection and analysis, performance evaluation of both software and systems, measures of software reliability, quality and complexity, and measures of software maintenance. Much deep research is needed in the field, and many researchers are turning their attentions to metrics work.

Finally, software engineering is going to be strongly affected by the dramatic advances in very large scale integration technology. This will permit the embedding of complex software programs into hardware. Rapid progress is being made in the area of designing signal processing algorithms so that they can be readily cast into hardware form. This synergism between hardware design and algorithm design is predicted to increase the speed of signal processing by several orders of magnitude. The success of this example suggests that this notion be carried over into other areas. However, there are many unanswered questions that need to be addressed by research. These include: how are software functions to be cast into hardware; how can correct functionality be ensured; what are the management strategies for modification, repair and replacement; and how does one assemble many chips which have software embedded on them into a useful system. The problems here are difficult. However, rapid progress may be made in selected areas.

Conclusion

We are experiencing an information revolution that will have as profound an impact on our way of life and our work habits as the industrial revolution did. The evolution from cottage industries to assembly lines in the industrial revolution is paralleled by an evolution from programming projects that emphasize individual brilliance and tricky optimization to projects that emphasize programming teams, structured design and automated software tools. Indeed, it is because of this change in emphasis and because of the critical role of software in system engineering that software research and development must be given high priority.

Software modernization will not only make software cheaper. It will allow computers to be used in new and imaginative ways that would not have been possible in the old technology. It is a vital factor in maintaining industrial and military competitiveness. However, software modernization is both a technical and a social process. The cost-effectiveness of new methodologies and programming languages will depend not only on their technical quality but also on the skills and attitudes of their users. Our ability to adapt to the information age will depend on our investment in human resources as well as on our investment in software resources. ■

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Profiles in Science

Jacob T. Schwartz is professor of Mathematics and Computer Science at the Courant Institute of Mathematical Sciences, New York University. His many publications and research accomplishments make him renown in the fields of functional analysis, quantum theory, spectral theory of operators, ergodic theory, and computer science. For many years he has been a Principal Investigator for the Office of Naval Research. He is a member of the National Academy of Sciences, and serves on the Editorial Board of several journals including the *Journal of Computer and System Science* and *Advances in Applied Mathematics.*

Professor Schwartz is chairman of the Computer Science Board of the National Research Council. He has been the recipient of many awards, including the Wilbur Cross Medal (Yale University), the Townsend Harris Medal (City University of New York), and the Steele prize (American Mathematical Society, 1981). ■

Permanent Magnet Materials: an Opportunity to Reduce Cobalt Consumption

by

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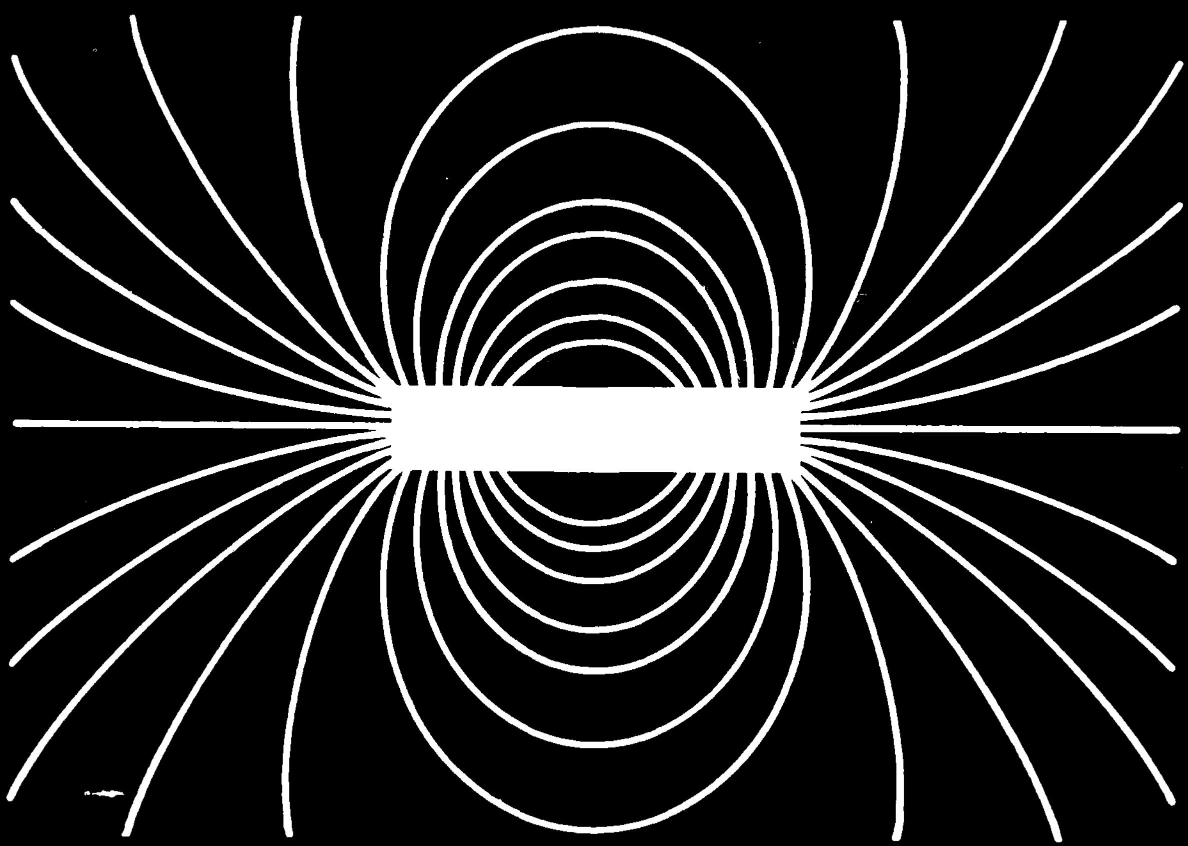

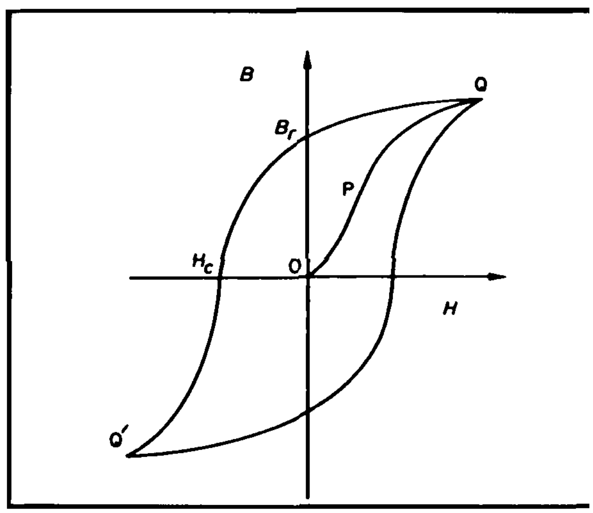
B
Q
Br
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H
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weber/meter^2, defined as a tesla. Conversion from CGS to SI units is simplified since one tesla = 10^4 gauss and one ampere/meter = $4\pi \times 10^{-3}$ oersted.

The behavior of a permanent magnet material that is exposed to a varying magnetic field is shown in Figure 1. When an initially unmagnetized permanent magnet is exposed to a gradually increasing magnetic field H, its magnetization M will gradually increase such that the induction B will follow the curve OPQ. As H is reduced to zero, M will remain positive such that $B = B_r$ at $H = 0$. As H is made increasingly negative, B continues along the curve to Q″, with $H = H_c$ at $B = 0$. As H is once again made increasingly positive, B follows the lower branch of the hysteresis loop back to Q. When the maximum value of H imposed on the sample is large enough to saturate the magnet (i.e. when M no longer increases as H increases), the area of the loop, and B_r and H_c, have reached their maximum values. This maximum B_r is labeled the remanence or residual magnetization; the maximum H_c is labeled the coercivity. Both B_r and H_c are major determinants of the usefulness of a permanent magnet; B_r indicates the strength of the magnetic field produced by a fully magnetized permanent magnet, while H_c indicates its resistance to demagnetization. It is in fact the value of H_c which determines whether a ferromagnetic material is labeled a permanent (i.e. "hard") magnet or a "soft" magnet. As will be noted below, commercial permanent magnets have H_c values ranging from several hundred to many thousand oersteds. In contrast, commercial soft magnetic materials have a H_c which is a small fraction of an oersted.

Figure 2 illustrates the differing behavior of the induction B and the intrinsic induction $4\pi M$ as function of H. Since the magnetization saturates, $4\pi M$ levels off at sufficiently high H while B continues to increase. H_{ci},the value of H at which $4\pi M = 0$, is called the intrinsic coercivity. Often, the "B-H curves" given for a permanent magnet material present in fact the $4\pi M - H$ relationship; for materials of low H_c, the B and $4\pi M$ curves are essentially equivalent. For high H_c materials, both the induction and intrinsic induction are often provided.

In addition to B_r and H_c, a third property of permanent magnets usually characterized is $(BH)_{max}$, the maximum value of B•H in the "second" quadrant, i.e. where B is positive and H is negative. This "energy product" indicates essentially, the "strength" of the magnet and is related to the total energy stored in the magnetic field; it is calculated in the second quadrant since this corresponds to the opposing direction of H and M encountered by a magnet in a dynamic application, e.g. in a motor. This $(BH)_{max}$ obviously

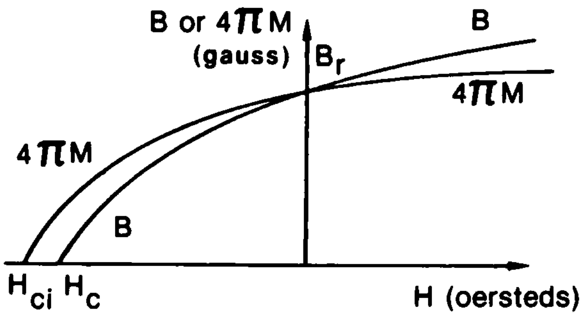

Figure 2. Schematic diagram of a section of the hysteresis loop illustrating the difference between the coercivity, H_c, and the intrinsic coercivity, H_{ci}.

depends on B_r and H_c as well as the shape of the hysteresis curve. For a given B_r, the theoretical maximum value of $(BH)_{max}$ is $B_r^2/4$, which occurs when $4\pi M$ remains constant at B_r at least down to $H = -B_r/2$. Further, the maximum B_r is the saturation value of $4\pi M$, so one approaches the maximum energy product when the M vs H hysteresis loop approaches a rectangular shape, and the maximum $(BH)_{max}$ value for a given crystalline phase or mixture of phases is thus $(4\pi M_{sat})^2/4$.

Origins of Coercivity

Useful permanent magnets may be based on either ferromagnetic or ferrimagnetic materials. In ferromagnetic materials such as body-centered cubic (bcc) iron, the atomic magnetic dipoles spontaneously align within a limited region, a magnetic domain. The degree of alignment is gradually reduced by thermal agitation, and it disappears at the Curie temperature, T_c. In ferrimagnetic materials, domains also occur and consist of two distinct sublattices which have differing magnetic amounts of opposite orientation.

Because the bulk material generally consists of many domains oriented randomly, the net magnetization can be negligible. However, the exposure of such a material to a magnetic field causes the domains to reorient along the applied field, leading to the increase in M as along curve OPQ in Figure 1. The preferred orientation of the domains does not fully disappear when the applied field is removed, leading to the residual magnetization, and a negative field (the intrinsic coercivity) must be applied to reduce the magnetization to zero.

Thus, understanding why a material is a good permanent magnet corresponds to understanding why the magnetic domains do not readily reorient in response to even small applied magnetic fields via a rotation process or the nucleation or growth of reverse domains. Many different mechanisms may restrain domain reorientation, and only a brief comment will be presented here; further discussion of this is available, e.g., in References 2 and 3.

The coercivity of presently available permanent magnets is due to an anisotropy arising primarily from one of two effects: magnetocrystalline anisotropy or particle shape and size effects. The magnetocrystalline anisotropy arises because the quantum mechanical interactions among the electrons lead to a lower energy when the spontaneous magnetization lies along certain preferred "easy" directions in a crystal. In cubic materials, symmetry produces easy directions that are $\leq 90°$ apart in rotation. Crystal structures having less symmetry will generally have fewer easy axes, thus hindering rotation further. Most desirably, the crystal structure will have only one easy axis requiring a 180° rotation, e.g. in hexagonal structures when the easy axis is perpendicular to the basal plane.

Shape anisotropy occurs because, in an elongated particle, an external field can more readily saturate the magnetization parallel to the long dimension. Further, in the absence of other factors such as crystalline anisotropy, a single domain elongated particle will have its spontaneous magnetization aligned along its long dimension, so that very fine particle or grain sizes are desirable. The "particles" do not need to be distinct entities; rather, a similar effect can be achieved in a multiphase bulk alloy when the magnetic phase having shape anisotropy is embedded in a second phase having different magnetic behavior. Enhanced coercivity can be achieved by combining the shape anisotropy with a crystal phase having at least moderate crystal anisotropy and partial alignment.

Commercial Permanent Magnets

Shown in Table 1 are representative examples of the types of standard permanent magnets now commercially available; subscripts, other than for the compounds, indicate weight percent. The ferrites now enjoy by far the greatest usage on a tonnage basis, due primarily to their low cost. The hexagonal crystal structures of these ferrites possess a large uniaxial magnetocrystalline anisotropy. Bulk magnets with high coercivity are produced by sintering ultrafine powders having particle sizes similar to the domain sizes, typically a fraction of 1 μm. Anisotropic magnets with higher B_r in a selected direction are made by first cold pressing the powder in the presence of a magnetic field which aligns the powder particles. While appreciable H_{ci} is achieved, the remanence is rather low.

The next most commonly used permanent magnets are a class known as Alnicos. In these alloys, a heat treatment is typically used to produce a very fine (200-400 A) microstructure by the spinodal decomposition of the alloy into two bcc phases based on Fe and NiAl; textured, elongated microstructures can be formed by applying a magnetic field during decomposition. The various combinations of H_c and B_r which are available in different Alnico alloys result

Table 1
Examples of "standard" commercial permanent magnets. Subscripts (other than for compounds) represent weight percent

	B_r(gauss)	H_{ci}(oersted)	$(BH)_{max}$(MGOe)
ALNICO 5 ($\sim Fe_{50}Ni_{15}Al_8Co_{24}Cu_3$)	13,100	700	6.5
ALNICO 8 ($Fe_{36}Ni_{15}Al_7Co_{36}Ti_6$)	8,500	1,600	5.1
FERRITES (e.g., $BaO \cdot 6Fe_2O_3$)	3,900	2,000	3.5
$SmCo_5$	8,500	16,000	18.0
Cu-Ni-Fe ($\sim Cu_{60}Ni_{20}Fe_{20}$)	5,700	590	1.85

from differences in the microstructure which arise from differences in composition and processing, especially thermomagnetic treatments. The Alnicos have desirably high B_r values but comparatively low coercivities.

Magnets based on the $SmCo_5$ phase have both high remanence and high coercivity and thus a high energy product. The coercivity of these alloys arises from the strong magnetocrystalline anisotropy of this hexagonal phase. Bulk magnets are made by sintering magnetically aligned fine powders (~ 2 to 3μm particles). While clearly superior to other materials, the high cost of these Sm-Co based magnets has limited their use.

There are, of course, other specialized permanent magnets available. For example, the Cu-Ni-Fe magnet is of use because its high ductility allows it to be readily shaped into strip or wire.

Commercial magnets are generally characterized by presenting their second quadrant behavior. Figure 3 shows the magnetic characteristics of three $SmCo_5$ alloys processed to have different remanences and coercivities. Associated with each magnet are two curves characteristic of that material. The "straight" line represents the induction while the curved line is the intrinsic induction; given next to each curved line is the $(BH)_{max}$ associated with that material, calculated from the straight induction line. Since B_i is relatively constant at low H, the $(BH)_{max}$ of these alloys approach their theoretical maximum.

For the Alnico-type alloys having $H_c \leq 1000$ Oe, the difference between B and B_i is small and is generally ignored. Thus, only one induction vs. magnetic field curve is given for such commercial magnets.

Shown in Table 2 are the characteristics of examples of relatively new permanent magnets now being introduced to the commercial market. Like the Alnicos, the Fe-Cr alloys depend upon a spinodal decomposition, in this case based on the Fe-Cr system. The main driving force for the use of these alloys is their lower Co content; useful alloys having as little as 5 wt% Co can be produced.[4] Secondly, these Fe-Cr alloys remain ductile after phase separation by spinodal decomposition has occurred, desirable in its own right but also making possible the enhancement of shape anistropy of the precipitates through mechanical deformation. Magnetic behavior similar to that of the Alnicos is achieved.

The Mn-Al-C alloys are of particular interest since they contain only inexpensive elements and can have magnetic properties superior to those of the ferrites. The ferromagnetic τ phase present in such magnets is metastable; it is formed from the high temperature equilibrium hcp MnAl phase by controlled cooling. The τ phase has a face centered tetragonal structure and an associated magnetocrystalline anisotropy. The carbon addition enhances the stability of the τ phase, making possible the production of a partially aligned bulk material by hot extrusion of this material. However, such a process is costly, making uncertain the future viability of this material.

Currently, the permanent magnet materials undergoing the most intensive investigation are the "2-17" alloys.[5] The Sm_2Co_{17} phase has lower anisotropy than the $SmCo_5$ phase, and it has been difficult to achieve high coercivities in the bulk form of this phase. However, the addition of elements such as Cu and Zr leads to increased coercivity, and the addition of Fe increases the magnetic saturation, making possible higher energy products.

Even better magnetic properties are obtained from compositions which lead to two phase microstructures consisting of both the 1-5 and 2-17 phases,

Table 2.
Examples of "new" commercial permanent magnets. Subscripts for Fe-Cr and Mn-Al-C are in weight percent.

	B_r(gauss)	H_{ci}(oersted)	$(BH)_{max}$(MGOe)
IRON-CHROMIUM ($Fe_{58}Cr_{24}Co_{15}Mo_3$)	13,500	600	5.2
Mn-Al-C ($Mn_{69.5}Al_{29.3}Ni_{0.7}C_{0.5}$)	4,600	2,900	4.1
$Sm_2(Co,Fe,Cu,Zr)_{17}$	10,600	7,000	~22
$Sm(Co_{0.65}Fe_{0.28}Cu_{0.05}Zr_{0.02})_{7.67}$	12,000	13,300	~30

the last example in Table 2. For this alloy, the optimum heat treatment produces a very fine microstructure (~ 0.1 μm grain size) of the 2-17 phase with the 1-5 phase at the grain boundaries. Such alloys have the highest energy product now available and also have higher energy product per unit of cobalt as compared to $SmCo_5$ or the Alnicos.

Although the cobalt content is being reduced in current commercial permanent magnets, the introduction of a Co-free medium (i.e. $(BH)_{max} \sim 12$ MGOe) or high performance magnet does not appear to be imminent. While much of the current research on permanent magnet materials has been aimed at increasing the value of $(BH)_{max}$, it is worth noting here that the high $(BH)_{max}$, such as is being achieved with the "2-17" alloys, is not necessary for all application, e.g. for electric motors. The calculations of Richter and Neumann[6] for ac synchronous type machines suggest that high magnetic energy levels (>14 MGOe) do not provide any significant advantages for permanent magnet machines for industrial or commercial applications when overall costs of building the machine are computed. Campbell[7] has reached the similar conclusion that magnets with energy densities down to 12 MGOe may yield comparable performance to those with 15, 18 or 25 MGOe for an axial field motor suitable for propelling an electric vehicle, where overall motor weight and energy efficiency are of primary importance. Alnico type magnets, even if their $(BH)_{max}$ could be increased somewhat, are not suitable for such applications because of their low H_c. Thus, there is potentially a large market for low cost Co-free permanent magnets having a $(BH)_{max}$ of 10-15 MGOe, independent of future Co shortages.

Materials Availability

It is seen above that the Alnicos and Sm-Co alloys (and to a lesser degree, the Fe-Cr alloys), the most powerful permanent magnets in terms of both B_r and energy product, contain significant amounts of Co. Cobalt is one of the most important of the critical, or strategic, elements. The free world has depended on Zaire for a large percentage of its supply of Co, ~ 60% in recent years.[8] The vulnerability of this source to interruption was demonstrated in 1978 when fighting in Zaire temporarily halted production. In reaction, the producer contract price increased from $6.40 per pound in February, 1978 to $25 per pound in February, 1979, with the spot price having reached a brief peak of about $50 per pound.[8] Prices have decreased gradually so that spot Co was selling for ~ $10 per pound in late 1981. The continued high price of cobalt and the potential for future supply interruptions due to political instability in southern Africa suggest that continued efforts to develop moderate to high performance magnets which contain no cobalt are justified; these could most likely be based on iron. Currently, about 1/6 of the free world usage of Co is for magnetic alloys, primarily permanent magnets. Displacement of this cobalt would lessen U.S. dependence on foreign suppliers and would lessen the pressure on alternative uses of cobalt, e.g. the ~45% of cobalt (7.2 out of 16 million pounds in the U.S. in 1980) that is now used in superalloys.[9]

Further, Sm is also an element in limited supply, but for other reasons. Sm is separated from the other rare earths present in the minerals monazite and bastnaesite. However, as can be seen from Table 3,[10] Sm typically comprises only 1-2% of the rare earth content of these ores. Thus it can be produced economically only up to levels where the other accompanying rare earths are in demand, even though the U.S. has vast reserves of bastnaesite that are currently being mined and processed. Even in the present situation, Sm is relatively expensive; Sm_2O_3 currently sells for about $18 per pound. If a much larger market for the desired Co-free magnets were to develop, e.g. in electric motors for automobile propulsion, sufficient Sm would not be available for it to comprise a significant fraction of the alloy. Rather, if a rare earth were used

Table 3.
The weight percent of each of the rare earth oxides present in typical samples of the three most common ores mined for their rare earth content.

		Monazite		Bastnaesite		Xenotime	
Light R.E.	La	23		32			
	Ce	46	93	49.5	98.7		10.6
	Pr	5		4.2			
	Nd	19		13			
Heavy R.E.	Sm	3		0.5		1.2	
	Eu	0.1		0.1		0.01	
	Gd	1.7		0.15		3.6	
	Tb	0.16				1	
	Dy	0.5		0.12	1.3	7.5	89.4
	Ho	0.09				2	
	Er	0.13				6.2	
	Tm	0.01				1.27	
	Yb	0.06		0.015		6	
	Lu	0.006				0.63	
	Y	2		0.1		60	

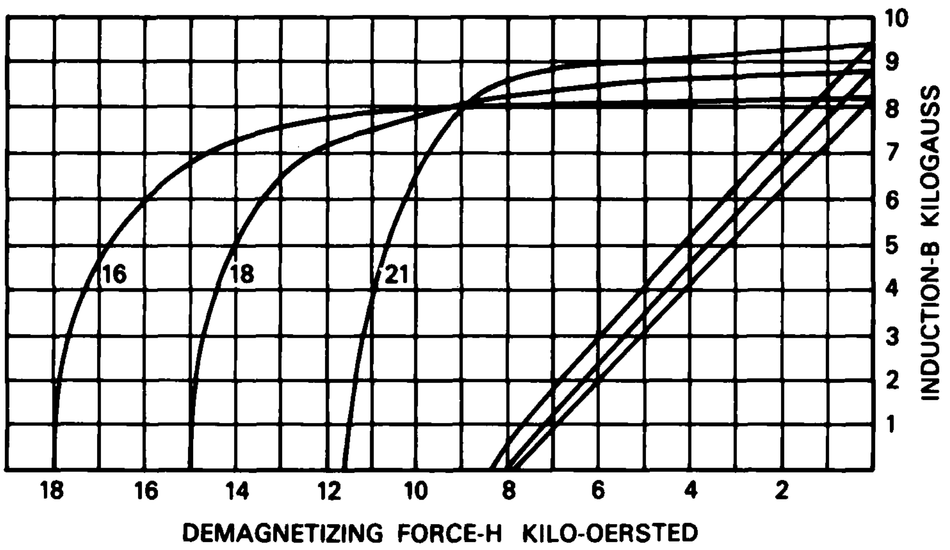

Figure 3. Magnetic induction and intrinsic magnetic induction for three different $SmCo_5$ magnets.

in the alloy, one would hope to be able to use the more plentiful light rare earths, or even mischmetal, the mixture of La, Pr, Nd and Ce in their naturally occurring relative abundance, which is available at only ~$5 per pound.

Research on Cobalt-Free Permanent Magnets

The research efforts sponsored by the Navy that are relevant to cobalt-free, medium to high energy product permanent magnet materials will be reviewed below. Three programs related to the crystallization of amorphous metals have already produced significant results while other programs studying a variety of approaches are now beginning.

Crystalline compounds such as $TbFe_2$ are of interest because they possess huge magnetostriction constants[11] and may be useful for high power transducers. As part of a program to investigate such materials, Clark had also studied[12] sputtered amorphous RFe_2 alloys, where R is one of the rare earths Tb, Dy and Sm, at the Naval Surface Weapons Center. The amorphous RFe_2 alloys have a very large coercivity at low temperatures, e.g. 30 kOe at 4.2 K for $TbFe_2$, whereas the polycrystalline sample prepared by conventional arc casting and annealing has a coercivity of 50 Oe. On the other hand, the high coercivity of the amorphous phase decreases rapidly with increasing temperature to ~120 Oe at room temperature; however, annealing of the amorphous alloy so as to crystallize it in a magnetic field leads to an alloy having a coercivity larger than that of the conventionally prepared crystalline alloy, e.g. a coercivity of 3.4 kOe and a $(BH)_{max}$ of 7 MGOe at room temperature. Coercivity at room temperature as a function of the temperature at which the amorphous alloy is annealed is shown in Figure 4. This observation showed that the crystallization of the appropriate amorphous alloys might be a method for achieving useful permanent magnets if the properties already observed could be improved somewhat; the fact that the high coercivity was achieved in the cubic $TbFe_2$ phase is also significant since it means that the crystal alignment step used in the production of magnets based on uniaxial phases such as $SmCo_5$ might be avoided.

It is noted that amorphous iron based alloy such as $Fe_{.81}B_{.14}Si_{.03}C_{.02}$ (subscripts in atomic fraction) which do not contain rare earths are exceptionally soft, i.e. have coercivities as low as ~0.02 Oe, and are thus being developed for many applications, e.g. transformer cores.[13] The coercivity mechanisms usually encountered are not possible in an amorphous phase, which lacks the directional anisotropy inherent in crystal structures and is generally compositionally uniform. The large low temperature coercivity in the RFe_2 amorphous structures is due to the interaction between the anisotropic electron cloud of a rare earth such as Tb and the "crystal field" due to the arrangement of its first and second neighbors, which is anisotropic even in a macroscopically isotropic amorphous structure. However, as the temper-

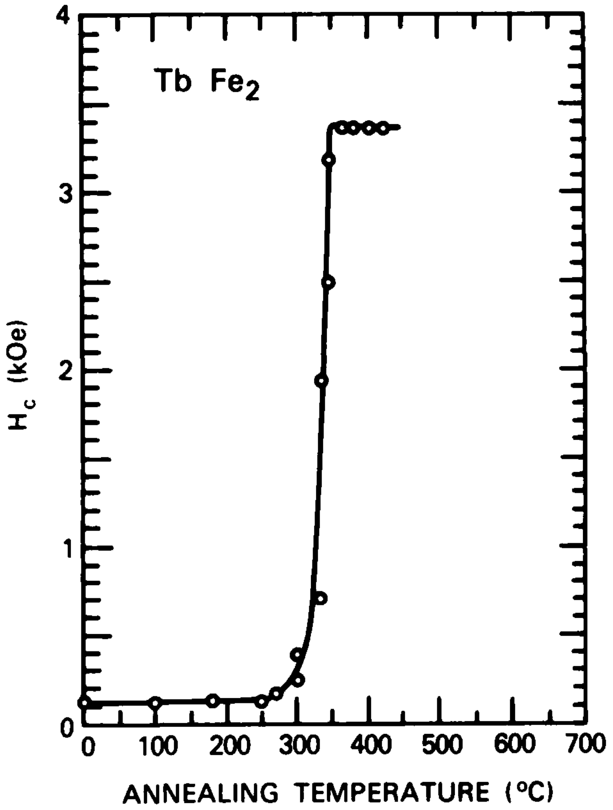

Figure 4. Room temperature coercivity as a function of annealing temperature for amorphous $TbFe_2$. The large increase in coercivity is associated with crystallization of the alloy.

ature increases, thermal fluctuations are sufficient to overcome the tendency of the local regions to have their magnetic moments oriented along their (localized) "easy" direction.

The second effort in this area to be described is being conducted at the G. E. Corporate Research and Development Center under contract to the Office of Naval Research. In it, J. J. Becker and others have initially concentrated on the crystallization of amorphous metal-metalloid alloys which are being extensively studied in their magnetically soft amorphous state in other programs.

As a first step, the magnetic properties after crystallization (heated 15 minutes at 525°C) of a large number of amorphous alloys which had previously been prepared for other reasons as ribbons by melt-spinning were scanned. For cobalt free alloys, a maximum H_c of 365 Oe was observed for $Fe_{.40}Ni_{.40}P_{.20}$. The observation that some abrupt changes in H_c occurred as a function of composition and the results of additional temperature runs made it clear that a more systematic study of the effect of composition and annealing treatment was needed.

To speed the exploration of the behavior of the alloys as a function of composition and annealing temperature, a current-pulse annealing technique was used. Ribbons were annealed by short (~1 sec) pulses of successively greater currents which produce successively higher, though not defined, temperatures. The pulsing and magnetic measurements are done in situ so that each sample can be fully characterized in minutes. The rapid heating rate of this technique is not considered detrimental since the highest H_c found by this technique was consistently higher than that previously measured after isothermal treatment of a given alloy.

The resistivity of the sample is also monitored, and shown in Figure 5 is a typical plot of relative

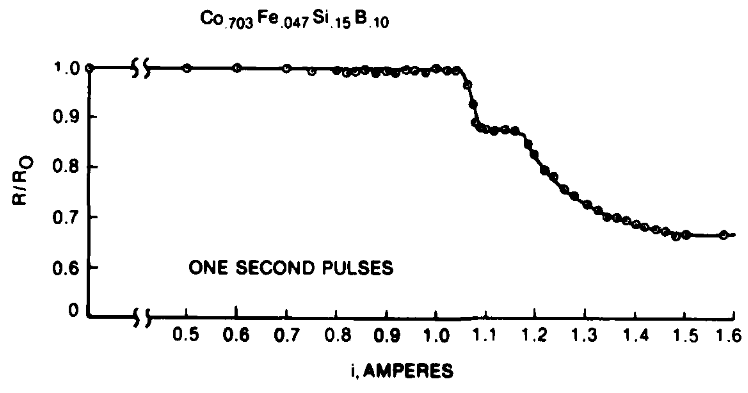

Figure 5. Reduced resistivity of the alloy as a function of the magnitude of the current pulse; increased current produces higher temperature, leading to an increased degree of crystallization and hence lower resistivity.

resistivity vs. applied current; the resistivity decreases as crystallization proceeds. In this case, crystallization appears to be a two stage process involving an intermediate metastable phase, a behavior observed for many other amorphous metals which exhibit R/Ro vs. temperature curves similar to the R/Ro vs. i curve of Figure 5. Figure 6 shows the coercivity as a function of the relative resistivity. The maximum coercivity is achieved for the intermediate state of crystallization, and the coercivity decreases greatly as the crystallization nears completion. Significantly, the ratio of remanence to saturation for this alloy is 0.82 in the as-annealed ribbon; such a material would not need to be aligned to obtain good magnetic properties. This implies that the phase(s) present has multiple equivalent, or nearly equivalent, easy axes, as would be the case for a cubic structure. Phases having uniaxial magnetocrystalline anisotropy would be expected to have a much lower remanence to saturation ratio; the alternative explanation of having a high degree of crystallographic alignment would appear to be unlikely for the given processing condition.

The H_c of the alloy of Figure 6 was in fact the highest coercivity achieved by crystallizing the (Fe, Ni, Co)—metalloid alloys, though this alloy is rich in Co. For Co-free alloys, the maximum coercivity achieved was 420 Oe for $Fe_{.40}Ni_{.40}P_{.20}$. While such coercivities are similar to those being used in Alnicos, a combination in one alloy of high coercivity, high saturation and low cobalt content sufficient to justify their commercial use has not been achieved.

Continuing efforts under this contract will consider the inclusion of other elements, including rare earths, in the alloys and will determine the relationship between microstructure, phases which are present and the magnetic properties of the alloy.

The third effort in this area is being conducted by N. C. Koon and B. N. Das at the Naval Research Laboratory. Amorphous Fe-B-R alloys wherein the rare earth R is typically present at low levels of 1 to 10 atomic percent are being prepared by melt-spinning and are then crystallized.

They were able to prepare fully amorphous alloys when the alloy contained some La, so initial studies concentrated on such alloys. Figure 7 shows the coercivity as a function of one hour anneals at the indicted temperatures. A comparatively high maximum coercivity of ~8 to 9 kOe is achieved, the highest coercivity produced. The rapid decrease in coercivity with increasing temperature may be due to grain coarsening or continued phase transformations; the marked sensitivity of H_c to annealing temperature is similar to that observed for the amorphous alloys having no rare earths, e.g. Figure 6.

Figure 8 shows the magnetization curve for this alloy; the shape of this curve suggests that the alloy has a multiphase microstructure. This is confirmed

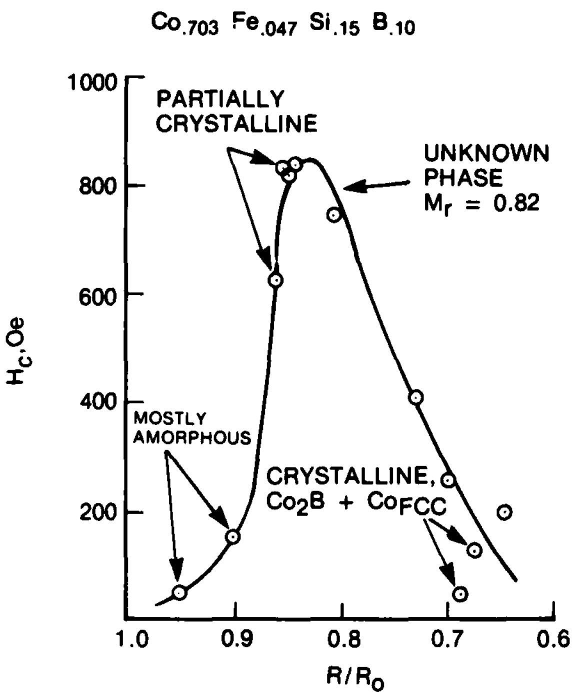

Figure 6. Coercivity as a function of reduced resistivity, a measure of the degree of crystallization.

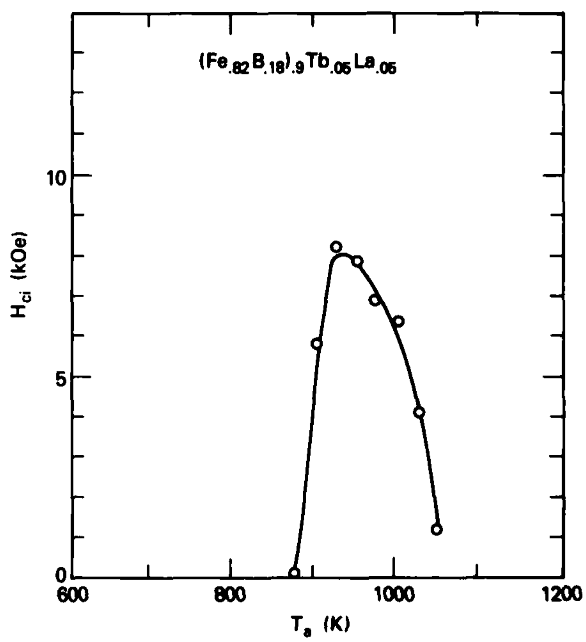

Figure 7. Coercivity as a function of annealing temperature.

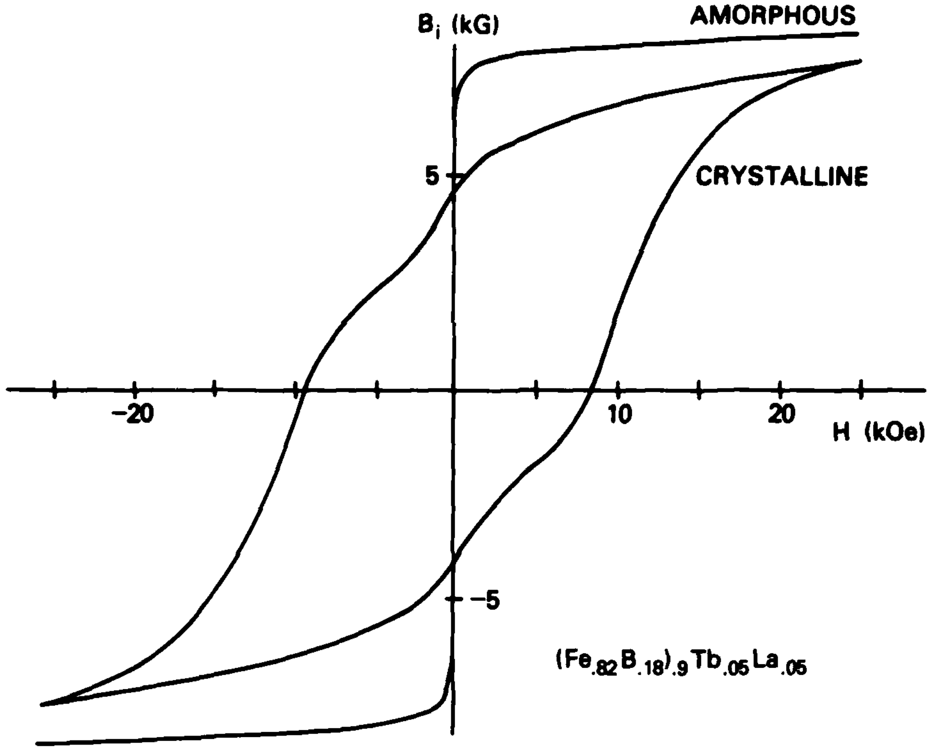

Figure 8. The hysteresis behavior for the amorphous alloy and after annealing to form a crystalline alloy with a maximized coercivity.

by TEM observations, which indicate a grain size of about 200 Å for an alloy having a maximum coercivity. Unfortunately, the saturation magnetization is reduced by dilution from La and by the ferrimagnetic coupling of the Tb and Fe moments. Further, the high slope of the magnetization curve near H = 0 also leads to a lowered $(BH)_{max}$. However, it may be possible to increase somewhat the remanence and energy product by using magnetic orientation of a powder.

Preparation of the amorphous ribbons is difficult. Comparison of data obtained using Mo and Cu radiation shows that the crystallinity observed in some melt-spun ribbons which contain no La, e.g. $(Fe_{.82}B_{.18})_{.95}Tb_{.05}$, is limited to a thin layer on the top surface of the ribbons. Further, pole-figure data show that this phase is highly textured with a highly diffracting crystal plane parallel to the ribbon surface. Combined with the limited penetration of even Mo radiation into the Fe-rich sample (enhanced by the low angles of interest in the diffractometer), standard X-ray diffraction patterns can be highly misleading since the observed crystallinity is often due to a heterogeneous surface nucleation, possibly of an oxygen stabilized phase.

Clearly, much remains to be explored, including the complete characterization of the phases present in the alloys having high coercivity. Since the compositional freedom (metalloid and rare earth level and identity) is so great, attempts to optimize this approach will require an understanding of the dependence of the bulk magnetic properties on the microstructure and the magnetic properties of the phases being formed. Further, rapid solidification of an alloy directly to a microcrystalline microstructure may also produce interesting magnetically hard materials. In any case, the demonstration of a coercivity of 9 kOe in a cobalt free alloy is an important advance in efforts to develop new permanent magnet materials.

It is noted that J. J. Croat has investigated similar topics at the General Motors Research Laboratories. He prepared amorphous $Pr_{1-x}Fe_x$ by melt-spinning for $0.45 \leq x \leq 0.90$.[14] Consistent with the observations of Clark, huge coercivities were observed at low temperatures, e.g. 62 kOe at 20 K. While this coercivity exhibited the expected pronounced temperature dependence, Pr rich alloys exhibited appreciable coercivity at room temperature, the maximum observed value being 2.8 kOe for $Pr_{.40}Fe_{.60}$, while for the highest Fe contents the room temperature coercivities "were negligible."[14] The origin of this high room-temperature coercivity is still uncertain, though it may be that the sample is in fact phase-separated or contains microcrystallites. Amorphous sputtered $Pr_{0.27}Co_{0.73}$ was also studied; the room-temperature coercivity of less than 100 Oe reached a maximum of 6.8 kOe for a two-hour anneal at ~420 °C and then decreased sharply,[15] thus behaving like the amorphous sputtered $TbFe_2$ discussed previously.

The use of a rapid solidification technology (RST) process such as melt-spinning in an attempt to produce new permanent magnets has much to recommend it. RST techniques are being used extensively in efforts to develop a wide range of advanced metal alloys,[16] and melt spinning in particular promises to be a quite economical manufacturing process. Further, the melt-spun ribbons of compositions of interest for cobalt-free magnets are often brittle, either as spun or after annealing, and can thus be readily comminuted to a powder. Most significantly, RST can be used to produce novel microstructures; otherwise unobtainable metastable phases may be produced, new ranges of composition and multiphase mixtures may become accessible and/or the small grain size typically desirable for high coercivity can be readily produced. Starting with the amorphous phase allows even more control over these aspects of the microstructure.

While the use of RST is one approach to the development of the desired cobalt-free magnets, it is not the only promising route available. Efforts are now beginning, under ONR support, to explore alternative approaches. One approach will be to produce ultrafine powders of candidate alloys (i.e. selected alloys having high magnetocrystalline anisotropy) directly by an arc process. Also, candidate iron-rare earth alloys which appear not yet to have been explored will be characterized. In a different approach, surfactants will be used to magnetically harden particles having shape anisotropy.

Whether or not any of the approaches described above lead to a new cobalt-free commercial permanent magnet, they will certainly lead to an increased understanding of the origins of coercivity in iron-based alloys and thus hopefully move us closer to the goal.■

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Spectral Computation of Triple-Deck Flows

Finite difference marching methods have dominated computational research in boundary layer flows in recent years. Rapid and accurate solutions to the boundary layer equations are routine on modern computers so long as the boundary layer is attached. However, the character of the boundary layer equations changes when separation occurs and finite difference marching techniques either fail or become difficult to implement. Flow reversal due to separation gives the flow a quasielliptic nature and it is not surprising that parabolic oriented marching techniques are not appropriate. Several "modified" marching methods have been developed and applied with limited success for weakly separated flows.

Professor Otis Burggraf at Ohio State Univesity has, with Office of Naval Research support, applied pseudo-spectral techniques to the solution of boundary layer flows with separation. The triple deck formulation is ideal for separating flows with inviscid/viscous interaction and is used in this research.

The technique is termed pseudo-spectral because the nonlinear inertia terms are evaluated in physical variables, although the main computations are made in spectral variables. The nonlinear governing equations are transformed from physical to spectral variables using the Fourier integral transform in the main flow direction together with finite-differences in the transverse direction. Performing computations in spectral space provides an ideal situation for separated flows in that each point in spectral space relates to all points on the path of integration in physical space thus accounting for both reversed and forward flow information in transform variable. Professor Burggraf has obtained rapidly convergent, accurate solutions for flows exhibiting large separated regions where other methods fail. The method has been applied to both incompressible and supersonic flows. The research is continuing and if its potential is realized, the rapid and accurate computation of complex viscous flows will become a tractable problem. ■

(Robert E. Whitehead, ONR)

Advanced Ceramics for Optical and Electronic Applications

by

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and
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Office of Naval Research

Introduction

In this paper we present current goals and the results of recent research in ceramic materials for advanced electronic applications, such as sensing devices and other optical, dielectric and piezoelectric applications. Some future possibilities are touched on briefly.

One of the most important factors in the success of the research described is the introduction of new concepts and techniques in the processing of materials. This has been the cause of the success achieved and will be even more important for future development as requirements become more demanding.

The basis for many of these new developments is the engineering or tailoring of materials for specific purposes. A widely used approach to accomplish this is the use of "composite" materials. These are combinations of materials of different properties. The idea is very old (e.g. concrete) but within the past few years the concept has been applied with great skill and sophistication. Composites today are made of elements ranging in size from the order of Angstroms (microcomposites) to millimeters (macrocomposites) and may be evenly distributed or arranged in ordered arrays.

Table I summarizes the material types, some of the specific materials under study, and the potential applications. In general the research summarized in Table I is aimed at enhancing the desirable properties of materials or improving the reliability and stability of the various devices. Although some of the approaches are relatively straightforward, involving a combination or refinement of existing technologies, others introduce completely new and untested concepts. Further, all of this research whether conceptually simple or complex, requires a substantial amount of processing development in order to produce the materials in the desired configurations.

Optical Fibers (Strength, Transmission)

The transmission losses in silica fibers have been reduced until they are very close to the intrinsic limit (Figure 1). Further improvement in these fibers is now centered on the strength and fracture properties.

Research on crack propagation in silica-based

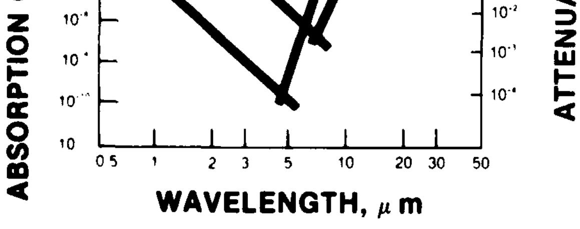
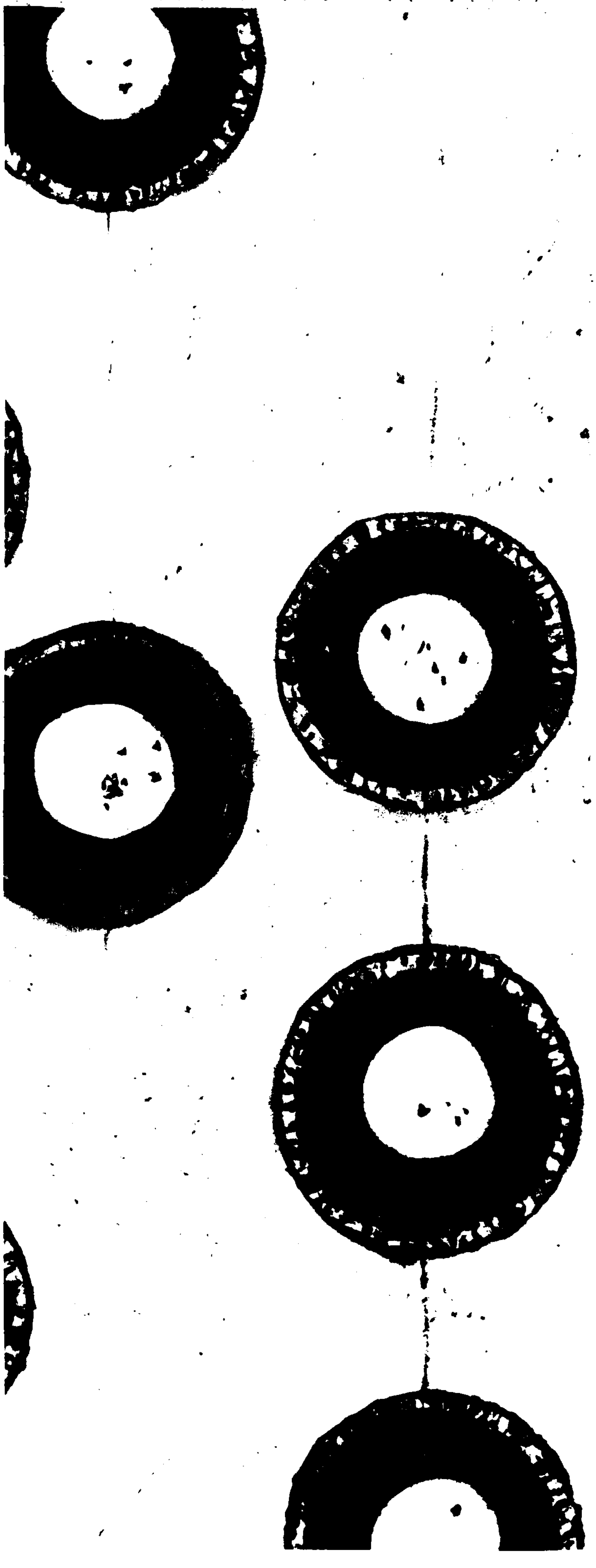


Figure 1. Optical Transmission of Materials as a Function of Wavelength for new fiber applications.



materials has demonstrated that water vapor promotes sub-critical crack growth which may result in catastrophic failure. Thus, current materials research is focused on finding coatings which will prevent moisture penetration into the fiber. Hughes Laboratory[1] has recently coated fibers with a metallic coating which was found to reduce sub-critical crack growth dramatically. Other coatings such as silicon nitride are also being investigated by industrial (Hewlett-Packard) and government (Ft. Monmouth) laboratories. While fabrication of silica based fibers has been very successful and has resulted in a major new technology, ocean systems will require even better transmission than the intrinsic properties of these materials permit. Thus further improvement in transmission will require a material which transmits at longer wavelengths (the infrared) and in which the intrinsic losses are lower (Figure 1).

Halide materials such as the heavy metal bromides have suitable optical properties and can be drawn into fibers.[2] At present, however, optical losses in the fiber form are high and work is concentrated on reducing the impurities and other imperfections which are responsible for such losses.

Optical Fibers (Sensors)

The application of an optical fiber as an underwater acoustic sensor (hydrophone) has been demonstrated by the Naval Research Laboratory (NRL). In such devices an optical wave is modulated by an acoustic wave through a photoelastic mechanism. While the feasibility of such a device has been demonstrated using existing optical fibers, the sensitivity could be greatly improved if a birefringence, which would preserve the polarization of the wave, could be induced in the optical core. Figure 2 illustrates one approach to creating such birefringence.

Another potential application for optical fibers is an electromagnetic sensor. For suc. an application the fiber must be coated with a piezoelectric or magnetostrictive coating which will convert the electromagnetic radiation to mechanical stress. This mechanical stress then modulates the optical properties in the fiber through the photoelastic effect as in the acoustic sensor. Figure 3 shows the configuration for such a sensor. It should be pointed out that while such sensors have been shown to be theoretically possible, they have not yet been verified experimentally.

Table I

Material Type	Examples of Materials	Applications
Optical Fibers		Undersea communications
Polarization preserving	Silica, Halides (TlBr)	
Ultra low loss		E/M sensors
Sensors		Acoustic sensors
Optical Windows	Ternary Sulfides	
8-14μm	$Ca_2La_2S_4$	Missile Windows
3-5μm	Partially stabilized ZrO_2	High Power Lasers
Optical Filters	CdZnS	Blue-Green communications
Dielectric capacitors	$BaTiO_3$ + additives	Guidance and Control systems
Millimeter wave components	$SrBaNbO_3$	Phase Shifters
Piezoelectrics	$Pb(ZrTi)O_3$ + Polymers	Hydrophones Projectors
Pyroelectrics	SbSI + Glass SbSI + Polymers	IR Detectors Vidicons
Magnetoelectrics	$BaTiO_3 - Ni_2Fe_2O_4$	

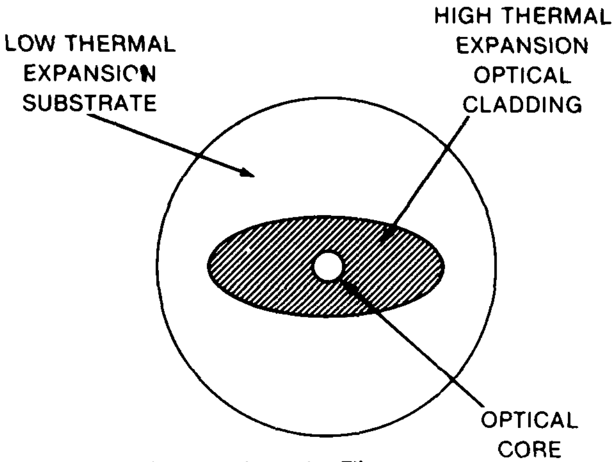


Figure 2. Polarization Preserving Fibers

Optical Windows

Missiles and other devices require windows for two regions in the infrared. In the 3-5 micron and 8-14 micron ranges the limiting factors for existing window materials are erosion and thermal resistance. Thus in addition to the optical properties, the fundamental properties of interest are the fracture toughness, strength and thermal conductivity. It has been established that the erosion resistance of a material increases as the fracture toughness increases. This suggests that the two-phase toughening mechanisms developed for structural materials can be applied to optical materials provided suitable optical transmission can be maintained. An example of such a composite material is provided by work at NRL which has developed a two-phase material (zirconia, partially stabilized with yttria) that appears quite promising for the 3-5 micron range. The optical transmission is satisfactory, the strength and fracture toughness have been increased greatly over materials now in use. This development was accomplished by combining experience based on ONR sponsored research at MIT, General Electric and Stanford on toughened ceramics for structural purposes and models of the optical transmission of two phase materials. The results of this work are summarized in Figure 4.

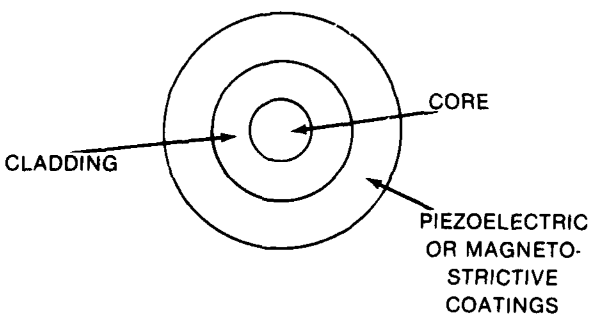


Figure 3. Configuration for an Electromagnetic sensor based on an optical fiber.

The toughening and optical transmission concepts for two phase materials are also applicable to materials suitable for 8-14 micron range. The actual synthesis of such a material, however, will depend upon new processing approaches applicable to materials such as ZnS, ZnSe and $CaLa_2S_4$.

Optical Filters

A new concept in optical filters has been introduced by Hughes.[3] This approach makes use of the dispersive properties of birefringent materials. It has been found that in some ternary sulfides ($ZnCd_ys_z$) the optical properties become isotropic at a sharply defined wave-length and thus transmit no light when placed between crossed polarizers.

If the material is also suitably electro-optic so that the principal optic axes can be rotated by the electric field then a sharp electrically controlled filter can result. The details of the operation and properties of such a filter are summarized in Figure 5.

Dielectric Materials

Two methods of achieving a very high capacity in a small volume are in current use. The first involves laminations electroded and stacked in the green state and fired to a monolithic piece (Figure 6). This

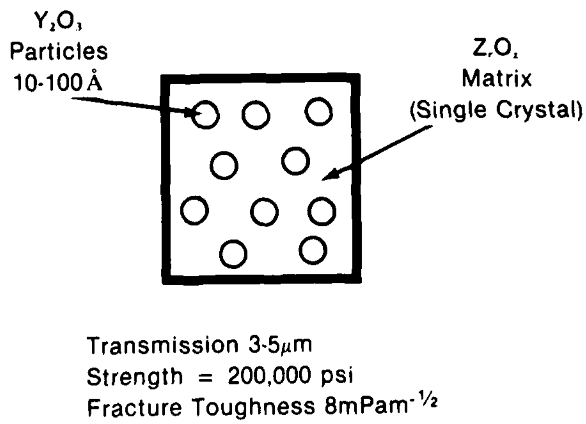


Figure 4. Schematic of Composite Optical Material, and relevant properties.

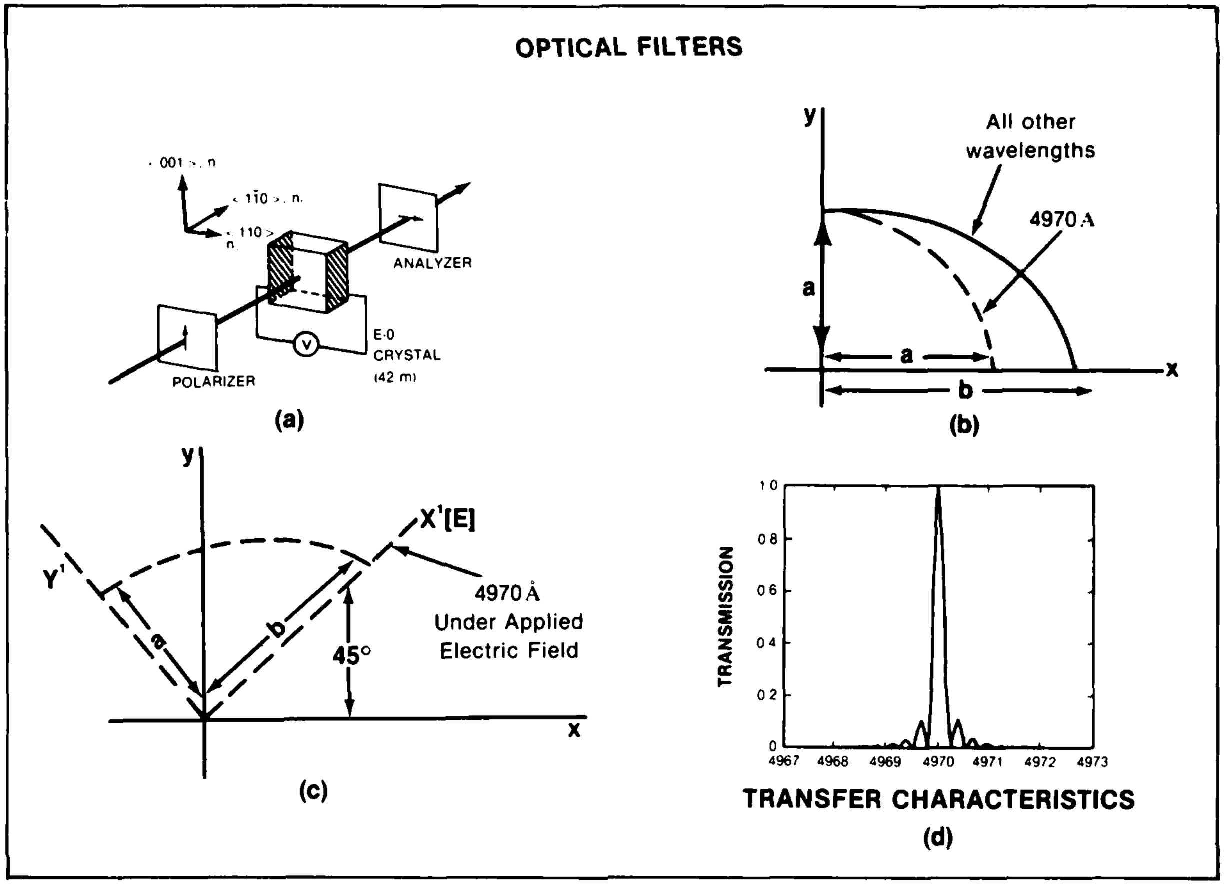


Figure 5. (a) Schematic of the optical system; (b) optical properties, isotropic $a_y = a_x$ at 4970 Å, anisotropic $a_y \neq b_x$ at all other wavelengths; (c) principal optic axes at 4970 Å under electric field; (d) transmission characteristics.

technology has now been developed but suffers from lack of reliability in certain situations. The difficulties are in part due to flaws and imperfections introduced during processing, and in part to chemical degradation arising from diffusion of specific chemical species such as ions and vacancies. Both of these sources of trouble are under investigation. Work on improved processing techniques and a fundamental study to identify the mechanisms responsible for the degradation are now underway. The benefit of such work is that it will result in reliable passive components, hence reliable guidance systems.

A second way of achieving a large capacity in a small volume is the barrier layer concept (Figure 7). In this approach, grains of a semiconducting barium titanate material which form the matrix or "substrate" are coated with a thin film of insulating dielectric. The very thin insulating coating results in a very large capacity. In general the electrical properties of such materials have not been completely satisfactory. Recently, substrates other than barium titanate have been tried with success and this opens up a wide field for exploration. To combine the barrier layer materials and the multilayer configuration should, in principle, afford the advantages of both and provide even greater capacities in smaller volumes (10 times present capacity for equivalent volumes). Although simple in concept, successful development of such new structures and microstructures will require some very sophisticated fabrication and processing techniques.

Another use of a grain boundary phase has been developed as a method of raising the saturation limit

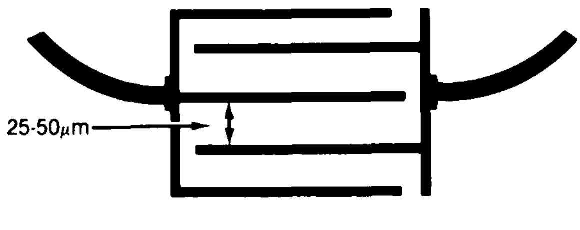


Figure 6. Multilayer Capacitors

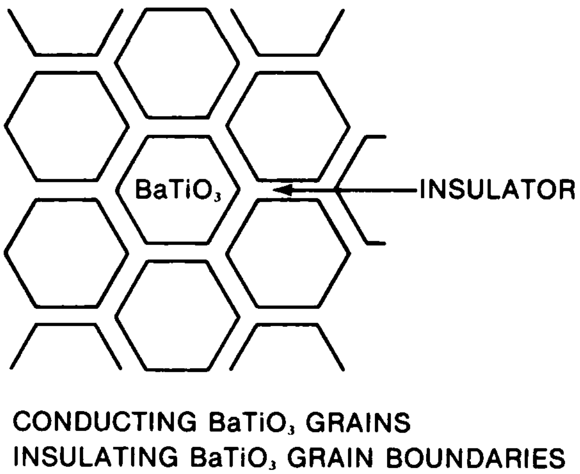


Figure 7. Microstructure of boundary layer capacitor material.

of high-voltage, high capacitor materials (Figure 8). In this approach the grains of the high permittivity ferroelectric material are coated with a material of low dielectric constant. Under high fields the combination acts as a voltage divider. As the voltage increases, a larger proportion appears across the low dielectric constant grain boundary material so that the high dielectric constant carries a lower proportion of the voltage and thus does not tend to saturate as easily.

Millimeter wave dielectrics

At present the millimeter-wave band (1-1,000 gigaHz) is not being used. This band has potential for a number of commercial and military applications such as guidance systems. The availability of components that can operate in this frequency range, however, is limited by lack of data on material properties. Thus, the development of advanced millimeter-wave devices will depend on the development of new components and materials. Such research is now underway as part of the Navy's program on dielectric materials. The first step in developing such components is to measure dielectric properties of materials in this frequency range. Further, new theoretical concepts such as those introduced by Rockwell and Hughes will provide guidelines for the selection of the most promising materials.

Certain classes of materials called ferroelectrics have very high dielectric properties (low frequency permittivities over 1000). Further, these permittivities can be changed by more than an order of magnitude by static electric fields. Since the region of interest is far below any atomic resonances in these crystal structures, it is expected that the low frequency dielectric properties will also exist at the millimeter-wave band. Changes in the permittivity with electric field at optical frequencies have been used to make many practical devices such as optic phase shifters and shutters. Therefore millimeter-wave components similar to the optical ones should be possible. The search for suitable materials for these potential applications is being

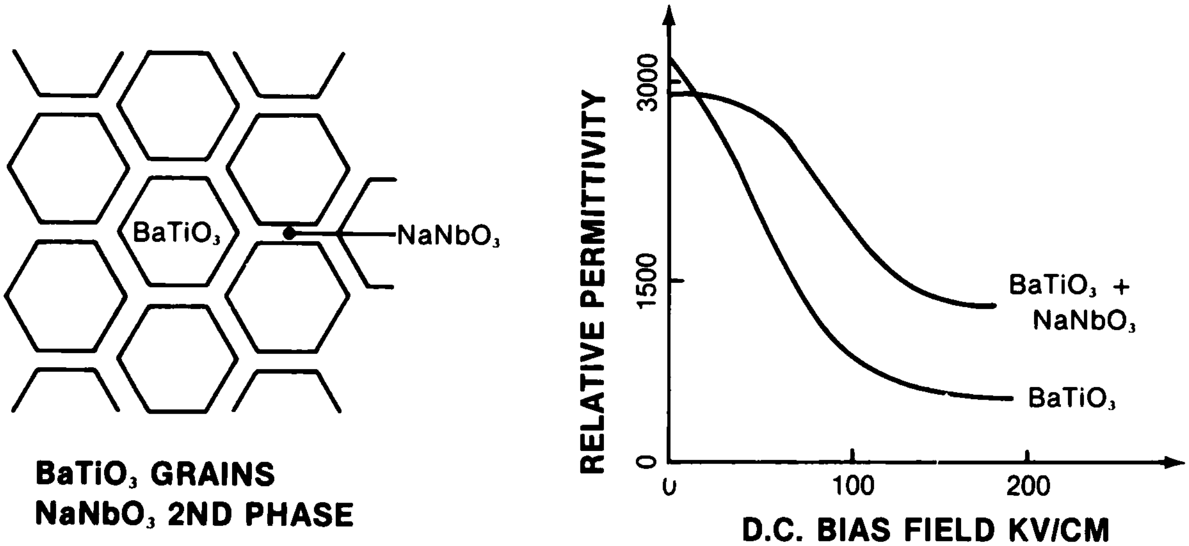


Figure 8. Comparison of the dielectric properties of BaTiO$_3$ and a BaTiO$_3$ + NaNbO$_3$ composite. Note lower saturation of the permittivity in the composite as the bias field is increased.

greatly assisted by theory. Such theory permits a calculation for the electric field dependence of the permittivity from the large amount of data in the literature on the temperature dependence of the permittivity and polarization.

Piezoelectric Composites

Work on piezoelectric composites has been very active in the past few years and has produced some promising materials. These efforts have included micro and macro composites and involved both ceramic-polymer and ceramic-ceramic combinations. The goals sought have likewise been diverse. For hydrophones the goal was to produce a flexible piezoelectric material with good response to hydrostatic pressure. For projectors the goal was to fabricate a transducer which would produce high power at low voltage.

The low hydrostatic response of present hydrophone ceramics occurs because the lateral and longitudinal piezoelectric effects are similar in magnitude and opposite in sign so that the overall response is low. A composite material approach provides an opportunity to decouple the lateral and longitudinal effects so that he full value of the longitudinal response is obtained.

The need for a flexible piezoelectric has been felt for a long time. Although a piezoelectric polymer is available which satisfies the flexibility requirement the piezoelectric activity is low and the piezoelectric composites offer a much higher response and more design flexibility for transducers. The composite approach was tried very early without success. Recent work carried out at Honeywell,[4] The Pennsylvania State University,[5] and the Naval Research Laboratory[6] has explored a wide variety of composite structures with encouraging results.

An example of a macrocomposite hydrophone material is shown in Figure 9. This material consists of piezoelectric rods longitudinally poled and embedded in an ordered way in a polymer matrix. This arrangement makes it possible to tailor the piezoelectric properties. (charge response) and dielectric properties (capacity) independently. Such independent adjustment of the properties can produce large figures of merit for hydrophones as summarized in Figure 9. Figure 9 also lists the applications and advantages of these materials. A microcomposite material has recently been developed by the Japanese.[7] This material has good hydrostatic response, but is not flexible.

For projector materials, ceramic-ceramic composites, both micro and macro, provide the best ap-

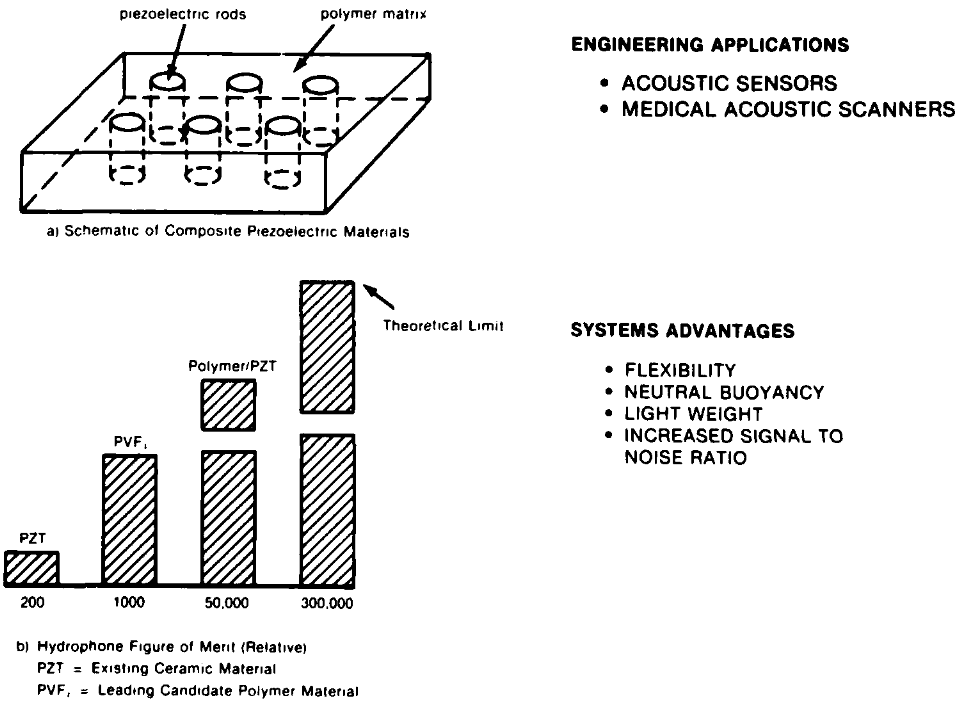
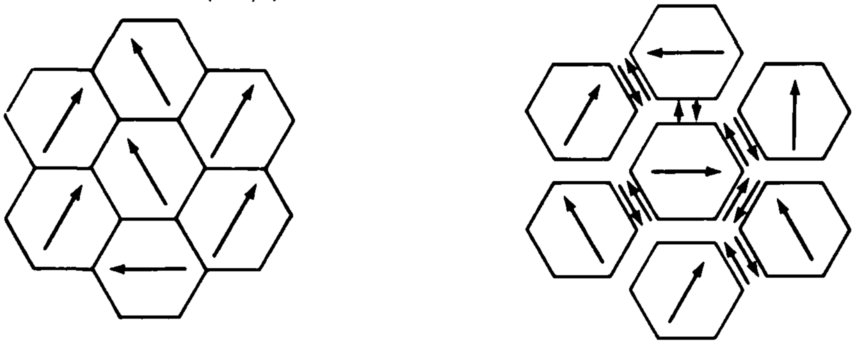


Figure 9. Composite Materials for Hydrophone Applications

Current Materials Pb(Zr Ti)O₃ — Proposed Composites



1. PZT grains are shown schematically as hexagons directly bonded to one another.
2. The permittivity (ε) is limited to ~ 1200.
3. The stresses between grains are the major driving force for instability.
4. Piezoelectric coupling $K_{33} \sim 0.7$.

1. The grains are separated and bonded by a second ceramic phase.
2. Permittivity may be extended to ~5,000. Control nonlinearity and electroelastic aging by antiferroelectric phase which limits charge transfer necessary to domain motion.
3. Controls aging by controlling internal stresses through elastic properties of second phase.
4. Coupling $K_{33} \sim .7$-.8.
5. Mechanical strength comparable to current materials.

Figure 10. Comparison of current material PZT to proposed new composites.

proach. The macrocomposite approach involves a straightforward application of multilayer capacitor technology (Figure 6) to tranducer materials. The benefit of this structure is that low voltages can produce high output power because the laminations need be only 25-50μm thick. The low required voltage permits operation of the transducer without a transformer resulting in lightweight compact systems. Small experimental units of multilayer materials have been found to exhibit clean wave-forms both in the lateral and thickness vibrational modes. Current materials used in these multilayer configurations are summarized in Figure 10. New microstructural composite transducer materials based on the boundary layer concepts previously discussed for dielectrics should provide additional significant advantages as summarized in Figure 10. In order to realize these advantages, substantial advances in fundamental understanding of material processing will be required.

Magnetoelectric and Pyroelectric

The composite materials discussed in previous sections involved simple combinations of the properties of each of the constituents. Now we will introduce a new concept in which the phases in the composite are designed to interact to create properties that are *not* present in either of the constituents. Magnetoelectric materials are an example of such a composite. In these materials, an interaction is created between the piezoelectric properties of one phase and the magnetostrictive properties of a second phase to produce a material that will convert magnetic signals to electric (voltage) signals. A schematic diagram of these composites is shown in Figure 11. An application of a magnetic field to the composite strains the magnetic phase ($NiFe_2O_4$) through the magnetostrictive effect. This strain produces a stress on the piezoelectric phase ($BaTiO_3$) to produce a voltage. Composites of this type have been produced by Philips Research Laboratories (Eindhoven) both by a direct sintering process and by directional solidification from the melt. The measured magnetoelectric properties of the material were found to be 20 times larger than those of any crystal with intrinsic magneto-electric properties.

The interaction of phases in composites can also be used to greatly enhance the pyroelectric properties. In these materials an interaction is created between the piezoelectric properties of one of the phases as a result of a mismatch in the thermal expansion

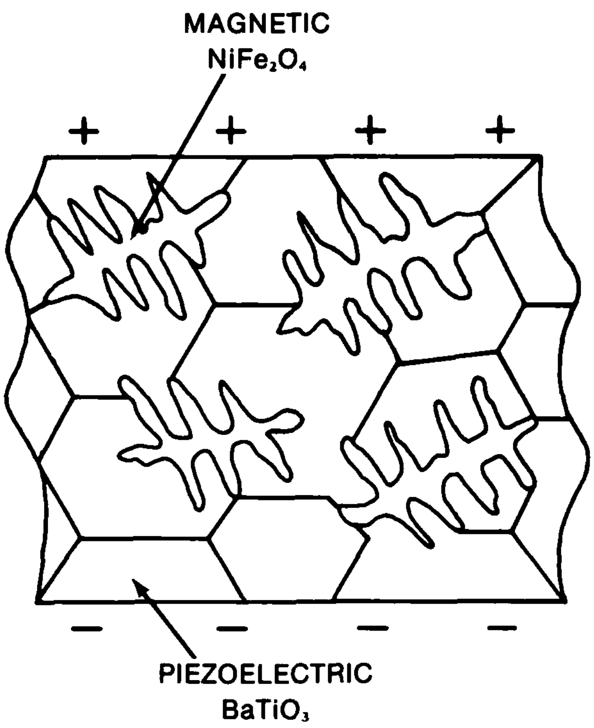


Figure 11. Composite Magnetoelectric

(strain) of the phases. A schematic diagram of such a composite is shown in Figure 12. Upon the application of heat to the composite each of the two phases strains in a different manner because of a mismatch in the thermal expansion coefficients. Such a mis match in thermal expansion produces stresses in the material, and if one or both of the phases are piezoelectric a voltage will be produced. Although research on such composites is in its very early stages, materials have already been synthesized with pyroelectric properties equivalent to lithium tantalate which is used in commercial applications. It is expected that these new materials will eventually find application in low cost IR detectors and vidicon displays.

Summary

In this paper we have illustrated the wide range of ceramic materials research, ongoing and potential, that could result in new materials for advanced electronic and optical applications.

Although the power of the composite approach has been clearly demonstrated by many examples, the possibilities for new materials extend far beyond those discussed here. It is well to emphasize again

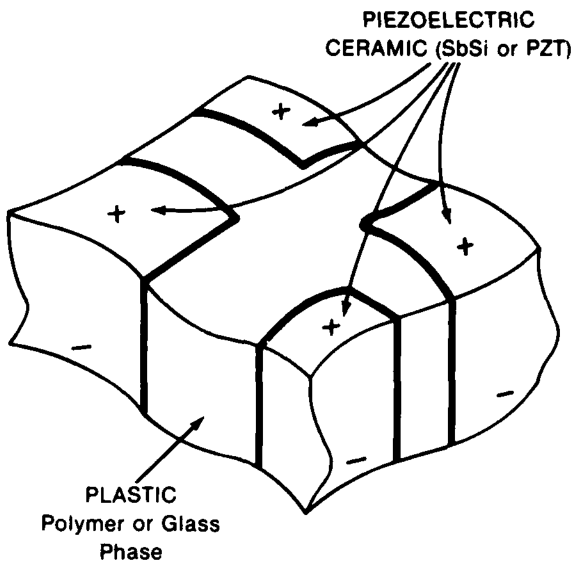


Figure 12. Composite Proelectrics Thermal Expansion Mismatch Between Two Constituents One of Which must be Piezoelectric.

that materials processing science must be advanced to achieve these goals. ■

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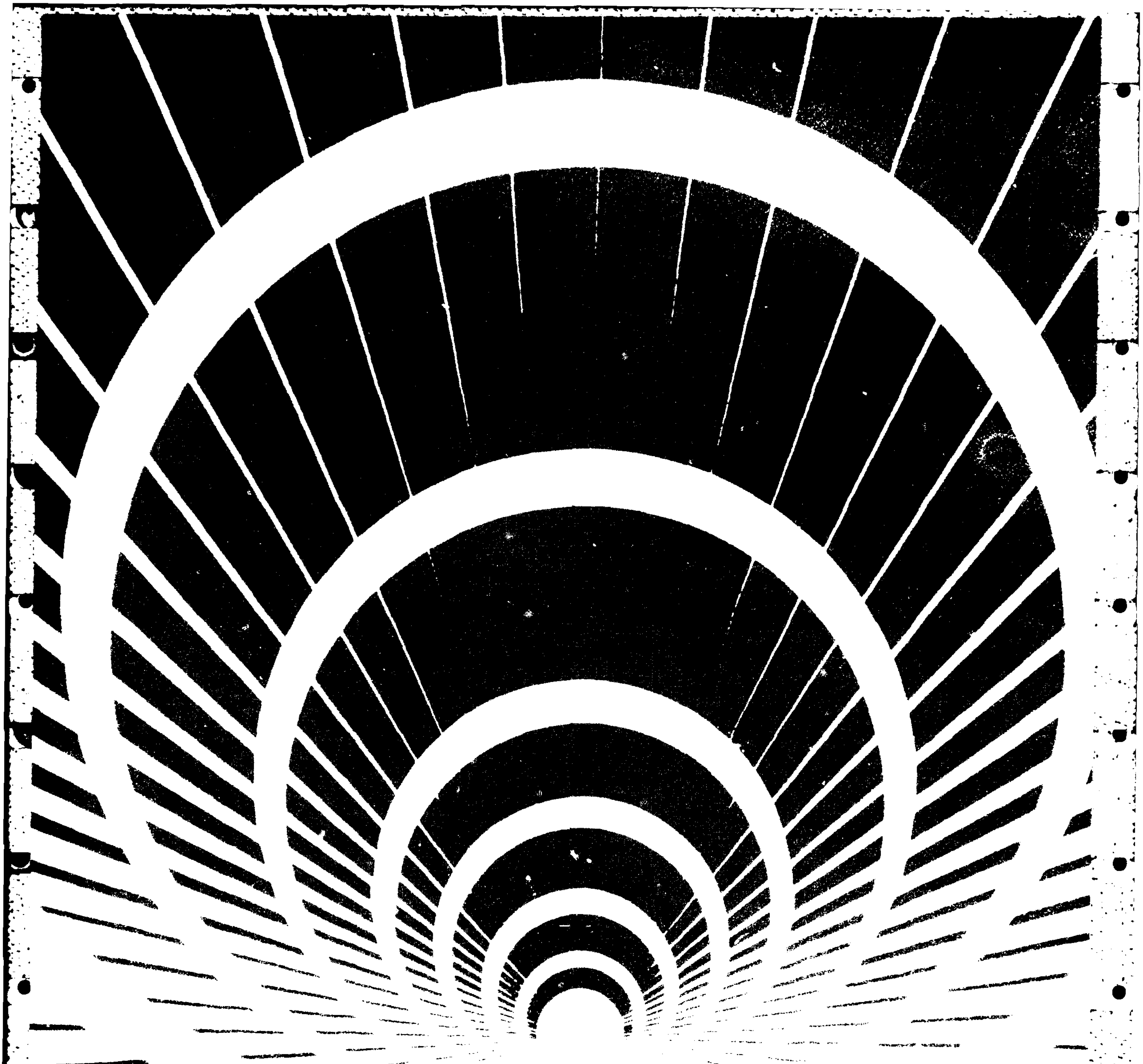

A Working Theory of Two-Phase (Gas-Liquid) Nozzle Flow

by

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A working theory of two-component two-phase (gas-liquid) nozzles was developed which includes interphase effects of velocity slip, droplet breakup, and heat transfer between droplets and the surrounding gas. Parametric calculations based on this model were compared with results from previous models of two-phase nozzle flows and with available experimental data. The two phase flow nozzle is a component of the Bi Phase turbine concept which is being investigated now for possible naval ship propulsion applications. This research conducted at United Technologies Research Center, East Hartford, Connecticut, is supported by the Office of Naval Research.

Introduction

The flow of two-phase mixtures through a nozzle is receiving increasing attention because many applications involve flows of a substance that is a suspension of liquid droplets in a gas. A typical example is a nozzle where a gas and a liquid at a condition of high pressure and low velocity are mixed at a nozzle inlet and then expanded through the nozzle to a condition of low pressure and high velocity. Among other applications, two-phase nozzles can be integrated with two-phase turbines for prime-mover applications and for geothermal power generation.

The major difference between single-phase (gas) nozzle flow and two-phase nozzle flow is the interaction between the phases. In two-phase nozzle flow, as the gas expands, drag forces transfer momentum from the gas phase to accelerate the liquid droplets, while heat is transferred between the liquid and the gas. However, the temperature of the gas phase decreases as the gas expands, therefore heat transfer from the liquid phase will partly offset this decrease, so the temperature decrease of the gas in a two-phase flow is less than that for the pure gas expanded through the same pressure. Hence, interphase effects must be considered in analyzing two-phase nozzle flows.

A number of previous investigations have proposed physical models for two-phase flows in nozzles. These previous models generally display one of two drawbacks. Either: only some of the significant interphase effects of velocity slip, droplet breakup, and droplet heat transfer were considered;[1-7] or these three effects were considered, but the model[8,9] was generally formulated with a view towards detailed design and not with the intention of conducting parametric analyses and optimization where many cases must be quickly examined yet with reasonable accuracy. Therefore, to avoid these drawbacks, a working theory was formulated which is suitable for parametric analyses and optimization yet includes the significant interphase effects of velocity slip, droplet breakup and droplet heat transfer as well as provides details of the local flow conditions throughout the nozzle.

Governing Flow Parameters

Preparatory to formulating a working theory of two-phase nozzle flows, the principal governing flow parameters were identified on the basis of previous investigations.[1-9] Figure 1 is a schematic of a converging-diverging nozzle with the governing flow parameters: the velocity (v), mass flow rate ($\dot{m}$), and temperature (T) of both the gas-phase (subscript g) and liquid-phase (subscript ℓ) streams, and the droplet diameter (D). The thermophysical properties of each stream must also be known. For the gas phase, these properties include the density (ϱ_g), specific heat (C_{pg}), thermal conductivity (k_g), and viscosity (μ_g).

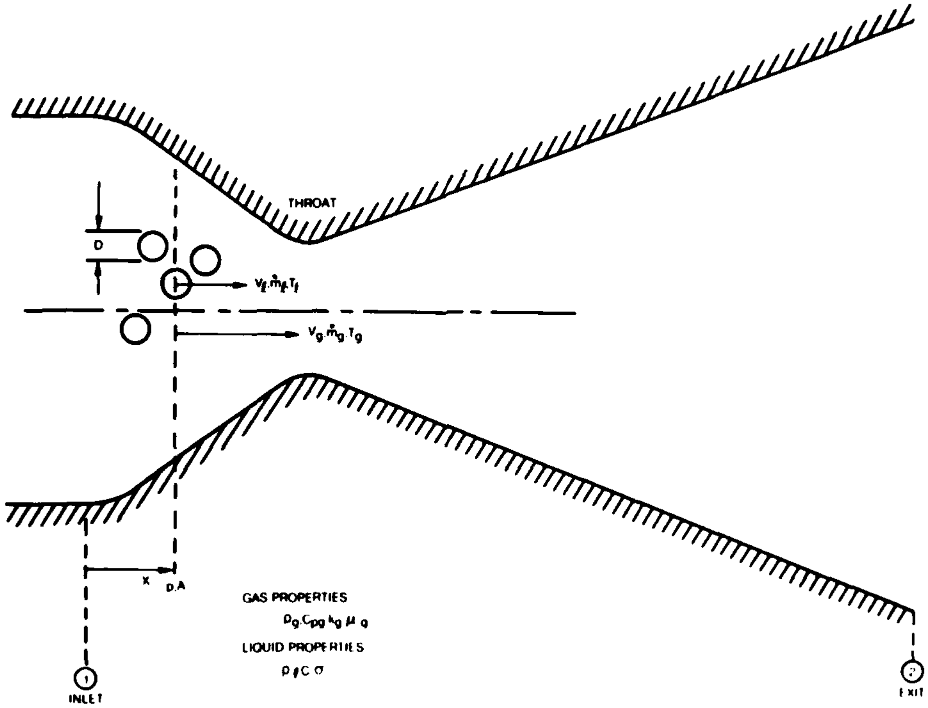

Figure 1. Governing flow parameters of two-phase nozzles.

For the liquid phase, these properties include the density (ϱ_l), specific heat (C), and the surface tension (σ) for use in estimating droplet sizes. The local differences in velocity and temperature between the two phases affect the interphase transfer mechanisms of momentum and energy. The velocity difference affects the droplet drag, the heat transfer coefficient between the liquid droplet and the gas, and the droplet breakup.

In general, there are two types of two-phase liquid/gas flows. If the gas phase is the vapor of the liquid phase, then the flow is "one-component" flow. If the gas phase is of a different chemical species than that of the liquid, then the flow is "two-component" flow. The expansion of a one-component system occurs along the saturation line, while the expansion of a two-component system can be nearly isothermal if the loading ratio is high enough. A nearly isothermal expansion is advantageous for a two-phase nozzle in a two-phase turbine.

Two-phase turbines are being considered[10] for propulsion applications because of their low-speed characteristics which result in reduced gearbox requirements. High-temperature synthetic oils (such as the Dowtherm family) seem to offer the most advantages as the liquid for this application where steam would be the gas phase. These oils have a density only about 15 percent less than that of water and a very low vapor pressure. Their specific heat is in the range of 0.5 cal/gm-C (0.5 Btu/1bm-F) which means that the liquid flow rate (and hence the loading ratio) will be high enough to result in a reasonably low nozzle exit velocity. Further, most of these oils are inert and reasonable vapor pressure characteristic, and is immiscible with the heat transfer oils under consideration for the liquid phase.

Formulation of Working Theory

A Model with Droplet Heat Transfer has been developed and computerized in a form suitable for parametric analyses. The model is designed for a wide range of operating conditions because it includes the effects of heat transfer between the liquid droplets and the gas phase, as well as the effects of velocity slip and droplet breakup.

The model assumes a two-component, two-phase mixture, where the liquid phase is in the form of droplets. One-dimensional flow, with variables changing only in the axial flow direction of the nozzle, was selected so both the model and the results will be tractable. Numerical marching-type solutions with the nozzle divided into numerous small axial segments of equal length have been selected because closed-form analytical solutions are possible only for certain simplified situations. The variations of the thermophysical properties of the gas and the liquid with temperature and/or pressure along the nozzle are included in the marching-type solution by recalculating the value of the property for the local temperature or pressure at each segment.

The following six basic equations describe the adiabatic one-dimensional two-phase nozzle flow: continuity, momentum, droplet drag, droplet breakup, energy and heat transfer. These equations describe the flow conditions in and across each nozzle segment of finite length, and each has been transformed into a form suitable for computerized numerical solutions, as described in detail in reference 11.

Continuity Equation

At a given nozzle cross-section, the total flow area (A) can be considered as a sum of the liquid flow area (A_ℓ) and the gas flow area (A_g). And for one-dimensional flow through a cross-section, the continuity equations for each of the two components can be combined with the sum of the areas to produce:

$$A = \dot{m}_g \left(\frac{1}{\varrho_g V_g} + \frac{r}{\varrho_\ell V_\ell} \right) \qquad (1)$$

where r is the loading ratio ($r = \dot{m}_\ell / \dot{m}_g$). This equation implies the assumptions that the gas does not dissolve in the liquid and that the vapor pressure of the liquid is so low that the liquid does not vaporize.

Momentum Equation

A differential force balance on a control volume with cross-section A and infinitesimal axial length dx describes the conversion of pressure drop (dP) into momentum:

$$d\dot{M} = -A\, dp \qquad (2)$$

The total momentum ($\dot{M}$) of the two-phase mixture is equal to the sum of the momentum of each of the two streams. The mass-weighted mean velocity ($\bar{V}$) is defined as:

$$\bar{V} = \frac{V_g + r V_\ell}{1 + r} \qquad (3)$$

The local velocity ratio is defined as: $K = V_\ell / V_g$. Then expressions can be obtained for the local phase velocities, V_ℓ and V_g, in terms of the local velocity ratio and the local mean velocity:

$$V_g = \left(\frac{1+r}{1+rK} \right) \bar{V} \equiv G\bar{V}$$

$$V_\ell = \left(\frac{1+r}{1+rk} \right) K\bar{V} \equiv L\bar{V} \qquad (4)$$

The perfect gas law is assumed for the density of the gas phase ($\gamma_g = PM_g/RT_g$). P is the pressure change over the length of the segment ΔX as the two-phase mixture flows from position X to downstream position, $X + \Delta X$. M_g is the molecular weight of the gas and R is the universal gas constant. If the assumption is made that the quantities T_g, G, L, and ϱ_ℓ vary only slowly over the small pressure increment ΔP, then the values of these quantities can be assumed to be constant over the small segment and can be assigned the numerical value that exists at the inlet of each segment. The values of these quantities are then recalculated for each segment. After manipulation, the momentum equation can then be integrated to:

$$\Delta V^2 = -\left(\frac{2}{1+r} \right) \left\{ \frac{RT_g}{GM_g} \ell n \left(\frac{P + \Delta P}{P} \right) + \frac{rP}{\varrho_\ell L} \right\} \qquad (5)$$

Droplet Drag Equation

Droplet drag provides the mechanism by which the gas-phase momentum is transferred to the liquid droplets. Using a droplet force balance, as shown in Figure 2, the acceleration force is equal to the drag force less the force caused by the pressure gradient of the gas phase. V_{slip} is the velocity slip between the two phases ($V_{slip} = V_g - V_\ell$) and a convenient definition[9] is the velocity slip relative to the mass-weighted mean velocity: $S = V_{slip}/\bar{V}$. The assumption is made that no mass transfer occurs between the phases. Hence, the loading ratio (r) is constant through the nozzle. The force equations shown in Figure 2 can be combined with the force balance ($F_{Drag} - F_{Press} = F_{Accel}$ and then manipulated to result in the differential of the slip velocity for an axial segment of finite length BX:

$$\Delta S = \frac{1+r}{2\bar{V}^2} \left(1 - \frac{S}{1+r} \right) \Delta \bar{V}^2 - \frac{3\varrho_g |S| S C_D (1+r) \Delta X}{4 \varrho_\ell L D} + \frac{(1+r)\Delta P}{\varrho_\ell L \bar{V}^2} \qquad (6)$$

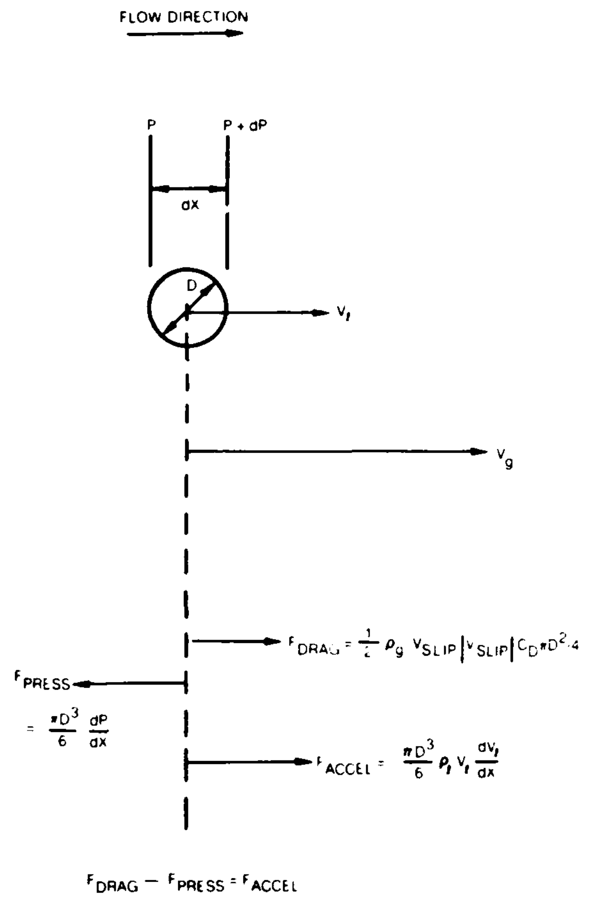

Figure 2. Force balance with drag on liquid droplet.

This equation is valid for numerical analysis if the axial segments are short enough so that the equation can be linearized over the segment, and quantities can be evaluated at their inlet values (except for differential quantities).

Droplet Breakup

Droplet breakup in a two-phase mixture is governed primarily by the ratio of the aerodynamic pressure forces and the surface tension forces. This ratio is known as the Weber Number:

$$We = \frac{\rho_g V_{slip}^2 D}{\sigma} \qquad (7)$$

The critical value of the Weber number, $We)_{Crit}$, is experimentally determined and represents the maximum droplet size in terms of droplet diameter, D_{max}, that can exist at the local flow conditions in a two-phase flow:

$$D_{max} = \frac{\sigma We)_{Crit}}{\rho_g V_{slip}^2} \qquad (8)$$

The generally accepted value of $We)_{Crit}$ is,[12] within a factor of about 2 (for example, see reference 13). However, recent droplet size distribution measurements by Alger[14] with steamwater nozzles suggest that the appropriate value of $We)_{Crit}$ should be approximately 1.0.

Energy Equation

The energy equation of the mixture states that the net energy flux into a volume element is zero. Hence, the total enthalpy of the mixture is constant, and the integrated form of the energy equation is:

$$\frac{V_g^2}{2} + C_{pg} T_g + r \left[\frac{V_\ell^2}{2} + CT_\ell + \frac{P}{\rho_\ell} \right] = \text{Constant} \qquad (9)$$

where the Constant term is determined from nozzle inlet conditions.

$$\frac{hD}{k_g} = 0.37\ Re_{Rel}^{0.6} \qquad (16)$$

For Reynolds Number in the range of 1.0 to 25, Kreith (Ref. 17) recommends the following correlation:

$$\frac{hD}{k_g} = \frac{\mu_g C_{pg}}{k_g} \left[2.2 + 0.48\ Re_{Rel}^{0.5} \right] \qquad (17)$$

Results and Comparisons

Parametric calculations were made to show the versatility of the computer model. Figure 3 shows the effect of inlet temperature on temperatures, velocities, and cross-sectional area through the nozzle. In one case, the inlet temperatures of the gas and the liquid are the same at 316 C (1060 R), while in the other case the inlet gas temperature is 56 C (100 R) cooler than the inlet liquid temperature of 1060 R. Near the inlet for the case with the 100 R differential, the steam is rapidly heated by the higher-temperature liquid DTA, until the steam expands sufficiently for both temperatures to begin falling shortly beyond the nozzle exit.

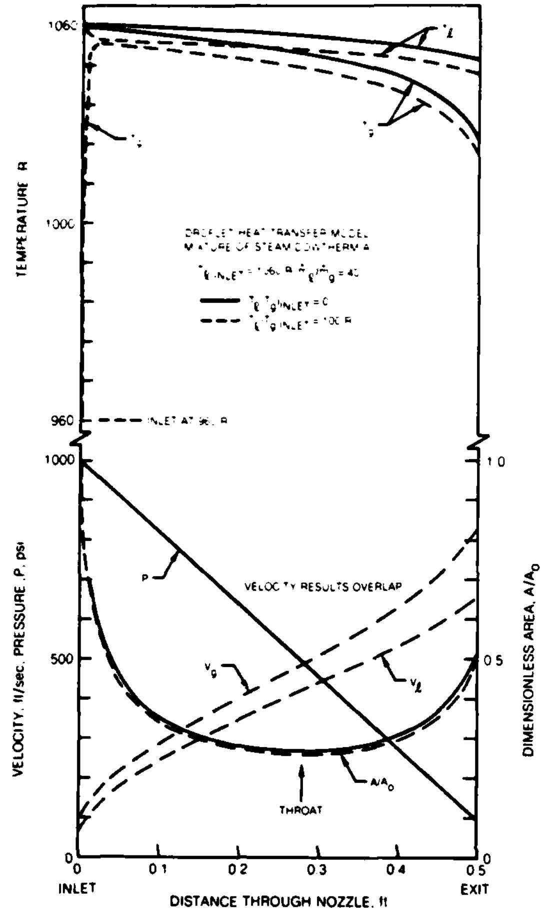

Figure 3. Effect of inlet temperature differential on nozzle results.

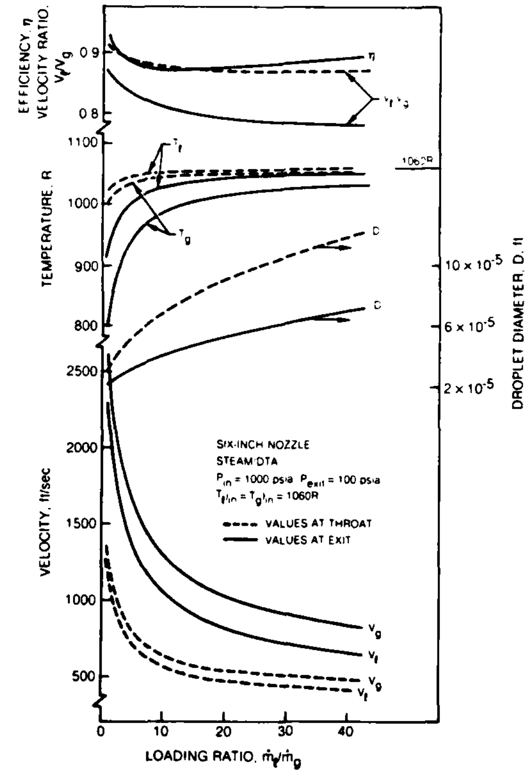

Figure 4. Effect of loading ratio on nozzle performance predictions

Figure 4 shows the effect of loading ratio on performance predictions of nozzle throat the exit conditions. As the loading ratio is reduced, both throat and exit velocities of both phases increase, and both throat and exit temperatures of both phases decrease. These situations are explained by reasoning that the effect of the liquid phase decreases as the loading ratio is decreased and hence the gas phase tends to behave increasingly as a pure gas. The slip velocity increases as the loading ratio is reduced and the droplet size decreases as a result, because the higher slip velocity means higher aerodynamic forces which tend to break up the droplets. The nozzle efficiency goes through a minimum, at first decreasing because of the higher slip when the loading ratio is reduced, but then increasing because the presence of the liquid phase has a lesser effect when the loading ratio is reduced further.

Table 1 compares velocity and temperature results at the exit of a 50-inch-long nozzle for the two-phase flow of a mixture of water and nitrogen at inlet conditions of 150 psia and 16 C (60F). The results from Rudinger's isothermal model are shown at V_ℓ/V_g = 0.7, the value at the nozzle exit which is also the approximate value throughout the nozzle obtained from the results of Elliott and Weinberg.[9] The exit velocity (V) calculated with the isothermal model is higher than the exit velocity calculated with either of the other two models, and hence, the isotropic nozzle efficiencies calculated with the isothermal model are optimistically higher also. Results from the Model with Droplet Heat Transfer are also shown for three different pressure profiles. The profile with dP/dX = constant is linear with distance between the inlet and the exit, while the 2-line and 3-line curvefits are shown in Figure 5 along with the optimum pressure profile for maximum mean exit velocity as calculated by Weinberg and Elliott. These selected pressure profiles are used to compare the results calculated from the Model with Droplet Heat Transfer with the results presented by Weinberg and Elliott,

Table I

COMPARISON OF THE MODELS

50-inch Nozzle with Nitrogen/Water
Inlet: 50 R and 150 psia
Exit: 14.1 psia
m,m_g = 40

Model	V_g	V_ℓ	$\bar{V}$	T_g	T_ℓ η	
	Exit Values					
	ft/sec			°R		
Rudinger Isothermal Model $V_\ell/V_g = 0.7$	437	306	309	520	—	0.758
Droplet Heat Transfer Model dP/dX = const	496	300	305	503	518.6	0.736
2-line Curvefit to Elliott and Weinberg P Profile	504	298	302	502	518.6	0.726
3-line Curvefit to Elliott and Weinberg P Profile	462	300	303	505	518.6	0.730
Elliott and Weinberg Model Optimum dP/dX	425	300	303	508	518.3	0.729

which correspond to the optimum pressure profile. The liquid exit velocity (and the weighted mean velocity), the exit temperature of the liquid and of the gas, and the isentropic nozzle efficiency, all of which are calculated with either of the three pressure profiles in the computerized Model with Droplet Heat Transfer or with Elliott and Weinberg's model and their optimum pressure profile, agree within one percent. The gas velocities, which were calculated in the same manner, differ by 18 percent. The model with Droplet Heat Transfer neglects friction, but this assumption is reasonable because the nozzles for a two-phase turbine application must be short in length in order to accommodate them in the available space. Further, frictional effects did not appear to be larger even in results for the 50-inch-long nozzle of Table 1.

Experimental data have been taken for a number of two-phase nozzles. However, only some of these data were taken with a two-component mixture, the type of system to which the Model with Droplet Heat Transfer applies. Experimental performance data[8] for a six-inch nozzle tested with a mixture of water and air are shown in Figure 6. Also shown are performance lines predicted for the actual nozzle contour by Elliott and Weinberg with their model.[9] The Elliott and Weinberg prediction labeled "Real" is based on a model that includes velocity slip, droplet break-up, and heat transfer, but no friction; while their prediction labeled "With Friction" includes friction in terms of wall boundary layer losses. The model with Droplet Heat Transfer was also used to make nozzle designs for a range of loading ratios at the inlet temperatures, velocities, and pressure of this six-inch nozzle, by assuming a linear variation of pressure drop with distance through the nozzle. (The nozzle contour produced from these design models would be different at each value of the loading ratio.) The results from this design model are also shown in Figure 6. The design-point performances of a series of nozzles compare well with the experimental data and show the same trend as the off-design performance of one nozzle.

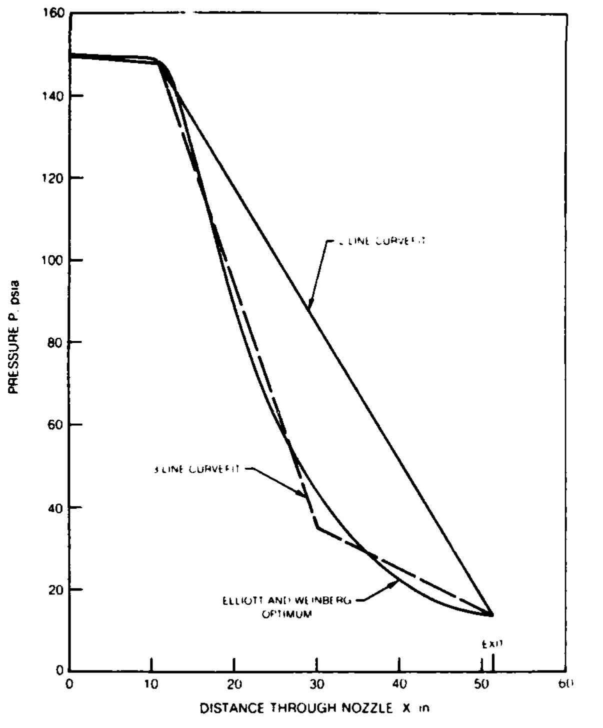

Figure 5. Pressure profiles for 50-inch water/nitrogen nozzle.

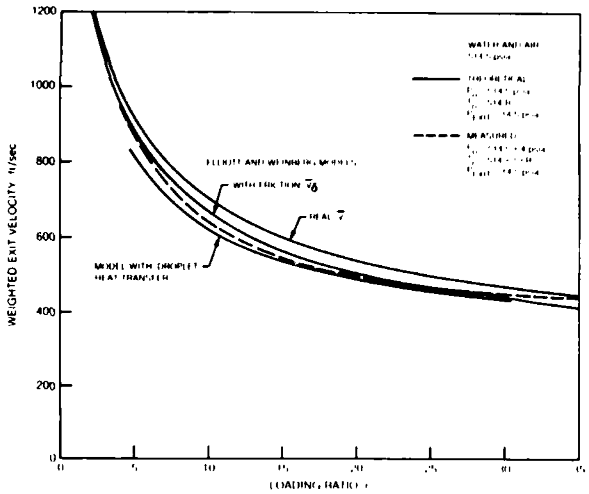

Figure 6. Comparison of computerized models with experimental exit velocities for six-inch nozzle and with Elliott and Weinberg models.

Conclusions

- A working theory of two-component two-phase (gas-liquid) nozzles was developed which includes the interphase transport of momentum and thermal energy but without mass transfer and frictional losses. This working theory provides reasonably rapid yet accurate computerized numerical solutions suitable for parametric and optimization analyses of these nozzles with gas-liquid flows.
- Previous two-phase nozzle theories generally display one of two drawbacks: either they considered only some of the interphase transport effects for simplicity of solution, or they used excessively tedious computational procedures to calculate design details of individual two-phase nozzles.
- The departure of two-phase nozzle behavior from that of a single-phase (gas) nozzle can be attributed to the interphase coupling of momentum and thermal energy transport. As a result, liquid droplets are accelerated by the expanding gas while heat transfer from the droplets retards expansion cooling of the gas which could expand nearly isothermally at a high liquid-to-gas loading ratio and with small droplets. ■

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Dr. Simion C. Kuo was a professor of thermal and energy sciences for many years at various universities before he joined the United Technologies Research Center in 1969. Currently, he is a Manager, Thermal Engineering at UTRC directing research in thermal engineering and advance propulsion/power systems. Kuo served as chairman/member in various ASME and AIAA technical committees, and the Advisory Committee on Sea Grant Project at MIT.

M. Keith Ellingsworth is a Scientific Officer in the Engineering Sciences Directorate at ONR for research programs in propulsion and tribology. His primary research areas are in the fields of aircraft and marine propulsion as well as tribology.

research notes

The Effect of Multiaxial Loading on the Hydrogen Embrittlement of Titanium Sheet

In a unique study of hydrogen embrittlement supported by the Office of Naval Research, Professor Donald Koss at Michigan Technological University has utilized sheet metal formability tests to determine the hydrogen embrittlement of commercially pure Ti sheet under multiaxial loading conditions. The results indicate that titanium is susceptible to hydrogen embrittlement under biaxial tension even though, at the employed strain rates, embrittlement does not occur in uniaxial tension. Hydrogen-charged material (980 ppm H) exhibits only 20 percent equivalent strain to fracture in biaxial tension while material with 60 ppm H possesses a 2½ times greater ductility (51 percent).

A Ti alloy similar to that tested here is a prime candidate material for nuclear waste containers. In this application, hydrogen evolution will occur at sufficiently long times and elevated temperatures to permit the ingress of hydrogen throughout the container. The behavior observed here indicates that while the Ti alloy may exhibit immunity to hydrogen embrittlement in uniaxial tension, the material may in fact be embrittled if multiaxial deformation occurs. Since accidental deformation, such as bending, will most likely include multiaxial deformation, the design of the containment vessel should take into account this aspect of hydrogen embrittlement. ■

(Bruce A. MacDonald, ONR)

Natural Language Understanding

Research to automate the comprehension of text in national language, i.e., the language in which people habitually think and communicate, is likely to lead to techniques allowing quick access to information in computer databases, and will make computer systems accessible to a wide user community. Ordinarily, work in natural language understanding is restricted to English, a language sufficiently complex to provide a challenging context in which to address basic problems in analyses of syntax and semantics. Professor Robert Wilensky, University of California, Berkeley, has been supported by the Office of Naval Research in a unique approach to natural language understanding, and his work has recently resulted in a technique with great potential for easily automating the understanding of several languages within a single computer system.

Professor Wilensky's innovation has been to create a theory of language in which phrases such as idioms and cliches play an important role. Previous approaches have emphasized individual words, their meanings, and rules for relating meanings to occurrences of words in an utterance, and have regarded most phrases as theoretically uninteresting or irritating special cases. In Professor Wilensky's view, phrasal structures are vitally important in most language processing, and he has built a system called PHRAN (PHRasal ANalyzer) which draws upon a knowledge base of English phrasal information. Moreover, the capabilities of PHRAN, in processing and responding intelligently to an impressively large subset of natural English language, have been extended to Spanish and Chinese by allowing PHRAN to access phrasal knowledge bases for those languages. Significantly, no changes had to be made to the PHRAN program code to tailor it to the additional languages, this in spite of the fact that Spanish has a freer word ordering than English, and Chinese shares with English only the most basic concepts of subject, verb, and object.

The accomplishment here is two-fold: a program demonstrating the utility of phrasal knowledge now exists which is unique in its capabilities for operating on several languages, and a methodology of program construction has emerged that enables a quick extension of system capabilities to new domains. ■

(Alan L. Meyrowitz, ONR)

Solidification Research at University of Florida

Professor G. J. Abbaschian is supported by the Office of Naval Research to perform research on grain refinement and microstructural modification during solidification. He has constructed a melting unit which permits the levitation of a metal specimen (roughly 5mm in diameter) above the levitation coil. The metal is induction melted; cycling of the sample through its liquid-solid range shows that marked supercooling can be developed prior to solidification. The temperature is monitored by an optical pyrometer and chart recorded. At maximum supercooling the sample can be rapidly quenched producing a large, rapidly solidified specimen suitable for structure-property evaluation. In this ONR project effects of inoculating powders will be determined on solidification structure and grain refinement. Solute redistribution will be evaluated as a function of supercooling. ■

(Bruce A. MacDonald, ONR)

Grain Refinement in Titanium

Mr. Mohan Misra, Head Metals Technology, Martin Marietta Aerospace, *visited* David W. Taylor Naval Ship Research and Development Center Annapolis to discuss his research (in part sponsored by the Office of Naval Research) on welding of titanium. Martin Marietta is interested in welding thin gage titanium sheet (~0.150 inch) for rocket pressure casings. The research approach and results of Mr. Misra impact the ONR titanium-100 program in the welding area. Specific research areas include liquid metal flow in the weld bead and the associated effects of surface tension; effects of mechanical stirring and pulsing on grain refinement in Ti-6A1-4V welds; and use of yttrium oxide inoculants to promote grain refinement in welds. Mr. Misra pointed out that weld cracking was encouraged by large columnar grains in the weld zone and grain boundary alpha phase. Questions to be answered include the following: How do the innoculants act as grain refiners? Can yttrium oxide transfer from the filler metal to the weld base? How is yttrium distributed in the weld metal and in what form? ■

(Bruce A. MacDonald, ONR)

RST Powder Metallurgy at P&W

Dr. C. M. Adam, Pratt and Whitney Aircraft Group, Government Products Division, with the support of the Office of Naval Research is investigating the wear resistance and toughness of Hadfield steels (Fe-10to14Mn-0.6tol.OC) made by using their centrifugal atomization rapid solidification (RS) powder process; other iron alloys are being supplied to Massachusetts Institute of Technology and Ohio State for their ONR programs. A larger "production" version of the powder-making equipment, having a batch capacity of 2,000 lbs. for iron alloys, has been completed. This P&W process and alloy development efforts have had substantial Defense Advanced Research Projects and Air Force Weapons Laboratory support. ■

(Donald E. Polk, ONR)

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(Bruce A. MacDonald, ONR)

High Strength "Two-Dimensional" Kevlar

Polyaramides are well known in the form of high modulus fibers which are used as reinforcing materials in high strength lightweight structures such as composites, cables and tires. Although polyaramides have high tensile moduli in the orientation (fiber) direction, they have little strength in the transverse direction and readily fibrillate laterally under stress. Results from the laboratories of Professors James L. White and John F. Fellers, Polymer Engineering, University of Tennessee, are therefore important in revealing a process which extends the strength properties of Kevlar-type materials into a "second dimension." They have developed a new process for making equally biaxially oriented films from liquid crystalline solutions of poly(p-phenylene terephthalamide) (PPD-T) (a Kevlar-type polymer). The process involves extruding solutions of PPD-T in sulfuric acid through an annular die and over an oil coated mandrel into a coagulation bath. Professors White and Fellers are funded by the Office of Naval Research.

The variation in mechanical properties with film orientation indicated striking effects. While high machine direction modulus (8×10^9 pascals) may be developed in uniaxial films, they are brittle and fibrillate readily in the transverse direction. However, once equal biaxial orientation is achieved, good in-plane properties may be obtained in all directions. Thus, moduli of 5.7×10^9 pascal and tensile strengths of 2.2×10^8 pascal were obtained in the plane of the film. Films with unequal biaxial orientation were also produced. These tend to have higher modulus/tensile strength in the direction of major orientation, the machine direction, but become brittle in the transverse direction. None of these films have been annealed under tension. Annealing Kevlar fibers under tension at temperatures of 300° to 500°C for 3 seconds is known to create a marked increase (a factor of 2 or so) in modulus and tensile strength. Typical modulus and tensile strength values for Kevlar fibers are respectively 8.3×10^{10} pascals and 3.6×10^9 pascals.

There are some striking observations on the molecular orientation development in the film process. First it is found that films extruded directly into the coagulation bath exhibit significant uniaxial orientation even though no tensions are applied. The second remarkable observation is the successful formation of an equally biaxially oriented film with biaxial orientation factors (f^B) as high as 0.35 and 0.45. Values of f^B_1 and f^B_2 of 0.5 represent an equal and complete biaxial planar orientation. While it has been previously established that it is possible to develop high levels of *uniaxial* orientation from liquid crystalline polymers, it has not been previously realized that such levels of equal *biaxial* orientation may be obtained. ■

(Kenneth J. Wynne, ONR)

Pulsed Hollow-Cathode Discharge for Extreme Ultraviolet Lasers

Recent proposals for very short wavelength lasers have pointed out the need for new types of electric discharge devices that are capable of producing significant densities of highly excited atoms and ions. Professor Stephen Harris of Stanford University, who is funded by the Office of Naval Research, has recently proposed a 200A° laser using doubly excited states of lithium which require the production of excited atoms in states having energies of 60eV at densities in excess of 10^{12} atoms/cm^3. Harris's group has recently developed a pulsed, hollow-cathode discharge that creates population densities of 4×10^{12} ions/cm^3 in the lithium ion at 59eV above the ion ground state. The new features at this hollow cathode discharge are that it is all metal and the discharge tube serves as a heat pipe in order to obtain high ground state densities. At very high current densities it yields appreciable excitation rates to high energy levels. As such, this device is expected to be useful for realizing discharge excited extreme ultraviolet lasers and for short wavelength sources based on anti-Stokes Raman scattering from highly excited metastable states.

(Herschel S. Pilloff, ONR)

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