OFFICE OF NAVAL RESEARCH JULY 1954

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RESEARCH REVIEWS

Field Emission Microscope Tube

NAVEXOS P-510

DEPARTMENT OF THE NAVY
WASHINGTON, D. C.

COVER PHOTO: The field-emission cathode has many important uses. It can detect, identify and measure the cathode contaminants which contribute to electrical instability. The remarkable properties of these emitters provide a basis around which many significant electronic devices may be designed in the future. See "A New Cathode Development," pp. 11-20.

Research Reviews endeavors to report briefly highlights of technical progress in research by Navy laboratories and contractors and the development of important naval research facilities. Articles which meet these broad criteria and possess a good degree of readability are welcomed. Manuscripts and changes of address should be sent to Code 740, Office of Naval Research, Washington, D. C.

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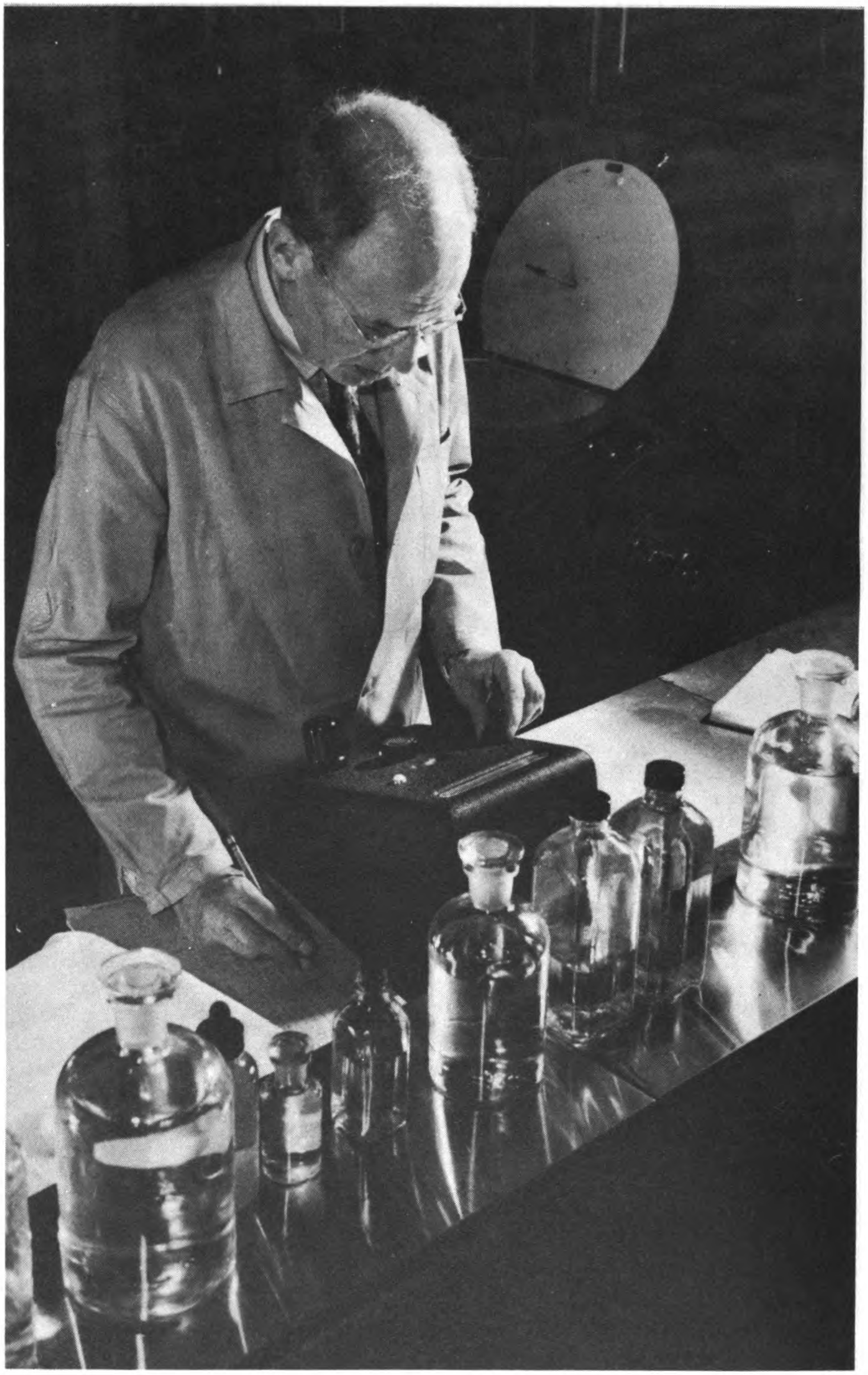
In This Issue



Basic chemical research is being conducted in university laboratories throughout the country through ONR support.

Basic Chemical Research in the Office of Naval Research

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It is eight years since the Office of Naval Research began to support research in laboratories outside the Department of Defense in partial fulfillment of its mission to make the results of research available for the improvement of naval operations. Unclassified basic research in almost every field of chemistry has been sponsored, though emphasis has been given to areas not under intensive development by agricultural, industrial, medical, and other interests.

Good coverage of fields has been achieved in part by deliberate division of funds by the Chemistry Branch among inorganic, organic, and physical chemistry with the present result that about 20, 30, and 50 percent of the funds go to those fields in the order written - least to inorganic chemistry because fewer opportunities are presented to the Office to sponsor work in that field, most to physical chemistry because it really includes several major fields such as colloid science, electrochemistry, kinetics and thermodynamics. Good coverage of fields has been achieved also through sponsorship of chemical research by other branches of the Office. There is a Biochemistry Branch with a well-rounded program. Much basic chemical research is sponsored in ceramics, extractive metallurgy, and corrosion by the Metallurgy Branch; in polymers, by the Organic Materials Branch; in combustion, by the Power Branch; and in quantum mechanics, statistical mechanics, molecular structure, absorption spectra, and thermodynamic properties by the Physics Branch. Indeed about half of the chemical research supported by ONR is sponsored by the Chemistry Branch and half by the other branches.

The size of the basic chemical program can be estimated from the following statements. The level of support has been nearly constant during the last five years; about five percent of the papers published in American chemical journals in 1952 were based on work sponsored by the Office; the research institutions, and sometimes other sponsors, contribute substantial support to the same research. These facts indicate that less than 5 percent of the information now published is obtained through ONR support.

It is probably not important to estimate whether this is 2 percent or 4 percent, but we believe that this relatively small contribution to chemical science is of great importance both to chemistry and to the Navy because the researches have been selected, as indicated in greater detail below, by a group of full-time employes of the Office, whose various backgrounds and familiarity with naval developments equip them well for this task. They have been assisted by consultation with a large number of eminent chemists who have served as advisers. Now that enough time has passed for the publication of many results of the sponsored research, the importance of the program to chemistry can be seen from critical writings such as those appearing in the Annual Review of Physical Chemistry.

In this brief paper we thought you would be interested chiefly in answers to two questions: Why have the particular researches supported been selected? What are the present trends in relative emphasis of fields?

Promise of great significance in the development of chemistry has been the prime characteristic of an acceptable research proposal; relationship to current naval needs and development is a second influential characteristic; encouragement of research in teaching institutions is the third factor in selection. There has been little solicitation of proposals so that the content of the program has been determined largely by the interests of the originators of proposals. Relatively few of the many American research chemists have requested the assistance of the Office. With twice the funds available, all meritorious proposals could have been accepted; with three times, all could have been accepted at the level of support requested. In general, the Chemistry Branch has tended to spread its funds by asking research chemists for reduced budgets in preference to rejecting some good proposals.

During 1946-1948 a small number of proposals were accepted solely to encourage research in teaching institutions where little research had been done for a decade or more. Proposals are no longer accepted for this reason alone. Also projects are not sponsored as part of the basic research program which have some obvious naval connotation but little promise of significant contribution to chemistry. These are supported by funds allocated to development programs where such research has significance. The various branches of ONR do extend their facilities to other agencies of the Department of Defense and accept funds for the support of chemical research which is important in the programs of these agencies. The Chemistry Branch also has a small fund of its own to support applied chemical research.

Many research proposals received fall into a few categories that cannot usually be accepted by the Chemistry Branch. It is difficult to avoid giving the impression that we think such research has no value. On the contrary we concur with the statement of the Editor of "Industrial and Engineering Chemistry" of several years ago, that we should not underrate the importance of the foot soldiers of scientific research who labor to fill in the gaps in knowledge left by the trail blazers. We do believe, however, that our limited funds should be used to support the areas where significant advances in chemistry may be expected. In following this principle we sponsor the research of many younger workers who have not yet realized their potentialities.

Small extensions of the range of applicability of general reactions in synthesis would be an example of unacceptable work. Correlation of physical constants or reaction rates with structure, unrelated to more significant research in the same laboratory, is another example. A member of our staff once asked a colleague why he was determining the heats of adsorption in a particular system. He replied that the information would surely be useful to somebody some time, and besides the apparatus was all set up, ready for use.

Let us pass on to a more positive description of those aspects of chemistry which are being actively supported by the Chemistry Branch, and give a brief statement of their scientific objectives and Navy applicability. This will illustrate the nature of some of the studies being pursued. In the field of the rates of chemical processes, much of the research is concentrated on fast chemical reactions. This includes systems where the reaction occurs in from less than one second to the order of a thousandth of a second. Here it is especially important to develop new techniques, some of which are largely based on recent electronic developments. In one of these methods, two liquid streams are so rapidly mixed that reactions occurring in 2 to 3 thousandths of a second can be followed. This technique has been applied to reactions involving water and is now being used to study the interactions between liquid fuels and liquid oxidants. The results have an important bearing on the selection of fuel-oxidant combinations for rocket and other applications.

Another related technique involves rapid mixing of gases and the following of the reaction by studying light absorption by one or more of the reactants. This has enabled the study of reactions of oxides of nitrogen and of ozone. The nitrogen oxides play an important role in the burning processes of gun propellants, as well as the combustion of fuels with nitric acid and related compounds as oxidizers. The results also affect the vapor-phase production of certain nitrocompounds which have been proposed as monopropellants. Another technique being explored is the use of shock waves to obtain very high temperatures and pressures rapidly and then to follow the behavior of the reactive species formed by light-absorption methods. In addition to the relationship between these fast reactions and Navy problems, they have an important bearing on new developments in the chemical manufacturing field. This is especially the case in the attempts to adapt configurations related to rockets and ram jets to the production of chemicals. In these systems reactants are heated rapidly and then cooled by expansion. Success in adapting these techniques to industrial processes depends on knowing the rates of the fast reactions occurring.

An interesting aspect of chemistry related to development of new and unique materials being pursued by the Chemistry Branch program is the preparation and investigation of properties of compounds of fluorine. Recent developments in the polymer field such as the development of Teflon, a plastic in which all the hydrogen atoms attached to the carbon atoms are replaced by fluorine, and Kel-F, in which the hydrogens are replaced by chlorine and fluorine, indicate that new plastics, lubricants and materials of yet unpredicted application should be forthcoming. One can anticipate, based on the work of other government agencies, that oil-resistant rubbers can be made from fluorine-containing materials. We are exploring new methods for making previously unknown combinations of fluorine with compounds containing carbon, with one or more other elements such as oxygen, nitrogen, sulfur, or silicon. One of the techniques being explored is the electrolytic method of preparing fluorine-containing derivatives. One investigator has developed new synthetic techniques leading to simpler methods of preparing fluorine-containing materials related to butadiene. These are expected to become the basic ingredients for the production of new plastic materials and fluids for varied applications.

Another approach to new materials is the series of efforts to prepare inorganic polymeric materials. These are based upon the formation of chemical bonds, between elements other than carbon, which are expected to have unique characteristics. For example, combinations of boron and phosphorus have recently been synthesized which have aroused the interest of industrial groups. These compounds are reported to withstand heating to $700^{\circ}F$ and resist the action of water and strong alkali to well above the boiling points of the latter. The compounds so far discovered are just a few of many interesting possibilities which are being studied under this program.

Phenomena and equipment related to the science of electrochemistry are of great interest to the Navy. Among these are batteries, corrosion and electrodeposition and electrotwinning of metals. Basic studies have increased the knowledge of the reactions occurring in a dry cell both during use and during shelf storage. The relationships being obtained between the nature of the material used and the conditions of reaction should give guidance to improvements in the LeClanche dry cell which finds many uses throughout the Navy. Related studies are leading to new types of cells whose applicability to Navy problems has not yet been specifically established. Studies using radioactive compounds which are important in corrosion and its control have led to a better understanding of the role of corrosion inhibitors and their behavior. Through the study of the rate and mechanism of reactions as they occur during the flow of current between electrodes, further developments along these applications are definitely foreseeable.

One further illustration of the program is the study of surface and colloid chemistry. Synthetic organic chemistry has made available to the Navy compounds, called detergents, which can be used for metal cleaning and for washing the clothing of personnel in sea water. These leave certain deficiencies which it is desirable to overcome and current studies on the behavior of these detergents are giving information on how these materials suspend oils and other materials. From a study of a number of these detergents it is anticipated that one can predict new structures with improved characteristics. Another field of study has been the adsorption of gases on charcoal, silica and other adsorbents. These studies give background for selection of materials for gas masks, for the elimination of noxious gases, and for use in chemical processes where removal of undesirable compounds is needed.

The initiation of basic research programs by several other agencies since 1949 has increased the number of policy-making, planning, and managing groups which deal with federal sponsorship of basic research, and has increased the number of chemists studying and selecting research proposals. This is an improvement because each agency can now sponsor the work which will most greatly aid it in the performance of its statutory mission; more basic chemical research is supported, and research chemists have access to more sponsors. One disadvantage is the difficulty of maintaining the necessary coordination among the agencies. This coordination can perhaps be limited to the provision of information to all the agencies concerning changes in the agencies' planning objectives and research opportunities.

Finally, prompt and adequate reporting of the results of the sponsored research is considered of great importance. In the simplest terms the Navy, through the Office of Naval Research, is buying results of research which, upon publication in the open literature and in technical reports for limited distribution, become available to the Navy's contractors and laboratories. Some of these results will be applied immediately because they supply the missing piece in the solution of a practical puzzle. Others, as we well know, will affect the development of the science and Navy technology for years to come.

Ocean Bottom Topography in the Western North Atlantic

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Startling new discoveries in the Western North Atlantic have been made by oceanographic vessels equipped with sonic sounders which record continuously on a greatly exaggerated scale. Heretofore unknown submarine canyons, abyssal plains, and seamounts have been found by expeditions expressly planned to cover areas that have been inadequately surveyed and their findings are of great interest to the Navy as well as to basic science.

Perhaps the most nearly unique features found on the ocean floor are submarine canyons, and they are also the most difficult to explain. Found both at abyssal depths and encroaching on the vast shallow continental shelves that surround the continents, these canyons have been attributed variously to earthquakes, faulting, spring sapping, subaerial erosion at a time of lowered sealevel, and to submarine erosion by turbidity currents. Each of these mechanisms requires a condition which limits the type of canyons that can be formed. For example, if all submarine canyons are to be ascribed to faulting, those found in areas that have been seismically quiet and where no faulting has occurred would be excluded along with those exhibiting meanders and those that meander on the abyssal plains of the deep sea floor. Likewise, spring sapping as a cause for submarine canyons demands that there be sufficient hydrostatic head present in the aquifer extending to the canyon area to force fresh water out of the strata against salt water at the same depth. Sea water being considerably denser, this seems to be a rather untenable hypothesis even in areas where such aquifers do extend offshore at the required depth.

Some of the early oceanographers attributed submarine canyons to subaerial erosion at a time of lowered sealevel, but, with the discovery of canyons in 2800 fathoms of water, such a process is difficult to imagine without admitting that the oceans were all but dry. Perhaps the most well supported phenomenon invoked to cause submarine canyons is the density, or more properly, turbidity current. This mechanism has found support by many submarine geologists, both from controlled laboratory experiments and from field evidence of contemporary erosion at great depths and in the presence of deep sea sands. However, the erosive power of turbidity currents is probably not great enough to carve submarine canyons in igneous rock, so that in areas where such a condition exists, a composite origin for submarine canyons is called for.

The most completely surveyed submarine canyon in the Western North Atlantic is the Hudson Canyon which extends from the 100 fathom curve, 90 miles southeast of New York Harbor, to the 2650 fathom plain 300 miles off shore. This 200-mile-long canyon is a chasm 1000 feet deep in places and has several major tributaries entering it at grade. The whole Hudson Canyon system cuts across the continental rise and continental slope and joins up with the depression in the continental shelf that marks the entrance to the Hudson River channel off New York Harbor. The Hudson Canyon system acts as a sluiceway down which sediment is carried by turbidity currents out to the abyssal plain of the deep ocean floor where the famous "deep-sea sands" are deposited over a huge delta-like plain. As stupendous as this feature is, it is dwarfed by the Mid-Ocean Canyon that exists east of the Newfoundland Grand Banks and probably extends from Greenland southward to a latitude of 37^{O}N, a distance of about 2000 miles.

Perhaps one of the most exciting chapters in deep sea exploration commenced near daybreak on 23 July 1952 when the KEVIN MORAN, at the author's request, changed course sharply to complete a box survey of a 60-fathom depression about 2 miles wide. For the next six days an intricate zig-zag survey was carried out, crossing and re-crossing the feature that was at first believed, by some of the members of the party, to be the manifestation of varying frequency in the sonic sounder's 60 cycle power supply. Often referred to as Northrop's 60 cycle canyon, this feature is the most striking example of turbidity current eroded canyons. Several deep sea cores taken by the expedition, both on the sides and in the bottom of the canyon, show definite evidence of turbidity current action. The material forming the turbidity current is thought to come, in part, from the melting glaciers on Greenland.

The sediment that is carried down these submarine canyons by turbidity currents finally settles out on the deep ocean floor and forms the sediment-covered abyssal plains. This "abyssal plain", as it has

Location of the Northwest Atlantic Mid-Ocean Canyon. Extended solid line shows that part of the canyon surveyed by the author on the KEVIN MORAN; dotted lines show locations of discrete crossings made by the ATLANTIS.

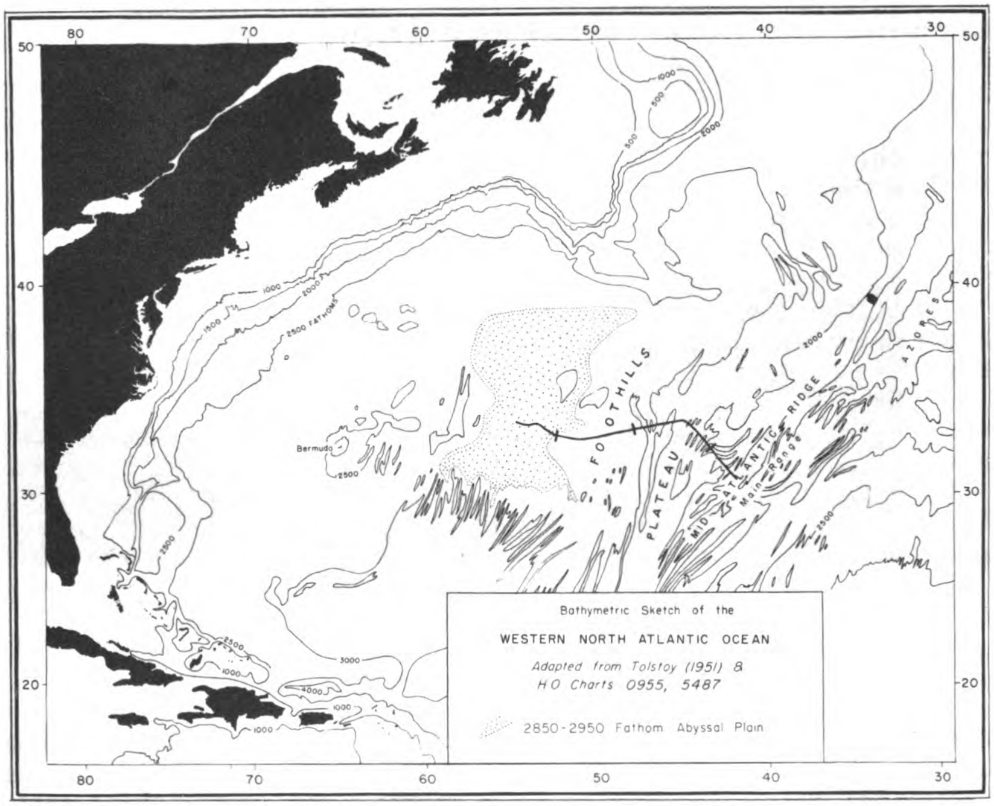

Chart showing the extent of the Abyssal Plain. Heavy track indicates portion covered by the ATLANTIS' First African Cruise, A-153.

come to be called, is characterized by its flatness and lack of topographic irregularities. Inasmuch as the floor of most of the North Atlantic is either uneven or mountainous, the limits of the abyssal plain are fairly well defined and criteria have been set up to delineate the various topographic zones according to roughness.

Another area of deposition for turbidity current eroded sediment is the Puerto Rico trench, deepest portion of the North Atlantic. This long narrow flat-bottomed trench, shown at the top of the next page, extends for 200 miles east-west about 80 miles north of Puerto Rico. The floor of the trench is flat at 4350 fathoms (uncorrected sounding) and is intermittently being covered with sediment carried by turbidity currents from the surrounding island platforms. This excess of relatively light material covering a local portion of this ocean deep causes a notable deficit in the pull of gravity over the trench, resulting in the observed negative gravity anomaly.

Interest in the topography of the ocean bottom is not restricted to erosional depressions and sediment-filled basins. On the contrary, recent bathymetric surveys have concentrated on surveying isolated topographic highs called seamounts. A seamount is an isolated elevation of the deep sea floor of approximately 3000 feet or more. In the Western North Atlantic, a chain of seamounts protruding 6000 to 10,000 feet above the general level of the ocean floor has been found to extend

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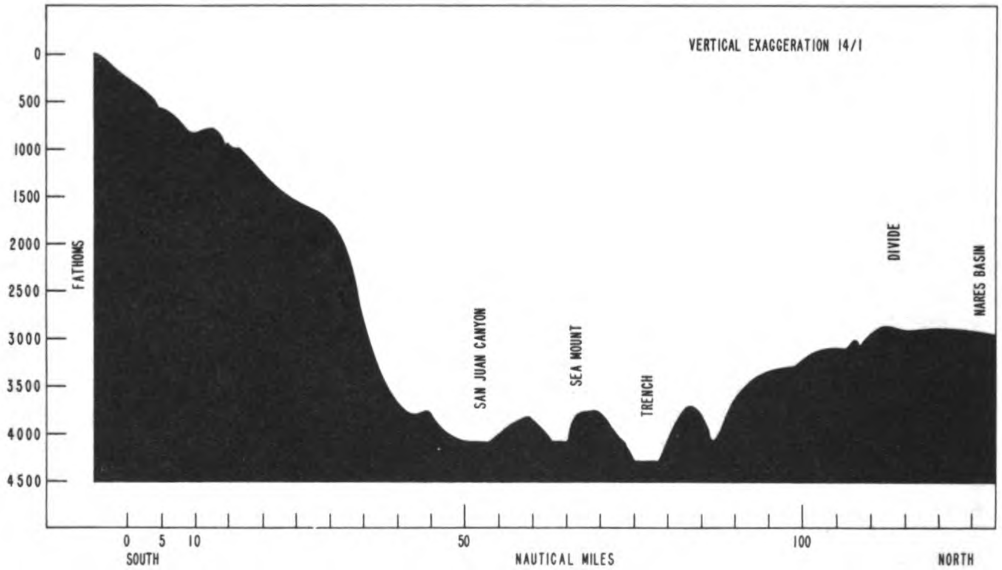

Bathymetric profile across the Puerto Rico Trench.

southeast of Georges Banks and curve around to include the Bermuda Islands. These huge cone-shaped peaks are seamounts, and because of their location, morphology, isolated position, and covering of early Cenozoic sediment, are thought to be extinct volcanoes, as is the case of Bermuda. They probably erupted in the Early Tertiary along lines of weakness set up by previous tengential stresses on the earth's crust.

One of these seamounts south of Georges Banks has a 40 cm layer of globigerina ooze on top, which overlies a 5 cm layer of coral and bryozoan fossils covering 20 cm of cobbles and pebbles. The cobbles were probably rafted there by floating ice during the Pleistocene epoch. The coral and bryozoan fossils are left over from a time of lower sea level, because these animals cannot live in the present 980 fathoms of water covering the seamount today. The globigerina ooze indicates deposition under present conditions.

These findings show evidence of a rise in sea level since the Pleistocene, but apparently the time of lowered sea level was too short to cause erosion of the seamount's peaked top, or else the seamount was never exposed to wave action. This is true of other seamounts in the North American Basin as no flat-topped seamounts, or Guyots, have been found to date. Further investigations of the canyons, abyssal plains, and seamounts by oceanographic expeditions equipped to take bottom samples and bottom photographs are being planned to bring new evidence to bear on these phenomena.

Hot Bacteria

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Thermophiles are organisms which grow above 55° C, but not at room temperature. Thermophilic, spore-forming bacteria are common in nature. Thermophiles are found living together with equally thermophilic algae in hot springs. Other strains have been unwelcome intruders in canneries, but most of our thermophilic cultures have been isolated from top soil or manure. Mysteriously, strict thermophiles occur at the bottom of the continental shelf. Many thermophiles grow in ordinary bacteriological culture media at temperatures as high as 75° C. and even 80° C.

For a long time biochemists have eyed these organisms as tools for studying the factors governing the heat-stability of proteins. It has been debated whether their key enzymes are more heat-stable than those found in the non-thermophilic counterparts of the thermophiles, or whether thermophily is primarily a dynamic state embodying a race between an accelerated synthesis and destruction.

For work with these organisms to be more reproducible, chemically defined culture media were devised which allowed dense growth; we excluded from the media not only such poorly defined ingredients as liver infusion and yeast extract, but also casein hydrolysate and other products containing variable and, what is sometimes worse, unpredictable amounts of trace elements. Instead, we have added to the simple carbon source (glucose) and nitrogen source (asparagin) not only the customary mineral salts, but also about one dozen trace metals. If these were supplied in small concentration, they would not sustain extensive growth, while larger quantities would prove toxic. To evade this dilemma, we are adding to the medium a chelating agent like citric acid or, preferably, a non-metabolizable complex former such as Versene (ethylenediamine tetraacetic acid, "EDTA"). The extremely active metabolism of thermophiles is reflected in rapid changes of the pH, the micro-organisms committing suicide by accumulated metabolic wastes. To avert this danger, we use non-metabolizable pH-buffers.

The absence of proteinaceous materials from the media eliminates coagulation phenomena and enables us to determine the amount of bacterial growth by simple and direct optical density determinations. By the combination of these factors, mass culture of thermophilic microorganisms has become practicable.

One of our objects has been the extraction of enzymes from the thermophiles and from their lower-temperature counterparts, to compare their heat-stability and to find the reason for their peculiar behavior. But the development of these improved culture media opened other unexpected possibilities. Nearly every known B vitamin was needed by one or another thermophile. The basal media for demonstrating these vitamin requirements are much simpler than those needed for the assay of vitamins with lactic acid bacteria as the assay organisms. It had been noticed that the experimental cultures, when incubated at 55° and higher, never showed obvious contamination; hence, it is not necessary with this simplified technique to sterilize assay media; the assays for B vitamins can be made into practical routine clinical tools. Furthermore, elimination of steam sterilization means that heat-unstable vitamins may be assayed.

One thermophilic bacterium appears to offer an appreciably more convenient assay for folic acid than is permitted by the other assay organisms. As folic acid is concerned in the transfer of the single-carbon fragments going into the synthesis of the purine and pyrimidine rings, a simplification in measurement of this vitamin is welcome to cell physiologists. Moreover, the method lends itself to the estimation of the folic acid titer in such material as the urine of pregnant women and to studies of its bearing on miscarriages and malformations of the fetus. The content of biological fluids of cobalamin (B_{12}) may be assayed with the aid of another thermophile in quantities of 1 mμg in 100 ml—i.e., in a concentration of 10 in one million millions. Numerous applications of our techniques suggest themselves for simple microbiological assays of many other vitamins.

Which enzymatic systems underlie these shifts in heat tolerance? In agreement with work from other laboratories, some strains of thermophiles show striking variations in absolute nutrition requirements with temperature; at elevated temperatures the requirements usually become more complicated. It would be interesting to chart the quantitative requirements for vitamins, energy and carbon sources, and other nutrients as a function of temperature. This should provide a good test of the "dynamic" theory of thermophily, and might tell why some thermophiles do not grow—at least in ordinary media—below 40°.

Preliminary comparative studies of mass cultures of thermophiles and the corresponding mesophiles have shown significant differences in the lipid content. There are scattered notes in the literature that the upper temperature limits for a variety of organisms, from bacteria to man, may be raised by supplying fatty acids in the diet. The greatly enhanced solubility of lipids in aqueous culture media at elevated temperatures allows for greater leeway in studying the effectiveness of lipid nutrients than has hitherto been possible. It also opens new vistas on the possible substitution of water-soluble factors by lipid-soluble vitamins and hormones and their microbiological assay.

Biochemists are becoming accustomed to the use of bacteria and other microorganisms as analytical reagents and as guides to metabolic pathways in higher plants and animals. The thermophiles, it would appear, are on the threshold of providing a whole new array of uniquely useful biochemical instruments.

A New Cathode Development

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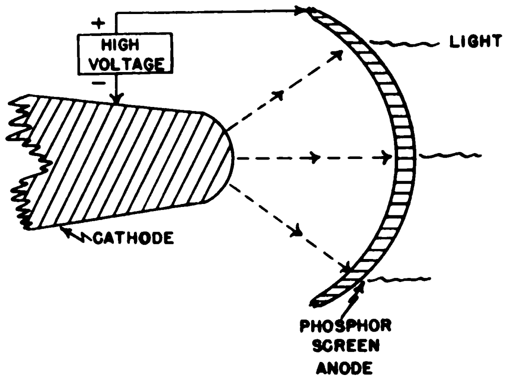
The tiny electron has become a very important part of modern warfare. It enables guns to be aimed at targets unseen by human eye. Planes and ships are guided on their missions by radar and beacons, whose performance is possible because of the properties of the electron; radar echoes have even been returned from the moon. In television, the electron permits transmission of visual images over long paths; elsewhere in communication, it can transmit voice around the world in a seventh of a second. The human brain has been outmoded in some areas by the development of electronic computers. These examples scarcely illustrate the enormous impact made on society by electronics, the industry which employs the small, negatively charged particles, called electrons.

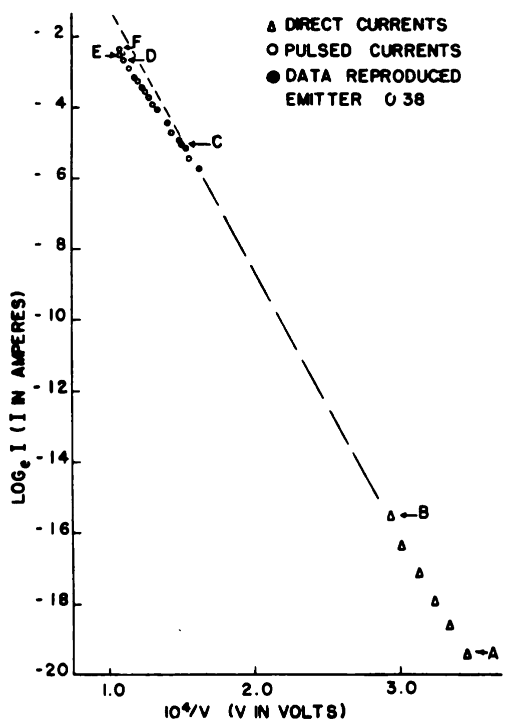
As the name suggests, electronics depends on electron sources, and in particular, vacuum tube devices require sources of electron currents in vacuum. A convenient source is found in the copious free conduction electrons in metals, which can be removed by several methods. In thermal emission, the metal is heated; in photoelectric emission, the metal is exposed to light or other radiant energy; in secondary emission the metal is bombarded with charged particles. Each of these emission processes is in wide use in electronics; however, the workhorse is thermal emission.

History has shown that new or improved electron sources are followed by important advances in electronics, in the form of devices built around the unique properties of each new cathode. There is one cathode, the field emitter, which has not yet had widespread application, although the cathode has a number of unusual properties which may permit significant electronic developments.

Perhaps the most remarkable properties of the field-emission cathode are its enormous electron-current density and microscopic size. The cathode will emit current densities as great as a hundred million amperes per square centimeter, or in other words about a million times the current density of its nearest competitor, the thermal cathode. For the engineer, this means that electron currents of several amperes can be obtained from a cathode which is so small that it can be seen by only the best microscopes. These properties of the field-emission cathode may permit accomplishment of new electronic tasks. Increased electron currents permit more power to be drawn from electronic devices; when, at the same time, the cathode size is reduced, the generation of high power can be extended to yet higher frequencies. Of course the advantages of high frequencies are both numerous and well known: for a few examples, a radar can more clearly distinguish close-packed ships in a convoy and is more difficult to "jam"; a communication system can be more readily "beamed" for a point-to-point communication and can handle more information through increased channels.



Arrangement for obtaining field emission from cold cathode due solely to a high cathode electric field caused by high voltage on a nearby anode, in this case a phosphor screen on which impinging electrons (dashed arrows) cause enlarged visible emission pattern.



A typical experimental relationship between field current I and applied voltage V for both direct current (triangles) and pulsed (circles) operation. A to C, space-charge free emission; C to D, space-charge-limited emission; D to F, high emitter temperature due to resistive heating initiates vacuum arc.

There are many other unique and apparently useful properties of the field emission cathode. Why then has it not enjoyed extensive application? Several answers may be found to this question: first, many of the cathode properties have just been determined; second, until recently the cathode has suffered from erratic and unstable performance; third, field emission has emerged from obscurity an insufficient length of time to attract the interest of large numbers of scientists and engineers as required for its widespread application. The present discussion is undertaken in order to describe the properties of this cathode, recent progress toward increasing its stability and life, and to suggest possible directions for useful development.

When a cold, needle-shaped metallic cathode in vacuum, such as that shown at the top of this page, is subjected to a high electric field, due to a positive potential of a few kilovolts on a nearby electrode, an electron current is observed to flow cathode to anode. This process, called field emission was discovered in 1897 by R. W. Wood. A unique property of the cathode was predicted theoretically in 1928 by Fowler and Nordheim and confirmed experimentally in 1940 by Fleming and Henderson: the emission process requires <u>no</u> energy to be added to the cathode. In this respect the field emitter is unique among cathodes in widespread use. A practical advantage results from this property; power sources required by other cathodes and associated equipment, such as filament transformers, are avoided. A saving in weight, power, heat dissipation, size and insulation difficulties is thereby effected. These factors are of course particularly important in airborne applications.

Another useful cathode property is that a small increase in applied voltage causes a large increase in field current. The relationship between current I and voltage V, announced in 1928 by Millikan and Lauritsen, is

$$I = Ce^{-B/V} \tag{1}$$

where C and B are constants. This equation stands correct today for low current densities, and is illustrated by the linear portion A-C of the preceding graph. The practical significances of equation (1) are several, one being that accurate control of the electron current is afforded by direct electronic methods. Similar control of thermal electron currents usually requires the complication of added electrode sturctures, since the emission process itself is dependent on temperature, a parameter which is rapidly varied only with difficulty; grid structures may be avoided in some cases when field cathodes are used. Its highly sensitive current-voltage relationship may permit single tube, precision voltage control devices in the kilovolt range; high gain transducers which convert mechanical motion into electrical response are another possibility.

Serious attempts were made during the period 1920-40 to apply field emission to X-ray tubes and electron microscopy; considerable patent art thereon can be found. These applications use another important cathode property; it is a point source of radially divergent electrons which can be focussed into a narrow beam or small spot by straightforward electron optics. Widespread use of these devices was precluded at that time by emitter instability; however, causes for instability have recently been identified and cured under conditions to be described later and use of these devices may now be reconsidered. Early workers recognized two causes of instability: poor vacuum and resistive heating of the emitter; however, their progress was inhibited by inability to resolve the geometric detail of the minute field emitters by use of available optical microscopes. As a result, both electric field and current density were uncertain, and these variables are fundamental to an understanding of the emission process.

In 1946, it appeared that these difficulties might at least be resolved by the use of several techniques which have recently become available to scientists. Electron microscopy could be used to resolve emitter geometry. Vacuums had been improved by a factor of more than a million, and at residual gas pressures of 10^{-14} mm of Hg, gas effects are minimized. The field emission microscope could be used to observe effects of cathode contamination and bombardment which were suspected to contribute to emitter instability; this technique is illustrated later herein. Finally, pulse electronic techniques were highly developed and, it appeared, could be

Electron micrograph of typical tungsten field emission cathode.

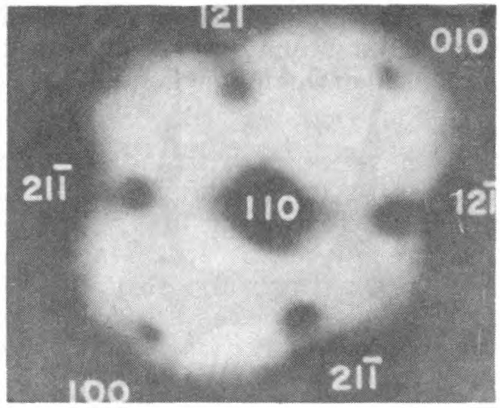
used to draw very large electron current densities for short periods of time while minimizing undesired cathode effects such as resistive heating, bombardment and contamination.

A research program was established in 1946 at Linfield College through initial support from Research Corporation in order to study further the emitter using the techniques just described; helpful suggestions received from J. E. Henderson aided the establishment and progress of the program. When, in 1948, the large current densities mentioned above were established experimentally, additional support was sought and obtained from the Office of Naval Research in order to determine further the cathode properties. In 1950, L. C. Marshall, then at the Microwave Laboratory, University of California, became interested in this program and extended funds through subcontract to investigate means for stabilizing the emitter for practical application. More recently the latter program has been carried on under direct Air Force support.

In describing the field emitter, one deals with both large and small numbers. For the emission of current densities 10^8 amps/cm^2, an electric field of nearly 10^8 volts/cm is required at the tungsten surface. To provide such fields with reasonable potentials, say a few kilovolts, on nearby electrodes, the cathode must be needle shaped, having a hemispherical tip of radius between 10^{-5} and 10^{-4} cm, as is shown on pg. 13. Such cathode radii are about equal to a wave length of visible light; hence, the cathode is not well resolved in an optical microscope and can better be "seen" through electron micrographs such as this one, in which the cathode is tungsten, fabricated by electrolytic etch.

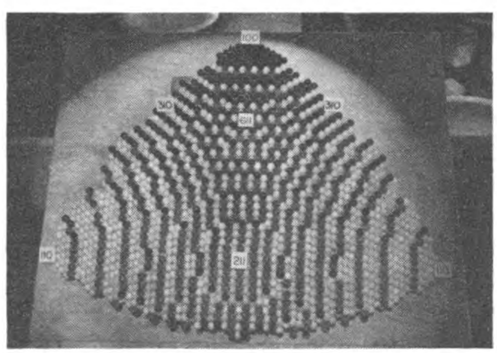
Cathode properties often limit the design and operation of vacuum tubes. As electron current density is increased, there accumulates a cloud of electrons just outside the cathode surface which repels other electrons trying to escape the metal. This phenomenon, called space charge limited emission, sets a definite limit on the value of current density which can be drawn conveniently from a given cathode. With most cathodes in common usage, electric field at the cathode is small and space charge is likely to be a problem; a current density of about 10 amps/cm^2 can be readily drawn from the plane thermal cathode with reasonable voltages, but further increases in current density are made at the expense of large voltage increases, due to space charge effects. On the other hand, space charge is negligible in field emission, unless the current density exceeds about 10^7 amps/cm^2, since the large electric field present is more effective in removing electrons from the neighborhood of the cathode surface. In other words, current density can be increased about a million times without space charge limitation when the field emitter is used instead of conventional cathodes. Field emission free of space charge is seen in the linear portion A-C of the curve on the bottom of pg. 12, in which the emission from clean tungsten is correctly described by equation (1). At C, the current density is 6×10^6 amps/cm^2.

From C to D the emission is space charge limited; above D, when current density approaches 10^8 amps/cm^2, resistive heating becomes appreciable and a further increase to F raises the emitter tip to temperatures near the melting point, initiating a violent vacuum arc in which the vaporized emitter material participates. Currents during the arc may exceed the initiating field current by more than a factor of one hundred; however, the emitter is likely to be melted and thus damaged through geometric change during the arc. The arc has several important contacts with practice. First, it sets a definite upper limit on the field current density which a given emitter can stand; stable emission is readily achieved by operating the emitter in the voltage range so that the critical current density is not exceeded. Second, the arc is an undesirable form of electrical breakdown when insulation is required and doubtless is experienced on a fairly widespread scale throughout the electronics industry; it may well account for tube failures in many cases. However, the arc can also be useful since it provides a convenient means for altering the shape and purity of the field emitter tip and may thus be used to effect the operation of several field emitters in parallel and to improve stability when effects due to impurities in the emitter are avoided.



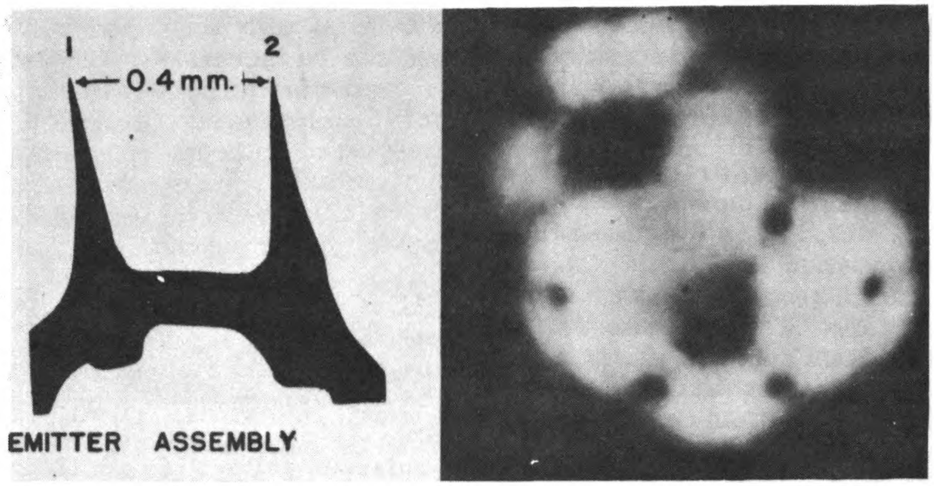
Emission pattern from tungsten cathode obtained with the arrangement shown at the top of pg. 12. Bright areas correspond to dense electron emission; dark areas show lack of emission, and are labeled corresponding to crystal facets similarly identified on the crystal model below.

Another factor which can limit the performance of vacuum tubes, particularly at high frequencies, is transit time; i.e., the time required for electrons to cross the gap between electrodes. Short transit times are desirable and require high electron acceleration away from the cathode surface and/or short gap spacing. The former is achieved, in the case of the field emitter, by the very large surface electric field; the latter, i.e., miniaturization of tube elements, is possible because of the small cathode size. For these reasons, electron transit times may be lowered in devices by using the field emitter.



A "marbles-for-atoms" model of a portion of a hemispherical tungsten field emitter tip with several crystal facets identified corresponding to areas in the emission pattern shown above.

A number of the unique properties of the field emission cathode have been discussed. The extent to which these can be given widespread use in electronic devices built around the cathode will depend on the



A B

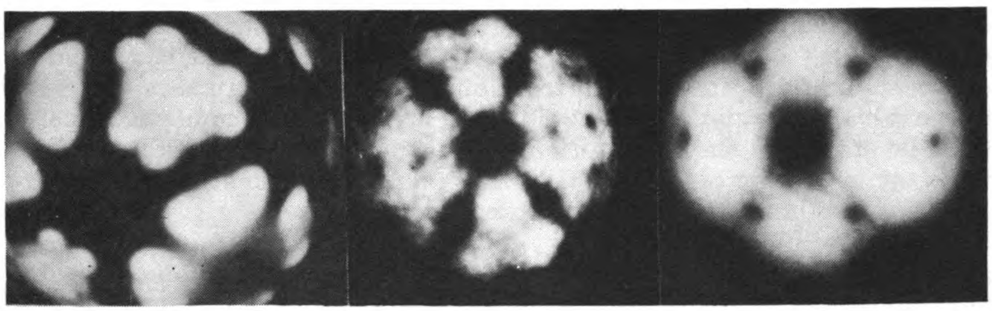
Experimental data confirming the parallel operation of two field emission cathodes: (A) emitter assembly showing two needle shaped tungsten cathodes 1 and 2 on a common support filament; (B) two simultaneous overlapping emission patterns, one from each cathode. (Compare patterns with that from the single emitter at the top of the preceding page.

extent to which its electrical performance can be maintained stable during required life periods and at useful levels of power and duty cycle. Considerable progress in this direction will be described next. Mechanisms contributing to emitter instability will be identified; since identification is best done through observations made with the field-emission microscope, that instrument will be briefly discussed. Finally, a method by which the cathode is stabilized during pulsed operation will be described.

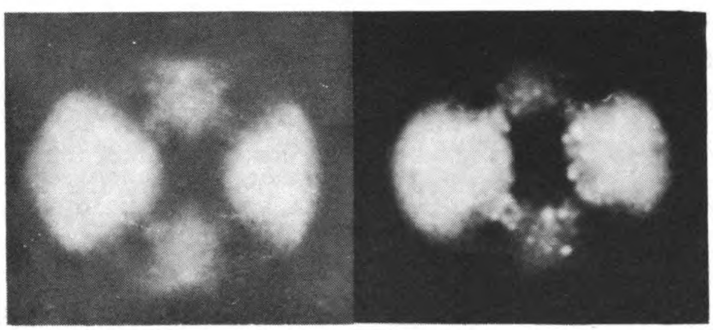
One of the most interesting displays in cathode physics is seen when a tungsten needle is pointed at a phosphor screen which is maintained at a positive potential of a few kilovolts relative to the cathode. This device, illustrated at the top of pg. 12, is the field emission microscope introduced by E. W. Mueller. A high electric field causes electron emission at the hemispherical cathode tip, the electrons diverging along approximately radial trajectories (dashed lines in the drawing) until they strike the screen on which is viewed an enlarged emission pattern, such as that shown at the top of pg. 15. In this pattern, the bright areas correspond to regions on the emitter surface where current density is high; the symmetrically arranged dark areas correspond to reduced emission and are a distinctive feature of the emission pattern. These areas correspond to faces on the single crystal emitter tip where atoms are close-packed and the surface is smooth, as a result of which electrons have difficulty in escaping the metal. This correlation is indicated by comparing the two illustrations on pg. 15, the one at the bottom being a "marbles-for-atoms" model of a portion of the single crystal tungsten hemisphere. Corresponding crystal faces in the model and emission pattern are labeled.

With this introduction to the emission pattern at hand, it is possible to illustrate another useful property of the field-emission cathode;

several cathodes can be operated in parallel with a common value of applied potential. In this way current can be increased to a desired level at a given voltage. The parallel operation of field emitters has been reduced to practice through several embodiments; the one illustrated on p. 16 consists of two needle-shaped cathodes mounted on a common support. Proof for the effective and simultaneous parallel operation of both cathodes is seen in their similar and overlapping emission patterns as also shown here. That the figure contains two distinct patterns, each characteristic of a single, clean tungsten emitter, may be judged by comparison with the picture at the top of pg. 15. These cathodes emitted a combined microsecond current of 0.33 ampere at a potential of 17 kv; however, a razor-edged emitter has yielded 4 amperes at 80 kv, which corresponds to a peak power of a third of a megawatt. There is no reason to expect that these will be limiting levels of current and power.



A B C



D E

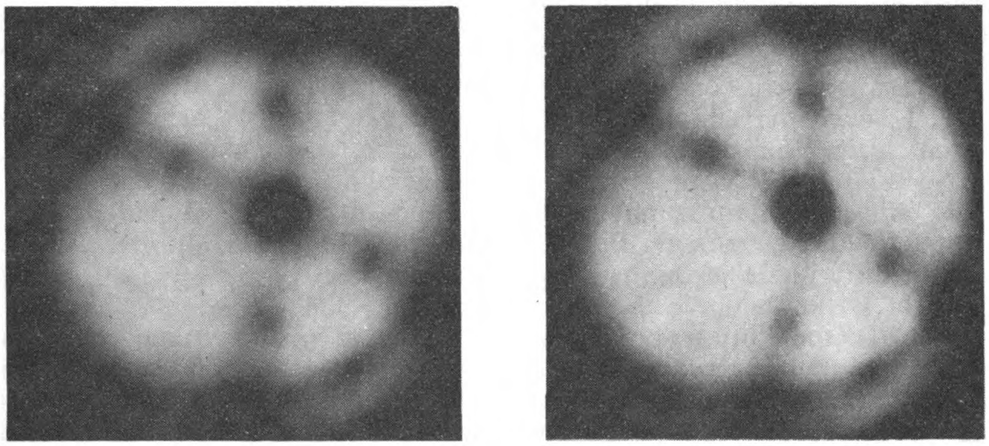
Field emission patterns from clean tungsten (A) and from tungsten cathodes with various surface coatings (B) through (E): (B) barium on tungsten; (C) thorium on tungsten; (D) oxygen on tungsten; (E) the effect of energetic helium ions on tungsten.

Returning to the question of emitter stability, two remarkable features of the field-emission microscope will be useful; namely, its linear magnification—easily a million times, and its high resolving power—about 40 angstroms. It is thus possible to distinguish electron emission from small areas on the cathode about 10 atom diameters in cross section; in fact, more refined arguments suggest that the outlines of large single molecules on the emitter surface can be "seen." As applied to the problem of emitter instability this is a most powerful tool, because effects due to the bombardment of the cathode by perhaps one atom, and certainly due to its contamination (poisoning) by as few as a hundred atoms or so, can readily be distinguished by the corresponding changes caused in the emission pattern. Let us next note several ways in which contaminants can alter emission from the cold cathode.

Consider for example the changes in the emission pattern that result when barium is evaporated onto the originally clean tungsten surface, that is, on the tip of the needle shown in the drawing at the top of pg. 12. The emission pattern from clean tungsten is shown on p. 17 (A); for barium-on-tungsten, the pattern is that shown in B, when the coating is less than a monolayer, that is, one atom thickness. The emission pattern in C, shows thorium-on-tungsten and has a remarkable snowflake-like symmetry which is readily identified. On the other hand, oxygen-on-tungsten appears as in D, which pattern is also distinctive and easily recognized. Thus the field-emission microscope can be used in many cases to detect and identify cathode contaminants and to measure the extent of contamination. This is important to the development of the stable field-emission source, since most contaminants alter the current-voltage relationship from that characteristic of clean tungsten and therefore are one cause of emitter instability. If the voltage is held constant, a coating of barium or thorium on tungsten increases the current; on the other hand a coating of oxygen decreases the current. Since residual gas, electrode surfaces, glass tube walls, etc., are sources of contaminants, which can reach the cathode when power is dissipated in the tube, such contamination, or poisoning, of the cathode surface is a probable process and doubtless accounts for much of the instability of field-emission cathodes reported by earlier workers.

The field-emission microscope permits identification of the cause of another type of electrical instability in which the current-voltage relationship is again changed. If helium is present at a pressure of 10^{-8} mm of Hg or more, the tungsten-cathode surface is gradually roughened due to sputtering when high energy helium ions impinge on its surface. At small localized surface projections, the electric field, and hence the field current density is increased; this effect is identified in E through the small "bright spots" corresponding to the small areas of increased current density. Two undesired effects can result; first the current-voltage relationship may be changed, and second, an arc may result from excessive current density. One may ask, is this problem experienced on a wider scale in other electronic devices? Helium from the atmosphere is known to diffuse through glass; through pyrex, for example, this source will result in a helium pressure of about 10^{-5} mm of mercury in a year's time.

It has been said that at least half of the battle is the recognition of the problems at hand. It has been shown that roughness or contaminants on the cathode surface contribute to its electrical instability. Knowing this, two methods for improving stability are seen: first, to reduce the amount of material which can bombard and contaminate the cathode, and second, to maintain a smooth, clean cathode surface in spite of incident material.



A B

Emission patterns from a thermally stabilized pulsed tungsten T-F emitter: (A) at the start of and (B) at the completion of a 200 hour life test; identity of patterns illustrates electrical stability achieved by this method. During most of the test, current was 0.2 ampere, voltage 40 kv, microsecond pulses at 300 p.p.s.

One means for accomplishing the former is to remove sources of material which can reach the cathode. Such sources are residual gases, contaminants on other electrodes or on glass tube walls, fragments of the electrode materials, etc. These sources are minimized by use of high vacuums and clean surfaces; work in this direction has yielded cold cathode stability for periods of a few hours for both steady state and pulse operation.

Another method, which has provided excellent cathode stability for periods as long as 200 hours during pulse operation, uses an intermediate cathode temperature to maintain a smooth, clean cathode surface in spite of incident material. When repetitive microsecond emission is drawn from the tungsten cathode which is stabilized by use of an intermediate temperature, the emission pattern shows none of the undesirable effects described in the illustration on pg. 17. Rather, the emission pattern remains that characteristic of clean tungsten during long periods of operation. For example, the pattern in picture A at the top of this page was taken before, and that in B was taken after, 200 hours of repetitive microsecond operation during most of which period the repetition rate was 300 p.p.s., the current was 0.2 ampere, and the voltage was 40 kv. The identity of the two patterns illustrates the electrical stability which was observed during the test; none of the pattern changes shown on pg. 17 associated with emitter instability were observed. Other emitters have been successfully operated at higher power but at lower duty cycles, a limitation which has been imposed by immediately available pulser equipment rather than by cathode performance.

Use of an intermediate temperature thus appears to offer considerable promise for stabilizing the pulsed emission of electrons from metals at high electric fields; however, it will probably not be useful for steady state operation (direct currents) since the cathode gradually distorts geometrically during continued exposure to both high field and high temperature. The desirable electrical properties of the tungsten field emitter are conserved at the temperatures used, although in the strict sense the emission is then neither field nor thermal and has been called "temperature-and-field emission," or in abbreviated form, "T-F emission." The energy which must be added to the cathode for this purpose is quite small in view of the microscopic cathode size and is negligible compared with that required by the thermal emitter whose major difficulties in this respect are avoided.

Will the field and T-F emitters receive widespread use in new and important electronic devices? Can they compete in dollar value with other devices using well-known cathodes? Answers to these questions can only be found through continued research and development. It is clear, however, that these emitters have remarkable properties around which significant electronic devices can be designed. Now, for the first time, there appears to be good prospects that stability and life can be obtained under useful conditions.

Altitude Record Set by Rocket Developed at NRL

The altitude record for single-stage rockets was set on 24 May, when the Naval Research Laboratory's Viking 11 reached a height of 158 miles above the White Sands Proving Grounds at Las Cruces, New Mexico. The previous record was set on 6 May, when the Viking 10 tied the old single-stage altitude record of 136 miles.

The Viking 11, measuring 45 feet and weighing 7-1/2 tons, topped that mark by 22 miles reaching a maximum speed of 4300 miles per hr. The rocket's warhead - carrying almost 1,000 lbs of electronic instruments to relay and record information about the outer atmosphere - was recovered intact 24 miles northwest of the launching site. The warhead is blasted away from the body of the rocket at optimum altitude and then falls free. Its bulky unstreamlined design serves as a brake in the heavy lower atmosphere.

The major experiment in Viking 11 was designed to measure the properties of the ionosphere, the layers of charged particles surrounding the earth which reflect radio waves and make possible long-distance radio communication. A transmitter was carried aloft and sent radio waves through the ionosphere to receivers on the ground.

Other upper-air experiments in Viking 11 were intended to determine the ion content of the atmosphere at high altitudes, its pressure, density and wind velocities. Emulsions prepared by the National Institutes of Health were placed within the vehicle to detect cosmic radiation. The rocket also carried a number of cameras to determine its orientation during flight, to measure the intensity of the daylight sky illumination, and to obtain wide-area photographs of the earth's surface. Many of the instruments were devoted to measuring the performance of the rocket itself. Most of the scientific information obtained from the rocket was transmitted to the ground during the flight by means of a radio telemetering system designed by NRL.

On the Naval Research Reserve

Fifth Anniversary Meeting of 9-8

NRRC 9-8, St. Louis, Mo. celebrated its fifth anniversary with a dinner meeting on 3 April at the Naval Air Station, Lambert Field, St. Louis. Prior to the dinner, officers of the unit and their guests enjoyed a conducted tour of the station. Also attending were the St. Louis Army RRC, representatives of the Air Force Reserves and Naval Ordnance Research Reserve Co. 9-7. Pictured on the left above, is CDR J. H. Carter, Commanding Officer of 9-8 with fellow officers and guests. LCDR A. T. Wordell, Program Officer for the Chicago Area, represented the Chief of Naval Research at the meeting.

Notes on Unit Activities

LT John H. Coleman has been assigned Commanding Officer of NRRC 6-14, West Palm Beach, Fla. He is a Director of the Radiation Research Corp. Lt. Coleman has been Officer-in-Charge of the West Palm Beach Panel of 6-10.

The NRRC 4-2 Panel at Willow Grove held its first meeting on 28 April. CAPT J. D. Hardy, USNR, is the Officer-in-Charge.

The NRRC 4-10 Panel at Cincinnatti has been meeting regularly twice a month and will probably be commissioned as NRRC 4-10 soon. LT Edwin Gud is Commanding Officer.

NRRC 4-3 (Pittsburgh) recently celebrated five successful years as a unit. At its last meeting, members attended an exposition of laboratory equipment held in conjunction with the Pittsburgh Conference of Analytical Chemistry and Applied Spectroscopy. LCDR Kenneth O. Stevenson is Commanding Officer.

CAPT Theodore Blanchard

New Director of Research Reserves

Last month CAPT Theodore Blanchard assumed his duties as Director of the Research Reserve Program. He comes to his present assignment from the U.S. Naval Receiving Station, Brooklyn, N.Y., where he was Executive Officer. The Captain is no stranger to ONR, having served as Liaison Officer for the Special Devices Program from 1948-50. In his present assignment, he is responsible for directing the activities of over a hundred Research Reserve units throughout the country.

CAPT Blanchard was born in Haverhill, Mass., but spent most of his youth in Highland Falls, N.Y., a community adjacent to West Point. He was appointed to the U.S. Naval Academy from his home state and graduated with the class of '24. Commissioned a Second Lieutenant in the Marine Corps, he served one year on active duty before going on to graduate work at Harvard's School of Business, where he received his M.B.A. in 1927. From then until the outbreak of World War II, he was associated with the National City Bank of N.Y., Traveler's Insurance Co., Hartford, Conn., and the Anaconda Copper Mining Co. He is now a Director of the Walker Laboratories in Mt. Vernon, N.Y., as well as the New York Port Society.

The year 1941 found him back on active duty - this time with the Navy, as LT Blanchard. During the war, he served as Commanding Officer of LST-73, Squadron Commander of LCT Groups 25 and 27 (Atlantic Fleet) and LCT (G) Group 8 (Pacific Fleet). He was also Executive Officer of the Amphibious Operations Training Element, Atlantic Fleet. His combat duty included the Battles of Kwajalein, Eniwetok, Saipan, Guam and Tinian. He worked with underwater demolition teams off enemy beachheads in the Pacific and led Army and Marine divisions onto the beaches on D-Days. LCR (G) - Group 8 suffered 76% casualties. His decorations include the Bronze and Silver Stars and he was twice awarded the Navy Unit Commendation.

CAPT and Mrs. Blanchard live in New Rochelle, N.Y. They have two children, a 17-year-old daughter and a 15-year-old son.

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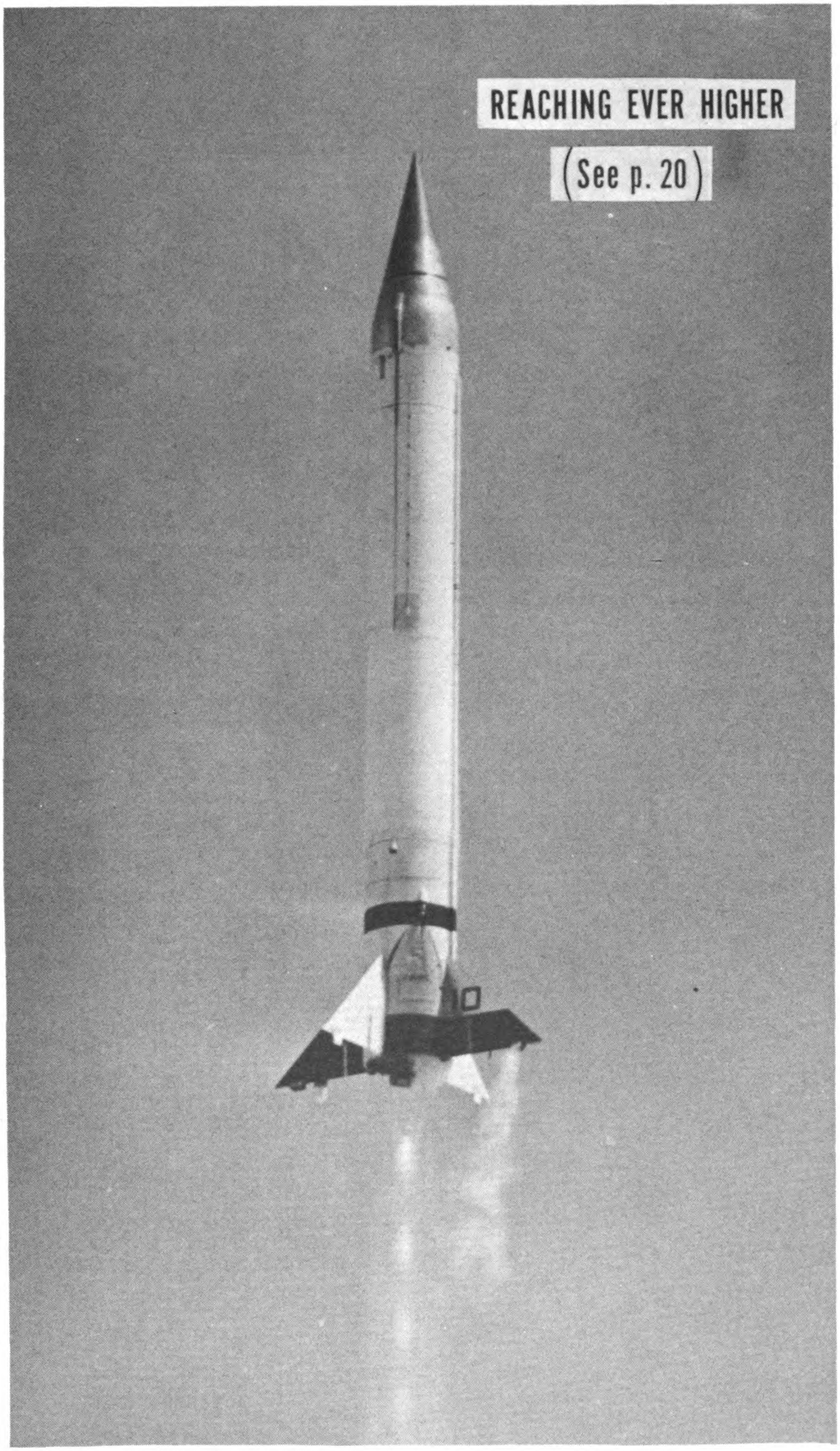
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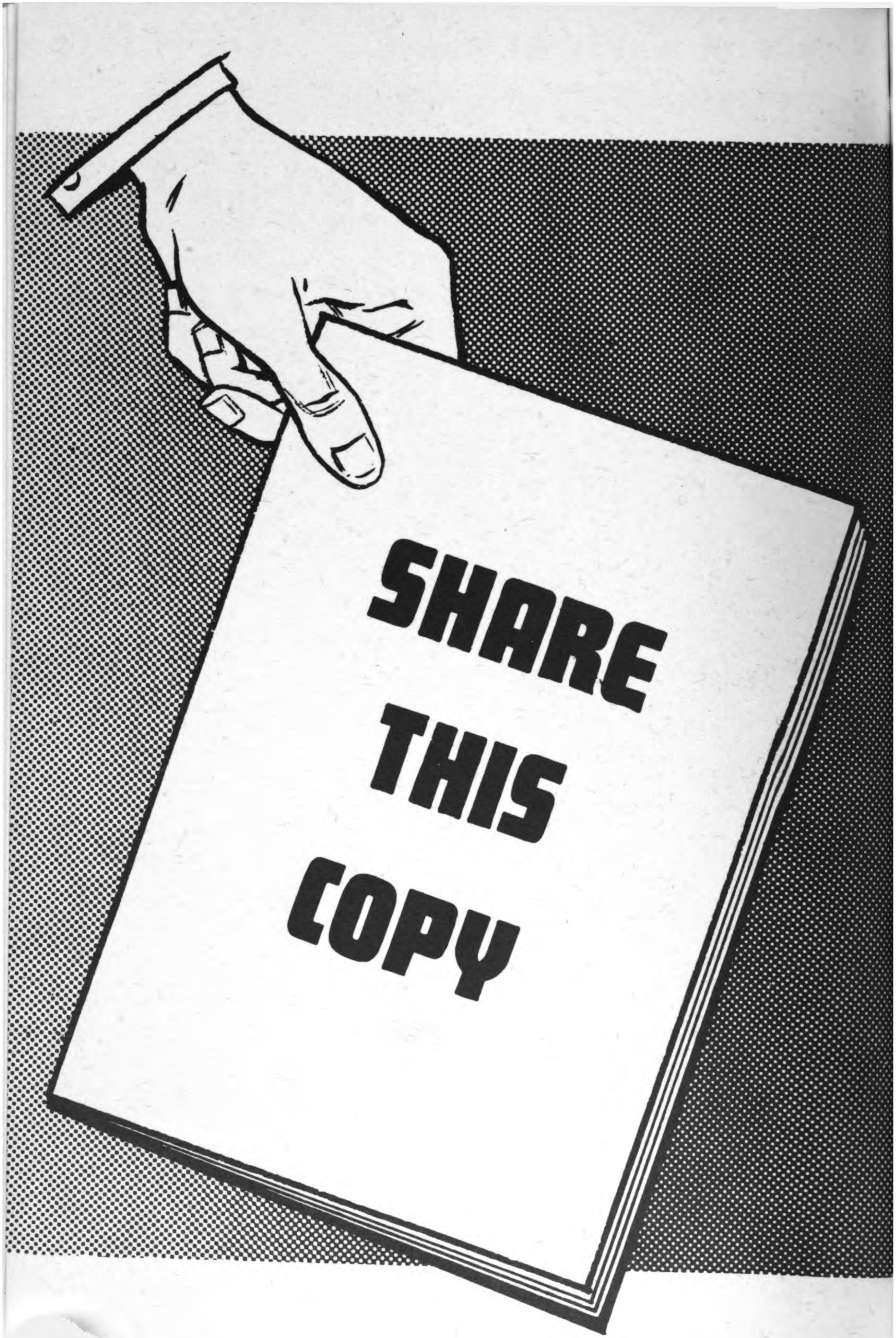
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