GROWTH OF UNIFORM CYLINDRICAL METALLIC

SINGLE CRYSTALS OF SMALL DIAMETER

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PREFACE

For purposes of conducting investigations into the properties of metals it is frequently desirable to have samples in very pure form, such as single crystals. Moreover, for certain measurements specimens of uniform cross section are required. To obtain uniform cylindrical single crystals, some method must be found to retain the cylindrical shape while the metal is being converted from the polycrystalline form to a single crystal. One such method utilizing crucibles with a uniform diameter aperture is depicted here. Such a project makes a suitable undergraduate research program in which both students and staff can participate. The pedagogical advantages to a physics department of such undergraduate research projects are described in this paper, and a "model" for comparing other tentative research projects is developed.

Great indebtedness and appreciation are acknowledged to Dr. H. E. Harrington for serving as major professor despite his many duties as Head of the Physics Department; to Dr. E. E. Kohnke for his helpful guidance in the field of solid state physics; to Dr. Leon W. Schroeder and Dr. D. L. Rutledge for their sincere interest and valuable suggestions; and to Dr. Robert E. Sweitzer for his kind assistance with some of the theoretical aspects of the problem.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF PLATES

CHAPTER ONE

NATURE AND SIGNIFICANCE OF THE PROBLEM

For the past several years there has been increasing interest in the value of undergraduate physics research, as evidenced by this statement in the American Institute of Physics Educational Newsletter of February 24, 1959:

> During the last eighteen months, visiting physicists have repeatedly pointed to the importance of providing research opportunities in physics in the smaller colleges. Physicists situated in these institutions need encouragement and assistance in carrying on small-scale, but significant research. Opportunities for research are often as important as the salaries offered in attracting competent young physicists to the staffs of colleges (1).

The pedagogical advantages to a small college physics department of a vigorous research program range from recruiting better qualified staff, to turning out better prepared physics graduates (2). In particular, there are certain specific advantages to the physics students from the type of undergraduate research to be defined here. Such a project acquaints students with the phenomenological aspects of current physics and impresses upon them the dynamic nature of physics. It also introduces the students to more sophisticated experimental apparatus and techniques than is ordinarily possible in traditional undergraduate laboratories. There is thus a better opportunity for students to develop both skill and insight into the concepts of physics.

It will be one purpose of this paper to indicate some of these advantages as they have appeared in the literature. A second purpose will be to describe in detail a research project that lends itself particularly well to the restrictions of the typical small college physics department. Such restrictions can be thought of as constituting criteria from which a "model" can be constructed.

It should be admitted that there are very definite difficulties to be overcome in attempting to initiate a program of research in the typical small college situation. Lack of adequate library facilities, for example, can be a serious handicap to research efforts. Another purpose of this paper will be to indicate a method of alleviating the problem of lack of research reference materials in the small college library.

A "small college" might be defined in various ways; Pake (2) defines "colleges" to mean four-year liberal arts colleges with no Ph.D. program. This definition will be satisfactory for our term "small college." Teaching loads in such insitutions can constitute another formidable obstacle to research activity.

However, there are also other obstacles that must be faced if research is to be attempted. Unlike the universities from which the staff members obtained their advanced degrees, the typical small college is not likely to have great quantities of expensive, research quality equipment available. The particle accelerator, x-ray apparatus, computer, large electromagnet, electron microscope, electron paramagnetic resonance spectrometer, or similar equipment that the staff member relied upon for his own research will probably not be available for continuing his particular research interests at the small college.

Obviously then, one consideration for an undergraduate research project must be availability (or initial cost) of requisite apparatus. Moreover, as physics equipment becomes more complex, maintenance expenses become a considerable departmental budget item. Prices of a replacement "tube" can range from a few dollars for an ordinary electron tube, through half-a-hundred or more for a geiger tube, to almost a thousand dollars for an x-ray tube.

Associated with equipment is potential experimental hazard for inexperienced personnel. The undergraduate laboratory type research to be proposed in this paper will assume active participation by staff and by undergraduate students. Presumably the research would represent current staff interest in some phase of experimental physics. If appropriate faculty laboratory supervision is impossible 100 per cent of the time it would seem very difficult to justify student experimentation with equipment entailing hazards of high voltages, radiation, or similar dangers. Safety, then, becomes another restriction on research possibilities.

Another consideration is that of level of difficulty of the proposed problem. Ideally, it would perhaps be just slightly beyond the students' present level of sophistication in mathematics and physics theory.

The foregoing conditions against which tentative undergraduate research projects might be "measured" can be considered to comprise a paradigm or "model" for undergraduate research. The model might be said to establish the following criteria: 1. Initial cost; 2. Continuing (or maintenance) expense; 3. Safety considerations; 4. Level of difficulty.

The problem to be described in detail in Chapter Three is the result of a serious effort to find suitable undergraduate research projects that fall within the enumerated restrictions. Thus it might be considered a specific example of the research "model" developed. The apparatus needed to engage in growth of metallic single crystals can be constructed very inexpensively. A pound of zinc having a purity of 99.9998 per cent can be purchased for about twenty five dollars and will yield dozens of crystals of a size suitable for many different types of experiments. Dental plaster of paris for the crucibles can be purchased at drug stores for about fifty cents a pound. The principal piece of equipment, the electric furnace, is constructed from nichrome or chromel wire which forms the heating element. The heating element is enclosed in an asbestos container made from asbestos paper. Cost of the furnace should be well under five dollars.

The mechanism for lowering the crucible slowly and evenly down through the furnace consists of a polystyrene piston floating on water in a large fruit juice can to which a pipe fitting is soldered. Again the cost factor is negligible.

Experimental hazards are at a minimum. The mathematical and theoretical level can range from just above sophomore physics to almost any desired upper limit.

Since solid state physics is an area of considerable current interest among physicists, it is also of considerable interest to most physics majors.

The research project presented here has been "student tested" for several years and found to be very satisfactory. It did not achieve its present status without a great deal of trial and error, false starts, and pursuits of blind alleys. After having made such attempts, one is inclined to agree with Schilling's (3) statement (page 198) that, "making provisions for undergraduate research requires considerable ingenuity." Moreover, (page 199) the staff members "...are at a loss when confronted by small college resources, to imagine how any kind of research could possibly be done under such circumstances." However, Schilling (3) continues, "there are many worthwhile problems to be solved that are within the range of resources of a good college; patient thought will in time bring them to light."

While no claim to "ingenuity" is made here, considerable "patient thought" has been expended in identifying what is felt to be a very "worthwhile problem."

Gilman (4) also (page viii) makes an interesting point, "it is somewhat ironic that although artificial crystal growth has had so much effect on various sciences, the process itself has retained more of the flavor of art than of science." It is hoped that the material presented in this paper will either improve the state of the art, or establish this particular project on a little more scientific basis.

CHAPTER TWO

HISTORY

Man has exhibited interest in metals for hundreds of years. However, this early interest was largely utilitarian and it is only in relatively recent times that serious research into the theoretical considerations of the solid state of metals has been attempted. Although the matter is not completely definite, it appears that two men, G. Tammann and H. Block must have been among the first investigators to produce single metallic crystals. Block's work on volume changes in solidification of molten metal was dated around 1911 while that of Tammann was in the early 1920's. However, as Buckley (5) indicates (pages 71-72) some felt that Block's ideas came from Tammann. At any rate, Tammann's name appears frequently in the literature in connection with a particular method of producing metallic single crystals.

Tammann discovered that by confining a molten metal in a long narrow tube tapered to a capillary at one end, he could produce single crystals by cooling the metal in the capillary first and then gradually extending the cooling from that portion. This method typifies one of the broad categories of metallic single crystal production--that of crystallization from the melt.

Many modifications were subsequently made on Tammann's method but all incorporated the basic characteristic of a small pointed section of the container that restricted the growth from a minute portion of the melt that solidified first. This portion became known as the "seed" and the layers of crystal that formed on the seed were said to "grow". The pointed or tapered section restricted the growth in such a manner that one crystal plane would survive at the expense of all the other possible orientations.

Bridgman's (6) method, for example, differed from that of Tammann only slightly. Bridgman enlarged the size of the container that extended beyond the capillary point allowing him to grow crystals of bismuth 2.2 centimeters in diameter. Bridgman also constructed his container in two sections separated by a narrow constriction, thus permitting evacuation of air and sealing off from the atmosphere. Bridgman's chief contribution was that he supported the tube vertically and lowered it from the furnace into a cooling zone of air or oil.

J. Czochralski (7) developed a method which with modification is widely used today to produce single crystals of germanium, silicon, and other such commercially significant substances, as well as metal crystals. The innovation consists of "pulling" or "drawing" the crystal from the melt. Czochralski's original purpose, according to Buckley (5) page 82, was not to produce single crystals but "to measure the speed of crystallization of different metals."

A small capillary tube was lowered into the molten metal which then entered the capillary, cooled, and solidified. The solidified portion acted as a "seed." The capillary tube was then slowly withdrawn, permitting a wire of the metal to be formed. The wire thickens if the rate of withdrawal is not optimum, thus the method yields a single crystal of varying diameter. One advantage of the method described in Chapter Three of this paper is that the crystals produced are of uniform diameter.

Although there are many other methods, the one used by C. A. Cinnamon (8) is illustrative and resulted in obtaining very large single crystals of zinc which is the particular metal discussed in Chapter Three. Cinnamon's article includes photographs of the large (60 cm long) single crystals which illustrate the beautiful mirror formed at the cleavage plane.

The essence of Cinnamon's technique, which was similar to that of P. Kapitza (9) rested in using an asbestos mold in which the rate of cooling was controlled by a series of independent heating coils which could be turned off individually. A further advantage lay in bringing the metal into the large portion of the mold through a much smaller diameter tube-like section which could be "seeded" with crystals of a desired orientation.

A second broad category of methods of producing metallic single crystals is that of recrystallizing in the solid. In this method the intent is to increase the grain size of some grains to such an extent that the enormous number of grains in a polycrystalline specimen will be reduced considerably. The ultimate goal is that conditions will be favorable for just one grain to increase at the expense of all the others, resulting in a single crystal.

Buckley (5) states, page 93, "Most workers are agreed that priority for the production of large single crystals by growth in the solid state belongs to A. Sauveur..."

The solid material is first heated (but not to its melting point) than strained, and then heated again under carefully controlled conditions.

J. Pintsch, whose work was published in 1918, developed a method of producing long continuous single crystals of tungsten wire by unrolling one spool of the wire onto another spool, and passing the wire through a heater at about 2500 degrees centigrade (5). The method has also been used for iron.

Metallic single crystals can also be grown by deposition from vapor and by electrolysis. Crystals grown from the vapor are small, their volume being on the order of a few cubic millimeters. The methods will not be described here because metallic single crystals of macroscopic size can be more practically produced by the methods already enumerated. However, Gilman (4) page 30, states that in recent years the discovery that filamentary crystals, called "whiskers" have unusual magnetic, mechanical, and surface properties, has given renewed emphasis to crystals grown from the vapor. G. W. Sears (10) and others have studied such properties in zinc whiskers grown from the triply distilled metal in vacuum.

Still another method of crystal growth which has become commercially important because of its application to growth of synthetic rubies is known as the "flame-fusion process," developed by A. Verneuil (11). The finely powdered raw material is fed into a flame, building up a "boule" of the crystal which may reach a mass of 40 grams and lengths of several inches (5). The method has the advantage of not requiring a crucible.

Perhaps it is evident from this brief historical sketch that most of the work on single crystals of metal has been done since 1900. Furthermore, very few significant innovations were made until the year 1952 when W. G. Pfann (12) developed his "zone melting" technique.

In this method, a narrow furnace encircles a crucible which contains a polycrystalline ingot of metal adjacent to a "seed" crystal of the same metal. The interface between the two pieces of metal is heated until they melt and thoroughly wet each other. The heat zone is then swept slowly away from the seed along the polycrystalline ingot. If conditions are right a single crystal results. Optimum conditions according to Lawson and Nielsen (13) page 19, call for a planar interface being maintained, a slow growth rate, and mechanical and thermal fluctuations held to a minimum.

The zone melting method has been successfully applied to a vertical position with the result that the crucible is eliminated. Called a "floating zone", the narrow molten zone of the metal maintains its configuration by surface tension.

Zone melting is also used to purify materials since the impurities can be swept along in the molten zone. Repeated passes can be made to increase the degree of purity.

It has been indicated (page 82) that the production of a metallic single crystal from the melt requires an arrangement whereby the atoms of the melt, or molten state, "freeze out" onto a nucleus, which is a single crystal itself, in such a manner as to perpetuate the lattice array of the nucleus (14).

Perhaps the most outstanding characteristic of single crystals is their purity; and it is for this reason that single crystals are in such demand. It is now recognized that only by dealing with single crystals of a metal can experiments to determine its properties be replicated with meaning. In fact, the "demand for single crystals...is echoed in every branch of research concerned with the solid state. The reason is not difficult to find. The foundation stones on which so much of the recent and staggering advances in our understanding of the solid state rests are, in fact, pure, single crystals. In metallurgy, the properties of metals are being rediscovered...Purity is of paramount importance also in the field of atomic energy...Pure crystals are required by physicists to investigate radiation damage, superconductivity, nuclear and electron resonance, and by chemists for research into molecular structure. And in no field is the demand for single crystals more incessant than in semiconductor research" (13).

Gilman (4) refers in his Preface to the present impetus on single crystal growth as a "materials revolution." He feels that we are "passing from a period when solid matter was used mainly in unsophisticated forms into a period when increasing emphasis will be placed on its use in the form of highly organized crystals."

Crystals containing less than one part per million impurity are often produced. A partial list of the uses of man made crystals (not restricted to metals) indicates the scope of application: frequency controlled oscillators (quartz); polarizers (calcite, sodium nitrate); transducers (quartz, Rochelle salts, ammonium dihydrogen phosphate); grinding (diamond); radiation detectors (anthracene, potassium chloride); infrared optics (lithium fluoride); bearings (aluminum oxide); transistors (germanium, silicon); magnetic devices (garnets); strain gages (silicon); ultrasonic amplifiers (cadmium sulfide), masers and lasers (ruby, gallium arsenide, calcium tungstate); lenses (fluorite); melting crucibles (magnesium oxide); and tunnel diodes (gallium arsenide) (4).

Although the list of applications of crystals may appear impressive, in the case of single crystals of metal the desire is primarily to have available the purest form of the metal for conducting investigations into the mechanical properties, the magnetic properties, the electrical properties, or any such properties so essential to a knowledge of the metal. The single crystal represents the purest sample of the substance that can be obtained.

CHAPTER THREE

GROWTH OF ZINC SINGLE CRYSTALS

It was pointed out in Chapter One that to be suitable for undergraduate research in the small college a project should be safe, relatively inexpensive, and of a suitable theoretical level to be both satisfying and challenging.

The growth of metallic single crystals meets these requirements very nicely. However, after deciding to investigate this aspect of solid state physics, the experimenter is immediately faced with another decision: which metal would be the best choice?

The refractory metals (those having high melting points, such as tungsten) present obvious experimental difficulties not encountered in those of lower melting points such as zinc. Table I illustrates a few of the more likely possibilities, their cost per pound, and percentage purity available. Table II lists some suppliers of metals.

Zinc is a good choice for other reasons also. For if one is to embark on a project of attempting to grow metallic single crystals, the question of what to do with them after they are grown should be considered early in the undertaking.

Here again the restrictions imposed on typical small college research facilities tend to govern the decisions. Elastic properties evoke the experimental possibity of an apparatus similar to the familiar sophomore experiments with Young's modulus. Such apparatus could presumably be

TABLE I

COMPARATIVE PRICE OF METALS

Metal	Per Cent Purity	Cost	Unit
Gallium	99.99	$ 2.50	gram
Gallium	99.999	3.25	gram
Tin	99.9999	34.50	500 gram
Indium	99.9996	3.80	troy ounce
Lead	99.9999	20.00	pound
Zinc	99.9998	25.00	pound

TABLE II

SUPPLIERS OF METALS

Name	Address
1. H. Cross Company	363 Park Avenue Weehawken, New Jersey
2. Jarrell Ash	26 Farwell Street Newtonville, Massachusetts
3. Aluminum Company of America	Continental Building St. Louis 8, Missouri
4. The Eagle-Picher Company	American Building Cincinnati, Ohio
5. United Mineral and Chemical Corporation	16 Hudson Street New York 13, New York
6. Vulcan Detinning Division	Sewaren, New Jersey

"homemade." Electrical properties, however, can entail such equipment as potentiometers costing over eight hundred dollars and not suitably "homemade." So it was decided to work with zinc with the idea of pursuing research later in the area of mechanical properties.

Zinc is one of a group of metals having a close-packed hexagonal type of crystal which seems to account for some of its mechanical properties. Shrager (15) lists (page 5) the metals having this type of structure: "Metals that crystallize in the close-packed hexagonal structure include antimony, beryllium, cadmium, cobalt, magnesium, titanium and zinc." Azaroff (16) on page 55 discusses closest packing, with some interesting natural examples on a macroscopic scale: "A close packing is a way of arranging equidimensional objects in space so that the available space is filled very efficiently. Such an arrangement is achieved when each object is in actual contact with the maximum number of like objects. A honeycomb is an example of a close packing found in nature."

The hexagonal crystalline structure of zinc gives it the following characteristic: if a weight is attached to one end of a zinc rod which is mechanically secured at the other end, the rod will gradually elongate and will not return to its original length after the deforming force is removed. This is called plastic deformation in contrast to elastic deformation which occurs if the specimen regains its original length. Kittel (17) points out on page 561 that if the plastic deformation is time-dependent it is called creep. Ziman (18) indicates (page 113) that metals are the most plastic solids.

At this stage in the project certain reference books are quite valuable. Preparation of Single Crystals, by Lawson and Nielsen (13) contains excellent descriptions of various methods by which single crystals are produced. It is obvious from the illustrations in this book that the small college investigator will not be able to build or buy some of the apparatus by which single crystals are commercially produced. The essential points on crystal growth are included, however, and valuable suggestions are made. Zone melting is mentioned as a powerful technique and reference is made to Pfann, who developed it. Pfann's (19) book is another valuable source. A third book to be highly recommended for this type of activity is Procedures in Experimental Metallurgy, by Seybolt and Burke (20). The entire book is relevant, as indicated from the stated purpose of the authors on page vii: "It is a primary aim of this book to describe most of the important laboratory techniques which are now used in the preparation of metals and alloy specimens for further study." Chapter twelve, however, is particularly helpful as it describes the preparation of metal single crystals.

Zinc does not require extremely high temperatures in order to be converted into a single crystal so the question of a suitable crucible is not as complicated as it might be with higher melting point substances. The author discovered that a carbon rod of the type used in arc-lamps could serve very well as a crucible. First it is cut in two lengthwise using a fine-toothed hacksaw. A small file can then be used to make a groove in the flat side of the carbon. The groove will accommodate a polycrystalline zinc filament.

The zinc filaments can be made by melting the zinc in a beaker. A glass beaker with a high melting point such as Vycor is very useful for melting larger quantities of zinc. However, experience proved that it was more convenient (and safer) to work with smaller quantities and use Vycor test tubes rather than beakers. Zinc can be purchased in rod or pellet form. The pellets have proved more valuable for our purposes for two reasons. First, they are easier to melt than chunks of zinc taken from half-inch diameter rods; second, they will fit into a test tube having a diameter of half an inch or smaller. The pellets used have a diameter of about 4 mm and were obtained from United Mineral and Chemical Corporation, 16 Hudson Street, New York 13, New York.

An ordinary Meeker burner will melt the zinc, which can then be drawn up into Pyrex glass tubing of desired inside diameter. The diameter of the tubing for these early investigations was not critical. For other methods involving a different type of crucible, the diameter of the tubing becomes significant, as will be discussed later.

Tubing of 3 mm inside diameter was attached to a vacuum pump by means of a rubber hose. The rubber hose was pinched and the glass tubing inserted in the molten zinc, with the vacuum pump running. The pinch clamp on the rubber hose was then slowly released and the molten zinc was drawn up into the tube. Although this method sometimes produced polycrystalline slugs of over 20 cm in length, more often it yielded large sections of zinc that were hollow. If the zinc was too hot and the vacuum hose opened too much, the zinc would flow quickly up the glass tube; and the outer portion of the zinc flowed up the glass walls faster than the inner portion did, producing a short section of solid zinc and a long section of zinc "tubing" which was not desired. On the other hand if the zinc happened not to be hot enough and/or the vacuum clamp released too slowly, the zinc would rise a short distance (5 cm or so) up the glass tubing and then solidify.

A better technique was developed by using a large rubber pipette bulb. This bulb attached to the end of a section of glass tubing about 30 cm long produced consistently good polycrystalline slugs of zinc with very little practice required of the operator.

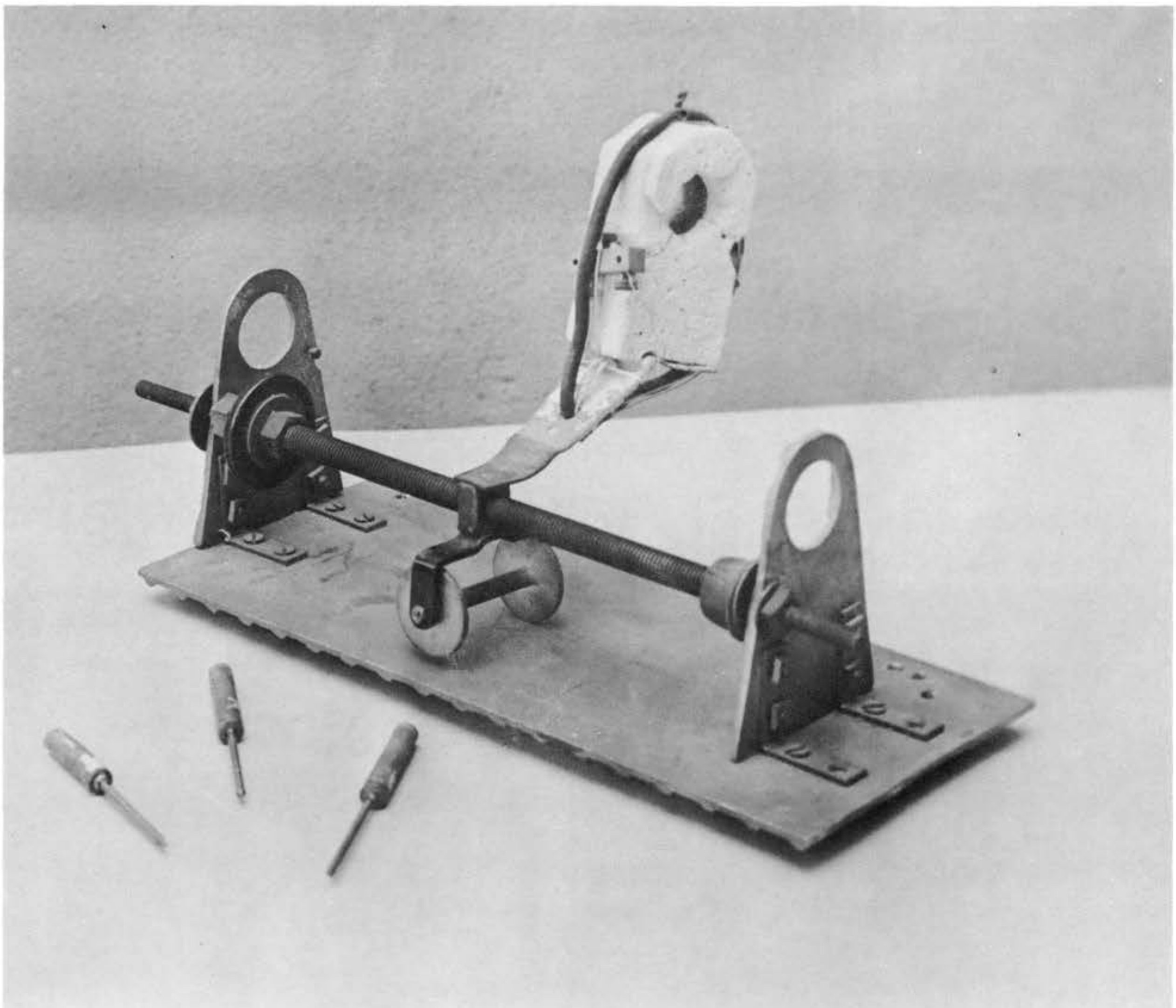
Since the successful method of producing uniform cylindrical single crystals evolved from other attempts at crystal growing, it might be well to discuss some of them for the benefit of others who might wish to pursue similar activities.

The first furnace constructed (PlateI) was of the zone melting type developed by Pfann (19). A threaded rod, 1/2 inch diameter and up to several feet long can be purchased from Sears Roebuck and Company. The rod was cut to a convenient length of 10-1/4 inches. Into each end of the rod and in line with its vertical axis a 3/16 inch diameter hole was drilled to a depth of 1/2 inch. This was then counter-sunk. The heads of two large (1/4 x 2-1/2 inch) round head bolts were then turned on the lathe into cone shapes which just fit into the counter-sunk holes in the threaded rod. This constituted the bearings of the system. The 3/16 inch hole (which was deeper into the threaded rod than were the counter-sunk holes) provided a small oil reservoir for lubricating the bearing surfaces. An aluminum framework consisting of a 14 x 6 inch bottom plate and two 4-1/2 x 3-1/2 inch uprights was simple to construct. Right angle brackets and small bolts were used to attach the uprights to the base plate. The uprights were separated a distance of 11-3/4 inches to allow the threaded rod to be mounted between them.

At one end of the threaded rod a small bakelite sheave (taken from the familiar force table apparatus of general physics) was mounted. The

Plate I

INEXPENSIVE ZONE MELTING FURNACE



hole in the sheave was drilled out to 1/2 inch diameter which allowed it to slip over the threaded rod. It was locked in position at one end by two 1/2 inch nuts brought up on each side of it. The sheave was for the purpose of turning the rod by means of a belt drive.

Next a large square nut with 1/2 inch diameter hole and threads to match the threaded rod, was soldered to a pair of wheels taken from a Hall's Carriage. The threaded rod was mounted at just such height that the wheels could roll along the aluminum base plate with the nut threaded onto the rod. In this way when the rod was turned slowly the wheels advanced (even more slowly) along the base and parallel to the rod.

A metal strap was soldered to the side of the square nut opposite the wheels. To keep the wheels from coming unsoldered, a wet rag was wrapped around the bottom of the nut. When soldering such massive (as compared to electronics circuits) pieces, a small soldering gun is ineffective and a Bunsen burner is needed to supply enough heat. Although soldered joints do not have much mechanical strength, they are strong enough for the use made of them in this apparatus.

The purpose of this arrangement is to provide a mechanical means for sending a zone-heater smoothly and slowly along a straight line path.

The zone-heater itself was made from a portion of very light, easy-to-work-with brick obtained from Mexico, Missouri. Such bricks, designated as G20, can be obtained from the A. P. Green Firebrick Company, 1018 East Breckenridge, Mexico, Missouri. The bricks have proved extremely valuable in all our furnace construction. They can be "sawed" in-two by merely drawing a fine wire back and forth across them. They have excellent thermal insulating properties. Very nice round holes can easily be cut in them simply by rotating thin walled metal tubing into the brick, like a large drill.

A section of brick 2-1/2 x 4 x 1-3/8 inches with a 1-1/8 inch diameter hole was mounted on the strap. The axis of the hole in the brick was parallel to the threaded rod. A length of nichrome wire was wrapped into a 1/4 inch wide heating coil.

Any small diameter rod can be used as a "form" for wrapping the heating coils. One advantage of "coiling" the heating element is that it increases the length, and consequently the electrical resistance of the wire. This permits heavier wire to be used which will last longer without burning out. As Seybolt and Burke (20) point out (page 7), wire smaller than 20 guage has a short useful life at all but the low operating temperatures.

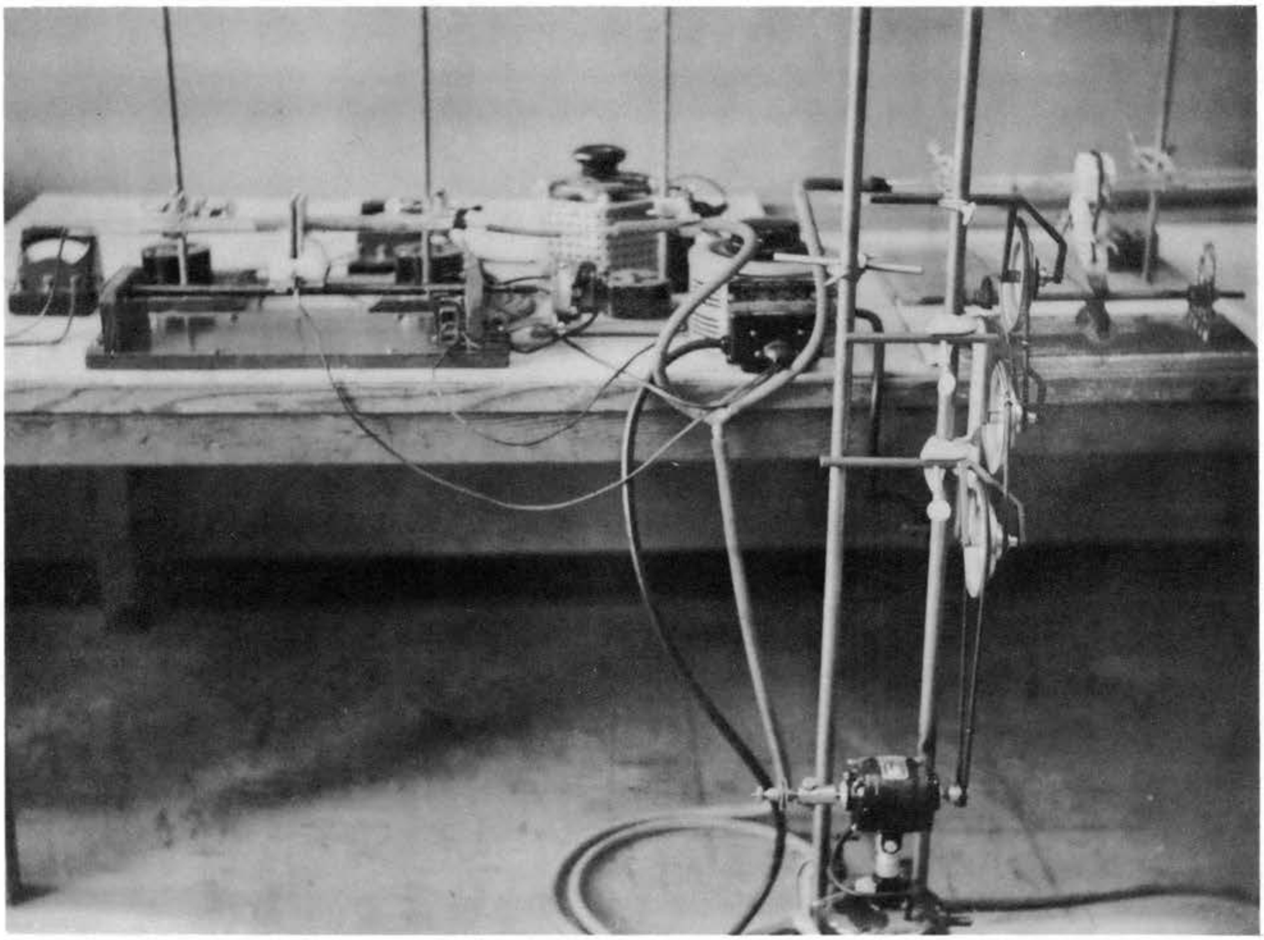
The heating coil was inserted into a vee groove scooped out of the interior of the brick. The groove was carefully centered inside the brick so that a heat zone 1/4 inch wide and approximately 1-1/8 inches in diameter now swept slowly along parallel to the threaded rod as the rod was turned.

Into the hole in the zone heater a Vycor tube, 3/4 inch diameter and about 20 inches long was inserted parallel to the threaded rod. One end of the Vycor tube was closed, the other end had a one hole rubber stopper with connection to a vacuum pump.

To drive the threaded rod, it was found that the only motors available (variable speed rotators from the general physics laboratory) turned much too fast. Three sets of wheel and axle apparatus (Plate II) from the general laboratory sufficed to reduce the speed to the point that the zone could be made to travel as slowly as 5 cm an hour.

Plate II

SPEED REDUCTION SYSTEM



The polycrystalline zinc filament was placed in the carbon crucible, which in turn was placed in the Vycor tube. The tube was carefully positioned inside the zone-heater so that the heater could pass from one end of the zinc slug to the other without touching the Vycor tubing.

Ends of the heating coil were brought out to small metal electrical connectors (available from Welch or Cenco) which make good connections by means of thumb screws. Flexible leads from lamp cord were brought to a Variac which was adjusted until the heating zone melted the zinc. It was found that an auxiliary heater (consisting simply of a single layer of nichrome wound around the Vycor tubing with about 1/2 inch spacing between turns) aided the process by keeping the zinc almost to the melting point. Prior to using the auxiliary heater, the zone-heater had to be operated at such a high temperature that it burned out frequently.

This simple zone melting furnace produced zinc single crystals after many attempts to find the proper relation between speed and temperature. As Hurle (14) puts it (pages 140-141): "The growth of good quality single crystals from the melt is still an art as well as a science and it is difficult to generalize on what are the conditions required for successful growth; they tend to differ from one metal to another."

We found that operating the zone heater at a temperature at which the zinc just melted (slightly greater than 420 degrees C) and a speed of about 6 cm/hour, produced single crystals from the 3 mm diameter polycrystalline filaments.

For this discussion a single crystal is defined as one which will cleave very easily along certain well-defined planes. These planes produce a beautiful mirror-like surface without any irregularities. Parallel cleavage will occur throughout the length of a single crystal. A single crystal of zinc will also be very "soft" and easy to bend; similar to a corresponding length of solder. Polycrystalline zinc, on the other hand, is quite rigid and difficult to bend. A more exacting and less destructive method of identifying single crystals requires an x-ray apparatus. However, the method of cleavage planes is satisfactory.

The Vycor tubing became blackened during each run, from condensation on its surface. Once when the Vycor had been cleaned and some of the distilled water was not removed, it was found that the next zinc crystal made was greatly corroded. The effect is mentioned here because it occurred with the furnace described here. It will be referred to again in Chapter Four as a possibility for future investigations. The surface of the zinc crystal was profusely pitted.

Although a much improved model of the zone melting furnace was subsequently constructed, this first model had an important feature to recommend it: it was constructed almost entirely of general physics laboratory equipment.

The improved model (Plate III and left of Plate II) utilized two guide wires to replace the Hall's Carriage wheels. Instead of a nut threaded onto a rod, a half-nut arrangement was used so that the zone could be picked up and replaced at any point on the threaded rod. This eliminated having to reverse the drive and move the system back down the rod as was required with the first model. A microswitch cut off the motor drive when it had swept past the ingot. A much finer thread was cut on the rod and a geared-down motor was attached directly to the rod.

One other method will be described because it offers a satisfactory way to grow crystals in a vacuum.

A bell jar with a rather large side-opening is required, (foreground,

Plate III

IMPROVED MODEL OF ZONE MELTING FURNACE

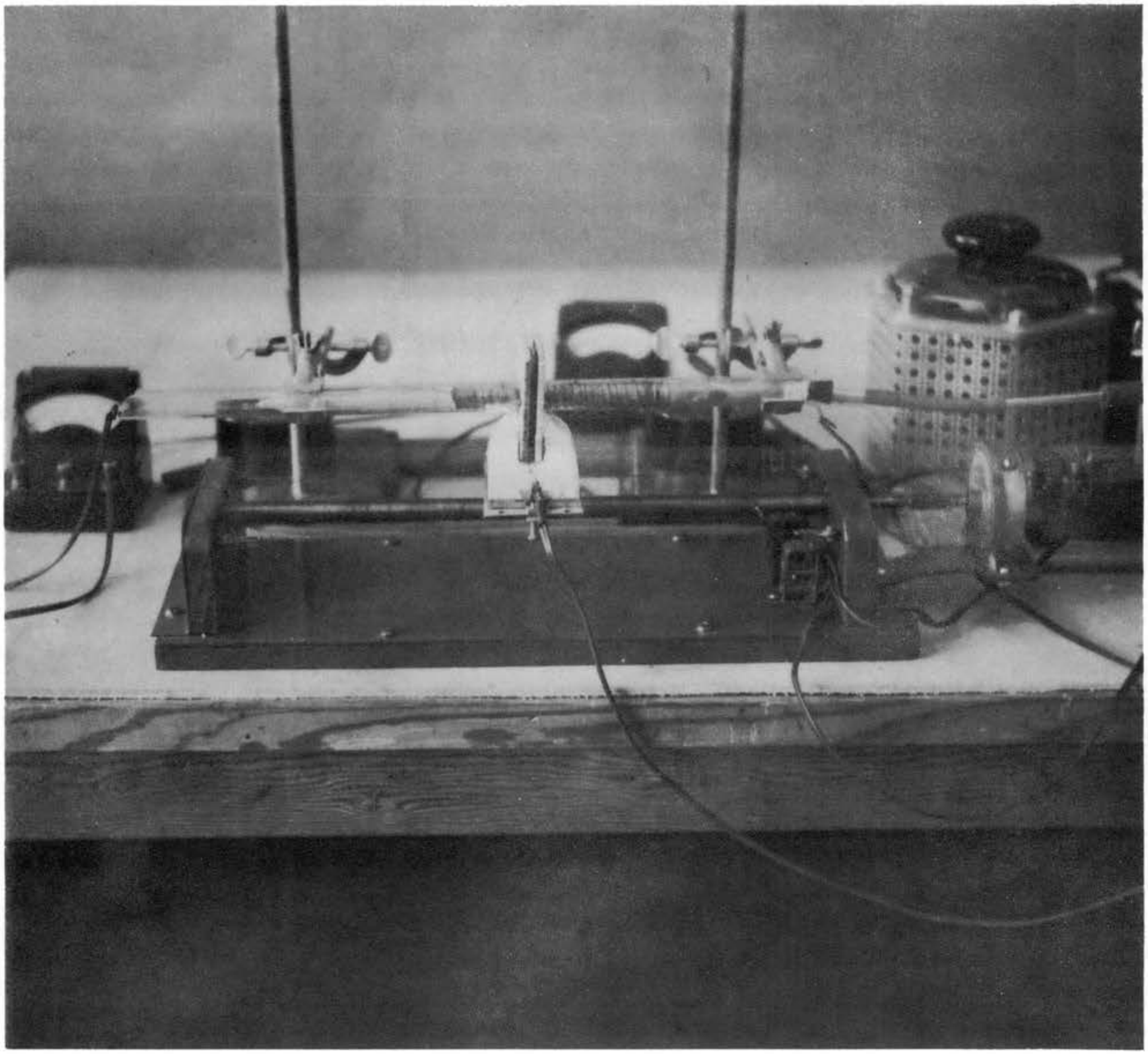


plate IV). From a welding supply house a large (1 inch diameter, 10 inch long) carbon rod can be obtained. Old dry cell batteries provide another source of fairly large carbon rods.

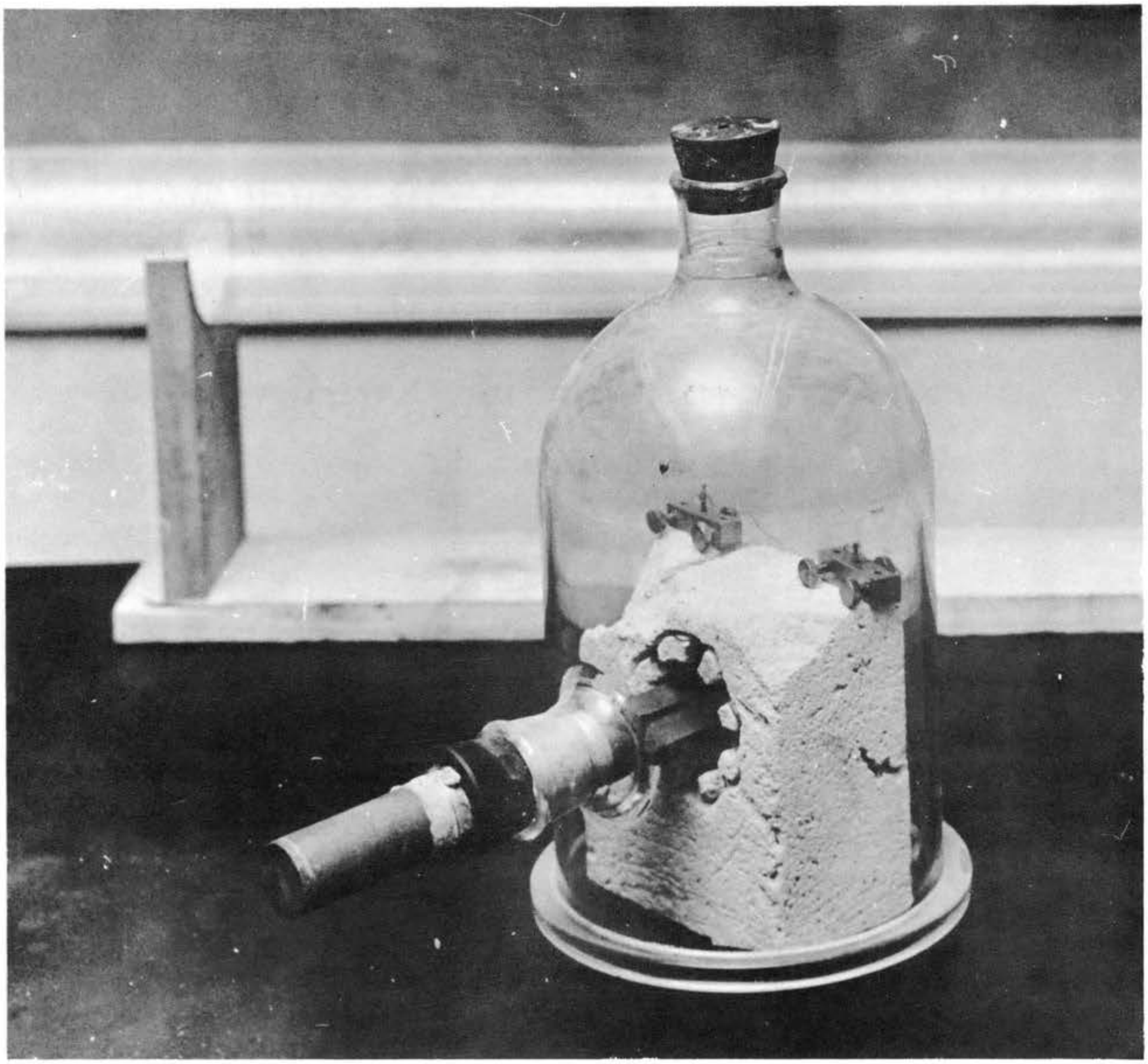
A portion of the rod near one end is grooved to contain the zinc. The groove is narrowed at one end. The rod is inserted into the side-opening of the bell jar in such a way that the rod protrudes outside the bell jar about three inches. A vacuum seal is made at this opening. It was found possible to make a satisfactory seal by wrapping asbestos paper over the carbon. The stopper, of course, had a hole 1 inch in diameter cut in it to allow the rod to pass through the stopper.

It was first planned to wrap a cooling coil of copper tubing around the outside end of the rod to serve as a heat sink. However, it was found that additional cooling was unnecessary. A small heating coil encircling the end of the carbon rod in the bell jar completed the apparatus. Electrical leads were brought in through a hole in the top of the bell jar. The current in the coil was increased until the zinc melted; then the current was decreased. The end of the rod protruding into the air cooled slightly more rapidly than the end inside the bell jar. Thus the zinc solidified at the pointed end of the groove first and became a single crystal.

Although a number of different methods of growing single zinc crystals were developed (in the background of Plate IV another type of furnace is shown which utilized a long tube of Vycor) they all had a common disadvantage: during the process of melting, the zinc, which was placed horizontally in an open "boat" had a tendency to flatten. For mechanical testing, a length of crystal with uniform cross section would be desirable.

Plate IV

VACUUM FURNACE



Clearly the "horizontal" approach needed to be abandoned in favor of a "vertical" method. Stockbarger (21) describes a method incorporating a vertical system adapted from that of Bridgman (6).

The method described here is similar (Plate V). The smooth walls of a soft drink bottle were used as the form for keeping the inside of the furnace cylindrical. Around the bottle, strips of asbestos paper dampened with water were wrapped until a wall thickness of about 1-1/2 inches was obtained. A mass of moistened asbestos paper of this size can be formed almost like stiff modelling clay. A square shape was given to the furnace with sides 4 inches long and 4 inches high. Small nails were inserted into the cylindrical hole to support the heating coil which was suspended from the nails in such a manner as to give an approximately uniform heating pattern.

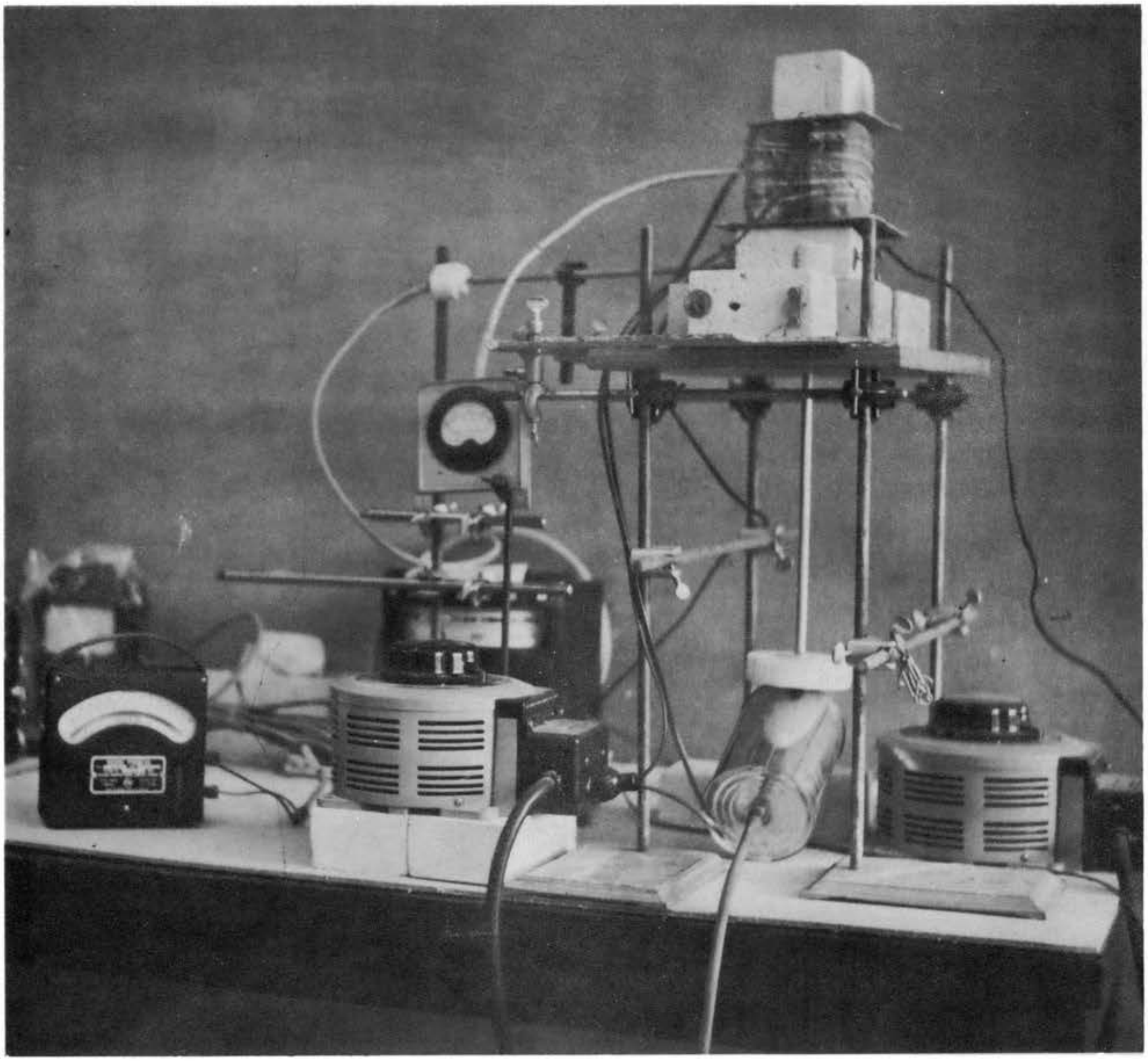
Four ring stands were used to support a 3/4 inch plywood shelf 16 inches above the table. The shelf was 11 x 20 inches with a 2 inch diameter hole cut in the center to allow the crucible to pass through. A piece of scrap steel plate 1/8 inch thick and approximately 6 inches square was used to obtain a sharp temperature gradient just below the furnace. A 1-1/4 inch diameter hole was burned through the plate with a welding torch. The plate was placed on an insulating brick on the plywood shelf and the furnace was set on the plate. Leads from the furnace were brought to a Variac.

A small hole was drilled in the center of one side of the furnace to accommodate a thermocouple with temperature scale.

Next a large tin can of the type that contains tomato or fruit juices was obtained and a brass pipe fitting soldered into a hole in the bottom

Plate V

VERTICAL FURNACE



of the can. A rubber drain hose was attached to the brass fitting. A polystyrene piston 4 inches in diameter, 1 inch thick was fitted to a section of 3/8 inch aluminum tubing 14 inches long. Half inch vertical slots were sawed into the top of the tubing vertically and the resulting "fingers" formed into a sleeve to accept the crucible.

The purpose of the piston arrangement was to provide a means of lowering a cylindrical crucible slowly and smoothly down through the furnace past the steel plate. Enough travel length must be provided to allow the crucible to be initially completely inside the furnace above the steel plate; and to finish its journey completely outside the furnace below the steel plate.

Glass tubing drawn out into tapered points of different small orifices sufficed to regulate the flow of water from the tin can cylinder. The glass tubing was inserted into the end of the rubber drain hose and the system was drained into a large beaker while time measurements were made of the rate of descent of the piston. It was found valuable to calibrate the various orifices before an actual "run" was made.

According to Stockbarger (22) the longer the time of crystallization from the melt, the better the chance of producing a single crystal (page 300). However, as Doremus (23) points out, the mechanisms whereby crystallization occurs are quite elusive. Longer growth time increases the chance of traffic vibrations in a school building. For the furnace described here, best results were obtained with an orifice that gave a "run" time of 90 minutes.

Perhaps the greatest experimental difficulty to be overcome in this type of crystal growth was that of the crucible. It was desired to grow crystals of relatively small diameter. Refractory materials can be purchased from many sources; Seybolt and Burke (20) give a fairly comprehensive list on pages 64-67.

Descriptive literature was obtained from many of these firms and two alundum crucibles were purchased.

Although the diameter was known to be larger than desired, it was felt that such a crucible would suffice for the "crucible experiment" that was undertaken next. The specific experiment was to attempt to alter one of these commercially produced crucibles in such a manner that it could be used repeatedly. The crucibles were not inexpensive (about $8.00 each), and the cost was prohibitive to destroying the crucible each time a run was made. These commercial crucibles had one very definite advantage: the inside walls were uniformly cylindrical and the "cone" inside at the lower end could be of any specified angular taper desired. The metal contained in such a crucible would thus be formed into an accurately known point. Since some investigations with single crystals might more profitably be pursued if carried out with crystals of varying orientations it was desired to investigate the effect of this crucible angle on the cleavage angle of the crystals grown. To do this, a supply of accurate crucibles with internal points of various angles was essential.

A diamond wheel was used to split one crucible lengthwise. All attempts to utilize this type of crucible proved futile. It was apparently impossible to prevent the two halves from separating slightly in the furnace.

The second crucible was then cut in a diagonal manner starting near the top at one side and extending to near the bottom at the opposite side.

The hope was that the two sections could be kept together during the melting period and then could be separated when the crystal had solidified. This attempt was also futile; the two portions of the crucible consistently slipped out of line.

Efforts were then made at drilling accurately pointed cylindrical holes into carbon. This proved to be impractical also.

A number of other possibilities were explored using variations of the methods mentioned as well as completely different approaches. One such completely different approach proved to be very satisfactory.

Dental grade plaster of paris can be obtained from drug stores for about fifty cents a pound. First attempts to use this material proved unsatisfactory because of its tendency to crack--either in the furnace or when the mold was withdrawn. However, because of its advantages of low cost and retaining accurate mold impressions, plaster of paris seemed to have the best potential of all the methods attempted to obtain satisfactory crucibles.

The humidity varies greatly with time in Louisiana. Thus a mixture of plaster of paris made with identical amounts of water would yield crucibles of quite different structure at different times; some would break immediately when they were heated while others would not. Aging them for a day or a week seemed to make a difference sometimes but not at others.

Annealing the crucibles in an oven eliminated the tendency toward cracking when they were in the furnace. Later the oven annealing was satisfactorily replaced by preheating in the vertical furnace where the crystal was to be grown. A period of 30 minutes was allowed to bring the crucible from room temperature to 400 degrees centigrade. The temperature was then brought to 700 degrees C in no less than 15 minutes. Plaster of paris crucibles seem to withstand 700 or 800 degree temperatures satisfactorily if they are brought slowly through the first 400 degree interval.

The second big problem to be solved was the breaking of the crucible when the molding rod was withdrawn. The molding rod was 1/8 inch diameter, making it just slightly larger than the inside diameter of the Pyrex tubing used to make the polycrystalline zinc slugs. Lengths up to several feet long of good quality machinable steel rods called "drill stock" can be purchased in various small diameters from hardware stores. The drill stock selected should be slightly larger than the inside diameter of the glass tubing used to make the slugs so that the slugs will then slip easily into the crucible. The hole in the crucible, of course, is made by pouring plaster of paris around the drill stock.

The drill stock was cut to convenient lengths of about 4 inches and a point having included angles of from 30 degrees to 90 degrees was then accurately machined on the end of each piece.

The nonpointed end of the rod was then inserted into a short piece of 3/8 inch outside diameter rubber tubing which served as a sort of handle. The drill stock molds are visible in the foreground of Plate I.

The problem of the plaster of paris cracking when the rod was withdrawn was solved by melting a small amount of paraffin in a beaker of hot water. The melted paraffin formed a thin film on the surface of the water and into this the pointed rod was inserted and withdrawn. With a little practice a very thin, uniform coating of paraffin could be made to adhere to the rod. Care should be taken that the paraffin does not form a "blob" on the point of the drill stock rod because this will be reproduced in the plaster of paris.

The rubber tubing and included rod were now wrapped in a piece of paper in such a manner that the paper formed a hollow cylinder of the same inside diameter as the outside diameter of the rubber tubing. This diameter becomes the outside diameter of the crucible and can be adjusted by the thickness of the rubber tubing used. Although various diameters were used, the one most consistently producing single crystals was of 3/8 inch diameter.

The pointed rod will now occupy a position in the center of the hollow paper cylinder. The paper should extend an inch or more beyond the point of the rod. This portion becomes the bottom of the crucible and is mounted in the sleeve of the aluminum rod floating on the polystyrene piston.

A small amount of plaster of paris is mixed to the consistency of thick cream. It was found that excess water at this stage was not critical as it simply ran out of the mold. It was better to have the mixture too thin than too thick. This mixture was then poured into the paper cylinder containing the pointed rod.

The entire assembly is left undisturbed in a vertical position until the plaster of paris is thoroughly hardened. Depending on temperature and humidity this is usually a matter of an hour or so. The paper can then be carefully removed. Overnight curing is recommended at this point. Then the plaster of paris crucible is heated gently over a cool Bunsen burner flame. After a few minutes the heat melts the paraffin on the rod and the rod can be withdrawn without breaking the crucible.

One now has a crucible with accurately cylindrical walls, and a point of the desired angle. The crucible must be handled gently as it breaks easily.

Having prepared the polycrystalline zinc slug by the method previously outlined, the slug is now inserted carefully into the crucible. Filing the end of the slug that is inserted into the crucible helps prevent scoring the walls of the crucible and knocking tiny bits of the crucible into the pointed cavity.

The crucible is now inserted into the sleeve of the aluminum rod and water is poured into the tin can cylinder so that the piston floats up and raises the crucible up into the furnace. The upper portion of the aluminum rod was held in line vertically by passing it through a hole in a clamp of the type used with optics equipment.

Before the furnace is heated the system can be checked from above to make sure that the crucible and its supporting rod are aligned vertically and that the crucible is approximately centered in the furnace.

It should be pointed out that the thin walls of the aluminum rod will melt if they are brought up into the furnace. The crucible should only be far enough into the furnace to assure that all of the contained zinc slug will be above the steel temperature gradient plate. A portion of firebrick is then placed on top of the furnace as a cover. It is important to cover the furnace as this reduces by a considerable factor the amount of current needed to obtain a given temperature.

The temperature is now brought slowly (30 minutes) to 400 degrees C to "cure" the crucible. It can then be raised more rapidly (15 minutes) to 700 degrees C. The pinch clamp on the drain hose is then removed and if the proper orifice has been chosen for the glass drain tube control the crucible should just pass through the hole in the steel plate in about 90 minutes. Two hours or even three would be better if vibrations could be controlled. However, in our situation it was found that the advantage gained by the slower growth rate was offset by the increased likelihood of vibration during the longer time.

As described elsewhere, the polycrystalline zinc melts, then the crucible containing the point of the melt emerges from the furnace and a seed solidifies. One orientation grows at the expense of all the others and if all other factors have been carefully controlled a single crystal is quite probable.

The plaster of paris crucible can be tapped lightly or even snapped with the fingers to remove the crystal. The zinc will feel quite limber if it is a single crystal. A portion of the end opposite the point can be broken and if it is single it will cleave quite easily into a smooth shiny surface.

We have not yet found a correlation between the cleavage angle and the angle of the crucible point. Table III shows a tabulation of cleavage angle for given crucible angles. The cleavage angle is defined as the angle between the axis of the cylinder and the cleavage plane. Because of lack of a precision goniometer, cleavage angles are expressed to the nearest degree. The crucible angle is defined as the angle between the vertical and the slanted side. The factors involved in such a correlation study are obviously another practical extension of this type research problem. Additional extensions are discussed in Chapter Four.

TABLE III

CRUCIBLE ANGLE AND ANGLE OF CLEAVAGE PLANE

Crucible Angle in Degrees	Cleavage Angle in Degrees
15	40
15	63
15	31
15	54
15	60
30	40
30	63
30	39
30	72
30	45
30	35
30	56
45	42
45	50
45	53
45	53

CHAPTER FOUR

HEURISTIC CONSIDERATIONS; SUGGESTIONS FOR FURTHER INVESTIGATION

Metallic single crystals have been produced before. Seybolt and Burke (20) point out on page 316, that single crystals of bismuth, for example, have been produced by such a relatively simple technique as carefully melting a portion of bismuth on a microscope slide and (just as carefully) cooling it. However, one of the principal reasons for producing single crystals of a substance is to make available extremely pure samples for testing. A single crystal that has been grown on a microscope slide is unsatisfactory for some tests.

Such physical properties as electrical conductivity, magnetic characteristics and mechanical behavior are of considerable importance in furthering the theory of the solid state. Brooks (24) states, page 19, "solid state theory has been most successful when theory and experiment have gone hand in hand."

A study of the literature indicates that mechanical properties of metallic solids could profitably be investigated. Savitsky (25) feels "...the study of mechanical properties has great practical and scientific value and is being applied with increasing intensity in research on solids, mainly metals and alloys."

Ansell (26) on page 51 states "...of prime interest to materials scientists...is the response of metals to an applied stress."

Beavers and Honeycombe (27) on page 475 make the comment, "Many casual observations on the ductile fracture of single crystals have been made from time to time, but although cleavage fracture has received much attention in recent years, little systematic study has been made of ductile fracture."

The theory remains open to improvement. In fact, according to Parker (28) on page 57, "...no theory adequately explains the complex behavior of metal under stress."

Zener (29) indicates, "It seems likely that the important developments of the next generation will come about by the application of the principles of physics, chemistry, and mathematics to the study of structure, properties, and behavior of metals." Such statements as these are to be considered when one is seeking suitable undergraduate research projects. Investigations of mechanical properties offer certain experimental advantages in that they do not require expensive items of equipment. Furthermore, the apparatus entailed in mechanical properties investigations lends itself well to student design and construction. However, most mechanical tests (for example creep measurements, fatigue, and fracture investigations) would be facilitated by uniform, cylindrical samples. For that reason it was decided to develop a method for producing such samples. Moreover, there are certain definite advantages to be gained by producing samples of a size suitable for microtesting. As Savitsky (25) states, page 38, "...use of small samples is especially advantageous...in experiments on single crystals..."

The literature indicated that the state of the science as late as 1959 was such that even the fundamental definitions remained to be established. According to Keyser (30), page 93, "Universal agreement has not been reached on the use of the terms _fatigue strength_, _fatigue limit_, _endurance strength_, and _endurance limit_." While such a situation presents some confusion and frustration it also affords opportunity. Creep measurements in particular seem to provide a worthwhile area for future experiments with single zinc crystals. Dunkle and Weiman (31) selected zinc because, "Zinc was chosen for these experiments because it is a hexagonal metal having a unique slip system which creeps readily at room temperature." The fact that creep experiments with zinc can be conducted at room temperature could be significant to the small college situation. Table IV shows creep temperatures for some other common metals (30).

As another possibility for utilization of the cylindrical type of zinc single crystals described in Chapter Three, slip itself could be investigated. "Slip planes of metals crystallizing in the body-centered-cubic lattice have yet to be determined...Slip is a complicated physical process; its mechanism is still not clear...Research on plastic deformation...has only begun" (25). After investigations with zinc, a body-centered-cubic type of crystal could be explored.

One could, from a background of single crystal growth, pursue a study of the effects of dislocations on mechanical properties. Read (32) suggests, "Other properties (such as mechanical strength) are highly sensitive to crystal perfection; even one imperfection of the proper type could reduce the strength by orders of magnitude. Internal friction and creep rate are other structure-sensitive properties."

The dislocations can be observed by a technique known as "etching" which is certainly not outside the capacity of the small college budget.

TABLE IV

"TEMPERATURES ABOVE WHICH CREEP BECOMES OF PRACTICAL CONCERN FOR SOME COMMON METALS"

Alloys	"Creep Temperature"	Approximate Melting Range
Lead, tin, zinc	Room temperature	350-800°F (175-420°C)
Aluminum	200-400°F (95-205°C)	900-1200°F (480-650°C)
Brass and Bronze	300-400°F (150-205°C)	1500-1950°F (815-1065°C)
Carbon Steels	650°F (345°C)	2400-2750°F (1315-1510°C)

On page 115 of the work edited by Newkirk and Werwick (33) it is stated, "The formation of etch pits at dislocation sites in crystals is now a well known and much used experimental fact. Although the fundamentals of etching phenomena are little understood, preferential etching at dislocation sites is presumably associated with the excess energy (core energy and elastic strain energy) localized there."

What seemed to be an experimental difficulty in our first work with the production of zinc single crystals by the zone melting furnace might present a possibility for future investigation. Some of the samples emerged from the zone melting treatment badly pitted as if they had been attacked by acid.

It was discovered that this effect occurred as a result of a trace of moisture being present in the Vycor tube that contained the carbon crucible supporting the zinc. Microscopic comparisons might be made between crystals etched by the usual technique and those pitted by reaction with water vapor at high temperatures. If the water reacts on a preferential basis the way the etching solution does, perhaps a study of such reactions might furnish additional information on surface energies.

Zinc has some particular advantages other than the characteristic that it creeps at room temperature. It is valuable for x-ray work in the event that a department has, or can arrange, access to x-ray apparatus. "These results on zinc...substantiate the view that, at least, some elements with intermediate or high atomic number can be favorable for detailed studies with... x-ray technique. The low penetration of x-rays in zinc permits good resolution of dislocations by allowing only a limited superposition of the many dislocations which occur in depth below the crystal surface" page 572, (33).

In the area of mechanical testing much remains to be accomplished even though it is a relatively old field when compared to solid state physics. "Although metal working was known in ancient times and has now reached enormous proportions, and although the processing of manufactured products is governed by means of mechanical tests, the theoretical principles of mechanical testing are still in the most elementary stages" (25).

It would seem therefore, that opportunity exists for the development of new testing devices or for the improvement of old ones. "Torsion is seldom used in mechanical testing of alloys...however it has certain advantages such as stability of shape of the tested sample, the possibility of precisely measuring the shear resistance, and so forth" (25).

The zinc single crystals in cylindrical form should also be convenient for investigating certain electrical characteristics such as conductivity, and the effect (if observable) of "loading" such a crystal mechanically. The literature indicates that changes in creep rate occur during electropolishing (34). These and other electrically related projects might be satisfactory extensions of the growth of zinc single crystals.

And one need not be restricted to zinc. The techniques and experience gained from the growth of one type of metallic single crystal should make possible a number of additional studies. Single metallic crystals of alpha brass might be utilized for a study of the "Bauschinger effect" mentioned by Seitz (35). According to Weimber (36) "The Bauschinger effect is the observed lowering of the yield point, or elastic limit, after previous plastic strain in the reverse direction...It is the opposite of work hardening..."

Finally, it should be pointed out that any effort to establish a worthwhile undergraduate research project <u>must</u> be accompanied by considerable library work. Such pursuits on the part of either the instructor or the student (hopefully <u>both</u>) will almost inevitably result in a plethora of interesting and intriguing avenues presenting themselves. Some of these, of course, might prove completely impractical for the small colleges, and in this respect as in so many others relating to research, the small college instructor has the disadvantage of not being able to consult at least one (and possibly several) experienced researchers within his own department. (One of the problems facing a small college has been identified as the "critical size" of staff required to keep a physics department operating successfully. According to Pake (2) and others, departments of only two or three staff members could anticipate serious difficulties regardless of ability and desire).

But if the small college does suffer from this standpoint, and it should probably be admitted that it does, it also has a very definite advantage over the large university in the selection of research areas. The staff in a small college, being relatively free from the so-called "publish or perish" pressure can pursue research simply for pleasure. If a problem appears interesting it can be attempted. If it proves unsatisfactory it can be dropped.

The following citations from the literature refer to some of these "intriguing avenues" that may or may not be practical for the small college, but that seemed appealing.

"In recent years scientists and engineers working in the fields of metallurgy, ceramics, and polymer chemistry have come to agree that there are many basic phenomena which are common to metals, ceramics, and plastic-type materials...The new field of Materials Science has thus been developed to promote the advancement of all three types of materials" (26).

In his article (page 7) entitled, "Dislocations in Ceramic and Metal Crystals," Gilman, in this same reference (26) states, "Although crystal dislocations were invented to explain the plastic behavior of metals and most of the early theory was developed with metal crystals in mind, it seems clear that the final stages of research and development of knowledge about dislocations will be concerned with their behavior in ceramic crystals."

"...there is not much difference in the static properties between metals and ceramics because these physical properties are comparable for them" page 72, (26).

On page 73, in comparing "the structures of two crystals after a certain amount of plastic bending followed by annealing. Again the gross features are much the same. In this case a zinc crystal (a) that has been bent and then annealed to polyonize it is compared with an aluminum oxide crystal (b) that has been bent and annealed. The polygon boundaries look much the same for the two substances" (26).

"Until recently...little systematic attention was paid to the properties, reactions and behavior of intermetallic compounds, per se... Research effort in this area was exceedingly small;...The studies of mechanical properties, deformation and fracture behavior...assume key roles in the current research activity on intermetallic compounds" (37).

"Rules for solid solution alloying of intermetallic compounds have been reviewed...Surprisingly there are few experimental studies of the effects of such alloying on mechanical properties" (37).

"Although a number of investigators have studied the electrical, thermal, and optical properties of titanium dioxide, little information regarding the plasticity of the material is available" (33).

"In the case of the samples which have twinned, it is believed that fracture occurs as a result of literally pulling the atomic planes apart; i.e., the theoretical strength has been reached...attempts have been made to determine the crystallographic orientation of the fracture but the results have been inconclusive...The exact details of the fracture vary somewhat from sample to sample..." (38).

According to Forrest (39) page 251, "attempts have been made to predict the creep occurring under fluctuating stresses on the simple assumption that for any instantaneous value of a varying stress, the creep rate will be the same as in a static creep test at that stress, at the same time from the beginning of the test. However, these attempts have not been sufficiently supported by experimental evidence to warrant their use in design."

The field of ceramics and cermets is of considerable interest because of the need for structural components with high melting points.

The tendency of ceramics to fracture in a brittle manner has led to research efforts to overcome this drawback. As Parker points out on page 52 in his article, "Status of Ductile Ceramic Research," in reference (24), "Prior to about 1956, little thought seemed to have been given to the possibility of developing a class of ductile refractory ceramic materials. Since then, however, the level of activity in this research area has continuously increased."

The study of many of the problems associated with analyzing the results of deformations in single crystals is facilitated by microphotography. Tolansky's (40) book devoted to this topic presents some excellent applications of an optical interferometer and metallurgical microscope to many crystalline studies. It would seem that some of the techniques and applications mentioned in this book would be quite appropriate for the small college research program.

More sophisticated instrumentation would, of course, increase the research opportunities. In this regard one might first want to consider obtaining a metallograph with accessories permitting high temperature observations. Table V gives some suppliers of this type of equipment. Prices are less than $6,000.00 from these vendors.

The next appropriate item of equipment might be an x-ray apparatus. Diffraction studies by means of x-rays have been one of the most significant contributors to the progress of solid state theory.

An electron microscope would greatly enhance the possibilities for research in the area that has been described here. In the work edited by Thomas and Washburn (41) many of the significant findings of transmission electron microscopy pertaining to crystal strength have been compiled.

TABLE V

SUPPLIERS OF METALLOGRAPHIC EQUIPMENT

Description	Vendor	Address
Dynazoom Metallograph	Bausch and Lomb, Inc.	17313 Bausch Street Rochester, New York 14602
Binocular Model BUX-11	Unitron Instrument Company	66 Needham Street Newton Highlands 61 Massachusetts
Panphot Camera Microscope	E. Leitz, Inc.	468 Park Avenue South New York, N. Y. 10016

But a number of very challenging opportunities for small college research projects can be undertaken just from the growth of cylindrical metallic single crystals; and with very modest expense.

A final comment regarding research projects and expense concerns the matter of library materials. Lack of research library facilities can be the most formidable obstacle with which the small college must cope; for it would seem that almost any research project worthy of the name would first require a literature study.

There are several very valuable sources of reference material available to the prospective researcher in the small college. Industrial firms, for example, are very generous in making current publications from their own research activities available. The Public Relations Department, United States Steel Corporation, 71 Broadway, New York 6, New York, mails out a very convenient form listing their publications. By merely marking the appropriate number and returning a postage paid card, bound reprints can be obtained. References (42) to (53) displayed in Table VI represent a very small sampling of the type of articles the author has obtained in this manner. These references, naturally, are primarily concerned with metals research. But they cover a surprising range of topics of possible interest to the small college investigator; and they are reprinted from nine different journals.

Other companies that handle equipment used primarily by research workers frequently publish a journal of their own or have lists of reprints available for the asking.

Still another source of reference material is the author of the particular article, himself. Reprints are in many ways the most convenient reference materials of all because they can be taken right into the laboratory and they can apply directly to the investigation being conducted. Practically every book and article will contain some type of bibliography. From this beginning, one can obtain names of people who are, or were, active in the field. The Directory of American Association of Physics Teachers, and similar listings of scientists (which are usually available in even small libraries) affords many current addresses. Frequently, the authors, if asked for a reprint in a particular area, will be kind enough to include other reprints of theirs in related areas.

References (54) to (60) displayed in Table VII represent some reprints obtained directly from authors.

The librarian represents another very important source of reference material. Librarians can obtain whole volumes of bound journals from other librarians on inter-library loan for a day or so.

Books, of course, are also available on loan from other libraries and are not subject to the limited time restrictions that are imposed on journal loans.

TABLE VI

REPRINTS OBTAINED FROM UNITED STATES STEEL

	Title	Author
1.	Survey of Various Special Tests Used to Determine Elastic, Plastic and Rupture Properties of Metals at Elevated Temperatures	F. Garafalo
2.	Photo-Emission From Metal Surfaces Measured With Gieger Counters	M. A. Conrad and S. Levy
3.	Some Elastic Properties of an Edge Dislocation Wall	James C. M. Li
4.	An X-ray Fluorescence Method of Analysis of Microsamples	B. G. Reisdorf
5.	A Direct Determination of the Anisotropy of the Surface Free Energy of Solid Gold, Silver, Copper, Nickel, and Alpha and Gamma Iron	B. E. Sundquist
6.	Planar Stress Field of a Dislocation in an Anisotropic Plate	Y. T. Chou
7.	The Effect of Metallic Impurities and Temperature on the Anisotropy of the Surface Free Energy of Solid Metals	B. E. Sundquist
8.	The Magnetic Aging of Low-Carbon Steels and Silicon Irons	W. C. Leslie and D. W. Stevens
9.	Principles of Stress Corrosion Cracking as Related to Steels	J. F. Bates and A. W. Loginow
10.	Effect of 500°C Aging on the Deformation Behavior of an Iron-Chromium Alloy	M. J. Marcinkowski R. M. Fisher and A. Szirmae
11.	A Study of the Magnetic Domain Configurations in Fe-Co Solid Solutions	M. J. Marcinkowski and R. M. Poliak
12.	The Effect of Crystallographic Orientation on the Oxidation of Tin	W. E. Boggs, R. H. Kachik and G. E. Pellissier

TABLE VII

REPRINTS OBTAINED FROM AUTHORS

	Title	Author
1.	The Apparatus and Technique for Growing Large Specimens of Single Crystal Zinc	C. A. Cinnamon
2.	The Thermal Resistivity and the Wiedemann-Franz Ratio of Single Crystal Zinc	C. A. Cinnamon
3.	Grain Boundary Sliding Versus Grain Boundary Migration in Creep	N. R. Adsit and J. O. Brittain
4.	Creep in Zinc Single Crystals at the Temperature of Liquid Nitrogen	H. P. Stüwe
5.	Theory of Creep Limited by Self-Diffusion	R. W. Christy
6.	Some Observations on Creep in Zinc Single Crystals	H. P. Stüwe
7.	Growth Conditions for Single and Optically Mosaic Crystals of Zinc	C. A. Cinnamon and A. B. Martin

CHAPTER FIVE

EDUCATIONAL ASPECTS OF RESEARCH TO THE SMALL COLLEGE

History may record that one of the most significant by-products of mankind's successful launching of artificial satellites was the effect it had upon science education. The efforts of the School Mathematics Study Group and the SMSG so-called "modern mathematics" that has come into the public schools during the years since 1957 are now well known. Other efforts such as the Chemical Bond Approach, the Chemistry Study Programs, and the Biological Sciences Curriculum Study (BSCS), have also been well recognized.

The corresponding work of the Physical Science Study Committee was organized in 1956 and introduced a radically new physics course into the secondary schools in 1957 (61). Approximately 75,000 students were registered for the PSSC physics course in 1961-1962 (62). The dramatic growth of enrollment in the PSSC course in secondary schools has caused some concern about the elementary college physics courses being offered. The question is whether they should be revised because of the more sophisticated nature of the entering freshmen after having taken the newer high school courses. According to some, the "enrollments in PSSC and SMSG courses are still growing rapidly, and we can soon count on a major fraction of students entering college having been taught these courses. The present slow rate of change in our programs <u>cannot</u> meet the need fast enough" (62).

Such concern for the situation as it exists in the state of Louisiana at present is apparently unwarranted. Table VIII shows a portion of the results of a survey made jointly by the author and Dr. T. Eugene Holtzclaw, Dean of the School of Education, Northeast Louisiana State College. PSSC physics courses are being offered in only 18 of the 238 schools responding. The information was obtained during the second semester, 1965. Although not shown in Table VIII, the distribution of PSSC physics courses with relation to population of the town indicates clearly that the larger population centers predominate in offering the PSSC program. In fact, four urban areas, Baton Rouge, New Orleans, Shreveport, and West Monroe, appear to be the only ones offering PSSC in Louisiana.

However, concern for the college physics curriculum has been based on other pressures than that of the PSSC high school physics course. During the past decade a number of meetings have occurred at which physicists discussed many of the problems to be faced, not in physics *per se* but in *physics education*. The purpose of this chapter is to review the various efforts made by organized groups of physicists toward curriculum improvement, and to include specific recommendations that justify the type of undergraduate research program presented in detail in this paper.

The Carleton Conference (63) was held in Northfield, Minnesota, at Carleton College, in September, 1956. It was the result of a previous conference on the Production of Physicists held at the Greenbrier Hotel, White Sulfur Springs, West Virginia, in 1955 and referred to since that time as the "Greenbrier Conference." Although the Carleton Conference restricted its efforts to the improvement of *introductory* physics courses, some points were established that appear repeatedly in physics curriculum studies since that time.

TABLE VIII

RESPONSES TO QUESTIONNAIRE ON PSSC PHYSICS COURSES IN LOUISIANA

Question	Number of Responses		
	Yes	No	No Response
1. Have you ever offered the PSSC physics course?	23	211	4
2. Did you offer the PSCC physics course this year (1964-1965)?	18	214	6
3. Do you plan to offer the PSSC physics course next year (1965-1966)?	25	195	18

For example, one of the major conclusions reached at the Carleton Conference (63) was that, "physics should be taught as a growing subject and the student should be given illustrations of problems on present frontiers." A properly selected research project can perhaps approach this goal with less contrivance or artificial "forcing" than can be done in any traditional course.

It was also pointed out (63) that physics affords the student an opportunity "to approach and solve new problems using verbal formulation, mathematical analysis, or experimental manipulation." Again, undergraduate research presents these opportunities perhaps better than could any single traditional course. Finally, the Carleton Conference, as have many conferences since, expressed the view that there is large room for improvement in the laboratory phase of physics instruction.

It is in this area, of course, that an experimental type research project offers the greatest pedagogical advantage.

In June 1957, at the University of Connecticut, Storrs, a Conference on Laboratory Instruction in General Physics, was held. Like the Carleton Conference, even though the discussion was aimed at general physics, the groundwork was established for many phases of undergraduate laboratory programs.

> "The study of physics must not be divorced from the phenomena ...The laboratory should definitely provide the student with an opportunity to know physics as a process of inquiry leading to theory, not as a mere accumulation of inert information...In the laboratory, the student should be a "physicist for a day." He should encounter the joys and sorrows of experimenting, elation and despair. He should come upon the unexpected, run up blind alleys, and work himself out of tight places" (64).

By its very nature an undergraduate research course presents the student with ample "blind alleys" and opportunity to meet the "unexpected." Unlike the formal laboratories associated with the traditional undergraduate program, the research project continues from one week to the next, or from one day to the next, depending on the student. Nor can he obtain from his student associates a complete "briefing" on the anticipated difficulties with a specific experiment and how to overcome them.

Perhaps the most significant argument in favor of an undergraduate research project was the statement (64) that, "there was almost unanimous agreement among the conferees that the laboratory should require more independent thinking and should serve more as an introduction to research than it has in the past." Considering that the conference was concerned with the general physics laboratory program, it seems safe to assume that approval would certainly have been given to advanced laboratory programs being conducted on a research-type approach. This hypothesis seems verified in light of their recommendation that physics departments be encouraged to experiment with new laboratory practices (64). The final quotation to be taken from the work of the Laboratory Conference (64) seems to endorse the pedagogical advantages of a research type laboratory approach particularly well: "...most students accomplish most when they are stimulated by being faced with the need of determining something unknown to them, in the sense that it is a quantity or result that cannot be found in standard tables." One has only to compare the "enthusiasm level" of students performing Millikan's oil drop experiment or Thomson's E/M experiment to that of students attempting to develop a better method for the growth of metallic single crystals, to be convinced of the truth of the committee's statement.

Twenty-seven participants attended the Carleton Conference. The Conference on Laboratory Instruction was also rather small. It became apparent that the educational goals of physicists might be achieved more quickly if there were some type of large scale coordination. Consequently, a representative group of physicists all of whom were interested in college teaching held a series of three meetings in 1959 and 1960. The meetings were supported by the National Science Foundation and sponsored by the American Association of Physics Teachers (65). "The objectives of these meetings were to analyze the aims and substance of college physics courses and the resources for improving such courses, and to formulate plans for the improvement of the teaching of physics at the college level throughout the country."

This group (65) recommended, concerning curricula and course content that the "potentialities of new and unconventional structure should not be ignored." Moreover, they felt that additional study needed to be given to the problem of effective use of the laboratory (65). This would seem to lend support to the attempt reported in this thesis of introducing an undergraduate research course into the curriculum with one goal being the improvement of laboratory instruction.

Perhaps one of the most significant recommendations to come from the Conference on the Improvement of College Physics Courses was that there be established a Commission for the Improvement of Instruction in College Physics. Such a Commission was created in 1960 by the American Association of Physics Teachers. It was called, the Commission on College Physics (62).

The Commission with the cooperation of the National Science Foundation and the University of Denver arranged a conference on the subject of curricula for physics majors; to be attended by college physics instructors from institutions not offering the doctorate in physics. Northeast Louisiana State College sent a representative from its physics department.

The Denver Conference demonstrated that there is wide variation among the curricula required by small colleges for their physics majors (66). In addition, the small colleges were experiencing difficulty in establishing and maintaining their graduates in graduate institutions.

This point probably received increased emphasis because it was the central theme of an article by George Pake (2) which was distributed at the conference. The article was entitled, "Can Four-Year Colleges Prepare Physics Majors for Graduate Work in Physics?"

Pake was raising a very significant question for those physicists who were responsible for college physics programs. Pake listed five reasons why he felt that students from the colleges tended not to do as well in graduate work as students who had taken their undergraduate work at a university. (He defined "colleges" as four-year liberal arts colleges with no Ph.D. program, and "universities" as those institutions with both undergraduate and Ph.D. programs in physics.) Pake's fourth listed reason was: "(4) No research (or at least very little.)" Pake elaborated on the five topics and his comments on items three and four are included together here as they were in his paper.

> "Causes 3 and 4, equipment shortage and lack of research, mean that the student sees little of the paraphernalia of present-day physics. He obtains an incomplete picture of what physics is, and he is overwhelmed when thrust into the large graduate institution."

Here then is a pedagogical advantage of undergraduate research that has not previously been emphasized; one that might be considered somewhat more subtle than the others mentioned. It has been the author's experience that almost all undergraduate students when first attempting research have one approach in common. They flounder.

They are not "overwhelmed" but they definitely flounder. One has only to imagine them in a university environment, pressured by course work, competing with students who know the teachers, know the complex enrollment routine, and are familiar with the undergraduate laboratories they may be expected to conduct; one has only to think of those potentialities to get a vivid picture of college students being "overwhelmed" in the large graduate institutions. Certainly the "toughening" he undergoes by participating in an undergraduate research program should be of value to the student.

With encouragement and guidance, moreover, the floundering gradually gives way to more purposeful activity. The trips into the professor's office to seek assistance become less frequent; and absolute insecurity is replaced by a modicum of confidence and initiative. It is at this point that enthusiasm begins to appear; enthusiasm that is almost impossible for the instructor not to share.

Which introduces another pedagogical advantage of undergraduate research--its effect on the staff at a small college. According to Pake (2) page 683, the "chief deterrent to the acceptance of teaching positions in liberal arts colleges by new Ph.D. graduates is the heavy teaching load and the absence of research opportunity."

Pake's comment is strengthened in an article by Walter H. Kruschwitz (67) concerning physics research in non-Ph.D. granting institutions. "Approximately 38% of the schools have used the possibility of doing research as an enticement in hiring staff members...There seems to be somewhat of a trend to use research as a bait to entice competent young Ph.D's into the teaching profession."

Although he feels that the colleges face some severe problems in preparing physics majors for graduate work, Pake (2) lists (page 684) three proposals as tentative solutions. It is interesting to note that all three entail research in the college.

"(I.) NSF support of research in the colleges with separate funds not competed for by the universities.

"(II.) Initiation of a Masters Degree program in more of the larger colleges.

"(III.) Organization of the small department research group about one field of present-day physics."

Herbert Priestley (68) Chairman of the Physics Department at Knox College, Galesburg, Illinois, agrees with Pake up to a point that there are advantages in: "...establishing a modest research program in the college department, with obvious benefits to professional competence of the staff, recruitment of additional faculty, and graduate orientation of students." However, Priestley goes on to point out that creative teaching must receive equal status with creative research.

The Denver Conference supported the report of the Carleton Conference. In addition, the Denver Conference (66) went on record (page 161) with the strongest recommendation up to that time for <u>undergraduate research</u>:

"All colleges and universities should at least consider a program of research and independent study for the undergraduate physics major and the superior students should be encouraged to participate in these activities." Moreover, at the Denver Conference a paper entitled, "Independent Study and Research in the Undergraduate Physics Curriculum," was presented by Harold K. Schilling (69). In this paper the plea was made that physicists themselves should recognize the importance of undergraduate research to the training of physics majors and should demand its recognition by administrators and public. Schilling (69) listed specific advantages of such research as: (1) permitting an extension of this type of graduate activity down into the undergraduate curriculum in the same manner that quantum mechanics and relativity have come into the undergraduate curriculum--with resultant intellectual challenge to the better students; (2) furnishing a more accurate method of predicting what success students are likely to have in graduate school; (3) permitting students to find out if research is <u>not</u> for them. His final point is best stated in Schilling's (69) own words: "Having visited many colleges, I find the observation inescapable that, as a group, those in which research has become traditional have an atmosphere of vitality in scholarship, an air of intellectual progress, and a record of turning out superior students, that are rarely found in others. While I admit seeing not a few university physics departments where utter preoccupation with research seems to have reacted unfavorably on the quality of teaching, I have never seen such a situation in a college department which has included research in its undergraduate curricular offerings."

Certainly one of the most eloquent arguments from the literature, supporting undergraduate research is that given by Schilling (69) at the Denver Conference.

> "Since the exploratory and creative urge toward research is indispensable to the growth and well-being of physics, it is imperative that physics education nurture it even at the undergraduate level. To put it another way, if the purpose of the physics curriculum is to introduce beginners to the work, thought, and spirit of the physics community, it must make explicit provision for research experience..."

A total of 178 physics teachers representing 174 institutions attended the Denver Conference (62). Immediately following the Denver Conference, two conferences were set up at the University of Michigan with the support of the National Science Foundation. These became known as the First and Second Ann Arbor Conferences.

The first Ann Arbor Conference was held in May, 1962, and attended by 51 faculty members representing 47 institutions. The Ann Arbor Conferences were to include personnel from Ph.D. granting institutions and 46 of the 47 institutions represented at the First Ann Arbor Conference did offer the Ph.D. degree.

"At both the Denver and Ann Arbor Conferences, there was general agreement that the demonstration lecture and the laboratory are essential if the student is to be kept aware of the fact that all of physics is intimately tied to phenomena. There was also agreement that the laboratory needs improvement more than does any other portion of physics teaching" (62).

"Physics departments are rated by most physicists in terms of their research productivity, the quality of their graduate programs, and their success in producing undergraduate majors, with the weighting favoring the first of these" (62).

The Second Ann Arbor Conference held in November, 1962, had 74 participants most of whom had attended either the Denver Conference or the First Ann Arbor Conference. Representation was about equally divided between Ph.D. granting and non-Ph.D. granting institutions (70).

A person searching the literature for reports of curriculum studies in physics will probably become impressed with two dominant themes that recur repeatedly in the recommendations of physics committees:

(1) There is no one "perfect" course, series of courses, or curriculum that can do all that needs to be done in physics.

(2) Educational experiments (presumably such as the type depicted in this thesis) are encouraged.

As the Second Ann Arbor Conference (70) stated, "...the conference gives whole hearted support to any and all carefully designed pedagogic experiments."

The specific recommendations of the Second Ann Arbor Conference (70) that tend to support an undergraduate research program are associated with the desire to keep a strong laboratory program in all physics curricula and to enable physics graduate students to pursue graduate level research:

"...every physics major should acquire competence in approaching a new topic phenomenologically, as well as in terms of theory."

"...every beginning graduate student should be ready to enter a graduate laboratory course,...or to begin graduate level experimental research."

"...a laboratory can play a unique role in introducing the student to experimental research and in helping him to recognize the part that it plays in the development of physics."

It is obvious that many conferences have been held during the past few years, in which highly interested physicists have cooperated in the attempt to improve the teaching of physics. However, as Karplus (71) points out in his Science Curriculum Improvement Study, "interest and good will of gifted individuals are not enough to mount an attack on the complex problems of modern education; the current ferment in science education is in part also due to the availability of substantial funds for the support of cohesive research efforts." In this regard, most of the conferences reported here have received financial support from the National Science Foundation.

In tracing the various recommendations concerning curriculum improvement for undergraduate physics, a deliberate effort has been made to include those recommendations which can be interpreted as lending support to the inclusion of some type of undergraduate research attempts by the small colleges. For purposes of summary and at the risk of being much too succinct, the events will be listed here sequentially in chronological order.

	Date	Group	Recommendation and/or Action
1.	1955	Greenbrier Conference on Production of Physicists	Recommended another conference to discuss the introductory college physics courses because of their effect on the production of physicists.
2.	1956	Carleton Conference	Recommended physics be taught as a growing subject...student should be given illustrations of present frontiers. Laboratory instruction needs improving.
3.	1956	Physical Science Study Committee (PSSC)	Introduced new high school physics course (which was of such high quality as to require continued examination of introductory college physics courses).
4.	1957	Storrs Conference on Laboratory Instruction in General Physics	Student should experience joys and despairs of experimenting. Laboratory should serve as an introduction to research. Departments should experiment with new laboratory practices. Students are stimulated by the unknown.
5.	1959 1960	Conferences on Improvement of College Physics Courses	Established Commission for Improvement of Instruction in College Physics. Recommended additional study on effective use of laboratory. Planned a Conference at Denver.
6.	1961	Denver Conference on Curricula For Undergraduate Majors in Physics	Pake's paper brought out problems of small colleges caused by lack of research. Pake recommended research in college as an aid to student when he attends graduate school; also as an aid in obtaining small college staff. Conference recommends all colleges and universities consider a program of undergraduate research. Schilling's paper recommended that physicists themselves demand undergraduate research recognition. Listed specific advantages to the small college of undergraduate research in the curriculum.

7.	1962	First Ann Arbor Conference	Laboratory needs improving more than does any other portion of physics teaching.
8.	1962	Second Ann Arbor Conference	Supports all carefully designed pedagogic experiments. Encouraged strong, dynamic laboratory. Decided there is no single "perfect" physics curriculum which can be recommended for all institutions.

The recommendations by the various conferences have, in recent years, been augmented by reports of educational experiments from individuals or groups of individuals. Douglass and Strandberg (72) present an excellent report of one such experiment that was attempted at Massachusetts Institute of Technology. In addition to confirming the desirability of research opportunities for physics students prior to their graduate school days, it is interesting to note that physics personnel in an institution of such scientific stature as MIT recognize the difficulties of producing innovations in teaching methods.

"It is not generally recognized--none the less it is true--that innovations in teaching methods require just as much work and come into being with as great difficulty as discoveries and innovations in fundamental research" (72).

In their report (page 709) some very strong recommendations are made for undergraduate research. "...is it not possible to shorten the length of time before which the student comes in contact with professional physicists and gets a glimmering of what research is?... What is needed is a system that allows the faculty member to come in contact nontrivially with the student in a research situation..."

After describing the educational experiment, which consisted of having students interact in a series of research situations at MIT supervised by various members of the staff who were presently engaged in those specific research endeavors, Douglass and Strandberg (72) stated: "In addition, during this experiment, the deficiencies of physics education at every stage were made very evident to us. We have attempted to point this out in our discussion. We would like to conclude with a muted plea for more research at every level of the teaching of physics."

From the references cited, the following major findings and conclusions can be extracted:

1. Physicists have become quite concerned about the curriculum for the undergraduate physics major.
2. One of the areas that is most in need of pedagogical improvement is the laboratory.
3. There is no universal "cure-all" curriculum.
4. Undergraduate research programs can be of great benefit to a college physics department by:
    a. Acquainting students with the phenomenological aspects of current physics.
    b. Impressing upon students the dynamic aspects of physics.
    c. Acquainting students with more sophisticated experimental apparatus and techniques than is ordinarily possible in the traditional undergraduate laboratories.
    d. Attracting more Ph.D. level staff members.
    e. Better preparing physics majors for their future graduate school experiences.

Moreover a "model" of undergraduate research can be established based on the criteria of: 1. Initial cost; 2. Continuing (or maintenance) expense; 3. Safety considerations; 4. Level of difficulty.

Such a model-building approach proves fruitful in selecting appropriate projects. In particular, growth of metallic single crystals meets the requirements of this model and can be recommended as a suitable undergraduate research project.

BIBLIOGRAPHY

1. AIP Educational Newsletter 2. New York: American Institute of Physics, 1959.

2. George Pake, Am. J. Phys. 29, 678-684 (1961).

3. H. K. Schilling, Am. J. Phys. 30, 198-199 (1962).

4. J. J. Gilman, The Art and Science of Growing Crystals. New York: John Wiley and Sons, Inc., 1963.

5. H. E. Buckley, Crystal Growth. New York: John Wiley and Sons, Inc., 1958.

6. P. W. Bridgman, Proc. Am. Acad. Arts Sci. 60, 303-383 (1925).

7. J. Czochralski, Z. physik. Chem. 92, 219-221 (1918).

8. C. A. Cinnamon, Rev. Sci. Instr. 5, 187-192 (1934).

9. P. Kapitza, Proc. Roy. Soc. (London) A119, 358-442 (1928).

10. G. W. Sears, Acta Met. 1, 457 (1959).

11. A. Verneuil, Compt. rend. 135, 791-794 (1902).

12. W. G. Pfann, J. Met. 4, 747 (1952).

13. W. D. Lawson and S. Nielsen, Preparation of Single Crystals. London: Butterworths Scientific Publications, 1958.

14. D. T. J. Hurle, Progress in Materials Science 10. New York: Pergamon Press, 1962.

15. Arthur M. Shrager, Elementary Metallurgy and Metallography. 2d ed. New York: Dover Publications, Inc., 1961.

16. Leonid V. Azaroff, Introduction to Solids. New York: McGraw-Hill Book Company, Inc., 1960.

17. Charles Kittel, Introduction to Solid State Physics. 2d ed. New York: John Wiley and Sons, Inc., 1960.

18. J. M. Ziman, Principles of the Theory of Solids. Cambridge: Cambridge University Press, 1964.

19. William G. Pfann, Zone Melting. New York: John Wiley and Sons, Inc., 1959.

20. A. U. Seybolt, and J. E. Burke, Procedures in Experimental Metallurgy. New York: John Wiley and Sons, Inc., 1953.

21. D. C. Stockbarger, Rev. Sci. Instr. 7, 133 (1936).

22. Crystal Growth. Discussions of the Faraday Society. London: Butterworths Scientific Publications, 1959.

23. Growth and Perfection of Crystals. Edited by R. H. Doremus, B. W. Roberts, and David Turnbull. New York: John Wiley and Sons, Inc., 1958.

24. Harvey Brooks, Properties of Crystalline Solids. Philadelphia: American Society for Testing Materials, 1961.

25. E. M. Savitsky, The Influence of Temperature on the Mechanical Properties of Metals and Alloys. Stanford: Stanford University Press, 1961.

26. Fundamental Phenomena in the Material Sciences. Sintering and Plastic Deformation. 1. Edited by L. J. Bonis and H. H. Hausner. New York: Plenum Press, 1964.

27. Fracture. Edited by B. L. Averbach, et. al. New York: John Wiley and Sons, Inc., 1959.

28. Earl R. Parker, Brittle Behavior of Engineering Structures. New York: John Wiley and Sons, Inc., 1957.

29. Clarence Zener, Elasticity and Anelasticity of Metals. Chicago: The University of Chicago Press, 1960.

30. Carl A. Keyser, Basic Engineering Metallurgy. 2d ed. Englewood Cliffs: Prentice-Hall, Inc., 1959.

31. F. Dunkle and A. L. Weiman, J. Appl. Phys. 24, 283 (1953).

32. W. T. Read, Jr., Dislocations in Crystals. New York: McGraw-Hill Book Company, Inc., 1953.

33. Direct Observations of Imperfections in Crystals. Edited by J. B. Newkirk and J. H. Wernick. New York: Interscience Publishers, 1962.

34. F. D. Coffin and S. L. Simon, J. Appl. Phys. 24, 1333 (1953).

35. Frederick Seitz, Physics of Metals. New York: McGraw-Hill Book Company, Inc., 1943.

36. Elliot H. Weinberg, J. Appl. Phys. 24, 740 (1953).

37. Mechanical Properties of Intermetallic Compounds. Edited by J. H. Westbrook. New York: John Wiley and Sons, Inc., 1960.

38. Dislocations and Mechanical Properties of Crystals. Edited by J. C. Fisher, et. al. New York: John Wiley and Sons, Inc., 1957.

39. P. G. Forrest, Fatigue of Metals. Oxford: Pergamon Press, 1962.

40. S. Tolansky, Surface Microtopography. New York: Interscience Publishers, Inc., 1960.

41. Electron Microscopy and Strength of Crystals. Edited by Gareth Thomas and Jack Washburn. New York: Interscience Publishers, 1963.

42. F. Garofalo, J. Basic Eng., 867 (1960).

43. M. A. Conrad and S. Levy, Nature 189, 887 (1961).

44. James C. M. Li, Acta Met. 8, 563 (1960).

45. B. G. Reisdorf, Sci. and Tech. 8, 163 (1961).

46. B. E. Sundquist, Acta Met. 12, 67 (1964).

47. Y. T. Chou, J. Appl. Phys. 34, 3608 (1963).

48. B. E. Sundquist, Acta Met. 12, 585 (1964).

49. W. C. Leslie and D. W. Stevens, ASM Trans. 57, 261 (1964).

50. J. F. Bates and A. W. Loginow, Corrosion 20, 189 (1964).

51. M. J. Marcinkowski, R. M. Fisher, and A. Szirmae, Trans. Met. Soc. AIME 230, 676 (1964).

52. M. J. Marcinkowski and R. M. Poliak, Acta Met. 12, 179 (1964).

53. W. E. Boggs, R. H. Kachik, and G. E. Pellissier, J. Electrochem. Soc. 111, 636 (1964).

54. C. A. Cinnamon, Rev. Sci. Instr. 5, 187 (1933).

55. C. A. Cinnamon, Phys. Rev. 46, 216 (1934).

56. N. R. Adsit and J. O. Brittain, Trans. Met. Soc. AIME218, 765 (1960).

57. H. P. Stuwe, J. Appl. Phys. 30, 450 (1959).

58. R. W. Christy, J. Appl. Phys. 30, 760 (1959).

59. H. P. Stuwe, J. Appl. Phys. 29, 566 (1958).

60. C. A. Cinnamon and Albert B. Martin, J. Appl. Phys. 11, 487 (1940).

61. "Physical Science Study Committee. A Planning Conference Report," Phys. Today 10, 28 (1957).

62. "Progress Report of the Commission on College Physics," Am. J. Phys. 30, 682 (1962).

63. "Improving the Quality and Effectiveness of Introductory Physics Courses: Report of a Conference Sponsored by the American Association of Physics Teachers," Am. J. Phys. 25, 417 (1957).

64. "Laboratory Instruction in General College Physics: Report of the Committee on Conclusions of the Conference on Laboratory Instruction in General Physics," Am. J. Phys. 25, 436 (1957).

65. "Report of Conference on the Improvement of College Physics Courses," Am. J. Phys. 28, 568 (1960).

66. "Report of the Denver Conference on Curricula For Undergraduate Majors in Physics," Am. J. Phys. 30, 153 (1962).

67. Walter H. Kruschwitz, Am. J. Phys. 30, 749 (1962).

68. Herbert Priestley, Am. J. Phys. 30, 584 (1962).

69. Harold K. Schilling, Am. J. Phys. 30, 191 (1962).

70. "Recommendations of the Second Ann Arbor Conference on Undergraduate Curricula For Physics Majors," Am. J. Phys. 31, 328 (1963).

71. Robert Karplus, J. Research in Sci. Teaching 2, 293 (1964).

72. D. H. Douglass, Jr., and M. W. P. Strandberg, Am. J. Phys. 31, 708 (1963).

73. Handbook of Research on Teaching. Edited by N. L. Gage. Chicago: Rand McNally and Company, 1963.

74. M. V. Klassen-Neklyudova, Mechanical Twinning of Crystals. New York: Consultants Bureau, 1964.

75. A. H. Cottrell, Dislocations and Plastic Flow in Crystals. Oxford: Clarendon Press, 1958.

76. Imperfections in Nearly Perfect Crystals. Edited by W. Shockley et. al. New York: John Wiley and Sons, Inc., 1959.

77. A. Rotherham, Creep of Metals. New York: Reinhold Publishing Company, 1951.

78. A. H. Sully, _Metallic Creep and Creep Resistant Alloys_. London: Butterworths Scientific Publications, 1949.

79. J. C. Jaeger, _Elasticity, Fracture and Flow_. London: Methuen and Co., Ltd., 1956.

80. John R. Low, _Fracture of Metals_. Oxford: Pergamon Press, 1963.

81. Gregory H. Wannier, _Elements of Solid State Theory_. Cambridge: Cambridge University Press, 1960.

82. Paul G. Shewmon, _Diffusion in Solids_. New York: McGraw-Hill Book Company, 1963.

83. T. S. Hutchison and D. C. Baird, _The Physics of Engineering Solids_. New York: John Wiley and Sons, Inc., 1963.

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