DEVELOPMENT OF A GRADUATE AND RESEARCH PROGRAM IN FLUID MECHANICS

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As many of those hearing this paper are aware, fluid mechanics as used by the Civil Engineer has had an evolution from hydraulic engineering; which is a science largely of empirical coefficients, tables, and charts, to solve specific problems of the flow of water. There were many conflicting items of information regarding hydraulic design criteria because of the very limited knowledge of the fundamental principles of fluid motion involved.

Gradually there has been an increase in the understanding of the fundamental principles governing the behavior of fluids and the extension of these principles from one fluid to another. As far as the Civil Engineer is concerned, the two most important fluids with which he is concerned are air and water; in either a pure or polluted state. Consequently, it is necessary for him to study how the principles of fluid mechanics which have application to all fluids can be brought to bear on understanding and predicting the mechanics of flow of air and water. Using this modern or fluid mechanics approach, the Civil Engineer now has access to a wide and significant range of application of the variables involved which was not previously available from any of the empirical formula of hydraulics.

Not only have great strides been made in scientific basis of fluid mechanics in that it has widespread application for all types of gases and liquids, but research and development are carrying this knowledge to a continually higher level of sophistication with respect to mathematics and basic physical principles.

This paper is intended to discuss the philosophy behind the development of a broad graduate program in the field of fluid mechanics for civil engineers. It is built around the basic concept of the hydrologic cycle and the various steps involved in that process.

Also assumed in this paper is that a balance will be developed and maintained among sponsored research and institutional research, and graduate faculty and graduate students. That a balance is required in the relative financial dependence

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of a program on sponsored research support and institutional research support is emphasized by the following quote from a report entitled "Sponsored Research Policy of Colleges and Universities" (1):

> The Committee recognizes many advantages which sponsored research has provided. It has expanded the volume of research in the colleges and universities. It has made a large contribution toward the advanced education of students, particularly in science. Many of our graduate schools could not have maintained their current enrollment and output had not sponsored research increased their capacities and provided employment opportunities for able but financially needy potential graduate students. In addition, sponsored research has in many instances improved the quality of advanced education by providing large-scale equipment otherwise not available to the institution. It has increased the scientific productivity of our leading scholars by furnishing them with academic assistance and equipment. Sponsored research has provided enlarged thesis opportunities, which have given new dimensions to graduate training. The larger-scale projects afforded by government have enabled young men and women to acquire research techniques which can be learned only by participation in organized team research. The result is that our institutions are turning our qualified research men and women who are more immediately useful to industry and to the government research laboratories than they would have been under older training methods.
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> Despite these obvious advantages of sponsored research, colleges and universities must recognize its hazards. They have a heavy obligation to minimize these hazards, whether the research is supported by government, industry, or foundations. Among the more important are the following:
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> a) Such research may seem so attractive financially as dangerously to divert the scholars in our universities from research which extends the boundaries of knowledge and to bend their interest too much toward matters of immediacy, thus drying up the principal wellspring of fundamental knowledge.
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> b) The attractiveness of sponsored research may divert an improper amount of attention and interest from the academic program, thereby affecting the quality of our education.
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> c) Such research may emphasize certain fields of knowledge at the expense of others, with the result that important areas of scholarship and research may be neglected simply because funds are available more readily in those fields in which sponsors are interested--a danger which becomes more serious when institutions use a substantial part of their own unrestricted funds in the sharing of the direct or indirect costs of sponsored project research.

d) The control and accounting procedures required by the government may subtly change the character of educational institutions, thereby reducing the value of their special type of environment for creative work, which includes independence of the investigator, relative simplicity in management, and sympathetic understanding between administrative and academic personnel.

e) Cancellation of contracts may leave the institution with long-term commitments to the graduate student program, to the staff, and for facilities, that may be financially embarrassing or disastrous.

The problems evident from the above quote are discussed in further detail in an excellent book by Charles V. Kidd, American Universities and Federal Research (2) issued in 1959, five years after the above report. It is worthy of noting that most of the problems remain the same even after five years of elapsed time.

Objectives of a Program

In order for any extensive and progressive graduate program to be successful, it must be developed within an appropriate administrative environment, and it must fit within general institutional objectives. If this is not true, the development itself will be an uphill task and it will not be possible to maintain advances which are gained, particularly in staff and student quality and quantity.

Basically, the objectives of a graduate program are two-fold:

1. The development of the science.

2. The development of manpower or human wealth (trained scientists and engineers).

Each of these is dependent on the other for its own existence. In other words, the science itself cannot be advanced without capable and well-trained human wealth and the proper training of the human wealth depends upon a program of advancement of the science.

Development of the Science

Developing the science involves a process of first understanding thoroughly established ideas and research so that a solid base of knowledge has been provided for discovering new information from research, and building the base more firmly for future generations. This part of the program should involve the development of new abstract theories and principles which are then studied through fundamental research to establish their validity. Once these fundamental principles have been established, they can then be applied to problems of design on a trial basis. Applied research can be used to test these designs in the form of models before they are actually built as prototypes in the field. Once a prototype has been

constructed, it is then ready for testing and evaluation--which means the construction of the prototype must have built-in the necessary instruments and equipment for carrying out the subsequent testing and evaluation. Finally, basic and applied scientific knowledge must be revised to conform with the results of prototype tests.

Typical examples of the frontiers of scientific knowledge which must be advanced in civil and sanitary engineering are:

1. The development of a better understanding and application of the diffusion processes so intimately involved in problems of air and water pollution. Especially lacking is a sound basis of the theory of turbulence which is so intimately involved in the diffusion process.

2. A much better understanding is necessary of such matters as basic meteorological phenomena, air mass analysis, and the interaction of air masses before it will be possible to predict atmospheric conditions and accomplish any significant degree of control over them for the benefit of man.

3. The development of scientifically sound basis for the design and interpretation of alluvial channel models.

Development of Human Wealth

The development of highly educated engineering and scientific human wealth involves the utilization of formal classroom programs, a seminar program, and a research program integrated together. Educating engineers in a graduate program for working in the last half of the 20th century requires that the well-educated man have a sound knowledge of not only the facts involved, but also the techniques of research and the way in which facts are discovered. Therefore, an extremely important part of the education of a graduate student is his participation in the various aspects of a research project which involves: clearly delineating a problem by applying known methods of analysis, developing a plan for obtaining data to help solve the problem, analyzing the data, drawing conclusions, and establishing new principles, as well as a solution to the problem. The same general process must be used in connection with design where fundamental principles are applied to a practical problem. While in graduate school the student should have the opportunity of going through this process, both in the laboratory and in the classroom on numerous occasions. In order for this process to be most successful, it is important that a considerable program of research be a part of the environment surrounding the student. Futhermore, his professors should be involved in this research and should be leaders in the profession by helping to advance the frontiers of knowledge through research.

In addition, the student should have the opportunity to present his findings (from either the laboratory or the library) before a group of his peers and be required to defend and explain what he has found or concluded.

Fluid Mechanics in Other Fields

There is a considerable need for the more broadly educated individual in a given subject--such as biology--who has an understanding of fluid mechanics to the extent that he can apply these principles wherever fluids are involved in connection with biological organisms. For example, in the physiology of plants and animals, there is much concerning the movement of fluids which is of great importance. However, the authors are not aware of any programs existing where biologists take any signigicant program in fluid mechanics in order to apply it to physiological processes. The physical sciences utilize fluid mechanics much more extensively as illustrated by developments in magneto-hydrodynamics, plasma-dynamics, and meteorology.

Instruction and Research

Another objective of a graduate program in fluid mechanics is to develop and maintain a very close relationship between graduate instruction and research. In actuality, graduate education and research are inseparable. It was of interest to the authors to note that President Eisenhower's Science Advisory Committee also took this position in its 15 November 1960 statement entitled "Scientific Progress, the Universities, and the Federal Government" (3). To quote: "It is a fundamental contention of this report that the process of graduate education and the process of basic research belong together at every possible level. We believe that the two kinds of activity reinforce each other in a variety of ways, and that each is weakened when carried on without the other".

It is the opinion of the writers that high caliber instruction at all levels (both undergraduate and graduate) depends upon research. A much more dynamic program of instruction can be carried out if the faculty and the graduate students are continually involved in creative pioneering in research which is ever expanding the frontiers of knowledge. Such an atmosphere can also permeate the undergraduate instruction program and thereby make it much more dynamic.

The manner in which this atmosphere permeates the graduate and undergraduate program seems, however, to differ somewhat in practice from what is usually stated as an operating procedure. It is frequently stated that as an operating procedure all faculty should conduct research, even if they are teaching only undergraduate courses and that all graduate faculty should also teach undergraduate courses. Further, it is frequently argued that the administration of research programs can be separated from the administration of graduate and undergraduate institutional programs. It is found that frequently actual practice differs from the above.

It is usual to find that graduate faculty perform graduate level instruction and research but little or no undergraduate teaching; and to find that those who teach primarily at the undergraduate level do very little research or graduate instruction. That this is what is actually taking place is supported by Woodburne (4). Nevertheless, the presence of a research program does provide a stimulation at all staff and student levels.

Basic and Applied Research

Another objective should be to provide a close relationship between basic and applied research. The complete and well-rounded engineer is one who has been involved in both the basic research which establishes fundamental principles of very broad application and also the applied research which is aimed at discovering and developing a solution for a specific problem. There should not be a disproportionare amount of either of these types of research in the responsibility of an engineer. Each is very important in helping and stimulating the other. This does not preclude, however, the desirability of having scientists who devote full time to basic research. Applied problems, on the one hand, disclose areas of limited knowledge which should be studied as fundamental research in order to establish broad general principles. On the other hand, as these broad general principles are established, they in turn should suggest, to those working on them, various applications of these principles which will be useful to mankind.

Program of Instruction

Another important objective of a graduate program is to provide a broad selection of courses of instruction and programs for the student. These offerings should be provided to meet the needs of the student who is oriented in a highly theoretical direction, on the one hand, and the students who have a much broader and applied orientation, on the other hand. In other words, courses on water conservation and utilization are as important to the total program as are courses on non-linear mechanics and magneto-hydrodynamics.

Consulting

Another objective of a complete program should be to provide the staff an opportunity for consulting. Consulting on the part of engineering staff has a number of advantages, as follows:

1. It should lead to better teaching and research. I t should add a freshness and dynamic dimension to the teaching so that students really feel they are a part of applied problems in the process of being solved, and learning information which has immediate usefulness. Furthermore, consulting should stimulate a staff member in the direction of new basic research and applied research ideas. If the staff member is a really creative individual, consulting will certainly stimulate him in this way.

2. The staff member of a program of research and education such as that described herein should be much more desirable as a consultant because he is familiar with the frontiers of knowledge. He should be better acquainted with all of the various theories and information necessary to do the most creative consulting and concepted design work.

3. Consulting helps to attract the professor both because of the diversity of his program of work and because of the additional income.

Split Appointments

A total program should also provide the opportunity, at the institutional level, for split appointments -- i. e., having several sources of income such as sponsored research, special programs, and regular instructional funds. The alternatives involved in methods of financial support are all funds coming from a single regular institutional source such as instructional funds, institutional funds for an Engineering Experiment Station (usually state supported), research projects which are sponsored from outside funds, and special programs of an educational or semi-research nature. The split appointment involves a combination of any two or more of these various sources of funds. Although it has been argued in many cases that split appointments neither are workable or desirable, Colorado State University has proven to the contrary. To be sure, split appointments are more difficult to administer because of all of the details that are necessary to keep track of various changing sources of income. However, it has distinct advantages because it permits a much more varied program for a faculty member, and gives a diversity and latitude of operation for the director of the total program which is highly desirable for meeting new situations and modifying old ones. An additional difficulty is making arrangements for and being sure that the necessary funds are available for sabbatical leave and the granting of tenure. Again, however, this has worked no hardship at Colorado State University.

Institutional Support

Despite all its many advantages, the split appointment system cannot be successful without having the institution strongly behind the total program. In other words, the approach to personnel management and the general environment created by the University for the entire program must be highly conducive to the welfare and development of the program. The most critical point is that the administration must assume responsibility for fiscal support of a program if any particular source of funding should fail--the faculty member must never feel that his position at the institution will be in jeopardy if a particular contract or grant fails to materialize. Further, irrespective of the nature of the fiscal support, the University must support the faculty by providing the same status to all faculty on such items as tenure, rank, and fringe benefits.

When an organization, such as a department or college has developed a capability, as described in the foregoing parts of this paper, it has unusual capability also for being of service--locally, nationally and internationally--to business and industry, to state and federal governments, and to private citizens and organizations. In other words, such a department or college has a standby service capability which frequently is not and cannot be available any other way.

In the field of fluid mechanics, service can frequently be provided by helping in the calibration of meters, by working closely with designers through constructing and testing models of a given design, by establishing short courses and training service programs for practicing engineers and other personnel associated with engineering activities.

Unfortunately, some departments and colleges take the viewpoint that performing such service is beneath the dignity of an institution for development of professional engineers. To be sure it would be most unfortunate to have a department or college go to the extreme in providing service activities--especially if the department or college is then running competition with private organizations who are capable of providing such service and desire to do so. Another undesirable aspect of such activities develops when there is such a large program that it tends to dominate the atmosphere and activities of the department or college. In other words, such service activities should be provided in accordance with criteria based on the idea that the service will be provided only as long as it is not conveniently available elsewhere and it is not economically feasible for such service to be provided by existing or potential private organizations.

Service activities conducted with a proper balance can do much to provide employment for graduate and undergraduate students, to provide equipment which can also be used for research, to provide summer employment for some staff members, and to provide overhead funds which can be used to develop the department's program.

Graduate Instruction

The academic program of graduate instruction in water resources and hydraulic engineering aspects of fluid mechanics can be considered from the viewpoint of the curriculum, the research program, the faculty, and the students.

Curriculum

The principal basis of an academic curriculum in hydraulic engineering is fluid mechanics. This subject should form the fundamental broad basis on which a curriculum can be built in any direction desired. For the field of water resources or hydraulic engineering, the curriculum can be considered from the viewpoint of the hydrologic cycle. The specific courses which make up the curriculum should be built around the basic objectives of the program--which have been discussed in the early part of this paper.

Experience has demonstrated that, although a Master's degree can be obtained by an outstanding full-time student in one year, and the Ph. D. can be obtained in an additional two years, we do not feel it is in the best interests of the student to move so rapidly--except in very special cases. Therefore, we recommend that a program be built around the basic idea that most students will spend two years to obtain a Master's degree and at least an additional three years to obtain a Ph. D. In this way, the student can be involved in research and special programs which will help him immensely to broaden his basic understanding of his subject and its application to engineering problems. Furthermore, a program should be built around different needs and objectives of students concerned with fluid mechanics and water resources. Some students prefer a highly theoretical approach to the problem which indicates that, in the future, they will be involved primarily in research, academic instruction, or theoretical considerations. Other students are more interested in the applied aspects of water resources, and consequently they need to become acquainted, not only with the basic fundamentals, but with their practical application to specific problems of the conservation, development, and utilization of water resources. In addition to providing programs which meet the needs of American students, the U. S. and its universities are obligated to provide programs for the education of students from other countries of the world.

To meet the requirements of the foregoing types of students, it is necessary to have a broad base of course offerings which give a wide variety of selection, so that the academic program for a specific student can be tailor-made to his own interests and needs. Furthermore, in some cases, there might be available not only a Master of Science degree, but also a Master of Engineering degree for those students who have a narrow objective because of the work in which they will probably be involved. This Engineering degree is well-suited to foreign students. The Master of Engineering degree, as we conceive it, involves only the writing of a special report beyond an academic curriculum of course work which is more inclusive than the academic program for the Master of Science degree because of the substantial thesis requirement in the latter case.

In order to have a wide selection of courses for graduate students, it is frequently necessary to offer some courses on alternate years or perhaps only during every third year. In this way, the number in the class can be kept at a more efficient level, which is more effective, and it is not necessary to have such a large teaching faculty.

As mentioned in the first paragraph of this section, specific courses can be built around the basic concept of the hydrologic cycle. This is the concept used in the development of the Colorado State University program. It may be described as follows:

1. Atmospheric sciences, including the lower atmosphere below the tropopause and excluding the upper atmosphere and solar physics. Courses in this subject area should involve the interrelation of air masses and the relationship between air masses and geological formations. It should also include the dynamic processes which make up weather, and combinations of weather which make up climate. In the Rocky Mountain region, there is special concern with respect to the genesis and development of the various types of storms, such as hailstorms, thunderstorms and tornadoes. Courses should go from the basic principles which have a very general application to the more specific problems involving those aspects of atmospheric sciences which create the greatest problems to mankind.

2. Micrometeorology should include that part of weather and climate which has a direct interrelationship to man, plants, and animals at the earth's surface. It should include courses of study related to air-soil interface phenomena, such as evaporation, transpiration, boundary layer theory, diffusion and heat transfer.

3. Surface waters should include courses of study on the storage, conveyance, distribution, and utilization of water--together with the types of associated structures necessary to control and use surface waters. It should include surface and sub-surface application of irrigation water, open and closed conduit flow, analysis and design of concrete, earth and rock structures, and flood routing.

4. Ground water should include studies of both saturated and unsaturated media (i.e., multiphase flow), drainage, salinity, contamination and pollution, underground storage, artificial recharge, soil mechanics, soil chemistry and soil physics.

5. Bio-engineering should include a study of the relation of water to biological organisms and populations of biological organisms. It should be an interdisciplinary program, involving botanists, zoologists, foresters, veterinarians, as well as human medicine. Such a program should include an approach to the subject of water quality from the biological viewpoint--including the influence of biological environment upon water quality. The basic objective is associated with a study of the inter-relationship of the biological and physical aspects of the hydrologic cycle.

6. Supporting and service programs and courses should be offered by departments offering programs complementary to fluid mechanics and water resources. Such courses should include instrumentation, mathematics, physics, chemistry, statistical and computing methods, geology, project planning, public administration, range and forest management and demography. Of course, all students for the Ph. D. should be required to take a number of non-technical courses such as philosophy, language and world government.

Research

The importance of research as a part of a program of graduate instruction has been discussed in considerable detail in the forepart of this paper. It is important to emphasize again, however, that the optimum education for graduate students is to become immersed in an atmosphere of research and application of basic principles to specific and general problems. Therefore, it is extremely important to have heavy emphasis on research as a part of the total program of graduate instruction. This permits the graduate student to become involved in research designed to discover fundamental principles, as well as applied research intended to apply the fundamental principles to a specific problem. Even though the student may not be involved in the actual conduct of research in the future, he will constantly be concerned with the utilization of research data by analysing research information and drawing conclusions. Furthermore, the development in the individual of the logical system of analysis is excellent background for all fields of endeavor in which the student may later engage.

Faculty

It is well recognized that the quality of the university and any portion of the university is directly related to the kind, quality, and quantity of its faculty. When one considers an individual program of a university, such as hydraulic engineering, it is possible to have a strong program only if there is a substantial number of men on the faculty who are working in complementary fields. Furthermore, it is essential that there exist a number of "name" men who have key responsibilities for each of the major program's sub-divisions and who also assume major responsibility for the acquisition and leadership of junior faculty, working with the administration to provide adequate financing and to attract and guide graduate students.

All of the faculty members, but particularly the name men, need an administrative and academic environment in which it is possible for them to have substantial latitude to develop a program as they see fit. Probably one of the key needs in order that such an environment exists is an obvious knowledge on the part of all faculty members that the administration of the institution is very interested in and willing to support research and graduate instruction in every way possible. This appears to be largely an intangible in many respects since the attitude on the part of the administration is as much or more important than the particular level of institutional fiscal support which is made available to the research and graduate education faculty.

Adequate salaries play a key role in the development of a strong faculty. It seems feasible that while the administration should provide an adequate salary level, the name men on the faculty should assume substantial responsibility for assisting in making available adequate fiscal resources in order to meet the salary schedule. An adequate salary schedule on the part of the administration usually dictates that the graduate faculty will be paid at a higher salary level than many of the other teachers on the faculty. This appears to be entirely reasonable when one considers that a faculty member who teaches high school receives a higher salary on the average than one who teaches grade school. Further, an instructor of freshmen and sophomores at the university level receives a higher salary than does a high school teacher. If this pattern is followed, it is obvious that the faculty member who is working at the forefront of knowledge and is teaching primarily Ph. D. students should be the highest salaried teacher.

The administration of an institution must be sympathetic to providing faculty an opportunity to work either on nine or twelve-month appointments as the particular faculty member desires. Many faculty members prefer to be on a nine-month appointment in order that they can use their summers for industrial employment, the writing of textbooks or working on some research project with a government agency physically separated from the university campus, all done as a part of their professional development. Other faculty members develop such substantial on-campus research and graduate instruction programs that a twelve-month appointment is the most obvious thing for them to accept. In addition to allowing the faculty member an opportunity to select a nine or twelve-month appointment, the administration of a graduate instruction and research program at the departmental level should administer the department under a philosophy of permitting each faculty member to develop his program with such a balance between research, graduate teaching, and undergraduate teaching as that particular faculty member may desire. For example, some faculty members will prefer six months per year on research and six months on graduate instruction. Another faculty member might well prefer two months per year on research, three months per year on undergraduate instruction and four months per year on graduate instruction. Of course, in terms of man-months, there is always a substantial question in regard to the significance of the individual numbers. The numbers are most useful as a budgetary device.

Another very important item both in administering a graduate instruction research faculty and in providing the appropriate administrative environment for the development of a top program, is a well-defined, clear-cut policy on consulting. It is the opinion of the authors that the best policy in regard to consulting is that any professional faculty member is encouraged to accept consulting engagements for such time as he may feel able to devote to consulting, above and beyond his responsibilities to the institution. Furthermore, the faculty member should personally retain the consulting fee. It should be made very clear that the faculty member is to accept only consulting engagements

and not just additional work assignments during the period of his academic appointment at some salary such as $4.00 per hour. If the remuneration is not in excess of $75 to $100 per day at current price levels, we are inclined not to call the work consulting. As a practical matter a twelve-month employee frequently uses a part of his annual leave for consulting engagements. It is our opinion that a consulting policy which provides one day per week for consulting is not good. Furthermore, it is not philosophically sound to permit a faculty member to so-called work overtime for the institution on sponsored research and receive supplemental salary at what would amount to consulting rates.

Students

In order to have a broad graduate instruction and research program, it is essential that the program include both domestic and foreign students. With the background of professional experiences which each student has, both faculty and students gain if the program includes a substantial number of foreign students from various parts of the world in addition to the domestic students. It is our feeling that the appropriate balance should be approximately fifty per cent domestic students and the remaining fifty per cent distributed among students from several countries, and, if possible, countries with substantially different types of engineering problems, such as students in water resources from both humid and arid regions. There appears to be no particular magic to a fifty-fifty ratio; however, if the balance shifts to as much as seventy to eighty per cent foreign students, it appears to us that a separate program should be developed for a large segment of the foreign students. With such a separated program, it is possible to develop special courses designed specifically to meet the needs of these students in situations associated with their own countries. At this point, of course, it becomes a question as to whether this type of education can best be provided in the U. S. or whether institutions should be set up in the foreign countries staffed by faculty from the United States and other countries. An example of this is the Seato Graduate School of Engineering in Bangkok, Thailand (5) administered by Colorado State University.

One of the most difficult things to achieve in a graduate program is a selection process which brings together a group of students of relatively comparable ability. This is essential in order that there not exist in the classes students who are absolutely unable to compete or who, on the other hand, are wasting their time by devoting a substantial period of their lives in pursuing a graduate program for which they are not qualified.

It is becoming more and more a recognized pattern that in one way or another nearly every graduate student is supported financially and will have to be supported in the future at a financial level adequate not only for himself but also for the support of a wife and small family. It is the belief of the authors that whatever the price may be, both the universities and the nation should assume the responsibility for providing the fiscal resources necessary to attract graduate students in order that they complete their program. This fact is as much as anything a matter of survival of a free society as it is a practical matter of each institution being able to compete with other institutions for top graduate students.

Summary

The development and continuance of a strong and broadly-based graduate instruction and research program in hydraulic engineering is based upon institutional objectives and an institutional administrative philosophy which provides the type of environment that draws top-quality faculty and students. Top-quality faculty will be attracted if this appropriate administrative environment exists for research and graduate instruction and if adequate salaries are available. The faculty must then have substantial freedom to develop a broad instructional and research program based upon an organizational structure which permits each of several "name" men who are the key personnel in the faculty to draw junior faculty and graduate students, and as a part of their further responsibility to assist in providing the fiscal resources necessary to pay salaries, buy equipment, and construct facilities. The program should include both domestic and foreign graduate students who have available to them an academic curriculum consisting of courses of both a practical and theoretical nature in such numbers that a program can be developed to suit the objectives of each individual student.

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