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Part I

THE FUTURE OUTLOOK FOR NEW AND IMPROVED MATERIALS AND METHODS FOR MOSQUITO CONTROL

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In recent years we have made excellent progress in developing and utilizing new methods and materials for mosquito control. Two groups of workers—those primarily engaged in research and those primarily engaged in control operations—have been responsible for this progress. We all have seen increases in research effort as well as in the number and efforts of organized mosquito control organizations. We have also seen excellent cooperation between these two groups.

At present, satisfactory mosquito control depends upon methods of source reduction, including water and land management practices and the use of insecticides as larvicides and adulticides. For the future, research is exploring other methods or approaches to mosquito control. These other approaches include biological control, genetic manipulation, attractants, baits and lures, the sterility principle, and integrated control. In presenting this paper we recognize and emphasize that researchers and mosquito control specialists will continue to find and develop new, more effective, and safer insecticides and more efficient methods of applying them as well as better, more effective methods of source reduction. At the same time we also recognize that research now underway may well develop other approaches and the means of integrating different types of control measures to allow more effective, economical mosquito control. Therefore, it is our intention in this paper to summarize current mosquito control research activities and to give some indication of the direction that future research will take in utilizing both conventional as well as new approaches.

SOURCE REDUCTION AND WATER MANAGEMENT.—The first principle of mosquito abatement is control of surface water. The degree to which surface water can be drained from salt marshes depends upon a number of factors, including topography, location, size, type of vegetation, type of soil, rainfall, and height of tides and their altitude above main tide levels. The possibilities of impounding or otherwise managing surface water in any area depend on these same factors. It is therefore evident that proper water management is a technical operation which requires skilled people and careful planning. Different procedures may be required for individual marshes. Obviously, therefore, team research is needed. Entomologists and engineers, working together, can develop the proper systems for surface water control. Fish and wildlife workers should also be included on the team to develop an integrated approach that will prevent detriment to fish and wildlife. This team approach has been neglected. However, it is heartening to see how well the integrated approach has worked in Florida.

We have begun research on the salt marsh mosquito problem in Louisiana in cooperation with the University of Southwestern Louisiana, McNeese State College, and the Louisiana Mosquito Control Association. At present we are primarily concerned with studying the ecology of salt marsh mosquitoes and pinpointing problem areas. This kind of background information is essential to the development of proper water control procedures. However, we hope and expect that Federal and State Fish and Wildlife groups and engineers will actively work with us in devising and implementing such procedures. The main objective of the recent First Gulf Conference on mosquito suppression and wildlife management, which some of you attended, was to promote the formation of a unified organization to enlarge and sponsor cooperative research in developing surface water procedures that will be mutually satisfactory to all interests. We feel that the National Mosquito Control Fish and Wildlife Management Coordination Committee, which was instrumental in organizing this conference, is rendering a valuable service that will pay off in years to come.

Conservation of water for irrigation and actual irrigation has created serious mosquito problems in many arid areas of the West. Irrigation acreage is becoming larger every year and will continue to enlarge in proportion to the supply of water that will be made available through new Federal and State water conservation projects and wells. We know now that mosquito problems in reservoirs can be minimized by research, careful planning, certain water management practices, and the judicious use of insecticides. The Tennessee Valley Authority is an outstanding example of what can be accomplished. Unfortunately, many reservoirs have been constructed without considering prevention of mosquito problems. Others will doubtless be erected without proper research and joint planning. However, in order to develop the most effective water manipulation procedures, a subcommittee on Vector Control of the Interagency Committee on water resources was organized in 1961 specifically to guard against lack of planning by promoting and sponsoring cooperative research not only prior to construction of water conservation projects but also after their completion. The subcommittee is composed of at least 2 representatives from the U.S. Departments of Agriculture, Health, Education and Welfare, Interior; Corps of Engineers; U.S. Army; and the Tennessee Valley Authority.

Since its formation, the subcommittee on Vector Control has organized and sponsored 11 cooperative projects. It has been instrumental in obtaining funds to support several of these projects. The subcommittee is constantly looking for new projects to sponsor. Continued activity of this group in organizing research should improve the outlook for development of improved methods of water control, thus producing benefits in terms of more effective mosquito control and favorable environments for fish and wildlife.

CONVENTIONAL INSECTICIDES.—Less than 25 years ago we lacked the materials necessary for highly effective mosquito control. Consequently, there were relatively few organized mosquito control districts in Florida or in other States. These districts relied upon source elimination and water management procedures and upon fuel oil and paris green in larviciding. There were no effective adulticides. Then came DDT. Its magic ushered in a whole new era. New control districts were rapidly organized and budgets increased markedly. We believe it is true, therefore, that much of the success of mosquito control today can be credited to DDT and successor insecticides.

Insecticides are essential in mosquito control. In many situations, they are the single means of abating the mosquito problem. But, in general, insecticides should be used only as adjuncts to eliminative control measures. For several years after the advent of DDT, many mosquito control organizations relied largely on this material and neglected the basic principles of source elimination—draining, filling, and proper water management. Fortunately, about 15 years ago this trend began reversing itself because of the development of resistance to insecticides in many areas. Now, most of the mosquito control districts make proper use of all their tools and this attention makes for increasingly effective control programs. Continuation of this balanced approach brightens the future for effective control.

Today many types of insecticides are registered for mosquito control. DDT and several other chlorinated hydrocarbons are still used where resistance is not a factor. However, in general, the trend has been to drop these persistent materials in favor of the more toxic, less persistent organophosphates such as malathion, parathion, fenthion, and naled. These materials, effective at very low dosages, do not constitute any hazard to humans or domestic animals when properly applied. However, in some environments they may have deleterious effects on fish, wildlife, and beneficial insects. Research is therefore being pointed towards the development of new insecticides that are toxic specifically to mosquitoes and thus are relatively nontoxic to other insects, fish, wildlife, and humans. Excellent progress has already been made with such specific materials and the outlook for their further development is promising indeed.

During the past 2 years our Gainesville laboratory has found several new compounds to be highly effective against mosquito larvae at concentrations of 0.01 to 0.025 ppm. One of these compounds, American Cyanamid E. I. 52160, (*O,O*-dimethyl phosphorothioate *O,O*-diester with 4,4′-thiodiphenol), should be of special interest to mosquito control workers for larviciding because of its very low mammalian toxicity of about 3,000 mg/kg and the low dosage (0.016–0.048 lb/acre) required for control. This material has been given the trade name of Abate and should be registered in the near future. It is not promising as a mosquito adulticide and is relatively ineffective against house flies.

We have also made excellent progress in our search for more effective adulticides. Several compounds have been found to be 2 or 3 times as effective as malathion (standard) with a relatively favorable mammalian toxicity picture.

Our personnel in Florida are also making progress in their search for residual substitutes for DDT and other insecticides to use in the worldwide campaign to eradicate malaria and other mosquito-borne diseases. They have found several materials that are superior to DDT and that remain completely effective throughout the season. The outstanding material, Bayer 39007 (*o*-isopropoxyphenyl methylcarbamate), was still almost completely effective 63 weeks after it was applied in farm buildings. This new material appears to be specific against adult mosquitoes and its safety from the standpoint of mammalian toxicity compares favorably with that of malathion. Like American Cyanamid E. I. 52160, this material is relatively ineffective against house flies.

Our mosquito control research so far has demonstrated the feasibility of finding specific insecticides that will largely eliminate the hazards to fish, wildlife, and beneficial insects caused by currently used insecticides. New materials, including several now under investigation, should also solve environmental residue problems which result from the application of persistent insecticides. We are convinced that continued research will produce the conventional materials that mosquito control workers will need in future years to maintain and even increase the effectiveness of their control efforts.

New methods of applying insecticides for mosquito control also hold promise for the future. We have all followed the developments in ground and aerial fogging techniques. Within the past year we have heard a great deal about applications of low volumes of concentrated or undiluted insecticides. Enthusiasm for the principle has been stimulated by the successful application of technical malathion for the control of certain crop pests. The idea is not new to mosquito control. In 1949 studies in Alaska showed that applications of 0.25 and 0.5 pint of 20 percent DDT-oil solutions were fully as effective as 1.0 and 2.0 pints of 5 percent DDT-oil solutions against mosquito larvae and adults (F. S. Blanton *et al.* 1949; B. V. Travis *et al.* 1949). However, the current concern over residues and harmful effects on beneficial insects, fish, and wildlife dictated that mosquito control workers take another look at the merits of applying concentrated or undiluted insecticides. Results of work along this line in 1964 have not been published. However, we can report that studies in 1964 by T. D. Mulhern and C. M. Gjullin in cooperation with a number of California mosquito abatement districts showed that low volumes of parathion, malathion, and fenthion gave about as good control of mosquito larvae in irrigated pastures and croplands as the usual volumes of ½ to 1 gal/acre. Many additional tests will doubtless be conducted in 1965. Similar studies on low volume aerial spraying of malathion were conducted in Florida and Kentucky against adult salt-marsh mosquitoes. Reports of this work will be presented at this meeting.

Another interesting research project holding promise for the future is being conducted at our Corvallis, Oregon laboratory by Eddy, Plapp, Bigley and their associates. They are concentrating on the nature and mechanisms of insecticide resistance in mosquitoes and other insects. An example of the excellent progress they have made is their discovery of materials that are capable of overcoming resistance in malathion-resistant laboratory colonies of mosquitoes. Hopefully, further research will lead to materials that can be used against resistant insects in practical control programs.

OTHER METHODS OF CONTROL.—Biological control has traditionally meant the action of parasites and predators on an insect population. Today it may also include the sterility principle, genetic manipulation, and other approaches to control.

All stages of mosquitoes may be attacked by many natural parasitic and predatory enemies. According to Jenkins (1960) over 20 species of bacteria in 15 genera have been detected in mosquitoes. At least 16 genera of fungi have been shown to infect mosquitoes. Numerous protozoan parasites are quite common. Nearly 400 predators have been recorded as attacking mosquito larvae and 90 as attacking adults. Yet, in spite of all these biological agents, mosquitoes continue to thrive. We must employ an integrated approach to control them; that is, biological, chemical, and source reduction procedures.

Bacteria kill large numbers of mosquitoes. *Leptothrix buccalis* is highly effective in some situations. Other species frequently infest the breeding medium and destroy larvae. We know very little about the environmental requirements of these organisms. Research along this line would provide us with an understanding of how and when they survive in nature. Methods of propagation and dissemination need to be developed to explore their effectiveness against natural populations. Such methods would be especially desirable for rearing those species that infect mosquito eggs and either stimulate hatching or kill the embryo.

Fungi appear to have good possibilities for control of mosquitoes. Certain species of *Coelomomyces* are exceptionally promising. In some areas very high incidence of infection has been observed. However, in general, infection rates are low and produce no significant control effect. Here again, we need to know the biology of these organisms to utilize them to advantage in mosquito control.

Numerous species of protozoa attack all stages of mosquitoes. Perhaps the most promising are microsporidia of the genera *Nosema* and *Thelohania.* Several workers have investigated the microsporidia, but the most thorough studies were recently made by Kellen and coworkers in California. These workers found *Thelohania* in 16 species of mosquito larvae in nature and learned a great deal about the host-parasite relationships. Their findings encourage us to believe that these organisms can some day play an important role in the control of certain species of mosquitoes in specific types of environment. Further research may provide the knowledge needed to utilize these organisms.

Mosquito predators may be effective in controlling or minimizing populations. Fish, especially *Gambusia* minnows, are a good example. Nematodes, mites, and certain aquatic insects can cause heavy mortality of adults and larvae under certain conditions. However, research is needed to understand and thus eliminate the factors limiting their effectiveness.

To sum up, parasites, predators, and pathogens would appear to have great possibilities in mosquito control. However, expanded research is needed to find ways of establishing them in mosquito breeding environments so they will survive and prevent mosquito production. This is a difficult and complex biological problem, but we believe research can provide the solution.

Attractants, lures, and baits must also be considered as possible weapons. Although at present we do not have effective mosquito attractants, it is possible that research will develop chemicals, or radiation, or ways of utilizing these as attractants for practical use in mosquito control. The attractants could lure mosquitoes to traps, insecticides, cultures of mosquito diseases, or chemosterilants. We are aware that chemical factors—carbon dioxide, water, and components of blood and sweat—and physical factors—heat, movement, color, and sound—all can influence mosquito behavior. We may find that other stimuli, such as infrared radiation, will attract mosquitoes or definitely influence their behavior. In some species sound attracts males to the females. Recent preliminary research has not demonstrated that chemical sex attractants are present in mosquitoes, but such research is not yet completed. Increased research is needed to elucidate the nature of attractants, arrestants and other stimuli involved in the feeding of male and female mosquitoes on plant juices and sugar solutions, as well as the stimuli involved in the selection of oviposition sites. Studies of behavior along with studies of attractants are underway and being increased throughout the world. Hopefully, a highly effective, useful means of employing attractants in mosquito control will be developed.

Some recent excellent research on the genetics of mosquitoes has been conducted. Our knowledge in this area, increasing rapidly, could lead to the development of highly specific control measures. For example, strains developed to possess unfavorable genetic characteristics could possibly be reared in large numbers and released among natural populations to weaken or eliminate them. Genetecists speak of "meiotic drive," a term used to indicate the passage of genetic characters from one generation to the next. This meiotic drive could be a factor in devising means of transmitting unfavorable genetic characteristics to natural populations. Strains of mosquitoes that are autogenous or zoophilic or that produce only, or predominantly, males may be developed and used to replace vector or pestiferous species. You have heard in these national meetings research related to these genetic considerations. Hopefully, a practical method of mosquito control will emerge from this type of research.

Sterility, another new approach to mosquito control, is receiving research attention at the present time. We know of methods that cause sterility in different species of mosquitoes through the use of radiation, chemosterilants, and cytoplasmically incompatible strains. Research in the laboratory has demonstrated that males and females of different species can be rendered sterile by exposure to gamma rays or to chemosterilants administered to adults, pupae, or larvae. Furthermore, sterile males are capable of competing effectively with untreated males in mating with females of the species. However, research has not demonstrated means of translating successful laboratory research into effective practical mosquito control measures. Under consideration as possible means of utilizing the sterility principle are the sterile male release, the treatment of natural populations including the use of attractants, and integrated control methods.

Some field experiments on the sterility principle have been undertaken. Weidhaas *et al.* (1962) released sterilized males of *Anopheles quadrimaculatus* Say into the natural populations in central Florida. Morlan *et al.* (1962) released males of *Aedes aegypti* Linnaeus in Escambia County, Florida. Neither experiment demonstrated that control by this method was practical. Furthermore, additional studies with *A. quadrimaculatus* showed that the colonized strain, presumably through the colonization process itself, did not effectively compete with wild males in mating with wild females under natural field conditions. An experiment by Krishnamurthy (1963) demonstrated that the release of irradiated males of *Culex fatigans* Wiedemann resulted in the appearance of considerable numbers of egg rafts in which the eggs were embryonated but did not hatch. There was no reduction in mosquito abundance, possibly because the numbers released were inadequate; but the results were sufficiently promising to justify further studies.

Except for the possible use of the release of sterile males, it is not clear how the sterility principle might be applied to sterilize natural populations of mosquitoes without undue hazard to man, other animals, or plants. Chemosterilants are highly effective when introduced in the food of adults or when adults are exposed to residual deposits. However, at present, we do not have attractants or baits to formulate with chemosterilants so that sufficiently high proportion of the total population will be sterilized. Mosquitoes can be sterilized by administering chemosterilants in the larval breeding water, but mortality is often high when young larvae are exposed and relatively high concentrations of chemosterilants are needed. Additional investigations may develop more effective means of using chemosterilants to treat breeding waters. However, the principle difficulty in this method will be in hazards to man, other animals, and plants. Furthermore, resistance to the chemosterilant, apholate, was developed by larval selection in a laboratory colony of *Aedes aegypti.* (E. I. Hazard, *et al.* 1964.)

In all probability the sterility principle will be integrated with other methods of control. Insecticides or source reduction might be used to decrease the size of natural populations so that the release of sterile males would actually be more effective and economical than the continued use of insecticidal or source reduction methods.

Most discussions of insect sterilants are largely concerned with basic or applied research related to the development of control techniques. We would like to emphasize that the ability to sterilize insects also offers to entomologists an effective tool for biological research. Already studies have been undertaken to utilize sterilants in this way. These studies have been largely of the multiple-mating habits of females and of behavioral differences between strains of the same species of insect. Extremely interesting results have been obtained.

SUMMARY. To summarize briefly the outlook for the future, we can expect to see advances in both conventional and new approaches for mosquito control. We can also expect to see different methods of control integrated into future programs to take the greatest possible advantage of biological agents, insecticides, methods of source reduction, unfavorable genetic factors, and attractants. Even insecticide resistance itself may be turned to our advantage. For in the release of sterilized, diseased, or genetically inferior strains we may wish to reduce natural populations with insecticidal treatments without influencing the strains we release. To say the least, researchers and mosquito control specialists are confronted with interesting and challenging problems which will tax their ingenuity. Hopefully, their efforts will lead to new and even better tools for mosquito control programs.

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COOPERATIVE RESEARCH ON WATER MANAGEMENT FOR WILDLIFE, MOSQUITO ABATEMENT AND OTHER BENEFICIAL USE [1]

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Since the beginning of the century mosquito abatement programs have gradually developed in many parts of the country and have now become accepted as an essential part of modern living. When mosquito control programs are first introduced into an area they are definitely on trial. The methods used and sometimes the objectives of mosquito control organizations are viewed with suspicion by those whom they are designed to serve. Gradually these programs seem to earn the respect and confidence of the public they serve and acquire a position of responsibility and leadership in water management programs in areas where they operate.

In using a more positive approach to obtain greater support for mosquito control programs, it is essential to convince cooperators that mosquito abatement agencies are not in competition for ownership of water. It must also be established that mosquito control workers are interested in assisting in the development of multipurpose beneficial use of water and in so doing are seeking the support of water users to prevent the misuse of water that creates situations in which mosquitoes are produced. This type of an approach to water management and mosquito reduction is being attempted on the marshes bordering the Great Salt Lake in the vicinity of Salt Lake City, Utah. This program has gradually developed

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